RENIR

REsearch Network on Industrial Resilience

RENIR Working Papers

Mapping the Evolution of the Robotics Industry: A cross country comparison

Eric Estolatan
Department of Economics and Statistics *Cognetti De Martiis*, University of Turin

Aldo Geuna
Department of Economics and Statistics *Cognetti De Martiis*, University of Torino
BRICK, Collegio Carlo Alberto

Marco Guerzoni
Department of Economics and Statistics *Cognetti De Martiis*, University of Torino
BRICK, Collegio Carlo Alberto

Massimiliano Nuccio
RENIR - REsearch Network on Industrial Resilience, Collegio Carlo Alberto
Department of Economics and Statistics *Cognetti De Martiis*, University of Torino

April 2019, n. 01

https://renir.carloalberto.org/

Mapping the Evolution of the Robotics Industry: A cross country comparison

Eric Estolatan

Department of Economics and Statistics Cognetti De Martiis, University of Torino

Aldo Geuna

Department of Economics and Statistics Cognetti De Martiis, University of Torino
BRICK, Collegio Carlo Alberto

Marco Guerzoni

Department of Economics and Statistics Cognetti De Martiis, University of Torino
BRICK, Collegio Carlo Alberto

Massimiliano Nuccio

RENIR Research Network on Industrial Resilience, Collegio Carlo Alberto
Department of Economics and Statistics Cognetti De Martiis, University of Torino

Acknowledgements
Authors would like to thank ASPEN Institute Italia for the reference to some data from the report: *Digital disruption and the transformation of Italian manufacturing* by Geuna A., Guerzoni, M., Nuccio M., Pammolli F. and Rungi A. (2017) available at: https://www.aspeninstitute.it/aspenia-online/article/digital-disruption-and-manufacturing-transformation-italian-case-study

Abstract

Industry 4.0 may be regarded as an emerging approach to the adoption of next-generation robotics for industrial applications. Our study sheds light on the current state of robotics, with a particular focus on robots for industrial applications. The research combines publicly-available information from company press releases, news articles, peer-reviewed journals and trade and industry reports.

The paper is organized in four sections. Section 1 discusses some definitions of robotics and robotics sub-classes, and various robotics classifications. Sections 2 and 3 provide a snapshot of demand and supply of robotics, and offers some insights into select regional markets and global technological trends. Section 4 describes the challenges and opportunities surrounding robotics and Industry 4.0, and the future impact of these technologies.

JEL Codes:O33, L52, L63

Keywords: robotics, Industry 4.0, cyber-physical systems, industrial robots, co-bots

1. Introduction: the rise of cyber-physical systems

Digital technology has the potential to re-shape current industrial processes at a magnitude comparable to previous industrial revolutions. The first one which occurred the XIX century was characterized by steam and water; the second at the beginning of the XX century was related to electricity and moving assembly line, which steered mass production; with the third revolution of the 1980s we shift from the analog to the digital technologies. In his 2016 book, *The Fourth Industrial Revolution*, Klaus Schwab, Founder and Executive Chairman of the World Economic Forum, alludes to another phase of human production not only characterized by smarter and autonomous automation, but based on the complete integration of the cyber and physical dimensions. The so-called fourth revolution has the potential to transform not only the way things are produced and distributed but also the dynamics of customer engagement, value creation, management and regulation (Kagermann et al., 2013; Schwab, 2017).

Both industry analysts and observers associate the idea of the forthcoming industrial revolution to contemporary developments in German manufacturing (Kagermann et al., 2013). The huge interest in Industry 4.0 is influenced by the significant productivity gains expected from its full realization (see Table 1).

Table 1. Industry 4.0 productivity gains in Germany by 2025

Source	Year	Estimate (in billions EUR)		Productivity gains (%)	
		Lower-bound	Upper-bound	Lower-bound	Upper-bound
Deutsche Bank Research	2014	267	267	30.0	30.0
Bauer, et.al.	2015	78	78	NA	NA
Boston Consulting Group	2015	90	150	15.0	25.0

Source: Deutsche Bank Research (2014); Boston Consulting Group (2015); Bauer, et al. *in* Hermann, et al. (2015).

Since buzzwords emerge faster than the innovation waves they describe, conceptualization of Industry 4.0 remains vague although it can be considered the result of convergence among the advances made in several related information and communication technologies (ICTs) and in computer science (CS) (Monostori, 2014) such as artificial intelligence (AI), cloud computing, the Internet of things (IoT) and their accompanying robotics, sensor technologies, additive manufacturing and traditional manufacturing.

In an Industry 4.0 environment, manufacturing is envisaged to feature new machine systems called **cyber-physical systems** (or **CPS**) which emanate from the interaction of algorithms and AI enabled by physical machines. CPS have self-prediction capabilities and self-awareness which allow intelligent production capabilities on the shop floor ('smart factories'). Understanding of tasks by autonomous systems in

Industry 4.0 is based on explicitly represented knowledge about the machine, the task and the environment in the absence of detailed programming and human control, and enabling more flexible production processes (Rosen et al., 2015) and capabilities for customizable, small-lot production (Brettel et al., 2014).

In combining the abovementioned concepts Industry 4.0 can be regarded as a collective term for technologies and concepts in the organization of the value chain (Hermann et al., 2016). Within the modular structured Industry 4.0 smart factories, CPS monitor physical processes, create virtual copies of the physical world and make decentralized decisions. CPS communicate and cooperate with each other and with humans in real time, over the IoT, while the Internet of services (IoS) offers both internal and cross-organizational services that can be utilized by all members of the value chain.

Against this background, the increasing importance of robotics developments for realizing the Industry 4.0 future is quite clear.

2. Robotics: Definition and technologies

Robotics has advanced significantly since the first mechanical systems were conceived. Various technological breakthroughs in engineering, CS, information technology, and related sciences have pushed technical feasibility, and allowed various stakeholders to extend the potential of robots.

However, the concept of robots remains nebulous – as Joe Engelberger, regarded as the father of the industrial robot, once said: “I can’t define a robot, but I know one when I see one.” (reported in Carlisle, 2000). Finding an all-encompassing definition of a robot remains problematic since form-factors, intelligence and purpose vary significantly (Wilson, 2015). Depending on the informant, the definition changes: it might be the mechanical system placed behind a work fence in which case an autonomous vehicle is not a robot; it might be a contraption that displays autonomy and an ability to respond physically, or it might be an entire system of machines working together on the shop floor (Pearson, 2015).

The above developments increase the problem related to the definition of a robot: artificially-intelligent agents (AIAs) (e.g. software robots) are contentious for roboticists and industry stakeholders with some maintaining that a robot requires a **physical embodiment** (Wilson, 2015; Pearson, 2015; Perlongo, 2016). As a result, the term ‘robot’ can be overused with untrained industry observers quick to attach the label to any new technological development (Perlongo, 2016). Potential users are wary of the adoption of robots – their productivity gains are unproven, and older systems are more reliable (Leitão 2009; Brettel et al., 2014).

The International Organization for Standardization (ISO) and the United Nations Economic Commission for Europe (UNECE) through 2012 ISO-Standard 8373 define a robot loosely as a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions, for the performance of a variety of tasks which also acquire information from the environment and respond intelligently. The International Federation of Robotics (IFR), the sector's main special-interest organization, and other national industry associations, such as the US Robotics Industries Association (RIA) and the UK British Automation & Robot Association (BARA) espouse a similar definition (BARA, 2017b; IFR, 2017; RIA, 2017).

Various but related developments in hardware and software technologies, academic research and the industry itself have enabled a sustained expansion of nascent sub-sectors such as related to advanced industrial and practical applications. For instance, software systems refinements allow robots to not only interact physically with the environment but also modify it. In addition, installation of wide functional scope enables robots to become viable solutions in populated areas, and in almost any environment (air, land, sea space) and for any purpose (e.g. surgery, laboratory research, defense, and mass production of consumer and industrial goods) (Boston Consulting Group, 2015; Deloitte Consulting UK, 2015).

The continued advancements in robotics can be regarded as positive for the future workplace: as better robots are developed, they are able to perform tasks that are highly dangerous (i.e. nuclear power plant decontamination), repetitive, stressful, labor-intensive (i.e. welding) or menial for human agents. Furthermore, robots promise cost-efficiencies and greater accuracy and reliability relative to human agents (ABB Group, 2016; PwC, 2017).

2.1 Classifications by mechanical structures: Technological perspective

Robots vary widely in their users and suppliers and in their technologies and mechanisms. However, it is generally agreed that a robot must have the following capabilities: sensing, intelligence and motion. The interaction of these capabilities, the so-called **"sense-think-act" formula**, allows robots to perform tasks without external stimuli, thereby giving them autonomy – the technology's distinguishing feature.

Table 2. Robotics capabilities and definitions

Ability	Definition
Sensing	Robots employ sensing technology to acquire information about their environment.
Intelligence	Robots process information captured through sensor technology, and produce outputs for decision making, coordination and control.
Motion	Robots follow instructions automatically that are pre-programmed or generated in real-time based on sensor input to perform a deliberate, controlled and repetitive mechatronic action including point-to-point mobility.

Source: ABI Research, 2016.

While there are innumerable possible combinations of hardware and software that can be regarded robots, the construction of all machine systems shares a number of core components including sensors, end effectors and control systems (Consortium on Cognitive Science Instruction, 2017).

Robot sensors allow the robot to 'perceive' its environment, and allow the entire machine system to respond appropriately. Specifically, sensors allow for monitoring of parts locations and machine orientation during production which allows the robot to compensate for any variation in the process. Some important sensor types include visual, force and torque, speed and acceleration, tactile, and distance sensors (although the majority of industrial robots utilize only binary sensing) (USLegal, 2017). More complex sensor types include light detection and ranging (LIDAR) sensors which use lasers to construct three-dimensional maps of the robot's environment, high frequency sounds-based supersonic sensors, and accelerometers and magnetometers which allow the robot to sense its movement relative to the Earth's gravity and magnetic field (Consortium on Cognitive Science Instruction, 2017).

Robots (particularly robots in industrial applications) require an end-effector or an end-of-arm tooling (EOAT) attachment to hold and manipulate either the tool performing the process, or the piece upon which the process is being performed (MHI, 2017). The most common end-effectors are general-purpose grippers, the most common among them being finger grippers with often have two opposing fingers or three fingers in a lathe-chuck position; the grippers' strengths are augmented by pneumatics and hydraulics and may be equipped with sensory capabilities (through additional sensors) (BARA, 2017a; Consortium on Cognitive Science Instruction, 2017; USLegal, 2017). While these components are coordinated by the robot's controller, end-effectors require to be operated and powered independently, and require adaptation if the system is refitted for another task (US Patent and Trademark Office, 2017).

The robot's actions are directed by a combination of programming software and controls which facilitate automated functionality of the system allowing for continuous operation (MHI, 2017). Available robot control systems range from simple pre-programmed robots which perform only the simplest operations, to more complex robots which are able to respond appropriately in increasingly complicated environments (Consortium on Cognitive Science Instruction, 2017). Industry observers predict that innovations in software and AI will be crucial for the development of next-generation robots (Keisner et al., 2015). Industry stakeholders believe that the continued fall in sensor prices and the increasing availability of open-source robot software are helping to drive the technological possibilities of robots (Anandan, 2015).

Robots can be classified in various ways - according to their mechanical structure and mechanisms. Some of the most common categorizations are based on the robots' mobility, shape of the work envelope (the robot's area of operations determined by its coordinate system, joint arrangement, and manipulator length), and kinematic mechanisms (the movement allowed by the joints between robot parts) (Zhang et al., 2006; Asada, 2005; Lau, 2005; Ross et al., 2010).

Mobility-based classifications imply that the robot may be either fixed or mobile depending on its intended use (Lau, 2005). For instance, conventional robotic manipulators used in manufacturing are regarded as fixed robots. They can be moved only when the work is completed. In contrast, mobile robots are on wheeled platforms attached to tracks, or feature mobile legs. These portable systems are not restricted and can be moved according to production needs (PwC, 2014).

Classifications based on the robot's work envelope include the revolute configuration (selective compliance assembly robot arm or SCARA configuration being the most notable among its sub-classifications), the Cartesian configuration, the cylindrical configuration, and the spherical configuration (Ross et al., 2010).

Robots can be classified also according to their kinematic mechanism which is the movement that a combination (called a linkage) of robot links (or rigid bodies) in a system allows (Asada, 2005; Zhang, et al., 2006). Primitive linkages include prismatic joints (a pair of robot links makes a translational displacement along a fixed axis such that one slides over the other in a straight line) or revolute joints (pairs of links that rotate around a fixed axis (Asada, 2005) – connecting primitive joints leads to serial connections (or serial linkages). Asada (2005) explains that more sophisticated combinations can be achieved by combining primitive and serial linkages in parallel-links or series-links.

2.2 Classification by purpose: Industry classifications

The IFR and the industry more generally adopt two classifications of robots: industrial robots (IR) and service robots (SR).

Industrial robots (IR). An industrial robot is an automatically controlled, reprogrammable, multipurpose manipulator programmable along three or more axes, which can be either fixed or mobile for use in industrial automation applications (ISO 8373, 2012). Table 3 provides a list of the available IRs based on their mechanical structure and industrial application.

Table 3. Industrial robots (IRs) classification by mechanical structure and application

Category	Description	Industrial application
Linear robots (Cartesian and gantry robots)	Cartesian robot whose arm has three prismatic joints and whose axes are coincident with a Cartesian coordinate system	Handling for plastic molding Sealing Laser welding Pressing
SCARA robots	A robot with two parallel rotary joints to provide compliance in a plane	Assembly Packaging

Articulated robots	A robot whose arm has at least three rotary joints, great payload capacity and flexible mounting possibilities for optimizing working range might be combined with SCARA elements	Handling for metal casting Welding Painting Packaging Palletizing Handling for forging
Parallel robots (delta)	A robot whose arms have concurrent prismatic or rotary joints	Picking and placing Assembly Handling
Cylindrical robots	A robot whose axes form a cylindrical coordinate system	Medical robots (DNA screening, forensic science, drug development and toxicology)
Others		Robots in Hazardous Environments Operations under water Operations in atmospheres containing combustible gases Operations in space
Not classified		Automated guided vehicles (AGVs)

Source: Strujik, 2011, International Federation of Robotics, 2015

Regarding data collection, the IFR also considers robots with their own control systems which are dedicated to other robot systems such as IR (e.g. wafer handlers that have their own control systems although part of the cleanroom system in semiconductor manufacturing) (IFR, 2016b). IFR (2016b) collects data on IRs via its member associations; national robot associations can opt to provide additional data on all types of manipulating IRs in their region.

Service robots (SRs). The 2012 ISO-Standard 8373 defines a SR as a robot that performs useful tasks for humans or equipment excluding industrial automation applications. SRs fall into two categories: 1) personal SRs intended for non-commercial tasks such as personal chores (e.g. domestic servant robots, automated wheelchairs, and personal mobility assistance robots), and 2) professional SRs which are made for commercial tasks and are operated by properly trained operators (e.g. robots for cleaning public places, delivery robots used in offices or hospitals, fire-fighting robots, rehabilitation and surgery robots in hospitals).

Currently, there are very few organizations that maintain comprehensive statistics on SRs (IFR, 2016a). The IFR (2016a) disclosed that it gathers SR-related information through regular mailings to SR manufacturers to obtain sales-related and application-related information.

2.3 Emergent classifications: Interactive (Social) Robots

Interactive robots, often used interchangeably with SRs, is an emerging sub-set of robotics that represent the vision for next-generation robotic systems. These robots are expected to be viable in human environments where various forms of interactions with human agents take place, and are intuitive, easy-to-use, and responsive to user needs (Christensen et al., 2016). Because commercialization is at an early stage, IFR classifies interactive robots as either industrial robots or SRs–which latter includes captures the sub-set of social robots that exhibit social characteristics (KPMG, 2016).

While the realization of such systems remain highly challenging and restricted (ABB Group, 2016; Christensen et al., 2016), a cooperative environment between human agents and automated systems remains an attractive proposition because of its promise of distinct advantages relative to other configurations: for instance, it can combine the flexibility and adaptability of the former in complex tasks, and the consistency and high productivity in simple automated tasks (Michalos et al., 2010). Contemporary human-machine configurations in the workplace vary based on the form of support that the robot provides to the agent – often depending on the degree of assistance that the combination of sensors, actuators and data processing within the system can provide. Generally, robot systems and human agents perform their tasks either jointly or separately. The level of interaction is heavily influenced and limited by the ability of the entire environment to avoid collisions with human agents. Interactive robots promise cooperation that goes beyond collision avoidance (Krüger et al., 2009).

Current interactive robots fall into various categories: 1) robot assistant, 2) collaborative robots (co-bots), and 3) humanoid or anthropomorphic robots. Robot assistants are interactive and flexible robotic systems that provide sensor-based, actuator-based and data processing assistance (Helms et al., 2002). Designed initially by the German non-profit Fraunhofer Institute for Manufacturing Engineering and Automation (Fraunhofer Institute IPA), current-generation robot assistants are complex mechatronic systems consisting of mobile platforms with differential gear drives and energy supply for autonomous workflow (Krüger et al., 2009). They often are multifunctional, adaptable to varying automation requirements and provide interactive guidance for the user (Pew Research Center, 2014).

Collaborative robots or co-bots are human-scale, articulated robots that work directly with human agents. They were invented by Northwestern University McCormick School of Engineering professor Edward Colgate (with Michael Peshkin), and are mechanical devices that provide guidance through the use of servomotors while a human operator provides motive power (Krüger et al., 2009; Morris, 2016). In practice, the distinguishing feature of a co-bot is its ability to provide direct power support to a human agent in a strenuous task while maintaining a high level of mobility (Lau, 2005). While co-bots are employed mostly in manufacturing tasks[1], they are also used for non-traditional applications such a surgery (Delnondedieu & Troccaz, 1995) (see Table 4 for a list of popular collaborative robot types). Humanoid or anthropomorphic robots act autonomously and safely, without human control or supervision. They are not designed to be solutions to specific robotic needs (in contrast to handling robots on assembly lines) but are built to work in real-world environments, interact with people and adapt to their needs (Coradeschi et al., 2006; PwC, 2017). Besides their human-inspired design, humanoid robots have a distinctive safe lightweight structure (Krüger et al., 2009). Generally, these robots are designed for applications not covered by IRs (WTEC, 2012): assembly processes where position estimation and robot accuracy are significantly below assembly tolerance, tasks where robots work closely with human agents (and may require direct interaction with them), and processes where the robot target's dimensions are relatively uncertain (Albu-Schaffer et al., 2007).

Table 4. Prominent types of collaborative robots

Type	**Summary**	**Applications**
Power and Force Limiting	Incidental contact initiated by the robot is limited in energy in order not to harm the operator.	Small and highly variable applications
		Conditions requiring frequent operator presence
		Machine tending
		Loading and unloading
Hand Guiding	The operator leads the robot movement through direct interface	Robotic lift assist
		Highly variable applications
		Limited or small-batch productions
Speed and Separation Monitoring	Robot speed reduces when an obstruction is detected	Simultaneous tasks
		Direct operator interface
Safety-rated Monitored Stop	Co-bot responds promptly (stopping or moving) in the presence of its operator	Direct part loading or unloading
		Work-in-process inspections
		Speed and separation monitoring (stand-still function)

Source: Robotic Industries Association, 2014

---

[1] The employment of co-bots in industrial applications particularly in the automotive sector, is explored in later sections.

3 Robotics: market trends the global landscape

3.1 Rising demand

The robotics industry has experienced rapid growth in recent years. Robotics expert Frank Tobe's industry-dedicated Robot Report database provides snapshots of firm and research institution populations in 2012 and 2015 which demonstrate the sector's rapid growth.

IFR 2016 unit sales data suggest that 74% of global robot sales are attributable to five countries. China continues to be the largest robotics market with an installed install count of 87,000 industrial robots in 2016 (+27% on 2015). South Korea is the second-largest market with peak unit sales of about 41,400 units (8% more than in 2015) while Japan is the third-largest with peak sales of approximately 38,600 units (IFR, 2017). Both the US and Germany continue to be import robotics markets with respective peaks of 31,400 units (up 14% on 2015) and 20,039 units (up from 19,945 units in 2015). Other important markets include Taiwan, the sixth ranked global market, and Thailand and India, which are becoming prospective markets in Asia. In Europe, Italy continues to be an important market (the 7th-largest in the world) with around 6,400 peak sales (slightly down from 6,600 in 2015) while France and the UK have seen a resurgence in demand.

The sustained growth of the industrial robotics market is attributed mostly to the automotive sector: robotics sales CAGR from 2011 to 2016 was approximately 12%, and sector installed count for 2016 was approximately 103,300 units (or 35% of total robotics supply in that year) (IFR, 2017). In addition, the statistics suggest that the electrical and electronics sector is gaining in importance with 2016 installed count peaking at 91,300 units (or 31% of total robotics supply in 2016). Other valuable sectors identified by IFR (2017) are rubber and plastics (16,600 units) and metal and machinery (28,700 units); sales to all industries except automotive and electrical and electronics increased by 5% on average in 2016.

Relative to the industrial robots market, the SR subsector is at an early stage (although on a positive trend). IFR (2017) unit sales data show that the number of sold units in 2016 was 59,706 (up from 48,018 in 2015). Sales of SRs for professional use were highest in logistics (25,400 units or 43% of the total unit supply), defense (11,100 units or 19% of total unit supply), field (6,000 units or 10% of total unit supply), and medical (1,600 units or 2.7% of total unit supply) (IFR, 2017). IFR (2017) forecasts that these applications will remain the main growth segments for SRs between 2016 and 2019.

Despite these developments, there is a notable lack of clear market leadership in the contemporary landscape. In their census of US robotics, Leigh and Kraft (2017) note that the 28 robotics original equipment manufacturers (OEM) suppliers they identified are spread across 12 countries. Japan hosted multiple top robotics companies by install base in 2015, and is the closest to assuming a market leader position although China recently has overtaken Japan for IR supply and market size.

While Europe has been competitive in the technical and commercial aspects of the robotics landscape since the 1970s, uptake of these technologies remains uneven at the country level. Germany and Italy have embraced industrial automation but France and the UK for instance, are faced by opposition stemming from potential displacement of labor (William, 2016; Pape, 2017). The positions of these countries in the technological landscape vary: only Germany and Italy feature globally-recognized strengths and institutions in robotics development (GTAI, 2017; UCIMU, 2017) while the US remains an important innovation hub and market for robotics although currently, there are no American companies that can be considered market sector leaders (Cuban, 2016; Statt, 2017). Most firms in the US (and the wider Northern American region) are robot system integrators (IFR, 2017).

Nevertheless, in recent years, most (if not all) the abovementioned countries have launched robotics-related institutional programs, most of which are part of larger campaigns towards Industry 4.0 (see Appendix I for further country-level information). Most of these programs are multi-million, multi-stakeholder initiatives involving universities, research institutions and private firms in the development of domestic capabilities. Also, most are public-private partnerships with direct public funding, although a number enjoy a mix of complementary fiscal measures meant to spur private investment.

3.2 Uneven supply

As already mentioned, there is no clear leadership in robotics production. The dearth of production statistics from various countries makes it especially difficult to identify a leader. However, a few of the already identified markets such as Italy, Japan, and Germany host some of the major robotics producers. In particular, Japan and Germany are home to three of the ‘big four’ in industrial automation: FANUC and Yaskawa Motoman in Japan, and KUKA AG in Germany (Robotics Business Review, 2017).

Japan is closest to being the market leader and is regarded as one of the powerhouses in the industry. It has capabilities in both IR and SR production, with particular strength in the production of high-precision servomotors, cables and many different types and components for sensors which are essential for robot construction and maintenance – industry stakeholders have assigned them a separate classification ‘RoboTech’ (Lundin and Eriksson, 2016).

The most recent available analyses indicate that Japan is responsible for most global production and is home to robotics firms that are increasingly export-oriented (65% of their production goes for export) (Lundin and Eriksson, 2016; IFR, 2017. The Japanese New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Economy, Trade and Industry (METI) forecasts predict that the Japanese robotics sector will double in value by 2020, and that growth from 2020 to 2035 will be around 10% to 15%. Moreover, NEDO projects are expected to increase even in areas where Japan enjoys competitive advantage (e.g. RoboTech production).

Apart from hosting some of the most significant global robotics producers such as FANUC Corporation, Yaskawa, and Kawasaki Heavy Industries, Ltd. (Montaqim, 2015), Japan has a robust firm population producing a variety of robotics applications: in the case of manufacturing, there are IRs for automotives, electrical and electronics, chemicals, machinery and metal processing and logistics applications (Lundin and Eriksson, 2016).

Germany is another prominent producer and considered the world's third largest. Its domestic robotics industry includes three main sectors: robotics , integrated assembly solutions (IAS) and machine vision technologies (GTAI, 2017). Germany has recognized strengths in IR development, particularly in machine vision technologies and human-robot collaboration development (GTAI, 2017).

Most recent available data indicate that 2016 was another record sales year for German robotics companies, with a new high of 12.8 billion EUR (VDMA, 2017). Further, while current sales suggest that all sub-sectors posted increasing sales, IAS accounts for the highest number of sales (VDMA, 2017). Meanwhile, in terms of trade, VDMA (2017) statistics show that 57% of German robotics are exported, with China being the biggest market (accounting for 10%) and North America the second-biggest (9%). Overall, the industry association expects that 2017 robot sales will increase 7% as a result of increased foreign demand.

Germany's robotics industry includes some 500 companies including a few large firms and a large number of small and medium sized enterprises (SMEs) which specialize in specific application areas (IFR, 2017). Most of these firms belong to stable networks of firms, OEMs and lead suppliers (GTAI, 2017).

In addition, Germany has a strong academic researcher base working in various robotics sub-fields. For example: 1) the Institute of Robotics and Mechatronics which investigates developments across the entire robot development process, 2) the DFKI Robotics Innovation Center which focuses on robot technologies for use in dangerous environments (e.g. space, underwater, etc.), and 3) the Technical University of Munich and its work on CPS and other SRs (e.g. medical robots, humanoid robots).

Italy is another notable robotics producer, particularly for Europe. In addition to being the second-largest market in the region, Italy is a strong supporter of industrial automation in manufacturing (not surprising in light of Italy's manufacturing capabilities and history of technological competence).

The most recent statistics show the country's continued relevance in the global industrial landscape and its industry's export orientation (UCIMU, 2017). Industry analysts expect the sector to grow between 5% to 10% between 2017 and 2020 (IFR, 2017).

Industry statistics show that the domestic sector is composed 75% of large firms (revenue of over 5 million EUR), 17% of medium-sized firms (revenue between 2.5 million EUR and 5 million EUR), and 8% of small-sized firms (revenue less than 2.5 million EUR) (UCIMU, 2017). Most of the country's robotics firms are located in Northern Italy, particularly in the regions of Lombardy and Piedmont. While the former account for a larger firm population (33.4% against 25%), Piedmont shows a higher concentration of revenues (62.8%) and employees (60%). Some of the notable Italian producers include COMAU, Olivetti and DEA.

3.3 3Cs: Capital, Consolidation and Clusters

The sector's activity is evidenced further by the increasing number of funded robotics-related ventures and the consolidation among existing robotics firms. Tobe's Robot Report 2016 data on mergers and acquisitions (M&A) (Tobe, 2017b) and funding-related activities (Tobe, 2017c) emphasize the industry's activeness. Funding of robotics-related startups amounted to 1.95 billion USD in 2016 (50% more than 2015) while M&A activity amounted to at least 18.867 billion USD (Tobe, 2017c). As might be expected, Silicon Valley startups have enjoyed continued success to capital funding, with 5 of the top 10 companies funded in 2016 originating in Silicon Valley or the greater California area. Most of this capital has been invested in developing unmanned aerial systems (UAS), agricultural robotics, and self-driving systems (Tobe, 2017c). Preliminary funding data for 2017 YTD suggests that this trend is continuing: approximately 15 billion USD were raised for various robotics startups, mostly for the same robotics applications (The Robot Report, 2018). The Robot Report (2018) database suggests that multi-billion funding has been raised for the Chinese Didi Chuxing, the Chinese Uber (5.5 billion USD) and for Nvidia Corporation (4 billion USD, particularly for the development of chips for self-driving learning).

In relation to M&A activity, much of the consolidation seems to be directed to reinforcing market positions or entry by technology companies. In the US, one of the most prominent cases involves the online retailer Amazon's acquisition of warehouse automation provider Kiva Systems to improve productivity in its (Amazon's) facilities (Guizzo, 2012). Another example is Google's approximately 25 billion USD investment in AI R&D (Columbus, 2017).

For robotics-related companies and robotics firms, M&A strategies allow immediate participation in frontier technologies: automatic test equipment provider Teradyne acquired Universal Robots (UR) in 2015: 1) to maintain its competitive advantage in its core offerings, as its customer base clamored for automation of the manual processes around its testing offerings, and 2) to participate immediately in the emerging co-bot market where UR holds a nearly 60% market share (Robotics Business Review, 2015).

Recently, Asian companies have been at the forefront of the robotics M&A scene. Japan's Softbank has steadily built a robotics portfolio through acquisition of prominent international robotics startups – Aldebaran Robotics in France, and Boston Dynamics and Schaft in the US (Lundin & Eriksson, 2016). However, Chinese companies through their involvement in numerous landmark acquisitions deals, have been the most aggressive: some examples include AGIC Capital's purchase of Italian end-of-arms tool supplier GIMATIC Srl, AGIC, the state-funded Guoxin International Investment Corp.'s purchase of German IR integrator KraussMaffei Group, and the 5.2 billion USD takeover of German KUKA AG by the Chinese Midea Group (Tobe, 2015a).

Apart from capital funding and business consolidation, increasing agglomeration is another key feature of the contemporary robotics landscape. Start-ups and service robotics companies increasingly are locating near prominent universities and research institutions (e.g. Carnegie Mellon, MIT, Harvard, UC Berkeley, Stanford) or areas of innovation (e.g. New York city) while industrial robot companies are prevalent in traditional industrial regions (e.g. Germany and the UK) (Tobe, 2012; Leigh and Kraft, 2017). Specifically, favored regions in a number of countries have become robotics 'hotspots': e.g. Boston, Pittsburgh, and Silicon Valley in the US, the Northern Bavaria cluster, Ostwestfalen-Lippe, and Saxony in Germany, and the Piedmont region in Italy. These clusters foster a virtuous environment: collaboration between industry and research institutions allows for continued pushing of the technological frontier which attracts participation of more stakeholders .

3.4 China: The heart of robot production

As already mentioned, China remains the largest robotics market by sales in 2016. IFR (2017) suggests that in 2016 the country was the largest robotics market by both annual sales and operational stock (IFR, 2017).

The most recent IFR statistics indicate also the growing capabilities of Chinese domestic robotics companies. While the country continues to be a net importer (with foreign suppliers accounting for some 68.97% market share), Chinese robot suppliers are steadily strengthening their market position (from around 27% in 2014 to 31% in 2016) (IFR, 2017). China's dynamic rise in robotics is expected to continue due to the increasing number of international robot suppliers locating in the country, and the continuing maturation of Chinese manufacturing (IFR, 2017).

Among domestic stakeholders, local Chinese conglomerates and university spin-offs are spearheading the launch of various robotics-focused enterprises and subsidiaries that are seeking to challenge established robotics firms, primarily in product pricing (Bland, 2016). Most of these enterprises have strengths in handling operations for metal casting, plastic molding and stamping, forging, bending, and soldering (IFR, 2017). Examples include the Shanghai-listed machine producer for the plastics sector Ningbo Techmation's subsidiary, E-Deodar which produces IRs for the plastics industry that are 20%-30% cheaper than those supplied by of ABB and KUKA. Also the Chinese technology giant Baidu has various investments and partnerships in AI and machine learning (Bajpai, 2017). A spin-off example is Siasun Robot & Automation Co. Ltd (Siasun), a 17-year old Chinese Academy of Sciences (CAS) Shenyang

Automation Research Institute spin-off company working in robotic technologies and advanced smart manufacturing equipment.

China’s aggressiveness in robotics highlights the nation’s drive to become the market leader in manufacturing and manufacturing innovation embodied in the ‘Made in China 2025 (MiC 2025) plan. MiC 2025 is the first of three comprehensive plans to upgrade Chinese industry and transform China into a manufacturing power by 2049 through the adoption of advanced manufacturing technologies from abroad and the promotion of domestic brands and R&D capabilities (Xinhua News Agency, 2015). Some specific targets of MiC 2025 for the Chinese robotics industry are promotion of various robotics-related research for industry applications, and investigation of high-potential sub-fields such as SRs and social work robotics (MIT, 2016). Table 5 presents details of MiC 2025’s sector-specific Robot Industry Development Plan.

Table 5. Details of China's Robot Industry Development Plan

Objective	**Specific targets**
Larger production scale	Domestic robot supply > 100k units
	6-axis robots > 50k units
	SRs revenue > 30 billion RMB
Elevated production capabilities	Reach of international standards on Mean Time Between Failures (MTBF)
	Advancement in key robot technologies
Breakthrough in core components	CN firms' share in domestic market > 50%
	Capabilities to produce own robot components
Significant achievement in integrated solutions	Robot density > 150 robot units per 10,000 workers
	Integrated robot solutions > 30 solutions in traditional industries

Source: Macquarie Research (2016)

While details of exact sums and policy strategies to be expected from China are scarce (Lee et al., 2015), there is already significant activity at the provincial level. For instance, Guangdong province promised to invest 8 billion USD for automation-related projects between 2015 to 2017 (Bland, 2016). Knight (2016) quotes a higher estimate: 150 billion USD to equip Guangdong factories with IRs, and to establish two new centers for advanced automation . In addition, Lianoning province capital Shenyang has started a 7 million USD fund to support high-technology industries (Schuman, 2017).

Despite the broad-based efforts of the Chinese private and public sectors, observers have raised concerns about the nation's manufacturing aspirations. First, the competitive advantage of China's manufacturing sector relative to the global competition, is based mostly on labor-intensive production. Statistics suggest that it will remain low-technology (2016 value-added share was 19% compared to developed countries such as the US and Germany at around 30%) and its R&D capabilities remain weak (most R&D activities are hosted in developed regions) (Euromonitor International, 2017). Despite being the largest robotics market, analysts have reasons to believe that China will remain an industrial automation laggard: only 60% of Chinese companies use industrial automation software (such as, Enterprise Resource Planning), and robot density is only 49 units per 10,000 employees (Lee et al., 2015; IFR, 2016c). Moreover, correspondence with Chinese companies reveals that they are focused mainly on production automation rather than holistic integration of value chains through data analytics (that programs such as Industry 4.0 espouse) (Meyer, 2016). Realizing MiC 2025's vision will require a greater effort from the Chinese government to rectify uneven firm capabilities (Wang, 2017).

The Chinese robotics sector continues to be characterized by overinvestments and population instability: there has been rapid establishment of small robotics companies and lack of established Chinese robotics components (e.g. speed reducers, servo-motors, and control panels) manufacturers which might prevent the sector from achieving scale (Tobe, 2017a). Analysts predict that it could take China 5 to 10 or even 15 years to be able to manufacture products on a par with those of its German and Japanese counterparts (Macquarie Research, 2016; Manjoo, 2017).

In the area of debt financing at the local level, there is concern about over-capacity in local government debt instruments as Chinese municipalities race to participate in the robotics sector (Taplin, 2016). Taplin (2016) describes the case of Wuhu city, west of Shanghai in Anhui province which has incurred a debt of 332 million USD for the establishment of its robotics park, and plans to raise an additional 181 million USD to finance its development.

Last, a confluence of factors such as cost pressures and the emphasis on automation have led to some factories across China to engage in indiscriminate adoption of advanced automation processes and robotics. Knight (2016) describes the case of a Shanghai-based Cambridge Industries Group (CIG) factory that is replacing Chinese workers with automation, and plans to operate entirely-automated or 'dark' factories. Also, the Taiwanese consumer electronics manufacturer Foxconn Technology Group has announced plans to fully automate its Chinese factories and is currently able to produce 10,000 units of its Foxbots, IRs that will replace human labor (Statt, 2017). Industry observers are concerned that such activity could jeopardize China's still-enormous manufacturing workforce (Knight, 2016). Some believe that as complex manufacturing tasks are automated, most Chinese workers will be forced to move into the services sector (Williams-Grut, 2016).

4 Selected technological trends

4.1 Collaborative robots.

While in their infancy, collaborative robots (or co-bots) are expected to be a key driver of growth in the industry. Although they acquired market acceptance and recognition only recently (Lawton, 2016a; Lawton, 2016b; Universal Robots, 2016), the co-bot sector market was worth approximately 95 million USD in 2014 (Tobe, 2015b), and combined with digitization of mechanical systems are attracting industry stakeholders. For instance, co-bots were a major theme at AUTOMATA 2016, one of the sector's most prominent trade conventions (Tobe, 2016). The most important players in the category include Rethink Robotics, the producer of the popular robots Baxter and Sawyer, and Universal Robots, the makers of the world's first co-bot and the current market leader by installed base (Universal Robots, 2016). Table 6 lists selected robotics companies that are producing co-bots.

Analysts and stakeholders are optimistic that co-bots will become a billion-dollar trade sector by 2020, with bullish actors such as Barclays Capital forecasting a market valued at 3 billion USD in that year (ABI Research in Lawton, 2016a; Zaleski, 2016). Europe is expected to continue to play a significant role in the market's development for several reasons including: 1) the strong presence of European robotics manufacturers in the global landscape, 2) the activeness of European companies in maintaining their advantage in the emerging co-bots market (e.g. Universal Robots, ABB Group, KUKA), and 3) the strong robotics research base in the region (e.g. Fraunhofer Institute) (Bogue, 2016).

Various factors are fueling demand for co-bots including the more extensive human-robot collaboration they enable which is resulting in increased productivity on the shop floor (Shah et al., 2011). Early adopters particularly established carmakers such as Ford, Mercedes Benz and Toyota, have achieved productivity gains from using co-bots while also employing additional human workers (Nisen, 2014; Luxton, 2016; Zaleski, 2016)

Furthermore, unlike traditional industrial robots which are large in size and require significant investment (making them ideal for mass production), co-bots are compact and easy-to-use which makes them viable solutions for the untapped SME market which tends to feature low-volume and high-mix (Lawton, 2016b; Zhang, 2017). In addition, co-bots are affordable: Rethink Robotics' Baxter and Sawyer sells for 25,000 USD-30,000 USD (22,880.50 EUR-27,456.60 EUR)[2], Universal Robots' products range from 23,000 USD to 45,000 USD (21,050.06 EUR to 41,184.90) (Tobe, 2015b), and other co-bot variants are available for 20,000 EUR-40,000 EUR (Bogue, 2016). Bogue (2016) adds that these robots often have short payback periods, generally 12 months or less.

---

[2] FX rate on December 31, 2015 (report publication date) was 1 USD = 0.91522 EUR (via exchange-rates.org).

Finally, the design features of co-bots address safety concerns associated to traditional industrial robots. Co-bots are designed with rounded surfaces to reduce risk of damaging impact, pinching and crushing, and are equipped with integrated sensors to detect human presence and to stop in such conditions and force-limited joints to sense forces due to impact (Tobe, 2015b; Zaleski, 2016; Zhang, 2017). Thus, manufacturers and even service providers are able to employ co-bots for a variety of tasks beyond what industrial robots could accomplish (Tobe, 2015b; Lawton, 2016b).

Table 6. Collaborative robots of select companies

Company	Base of operation	Co-bot	Feature summary	Product status	Base price (in USD)
Rethink Robotics	North America	Baxter	2-armed co-bot	On sale	25,000.00
		Sawyer	1-armed co-bot	On sale	29,000.00
Universal Robots	Europe (Denmark)	UR3 robot	3-kg payload capable co-bot	On sale	23,000.00
		UR5 robot	5-kg payload capable co-bot	On sale	35,000.00
		UR10 robot	10-kg payload capable co-bot	On sale	45,000.00
MRK-Systeme	Europe (Germany)	KR5 SI robot	Co-bot software for robot systems	NA	NA
F&P Personal Robotics	Europe (Switzerland)	P-Rob 2	1-armed co-bot	On sale	NA
Robert Bosch GmbH	Europe (Germany)	APAS System	1-armed co-bot	In-house use	NA
ABB Group	Europe (Germany)	YuMi	2-armed co-bot	On sale	40,000.00
MABI Robotic	Europe (Switzerland)	Speedy 6 robot	6-kg payload capable, 1-armed co-bot	On sale	NA
		Speedy 12 robot	12-kg payload capable, 1-armed co-bot	On sale	NA
FANUC Corporation	Japan	CR-35iA	35-kg payload capable 1-armed co-bot	On sale	NA
KUKA*	Europe (Germany)	LBR iiwa	13.64-kg payload capable, 1-armed co-bot	On sale	100,000.00
Kawada Industries	Japan	HRP humanoid robot	2-armed co-bot	On sale	60,000.00

Source: Adopted from Tobe (2015a); Co-bots guide (https://cobotsguide.com); various company websites

*As already mentioned, KUKA AG was acquired recently by the Chinese Midea Group.

4.2 Medical and nursing care robots.

The ageing demographic in developed countries is likely to sustain the drive towards the development of medical and nursing care robotics. Robotics applications for a myriad of health-related issues are being developed (and commercialized) by various institutions across the world. For instance, the UK (often regarded a laggard in the overall robotics landscape) hosts several enterprises that are focused on medical care: Renishaw PLC is a Gloucestershire-based firm with expertise in robotics surgery – its neuro-robotic device, Neuromate, is used for various surgical procedures in several countries (e.g. UK, France, Germany) (Demaitre, 2016) while Cambridge Medical Robotics focuses on developing next-generation universal robotics systems for minimally invasive surgery (Cambridge Medical Robotics, 2017). In the US, Intuitive Surgical Inc. is generally considered a technology leader in minimally invasive surgeries involving cancer and highly-complex procedures (Intuitive Surgical, 2017). The company's core offering is the 'da Vinci' surgical system, a robotics platform that combines robotic interfaces and 3-D vision systems (Intuitive Surgical, 2017). In South Korea, Chonnam National University has been investigating the feasibility of robotics technologies for cancer and intravascular treatments (Hyun-chae, 2016) while the Korean conglomerate Hyundai Heavy Industries has made various investments in medical SRs with several robot deployments in medical centers across South Korea (Chougule, 2016).

In addition to the above efforts, several countries (particularly, Japan and South Korea) have launched institutional support for the development of medical robots. In Japan, particular emphasis is being put on SRs for medical and nursing care (Lundin and Eriksson, 2016). On-going projects listed by the Japan Robot Association (JARA) confirm these observations; they include several projects focused on medical care (see Table 7).

Table 7. Select existing Japanese robot projects

Project Name	**Project Summary**	**Cost**	**Start**	**End**
Project to Promote the Development and Introduction of Robotic Devices for Nursing Care	Development of assistive robotics for nursing care to reduce caregivers' burden in providing elderly care.	NA	JFY 2013	JFY 2017
Innovative Cybernetic System for a ZERO intensive nursing-care society	Development of cybernetic systems that combines the brain-nerve-muscular system, robots, and other devices to improve/assist humans who would otherwise require intensive nursing-care .	NA	NA	NA
Tough Robotics Challenge	Development of the fundamental technologies for outdoor robots, thereby leading to the development of autonomous robots for disaster response.	NA	NA	NA

Source: JARA, Retrieved from https://www.jara.jp/e/various/projects/index.html

Meanwhile, the South Korean government has identified medical and rehabilitation uses as a high-growth sub-sector in its robotics development program (Hong, 2017). Also, Hong (2017) mentions that the South Korean Ministry of Trade, Industry and Energy (MOTIE) has committed to sponsoring the introduction of five to ten robots in National Rehabilitation Centers, and ten to fifteen robots in assistive roles in general hospitals; in 2018, it plans to introduce five surgical robots in national hospitals.

4.3 Warehouse automation and logistics robots.

The continued growth of e-commerce is expected to sustain the appetite for warehouse and logistic robotics. Amazon's 775 million USD-purchase of market-leading Kiva Systems (rebranded Amazon Robotics) in 2012 (Rusli, 2012) served as a logistics industry proof-of-concept regarding the benefits of warehouse automation. Shifting consumer expectations has put additional pressure on service providers to automate. Industry estimates suggest that this market will be worth around 20 billion USD by 2020 (Tractica, 2017).

Table 8. Warehouse automation and logistics robots of select companies

Company	Base of operations	Robotic solutions features	Product status
Kiva Systems (Amazon Robotics)	North America	Autonomous mobile robot systems for orders fulfillment	In-house use
Locus Robotics	North America	Autonomous mobile robot systems for orders fulfillment	On sale
Fetch Robotics	North America	Autonomous mobile robot systems for orders fulfillment	On sale
Vecna Technologies	North America	Autonomous mobile robot systems for orders fulfillment	On sale
InVia Robotics	North America	Autonomous mobile robot systems for orders fulfillment	On sale
IAM Robotics	North America	Autonomous mobile robot systems for orders fulfillment	On sale
6 River Systems	North America	Autonomous mobile robot systems for orders fulfillment	In development
Magazino GmbH	Europe (Germany)	Autonomous mobile robot systems for orders fulfillment	On sale
Hitachi Solutions	Japan	Autonomous mobile robot systems for orders fulfillment	In development
Clearpath Robotics	North America	Autonomous guided vehicles	On sale
Aethon	North America	Autonomous guided vehicles	On sale
Grezenbach Maschinenbau GmbH	Europe (Germany)	Autonomous guided vehicles	On sale
Knapp AG	Europe (Austria)	Autonomous guided vehicles	On sale
KUKA Swisslog	Europe	Autonomous guided vehicles	On sale

	(Switzerland)		
MiR Mobile Industrial Robots	Europe (Denmark)	Autonomous guided vehicles	On sale
Starship Technologies	Europe (Estonia)	Autonomous guided vehicles	In development
Dispatch	North America	Autonomous guided vehicles	In development
Grey Orange India Private Ltd.	India	Autonomous goods-to-person system	On sale
Scallog	Europe (France)	Autonomous goods-to-person system	In development
RightHand Robotics	North America	Grasping technology	In development
Google, Inc.	North America	Unmanned aerial vehicles	In development
Balyo	Europe (France)	Vision systems for logistics automation	In development
Seegrid Corporation	North America	Vision systems for logistics automation	In development

Source: Adopted from Banker (2016); Romeo (2016); Tobe (2016); Bray (2017); various company websites

While Amazon's acquisition left the sector with no established leader in 2012, a combination of start-ups and acquisitions has been satisfying demand (see Table 8). The more notable start-ups include 1) Locus Robotics, a spin-off founded by Massachusetts-based Quiet Logistics to provide warehouse automation solutions to third-party logistics providers (DHL Supply Chain being its most important client), 2) Fetch Robotics, a San Jose, California-based producer of the mobile cargo system 'Freight' and the mobile manipulator 'Fetch' both of which work collaboratively with human agents in the facility; and 3) Aethon, Inc., a producer of automated guided vehicles (AGVs) that are also used in hospitals (Banker, 2016; Romeo, 2016; Clark & Bhasin, 2017). Apart from these enterprises, established firms are developing (or acquiring) their own logistics automation solutions: examples include 1) KUKA's acquisition of materials handling and logistics automation provider Swisslog, 2) Toyota Industries' purchase of the Netherlands-based Vanderlande Industries, another materials handling and logistics automation provider, and 3) Hitachi's Racrew, the company's mobile warehouse robotics system which is in development (Banker, 2016; Capron, 2017).

Various developments have made warehouse and logistics automation an attractive proposition. First, Amazon's deployment of robotic systems in 2012 demonstrated substantial cost reductions and productivity gains in warehouse management –recent research suggests that the firm saves around 22 million USD at each fulfillment center equipped with Amazon robots (Kim, 2016). Moreover, current-generation automation solutions are more adaptable, flexible and intelligent, allowing service providers to maintain zero-defect logistics processes and to rapidly expand services and facilities (D'Andrea *in* Capron, 2017; Parsons, 2017).

Finally, shifting consumer expectations (based on the rise of e-commerce) has put pressure on service providers to adopt automation technologies. In particular, the introduction of same-day delivery (and the resulting consumer preference for fast delivery) has raised various challenges for logistics and warehouse management such as 1) maintenance of multiple distribution facilities which often are located in rural areas have labor-related problems, 2) exacerbation of the ‘last-mile’ problem as goods are delivered directly to households, bypassing the retail stores. Robotics seemingly offer viable solutions to these issues (Clark & Bhasin, 2016; Romeo, 2016; Harnett & Kim, 2017; Bray, 2017).

5. Robotics and Industry 4.0: Opportunities and challenges

Despite its far-reaching effects and the current advances in relevant technologies, Industry 4.0 is in its infancy, and particularly in those aspects related to robotics. Significant problems need to be overcome for the operationalization of Industry 4.0.

First, considerably more research is needed into autonomous systems for emergent **self-organization** among production cells to enable learning capabilities and dynamic and evolvable reconfigurations (Leitão, 2009; Brettel et al., 2014). Such advances would allow systems to react faster, contribute to better decision making processes, increase the capability for small-lot production, and be more effective at helping enterprises identify constraints and opportunities (Brettel et al., 2014). In addition to work on the autonomy-related limits of existing agent technologies, there is emerging research and several ongoing projects on bio-inspired robot designs which would make it possible to build robots that mimic natural morphologies and self-organization (e.g. animal-like movements, self-organization and self-assembly behaviors in nature) (Pfeifer et al., 2007).

At firm level, the main issues are **firm capabilities and cyber-security**. RMS Robots is impeded by lack of powerful IT-systems and their integration with other systems, and inadequate employee-knowledge of production processes (Brettel et al., 2014). Leitão (2009) discusses similar issues related to user acceptance among enterprise managers and directors of emergent terminologies and distributed approaches to problem-solving. Also, achieving horizontal integration across heterogeneous institutions may be problematic due to trust and data protection issues, and security related to firm know-how and customer information (Jazdi, 2014; Wang et al., 2015a; Brettel et al., 2014). Existing system configurations continue to have vulnerabilities: an entire PLC network is easily accessible by a single search engine such as SHODAN (Wang et al., 2015a). In recent years, the US DHS issued warnings about hacking at industrial sites; vulnerabilities and actual hostile hackings have occurred in both private and public-sector facilities systems in recent years (Wang et al., 2015a).

At the shop-floor level, there are difficulties related to **components and agent configurations**. For instance, RFID-sensor tags are impaired in the presence of water and large amounts of metal (Brettel et al., 2014). Moreover, there are conflict resolution issues, production deadlocks, and handling production disturbances among intelligent agents during execution and negotiation (Wang et al., 2016; Monostori, 2014). When human agents are introduced into production dynamics, challenges arise related to the optimal configuration between machine self-organization and appropriate control methods (Monostori, 2014; Wang et al., 2015a). Nevertheless, continued improvements in smart factory pre-conditions seem to be addressing the issue of production deadlocks, and improvements to agents' decision making are already being explored (Wang et al., 2016). In relation to components, research is being conducted on digital twins which provide predictive capabilities through simulation (Rosen et al., 2015), and prognostics and health management techniques (e.g. a 'time machine' snapshot stored in the cloud) used to achieve self-awareness and self-prediction (Lee et al., 2014, 2015).

Finally, there are **interoperability, design and data standardization issues**. Existing ontologies in industrial applications are often proprietary, simplistic and hierarchical structures of concepts (Leitão, 2009). While there is a great deal of research on ontology methods, protocols and semantic interoperability (Pěchouček & Mařík, 2008; Wang et al., 2016), work is needed on integrating entire systems with related technologies (e.g. RFID technologies, wireless networks, etc. (Leitão, 2009). Table 9 provides a summary of the challenges and opportunities discussed above, ranked by its proximity to advancements in robotics research.

Table 9. Select Industry 4.0 challenges and research opportunities, ranked by proximity to robotics research

Challenges	Specific issues	Research opportunities
Emergent self-organization among autonomous systems		Alternative agent systems, e.g. bio-inspired robot designs (Pfeifer, et al., 2007)
		Adaptability and prediction mechanisms in agent-based systems, particularly regarding production disturbances (Leitão, 2009; Monostori, 2014)
	Multi-agent systems (MAS)	Distributive and autonomous capabilities (Shen, et al., 2006; Pěchouček & Mařík, 2008)
		Continued investigation on ontology methods and contract net protocols (CNP) (Wang et al., 2015b)
	Holonic manufacturing systems (HMS)	Consistency, reliability, and interoperability with available computing systems (Babiceanu & Chen, 2006)
Components and agent configurations	Sensor technologies	Continued development of related technologies, RFID technologies (Pěchouček & Mařík, 2008; Brettel et al., 2014)
	Production deadlocks and agent negotiation	Introduction of digital twins that provide predictive capabilities through simulation (Rosen et al., 2015)

	Human-machine symbiosis	Development of prognostics and health management techniques, e.g. remote diagnostics, time machine snapshots (Jazdi, 2014; Lee et al., 2014; Lee et al., 2015)
		Inclusion of human agents in system architecture design
		Development of user interfaces that allow for human interference, e.g. context-sensitive and context-broker systems (Gorecky et al., 2014)
		Development of user assistance systems (Gorecky et al., 2014)
Interoperability, design, and data standardization		Harmonization of ontology methods, protocols, and semantic interoperability (Pěchouček & Mařík, 2008; Wang et al., 2016)
		Identification and understanding of the relevant information in manufacturing big data (Wang et al., 2015b)
		Continued integration of autonomous systems with related technologies, e.g. RFID technologies, wireless networks, etc. (Leitão, 2009)
		Integration and accessibility of virtual systems, e.g. virtual reality (VR), simulation (Brettel et al., 2014; Monostori, 2014)
User acceptance	Unit predictability	Autonomous system behavior must remain predictable and stable for human workers (Leitão, 2009)
	Accessible integration	Methodologies development that support easy, fast, transparent and re-usable integration of physical automation devices (Leitão, 2009)
		Enterprise integration for SMEs that have isolated, heterogeneous, and obsolete legacy systems (Shen et al., 2006; Brettel et al., 2014)
Data protection and cyber-security		Continued development of cyber-security related technologies

Source: author's analysis

6. Conclusion

The development of AI has triggered new waves of technological investments in robots, and the establishment of a worldwide market at the core of Industry 4.0. Although both demand and supply of robots continue to be concentrated on a small group of countries - China, Japan, the US, Germany and Italy - multi-million programs have been launched at the global level with the support of research centers and universities. While in manufacturing intermediate demand for robots from car makers is pivotal, there is a dramatic expansion of human-machine and machine-machine interaction in the health-care and medical sectors, and in logistics.

From a technological perspective, the former distinction between industrial and service robots has been challenged recently by the rise of collaborative robots or co-bots which are easy-to-use and can adapt very well to diverse human-related needs.

We have yet to enter the robot age; there are many problems that need to be addressed. Self-organization and interoperability of CPS need further development to achieve complete automation of firms. On the human side, use of data is a major problem, and the ethical consequences of ubiquitous robotics more generally remains underrated. Eventual legitimate evaluation of the substitution of human labor and related technological unemployment must include provision of digital literacy and education programs to generate the new capabilities required by this future current technological revolution.

References

ABB Group. (2016). Special report: Robotics – ABB group. *ABB Review*. Retrieved from http://library.e.abb.com/

ABI Research. (2016). The Massachusetts robotics cluster: Massachusetts technology collaborative. *Massachusetts Technology Collaborative*. Retrieved from http://www.masstech.org/

Albu-Schäffer, A., Haddadin, S., Ott, C., Stemmer, A., Wimböck, T., & Hirzinger, G. (2007). The DLR lightweight robot: Design and control concepts for robots in human environments. *Industrial Robot: An International Journal*, *34*(5), 376-385.

Anandan, T.M. (2015). Robotics 2015 and beyond: Collaboration, connectivity, convergence. *Robotics Industries Association*. Retrieved from http://www.robotics.org/

Asada, H.H. (2005). Robot mechanisms. *Introduction to Robotics*, *3*. Retrieved from http://ocw.mit.edu/

Babiceanu, R.F., & Chen, F.F. (2006). Development and applications of holonic manufacturing systems: A survey. *Journal of Intelligent Manufacturing*, *17*(1), 111-131.

Bajpai, P. (2017). An in-depth look at Baidu's (BIDU) artificial intelligence aspirations. *NASDAQ*. Retrieved from http://www.nasdaq.com/

Banker, S. (2016). Robots in the warehouse: It's not just Amazon. *Forbes*. Retrieved from http://www.forbes.com/

BARA. (2017a). Robot grippers & end effectors. Retrieved from http://www.bara.org.uk/

BARA. (2017b). Robots. Retrieved from http://www.bara.org.uk/

Bland, B. (2016). China's robot revolution. *Financial Times*. Retrieved from http://www.ft.com/

Bogue, R. (2016). Europe continues to lead the way in the collaborative robot business. *Industrial Robot: An International Journal*, *43*(1), 6-11.

Boston Consulting Group. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston Consulting Group*, *14*.

Boston Consulting Group. (2015). The robotics revolution: The next great leap in manufacturing. *BCG Perspectives*. Retrieved from https://www.bcgperspectives.com/

Bray, H. (2017). Robots taking over in warehouses. *Boston Globe*. Retrieved from http://www.bostonglobe.com/

Brettel, M., Friederichsen, N., Keller, M., & Rosenberg, M. (2014). How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 perspective. *International Journal of Mechanical, Industrial Science and Engineering*, *8*(1), 37-44.

Cambridge Medical Robotics. (2017). Developing the next-generation universal robotic system for minimal access surgery. Retrieved from http://cmedrobotics.com/

Capron, J. (2017). A look into logistics automation – investment commentary. *ROBO Global*. Retrieved from http://roboglobal.com/

Carlisle, B. (2000). Robot mechanisms. *Adept Technology, Inc*. In 2000 IEEE International Conference on Robotics & Automation. San Francisco: California.

Chougule, S. (2016). Hyundai tests medical robots as prelude to global markets. *Robotics Business Review*. Retrieved from http://www.roboticsbusinessreview.com/

Christensen, H. I., Batzinger, T., Bekris, K., Bohringer, K., Bordogna, J., Bradski, G., ... & Eastman, R. (2016). A roadmap for US robotics: From internet to robotics 2016 Edition. *Computing Community Consortium*.

Clark, P. & Bhasin, K. (2017). Amazon’s robot war is spreading. *Bloomberg Technology*. Retrieved from http://www.bloomberg.com/

Clark, P., & Bhasin, K. (2016). Retailers fuel a warehouse boom, racing to keep up with Amaz0n. Retrieved from http://www.bloomberg.com/

Columbus, L. (2017). McKinsey’s state of machine learning and AI. *Forbes*. Retrieved from http://www.forbes.com/

Consortium on Cognitive Science Instruction. (2017). Parts of a robot. Retrieved from http://www.mind.ilstu.edu/

Coradeschi, S., Ishiguro, H., Asada, M., Shapiro, S.C., Thielscher, M., Breazeal, C., ... & Ishida, H. (2006). Human-inspired robots. *IEEE Intelligent Systems*, *21*(4), 74-85.

Cuban, M. (2016). Dear Mr. President, my suggestion for infrastructure spending. Retrieved from http://blogmaverick.com/

Delnondedieu, Y., & Troccaz, J. (1995, November). PADyC: A Passive Arm with Dynamic Constraints; A prototype with two degrees of freedom. In Proc. IEEE Conf. Med. Robotics Comp. Assisted Surgery, 173-180.

Deloitte Consulting UK. (2015). The robots are coming: A Deloitte insight report. Retrieved from https://www.deloitte.com

Demaitre, E. (2016). U.K. companies grabs a slice of the surgical robotics market. *Robotics Business Review*. Retrieved from http://www.roboticsbusinessreview.com/

Deutsche Bank Research. (2014). Industry 4.0: Huge potential for value creation waiting to be tapped. Retrieved from http://www.dbresearch.com

Euromonitor International. (2017). Industry 4.0: China to challenge Germany in race for Industry 4.0 adoption. Retrieved from http://blog.euromonitor.com/

Gorecky, D., Schmitt, M., Loskyll, M., & Zühlke, D. (2014, July). Human-machine-interaction in the Industry 4.0 era. In *Industrial Informatics (INDIN)*, 2014 12th IEEE International Conference, 289-294. IEEE.

GTAI. (2017). The robotics & automation industry in Germany. Retrieved from http://www.gtai.de/

Guizzo, E. (2012). Amazon acquires Kiva systems for $775 million. *IEEE Spectrum*. Retrieved from http://spectrum.ieee.org/

Harnett, S. & Kim, Q. (2017). Online retail boom means more warehouse workers, and robots to accompany them. *NPR*. Retrieved from http://www.npr.org/

Helms, E., Schraft, R.D., & Hagele, M. (2002). rob@ work: Robot assistant in industrial environments. In *Robot and Human Interactive Communication, 2002. Proceedings. 11th IEEE International Workshop on* (pp. 399-404). IEEE.

Hermann, M., Pentek, T., & Otto, B. (2016, January). Design principles for Industrie 4.0 scenarios. In *System Sciences (HICSS)*, 2016 49th Hawaii International Conference, 3928-3937. IEEE.

Hong, J. (2017). South Korea to boost its robot industry with a new development initiative. Retrieved from http://www.rvo.nl/

Hyun-chae, C. (2016). Leading micro-robotics research. *The Korea Times*. Retrieved from http://www.koreatimes.co.kr/

IFR International Federation of Robotics. (2016a). Classification of service robots by application areas. Retrieved from http://ifr.org/

IFR International Federation of Robotics. (2016b). Industrial robots – definition and classification. Retrieved from http://ifr.org/

IRF International Federation of Robotics. (2016c). World Robotics Report 2016.

IFR International Federation of Robotics. (2017). World Robotics Report 2017.

IFR International Organization for Standardization. (2012). ISO-Standard 8373.

Intuitive Surgical, Inc. (2017). SEC Form 10-K Annual Report 2017. Retrieved from SEC EDGAR database: http://www.sec.gov/

Jazdi, N. (2014, May). Cyber physical systems in the context of Industry 4.0. In *Automation, Quality and Testing, Robotics*, 2014 IEEE International Conference, 1-4. IEEE.

Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W. (2013). Recommendations for Implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 working group. Forschungsunion.

Keisner, C.A., Raffo, J., & Wunsch-Vincent, S. (2015). Breakthrough technologies: robotics, innovation and intellectual property. *World Intellectual Property Organization: Economics and Statistics Series*, *30*.

Kim, E. (2016). Amazon's $775 million deal for robotics company Kiva is starting to look really smart. *Business Insider*. Retrieved from http://www.businessinsider.com/

Knight, W. (2016). China is building a robot army of model workers. *MIT Technology Review*. Retrieved from http://www.technologyreview.com/

KPMG. (2016). Social robots. Retrieved from http://kpmg.com/

Krüger, J., Lien, T.K., & Verl, A. (2009). Cooperation of human and machines in assembly lines. *CIRP Annals-Manufacturing Technology*, *58*(2), 628-646.

Lau, S.D. (2005). Final report: Experimental study of robotic assembly and force control tasks. Retrieved from the Washington University in St. Louis Department of Electrical & Systems Engineering website: http://ese.wustl.edu

Lawton, J. (2016a). The collaborative robot market is set for phenomenal growth (part 1). *Rethink Robotics*. Retrieved from http://www.rethinkrobotics.com/

Lawton, J. (2016b). The collaborative robot market is set for phenomenal growth (part 2). *Rethink Robotics*. Retrieved from http://www.rethinkrobotics.com/

Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, *3*, 18-23.

Lee, J., Bagheri, B., & Kao, H.A. (2014). Recent advances and trends of cyber-physical systems and big data analytics in industrial informatics. In International Proceeding of Int Conference on Industrial Informatics (INDIN), 1-6.

Leigh, N. G., & Kraft, B. R. (2017). Emerging robotic regions in the United States: insights for regional economic evolution. Regional Studies, 1-13.

Leitão, P. (2009). Agent-based distributed manufacturing control: A state-of-the-art survey. *Engineering Applications of Artificial Intelligence*, *22*(7), 979-991.

Lundin, M., and Eriksson, S. (2016). Artificial intelligence in Japan. R&D, market and industry analysis. *EU-Japan Centre for Industrial Cooperation.* Retrieved from http://www.EUbusinessinJapan.eu/

Luxton, E. (2016). This factory is replacing robots with humans. *World Economic Forum*. Retrieved from http://www.weforum.org/

Macquarie Research. (2016). Robots. Retrieved from http://www.macquarieresearch.com/

Manjoo, F. (2017). How to make America's robots great again. *The New York Times.* Retrieved from http://www.nytimes.com/

Meyer, K.E. (2016). China's big bid for Germany's Industry 4.0 technology. *Forbes*. Retrieved from http://www.forbes.com/

MHI. (2017). Industrial robots. Retrieved from http://www.mhi.org/

Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., & Chryssolouris, G. (2010). Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach. *CIRP Journal of Manufacturing Science and Technology*, *2*(2), 81-91.

MIT Technology Review. (2016). Italy transforms itself into a high-tech hotbed. Retrieved from http://www.technologyreview.com/

Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. *Procedia CIRP*, *17*, 9-13.

Morris, A. (2016). 20 years later: Cobots co-opt assembly lines. Northwestern University: McCormick School of Engineering. Chicago: Illinois.

Nisen, M. (2014). Toyota is becoming more efficient by replacing robots with humans. *Quartz*. Retrieved from http://qz.com/

Pape, J.P. (2017). France should look to robotics. *Universal Robots*. Retrieved from http://blog.universal-robots.com/

Parsons, M. (2017). Automation and robotics: The supply chain of the future. *Supply Chain Digital*. Retrieved from http://www.supplychaindigital.com/

Pearson, J. (2015). The sheer difficulty of defining what a robot is. *Vice Magazine*. Retrieved from http://motherboard.vice.com/

Pěchouček, M., & Mařík, V. (2008). Industrial deployment of multi-agent technologies: Review and selected case studies. *Autonomous Agents and Multi-Agent Systems*, *17*(3), 397-431.

Perlongo, K. (2016). Robohub roundtable: Why is it so difficult to define 'robot'?. *Robohub*. Retrieved from http://robohub.org/

Pew Research Center. (2014). AI, robotics, and the future of jobs. Retrieved from http://www.pewinternet.org/

Pfeifer, R., Lungarella, M., & Iida, F. (2007). Self-organization, embodiment, and biologically inspired robotics. *Science*, *318*(5853), 1088-1093.

PwC. (2014). The new hire: How a new generation of robots is transforming manufacturing. Retrieved from https://www.pwc.com/

PwC. (2017). Artificial Intelligence and Robotics: Leveraging artificial intelligence and robotics for sustainable growth. *PwC India*. Retrieved from www.pwc.in/publications/

Robotic Industries Association (RIA). (2017). Defining the industrial robot industry and all it entails. Retrieved from http://www.robotics.org/

Robotics Business Review. (2015). Samsung Electronics launches new $100M robotics lab. Retrieved from http://www.roboticsbusinessreview.com/

Robotics Business Review. (2017). Meet the 2017 RBR50: Top 50 robotics companies. Retrieved from http://www.roboticsbusinessreview.com/

RIA Robotics Industries Association . (2017). Company profile – robotics industries association. Retrieved from http://robotics.org/

Romeo, J. (2016). Robots at the warehouse: Changing the face of modern logistics. *Robotics Business Review*. Retrieved from http://www.roboticsbusinessreview.com/

Rosen, R., von Wichert, G., Lo, G., & Bettenhausen, K.D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. *IFAC-PapersOnLine*, *48*(3), 567-572.

Ross, L.T., Fardo, S.W., Masterson, J.W., & Towers, R.L. (2010). Robotics: Theory and industrial applications. Goodheart-Willcox Company.

Rusli, E.M. (2012). Amazon.com to acquire manufacturer of robotics. *The New York Times Dealbook.* Retrieved from http://dealbook.nytimes.com/

Schuman, M. (2017). China, like U.S., struggles to revive industrial heartland. *The New York Times.* Retrieved from http://www.nytimes.com/

Schwab, K. (2017). The fourth industrial revolution. Penguin UK.

Shah, J., Wiken, J., Williams, B., & Breazeal, C. (2011, March). Improved human-robot team performance using chaski, a human-inspired plan execution system. In *Proceedings of the 6th international conference on Human-robot interaction* (pp. 29-36). ACM.

Shen, W., Hao, Q., Yoon, H.J., & Norrie, D.H. (2006). Applications of agent-based systems in intelligent manufacturing: An updated review. *Advanced engineering Informatics*, *20*(4), 415-431.

Statt, N. (2017). America may miss out on the next industrial revolution. *Verge*. Retrieved from http://www.theverge.com/

Struijk, B. (2011). Robots in human societies and industry. *Technology*, *10*(1), 183-195.

Taplin, N. (2016). China's robotics rush shows how its debt can get out of control. *Reuters*. Retrieved from http://www.reuters.com/

The EU Framework Program for Research and Innovation. (2014). What is horizon 2020? Retrieved from http://ec.europa.eu/

The Robot Report. (2018). The Robot Report database on firm funding. Retrieved from http://www.therobotreport.com/

Tobe, F. (2012). 1,000 robot makers! Retrieved from *The Robot Report*. http://www.everything-robotic.com/

Tobe, F. (2015a). The Robot Report's global directory and map exceeds 4,000 entries. *The Robot Report*. Retrieved from http://www.therobotreport.com

Tobe, F. (2015b). Why co-bots will be a huge innovation and growth driver for robotics industry. *IEEE Spectrum*. Retrieved from http://spectrum.ieee.org/

Tobe, F. (2016). AUTOMATICA 2016: Digitalization and collaborative robotics. *The Robot Report*. Retrieved from http://www.therobotreport.com/

Tobe, F. (2017a). China's strategic plan for a robotic future is working: 500+ Chinese robot companies. *The Robot Report*. Retrieved from http://www.therobotreport.com/

Tobe, F. (2017b). Over $19 billion paid to acquire 50 robotics companies in 2016. *The Robot Report*. Retrieved from http://www.therobotreport.com/

Tobe, F. (2017c). 2016 best year ever for funding robotics startup companies. *The Robot Report*. Retrieved from http://www.therobotreport.com

Tractica. (2017). Warehousing and logistics robots. Retrieved from http://www.tractica.com/

UCIMU. (2017). Il settore della robotica in Italia 2016. Centro Studi & Cultura di Impresa. Retrieved from http://www.ucimu.it/economia-e-mercato/analisi-economica/indagini-ucimu/

Universal Robots (2016). World Robotics report 2016 announces collaborative robots as market driver. Retrieved from http://universal-robots.com/

US Patent and Trademark Office. (2017). Classification of robots. Retrieved from http://www.uspto.gov/

USLegal. (2017). Robotics law and legal definition. Retrieved from http://definitions.uslegal.com/

VDMA (2017) Robotics + Automation. Sector portrait 2017. Retreived from https://rua.vdma.org/documents/106005/15570345/Sector%20Portrait_June%202017_1501160031011.pdf/98d14865-6764-4320-938a-736d6bc9b39b

Wang, B. (2017). Made in China 2025 plan is similar to Germany's Industry 4.0 plan. *Next Big Future*. Retrieved from http://www.nextbigfuture.com/

Wang, L., Törngren, M., & Onori, M. (2015a). Current status and advancement of cyber-physical systems in manufacturing. *Journal of Manufacturing Systems*, *37*(Part 2), 517-527.

Wang, S., Wan, J., Li, D., & Zhang, C. (2015b). Implementing smart factory of Industrie 4.0: An outlook. *International Journal of Distributed Sensor Networks*.

Wang, S., Wan, J., Zhang, D., Li, D., & Zhang, C. (2016). Towards smart factory for Industry 4.0: A self-organized multi-agent system with big data based feedback and coordination. *Computer Networks*, *101*, 158-168.

William, A. (2016). Are U.K. manufacturing and industrial automation turning a corner? *Robotics Business Review*. Retrieved from http://www.roboticsbusinessreview.com/

Williams-Grut, O. (2016). BERNSTEIN: China's insane spending on robotics is fundamentally changing capitalism. *Business Insider*. Retrieved from http://www.businessinsider.com/

Wilson, H.J. (2015). What is a robot, anyway? *Harvard Business Review*. Retrieved from http://hbr.org/

WTEC World Technology Evaluation Center. (2012). WTEC panel report on human-robot interaction: Japan, South Korea, and China. Retrieved from http://www.wtec.org

Xinhua News Agency. (2015). "Made in China 2025" plan unveiled to boost manufacturing. Retrieved from http://ycharts.com/

Zaleski, A. (2016). Man and machine: The new collaborative workplace of the future. *Consumer News and Business Channel*. Retrieved from http://www.cnbc.com/

Zhang, A. (2017). Collaborative Robotics – definitions, safety, and applications. *ABB Group*. Retrieved from http://library.e.abb.com

Zhang, Y., Finger, S., & Behrens, S. (2006). Introduction to mechanisms. *Rapid Design through Virtual and Physical Prototyping Project*, 39-245. Carnegie Mellon University. Pittsburgh: Pennsylvania.