Citi GPS

FACTORY OF THE FUTURE

Flexible, Digitalized, and Sustainable

Citi GPS: Global Perspectives & Solutions

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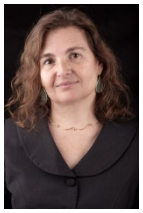

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FACTORY OF THE FUTURE

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As consumers, we have all become used to the benefits of mass production - consistent quality at a low price. This has been enabled by a century of progress in factory automation, starting from the advent of manufacturing assembly lines more than one hundred years ago. Manufacturing productivity gains stalled in the early 2000's, but we are now on the cusp of a new era of productivity, driven by the declining cost of technology (data and components), a pending explosion in wireless connectivity potential for industrial devices, and developments in advanced manufacturing, including robotics. Manufacturing will become "on demand', where we can order single bespoke items in real time, at the cost of mass production.

The Factory of the Future might conjure images of 'lights out' factories with lines of industrial robots, but the robots of the future will not be like those in the past — they will be easily integrated into human environments, and become as common as cars or phones. In this report, Professor Daniela Rus at MIT suggests that technology advances will allow us to build robots capable of taking on a much wider variety of tasks, working with some degree of autonomy, working side by side with people. By teaming machine learning, robot systems, and people together, the world of manufacturing could be reshaped. This means a whole approach to production and jobs that we cannot begin to imagine. It could mean smaller factories, located closer to population centers, making fewer generic standardized goods, and more customized products. Even robots themselves will be unidentifiable compared to their history. Two technologies — soft and origami robots — point to a future of manufacturing where machines and people work side by side.

In product development, the processes of designing, improving, and testing can all happen in a virtual environment, substantially reducing risks, time to market, and development costs. Product design has been software enabled for years, but the software simulation of testing, production and usage can shave years off product development times. Automatically generating the production "code" from this process enables "distributed manufacturing", further enabling the concept of localizing production.

Even beyond robotics, we are on the cusp of a revolution enabled by cheap data, computing, and components, as well as a pending explosion in wireless connectivity enabled by the rollout of 5G networks. This is not just about gathering data, but also enabling augmented reality to empower workers on the factory floor.

This is not without risk — Citi Economists show that manufacturing powerhouses like Germany and China are shaping policy around the expected upheaval. Fully digitized factories also raise crucial questions on cybersecurity risk.

In an era of trade tensions however, distributed manufacturing takes on a whole new appeal, and once consumers get used to bespoke production on demand, at mass-produced prices, there will be no going back.

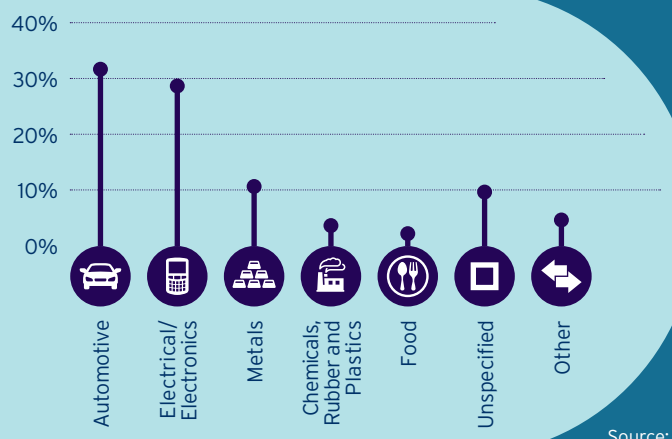
We hope you enjoy the report.

Factory of the Future: The Shift to Distributed Manufacturing

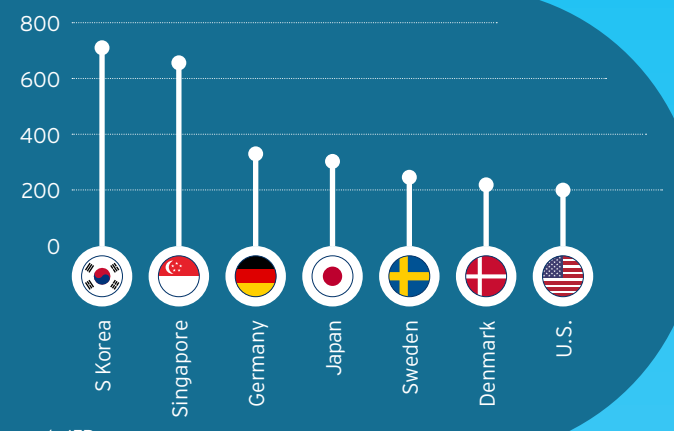
TODAY: ROBOTS HAVE ENABLED MASS FABRICATION

Industrial Robotics make up 78% of all robot sales and have the most uptake in the Automotive industry and in S Korea

Robot Penetration by Industry (2017)



Robot Density per 100K Employees in Manufacturing (2017)



Source: Citi Research, IFR

TOMORROW: ROBOTS WILL ENABLE A WORLD OF CUSTOMIZED PRODUCTION WHERE COMPUTATIONAL DESIGN AND FABRICATION PROCESSES WILL SUPPORT RAPID MANUFACTURING

What is the Factory of the Future? It is defined by three things…

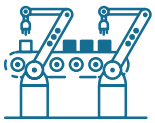
1

Flexibility

Mass personalization with on-demand production and supply chains

2

Digitalization

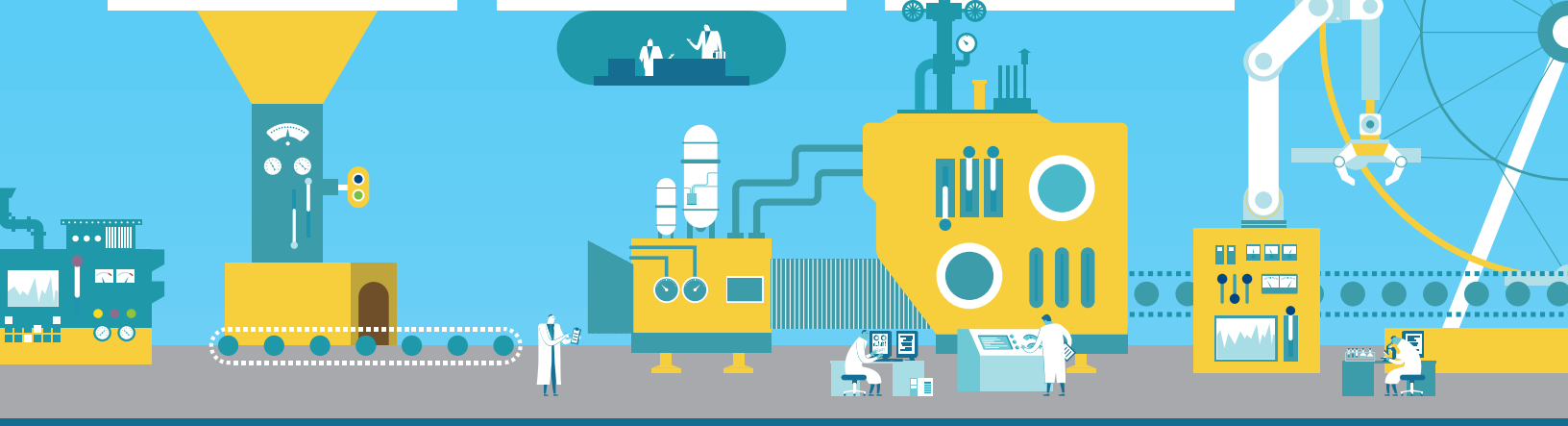


Design, production, and services are digitally driven with 'digital twins' for manufactured product

3

Zero Waste Manufacturing

A combination of energy efficiency and circular manufacturing.



WHAT RISKS DOES THE FACTORY OF THE FUTURE BRING?
The manufacturing industry could generate more data than any other sector in the economy creating cyber risk

A connected factory is estimated to generate **1 petabyte per day**, equivalent to 1.05 billion minutes of MP3 songs or 160 million books

Source: Intel

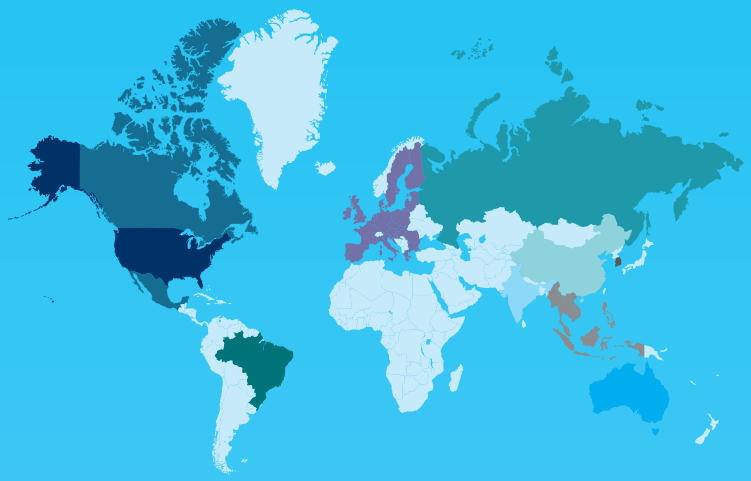
40% of manufacturing security professionals don't have a **formal data security strategy**

Source: Cisco

Manufacturing is the **third most attacked sector** for cyber behind Government and Finance

Source: IBM

LABOR COSTS IN THE OPERATIONAL AND ASSEMBLY PROCESS OF MANUFACTURING COULD BECOME LESS IMPORTANT
The value addition of manufacturing would move towards the larger end-consumer markets, led by the U.S., China, Japan, and Germany



U.S.	27%	EU	22%
China	11%	Canada & Mexico	4%
India	3%	ASEAN	3%
Brazil	3%	Russia	2%
Australia	2%	South Korea	2%
Rest of World	15%		

Source: World Bank, Haver, Citi Research

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The Factory of the Future

How Different the Factory of the Future Will Be

So what is the factory of the future? It is one where bespoke products can be made at the cost of mass production, and where manufacturing and supply chains become 'on demand'. It is being enabled through the mass connectivity of devices, through cheaper data collection, storage, and transmission, combined with advances in automation technology like robotics; it is being driven by consumers wanting bespoke products on demand at mass produced prices, and by manufacturers wanting shorter development lead times, lower production costs, and lower inventories.

It is one where products are designed, simulated, and tested digitally, and where these digital blueprints are translated automatically into production instructions ready for industrial control devices, to be sent anywhere in the world for production, leading to the potential for 'distributed manufacturing'. The 'digital twin' of the manufactured product (the car, the aircraft, the phone) will remain and constantly evolve over the lifetime of the product to mimic its real-world counterpart, improving the products lifetime performance.

It is one where augmented reality can aid in the setup and maintenance of the factory, and one where advances in robotic tools mean that dexterity, flexibility, and adaptability replace repetition and uniformity in the industrial process. Devices inside the factory are enabled with sensors and connectors and communicate over a dedicated 5G network, and where advanced manufacturing processes like robotics thrive.

It is one which enables circular manufacturing and where smarter product design and smarter production process design can improve the resource footprint, and one which enables the verification of the provenance of products and components.

Why Now?

Factory automation has seen a constant stream of improvements since the advent of the assembly line (~1913), industrial robots (1960s), Ethernet-enabled factory (1980's), and the advent of just-in-time and 'lean' manufacturing (1970s-1990s); even the theme of Industry 4.0 was first coined in 2011. Nonetheless, output per manufacturing employee has not increased notably in the U.S. since 2011, after enormous improvements from the 1970s through the early 2000's. We are now on the cusp of another wave of productivity improvement, driven by:

- The declining cost of data and computing;
- The declining cost of components;
- A pending explosion in the capabilities of industrial wireless connectivity (5G); and
- Significant advances in automation technology like robotics.

Why Does this Matter?

Manufacturing will be greatly impacted by several emerging technologies in robotics, artificial intelligence, and machine learning. Today, robots have enabled mass fabrication. Tomorrow, they will enable a world of customized production where computational design and fabrication processes will support rapid manufacturing.

Automation suppliers have gradually shifted their strategies towards software, but until recently this has been (largely) domain-specific software; many industrial automation companies are shifting towards digital and data-driven strategies:

- **It provides new revenue streams:** Predictive maintenance is valuable to the customer through increased uptime and reduced repair time. Supplying software-as-a-service (SaaS) for product and process design mutes the traditional cyclicality of industrial hardware sales. For software offerings, advanced analytics and machine learning can be put to work operating on data in managed services scenarios and significantly boosting the value of these already high-margin offerings. There are also whole new markets; industry research firm IoT Analytics puts the software industrial IoT market at $1.7 billion in 2018 growing to $10 billion by 2023, including both the contribution from the Industrial Internet of Things (IIoT) and Augmented Reality/Virtual Reality (AR/VR).

- **Manufacturers are demanding it:** Often through lower production costs and shorter development times. One major industrials player estimates development times for aircraft can be reduced from six years to 2.5 years using digital tools, and that machine commissioning times can be cut by 25%.

- **It is defensive in a period of technology disruption:** In the past, Germany has lost its leadership in sectors such as consumer & communication electronics or carbon materials. Against a backdrop of technology disruption, the German government has promoted 'Industrie 4.0' to retain leadership in industries like automotive, medical devices, and more. China is also promoting this shift. Geopolitical forces alongside technological advancements can accelerate the desire to localize or re-shore production closer to the end market, which is far easier when the process is digitized.

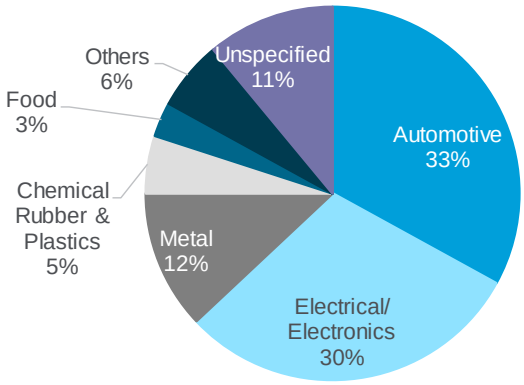
- **It is happening during a period of heightened trade tensions:** This may mean multinationals will need to reduce the concentration risk in their operations away from China. In the May 2019 joint survey of member companies, the American Chamber of Commerce in Shanghai and in China found almost 41% of respondents were considering relocating — or have already relocated — manufacturing facilities outside of China, versus only 18% of respondents having indicated the same in an earlier 2018 survey.

- **There is an increased focus on data on waste and resource usage:** Analysis by McKinsey, as part of a study with the Ellen MacArthur Foundation found material cost savings worth up to $630 billion per year by 2025 in EU manufacturing sectors by increasing resource productivity. In the U.S., a study found benefits of 250-350mn metric tons of CO_2 equivalent and $2 trillion in annual U.S. revenues could be generated from circular manufacturing. These points suggest that a move towards more circular manufacturing is likely to reduce costs for manufacturers.

We See This as a Secular Growth Theme Against Recent Cyclical Weakness

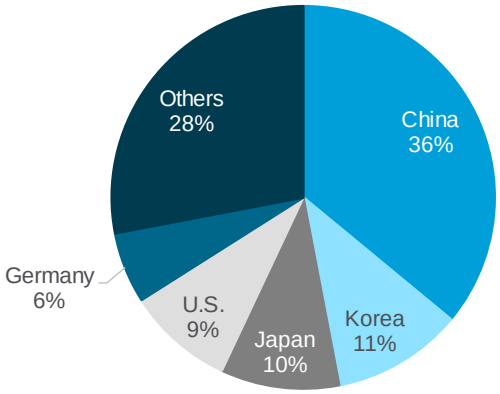
Many automation tools (from the assembly line itself to the industrial robot) have their roots in automotive markets, and automotive customers are still the single largest market for many factory automation suppliers, with electronics/tech hardware assembly another key market. Recent weakness in these markets has kindled fears for the growth outlook in automation markets. But as the technology spreads to other industries we see this current weakness as a soft period against a longer-term growth trend.

Figure 1. Global Robotics End Market Split by Industry (2017)



Source: Citi Research, IFR

Figure 2. Global Robotics End Market Split by Country (2017)

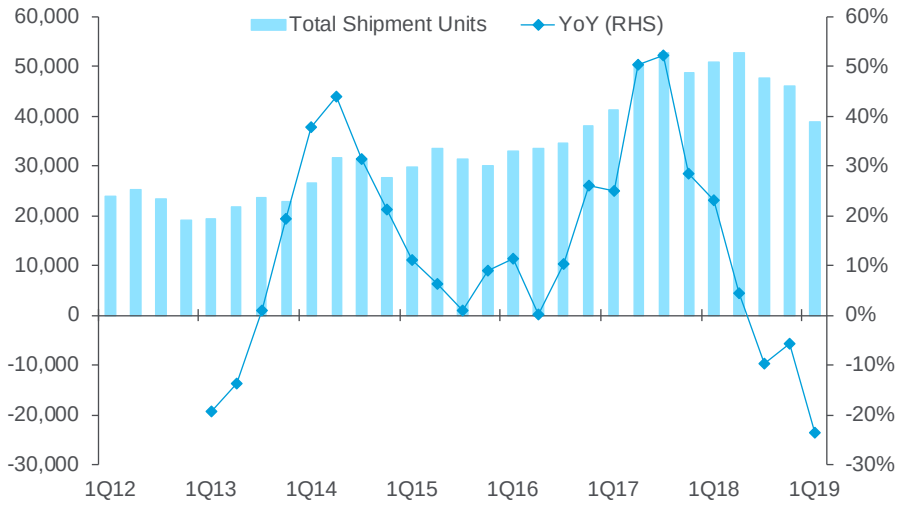


Source: Citi Research, IFR

According to the Robotics Industries Association (RIA), the North American association of robotics, North America saw a decline of 3.5% (in unit terms) YoY in robot orders in the first quarter of 2019, attributed to a decrease across most major industries including Auto components (-16% YoY), Plastics & Rubber (-16%), Electronics (-17%), and Metals (-17%). Looking at robot shipments versus orders, the decline was much sharper with a unit decline of 29% YoY. The RIA stated the weakness wasn't unexpected and is mainly due to tough comparisons, as 2018 was a record year, and long-term signs remain healthy. Data for Japan (from JARA, see chart below), show a similar decline in in the first quarter of 2019 for Japan.

As we explain throughout the report, we see substantial opportunity despite the current weakness.

Figure 3. Robot Shipments in Japan Have Seen a Dip in Recent Quarters



Note: Figures on left hand scale (LHS) note Japan robotics shipments
Source: Citi Research, JARA

What is the Factory of the Future?

New manufacturing technologies and the proliferation of data and computing power are combining with customer demands to shift to 'on-demand' manufacturing, driving significant changes in the way goods are produced. This has far-reaching implications for companies that supply and use these technologies, and also for employees and economies.

So what is the Factory of the Future? Definitions vary but we'd summarize as follows:

- **Flexible:** Mass personalization (the 'batch of one') requires fully automated production and supply chains. On-demand production and supply chains become key enablers. Rather than a world of fixed products created offshore, this is a world where everything exists in design or cyber space, where the customer creates the product they really want, and that product ends up being produced locally due to new advances in robotics and fabrication processes.

- **Digitalized:** Design, production, and service have to be digitally driven. To this end, companies talk of three 'digital twins' for manufactured products — a virtual version in design, in production, and in use. Key themes here include the data from connected devices — the IIoT — and the convergence of software and hardware. Digitization becomes a key enabler of distributed manufacturing, with 'digital twin' designs sent to and produced in fully-automated factories around the globe. Worker productivity can also be boosted by virtual and augmented reality devices to bridge the digital world and the real world in production, training, and service.

- **Zero waste manufacturing:** This not only refers to energy (and other resource) efficiency, but also the concept of 'circular manufacturing'. The United Nations Sustainable Development Goals highlight the need for responsible production.

Who Are Likely to Be the Disruptors?

The ultimate winner might be the consumer, but between corporate players we see two key battlegrounds — between the traditional industrial automation suppliers themselves, and over time between industrial automation companies and technology companies, i.e., 'new tech' vs. 'old industrial'.

- **Optimizing the process through 'vertical software':** 'Vertical software' is designed and used for a very specific industry, is already one of the largest and fastest growing software end-markets. The widespread adoption of connected devices creates a virtuous circle as more data collection allows more advanced analytics, and so further product and manufacturing process improvement through software. Vertical (i.e., industrial) software companies are increasingly competing with traditional industrial players, and while domain expertise (i.e., industry and application-specific knowledge) is key, we see this as an area of increasing competition.

- **Owners and interpreters of data:** It is too simplistic to say that data is the new oil; industrial data is valuable but not a commodity. Much industrial data is not readily available by default — the vibration of a motor is analog by default and needs to be interpreted and digitized. Domain expertise and an installed base are both key to collecting and contextualizing this data. We see industrial companies with large installed bases as having an advantage here.

- **Suppliers of advanced manufacturing systems:** While the penetration of robots in the automotive industry is quite high (>90% for some tasks), the penetration in general industry is far lower. The adoption of collaborative robots (cobots) to work alongside humans is still in its infancy. For years, robots have supported human activity in difficult, dangerous, and dirty tasks. Increasingly more capable robots that are able to adapt, learn, and interact with humans and other machines at semantic levels will create new jobs, improve the quality of existing jobs, and buy us time.

- **Suppliers of connectivity:** High reliability and low latency are key for connected industrial components, and we see enablers of connectivity (the suppliers of connectors and sensors, as well the enabling communication technologies) as benefiting, although the adoption of 5G presents its own risks of disruption for incumbents.

- **Cloud infrastructure is the backbone of the IIoT:** IaaS (Infrastructure as a Service, the 'bare bones' of servers, storage, and networks) and PaaS (Platform as a Service, to additionally include operating systems and database etc.) are key building blocks for Industrial IoT platforms; while industrial companies had moved towards PaaS models, the requirement for scale and technical expertise (rather than industrial expertise) is arguably beneficial to the cloud players here. Collaboration rather than competition between tech and industrials seem the most likely outcome here.

Figure 4. Robots in action…

Source: Dematic

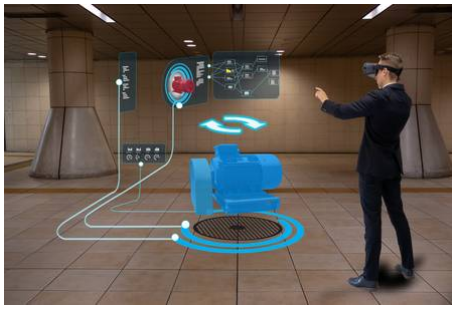
Figure 5. A Robot Gripper

Source: Robotiq

Figure 6. Training Using VR

Source: 123RF, Citi Research

Figure 7. Training Using AR

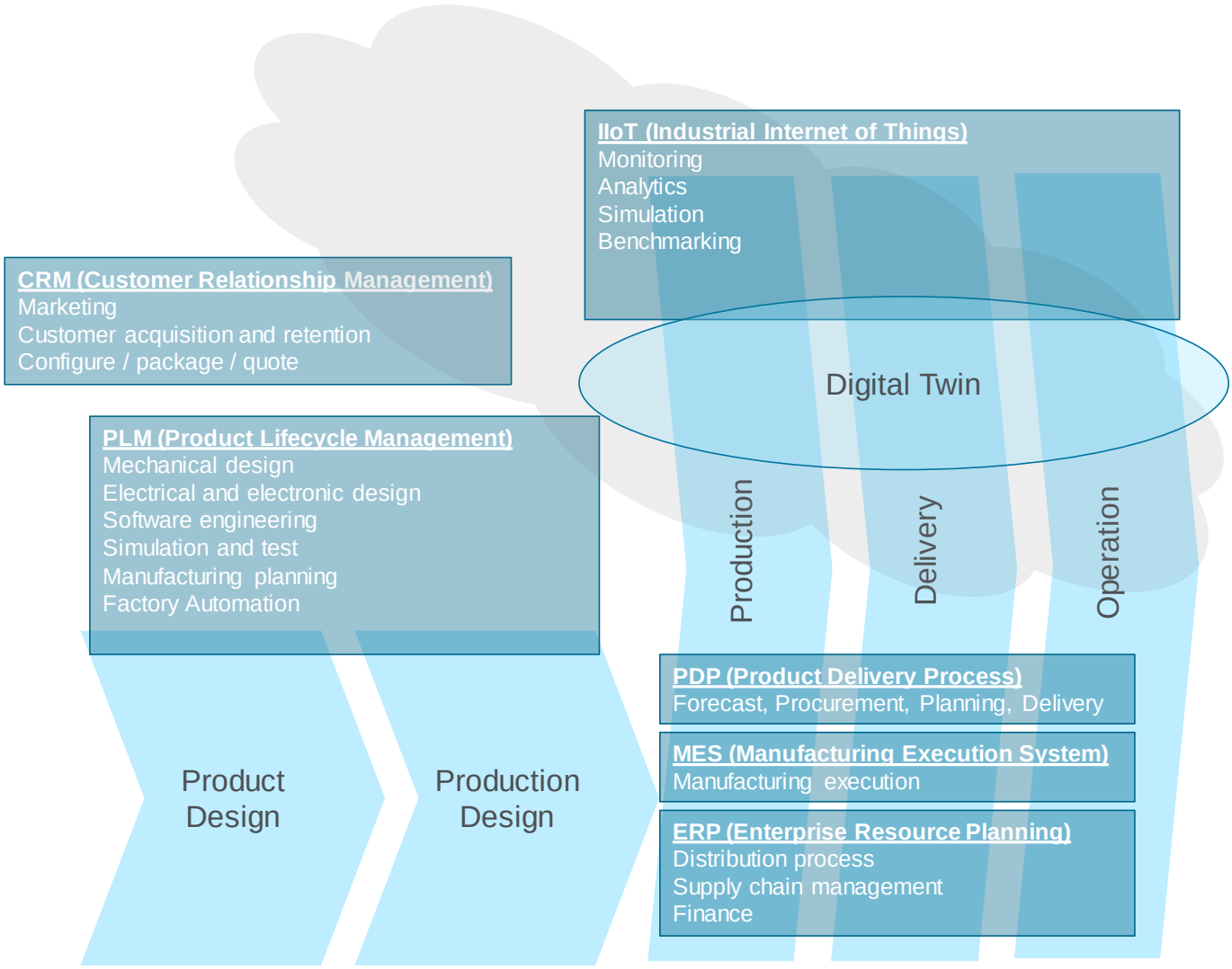


Source: 123RF, Citi Research

Figure 8. Workplace Leveraging AR

Source: 123RF, Citi Research

Figure 9. Inside the 'Digital Factory'



Source: Citi Research

Who Is Likely to Be Disrupted?

If distributed manufacturing means factories can be anywhere, what does that mean for labor, economies, and societies, particularly for manufacturing power houses like China and Germany? Will technology augment or replace the workforce, and if robots replace labor what is the impact on the workforce?

If earlier industrial revolutions were about capital versus labor, is Industry 4.0 all about data? How will factory owners, industrial automation companies, and software companies compete and collaborate to maximize the utility of this data? If the manufacturing industry produces more data than any other sector in the U.S. economy, what is the risk from cyber security?

Flexible Manufacturing

Distributed Manufacturing vs. Contract Manufacturing

Distributed manufacturing is not quite yet the Uberization of factories, but it does risk disrupting entrenched supply chains

Asset-light models of outsourcing manufacturing are not new — 'fabless' semiconductor manufacturing, where design and sales are kept in house but manufacturing completely outsourced, was first pioneered in the late 1970s and early 1980s. These models were built on long-term agreements; distributed manufacturing allows a much more flexible approach where small batches (or even a single product) are digitally instructed in real time — digital instructions to digital assembly massively opens up the number of factories that can produce a given component.

Contract manufacturing has been around for many years in industries ranging from consumer electronics to clothing. Foxconn, the world's largest contract manufacturer for consumer electronics, now has revenue of over $170 billion. As the name suggests, the manufacturing is contracted out with agreements lasting many months or years. In contrast, distributed manufacturing uses short-term outsourcing of manufacturing for a given product or component, potentially for only one unit to be made.

"*The idea of distributed manufacturing is to replace as much of the material supply chain as possible with digital information*"; WEF 2015

The concept of 'distributed manufacturing' was first popularized in 2015, when the World Economic Forum (WEF) listed distributed manufacturing as one of its ten 'emerging technologies' for 2015. WEF commented "*the idea of distributed manufacturing is to replace as much of the material supply chain as possible with digital information.*" In this example, if a company needs 20 subcomponents these can be precisely designed with plans digitally transmitted to potential suppliers, who can use these digital plans to feed a fully-automated manufacturing line to make the component. While simple in principle, there are limits; a 3D printer can be programmed to print any plastic object, or a lathe can be programmed to cut any metal shape, but a factory built to produce shoes cannot suddenly start assembling aircraft.

Distributed manufacturing is enabled by the digitization of design and production that we discuss later, and there are some benefits – and risks – to this development.

Key potential benefits include

- Reduction of inventory and transport times;
- Diversification of the supplier base;
- Optimizing industry capacity / lowering fixed assets ; and
- Differentiated experience for end customer.

Risks and disruptions could be:

- The disruption of traditional labor markets;
- The disruption of supply chains;
- The challenges of regulatory enforcement in industries where facilities may need to be certified (for example by the FDA); and
- The 'land grab' — both organically and through acquisition — to build IIoT platforms and access data may not always create value for every player; a small number of big winners may emerge.

Digital Manufacturing

We discuss the digitization trend in detail — in product design, in production, and in service — exploring the concepts of the 'digital twin' and the 'Industrial Internet of Things', or IIoT.

This also begs questions on data ownership and security, which we cover in our section on Managing Cyber Risk in Manufacturing

As the IIoT becomes more prevalent and industrial production leans more toward connectivity, data security becomes a bigger focus. According to Intel, a connected factory is estimated to generate 1 petabyte per day, the equivalent data of 1.05 billion minutes of MP3 songs, or data of 160 million books.

According to Cisco:

- Manufacturing produces more data than any other sector in the U.S. economy;
- 40% of manufacturing security professionals said they do not have a formal data security strategy; and
- There is a five-year lag-time in IoT adoption in factories due to cybersecurity concerns.

On connectivity, we discuss the theme of 5G telecom networks as an enabler of the factory of the future.

While there is much focus on the impact of technology on jobs, the role of technology augmenting, rather than replacing, workers is also prevalent. Cobots (collaborative robots) are designed for collaboration with workers and augmented reality (AR) can be used for instruction and guidance on production lines or for maintenance and service.

Green Manufacturing

The European Commission has targeted the 'Circular Economy' as part of its Horizon 2020 program, commenting that "*…the circular economy starts at the very beginning of a product's lifecycle — smart product design and production processes can help save resources, avoid inefficient waste management and create new business opportunities. By providing instruments and incentives to improve the production phase, the actions put forward will not only help save resources, but also boost innovation and cross-border trade in the EU single market*".

- **Better product design:** More durable products with replaceable parts — 'the circular economy'
- **Fewer resources in production:** German Auto manufacturer Daimler intends to cut CO_2 emissions at its new 'Factory 56' by 75% as compared to its existing S-Class production facility, including through having a CO_2 neutral energy supply.
- **A focus on by-products and waste:** One in which all waste products are productively reused and as such there is no absolute waste burden.

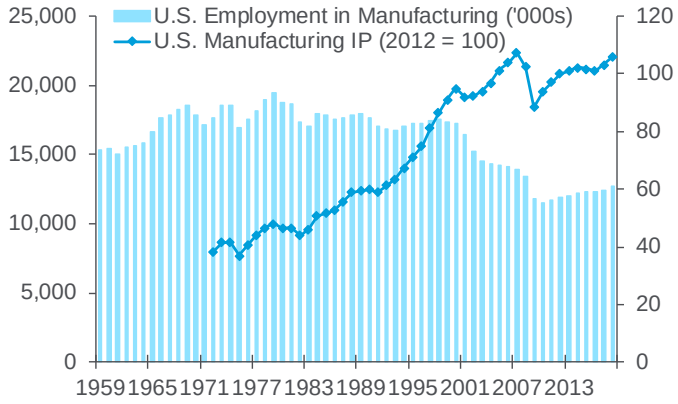
We explore this theme in detail later in a section on Sustainable Production and the Circular Economy.

New Technologies Are Defining Industrial Policy

The debate on automation and the impact on labor markets are not new, and one covered in earlier editions of the Citi GPS Technology at Work series. The impact of automation has been seen for years, although arguably the impact is less recently compared to the late 1990s and early 2000s. In the U.S., manufacturing employment in absolute terms peaked in 1979 (see Figure 10), and while manufacturing employment has been growing since the financial crisis, employment is not back above the level seen pre-financial crisis, and still far below the levels seen in the 1970s, 1980,s and 1990s. In output terms however, U.S .manufacturing output is close to a new high, only 1% below the 2007 output peak in 2018 (see Figure 10 below). If we look at output per employee however, U.S. manufacturing produces more than 3x more units per employee as compared to the employment peak in 1979. Output per employee has actually been quite stable since the financial crisis, with most of the improvement coming in the late 1990s and early 2000s.

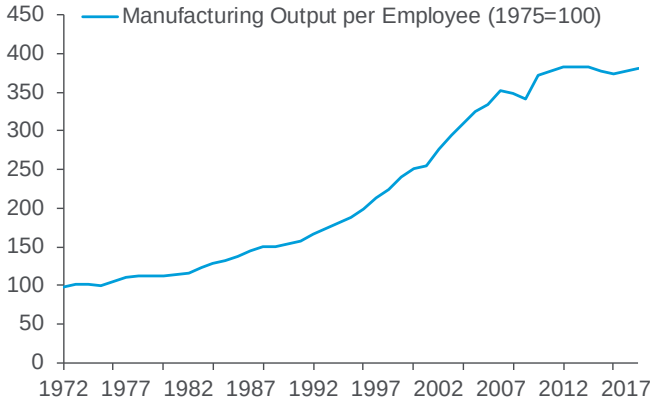
The digitization of industry and emergence of 'Industry 4.0' is however refocusing attention onto the impact of automation on manufacturing employment.

Figure 10. U.S. Manufacturing Employment vs. Industrial Production



Source: Citi Research, Datastream

Figure 11. U.S. Manufacturing Output per Employee



Source: Citi Research, Datastream

It All Started in Germany…

The term 'Industry 4.0' — for the fourth industrial revolution — was first coined by the German government. According to a European Commission paper, for Germany, Industry 4.0 is a "*national strategic initiative from the German government through the Ministry of Education and Research (BMBF) and the Ministry for Economic Affairs and Energy (BMWI). It aims to drive digital manufacturing forward by increasing digitization and the interconnection of products, value chains, and business models. It also aims to support research, the networking of industry partners and standardization.*"

The initiation, planned over 10-15 years, is based on the German government's High Tech 2020 Strategy, launched in 2011, and aimed as a "*strategic measure to consolidate German technological leadership in mechanical engineering*".

In Germany, the moniker 'Industry 4.0' has become the widely-adopted label for next-generation manufacturing, referring to the fourth industrial revolution (after the steam engine in the 18th century, the advent of the assembly line in the nineteenth century, and the introduction of automation technology in the 1970s). Since the launch of Industry 4.0 at the Hannover Trade Fair in 2011, we've seen an increasing number of companies define their strategies around the concept. The German government supports the initiative to ensure the global tech industry — largely based outside of Europe with software titans typically U.S. based and hardware specialists now largely Asian domiciled — doesn't benefit to the detriment of Germany's manufacturing industry.

… with China as the Driver

China's growth in higher value-added manufacturing has been a theme running for years, although the 'Made in China' 2025 plan, introduced by Premier Li Keqiang in 2015 formalized the initiative. While the 'Made in 2025' program may have been de-emphasized publicly, the tenets of achieving higher domestic share targets in critical industries will still resonate and likely intensify due to U.S.-China tensions.

Expedited by the recent trade war with the U.S. and increasing wages, the shift is visible; China is moving away from low-end goods (textiles, food products etc.) to medium high-tech goods (vehicles, electrical machinery, construction machinery etc.), and is now the world's largest producer in the latter (32% global share according to the National Science Board). Moreover, this is helped by not just the large domestic market but also the country's growth in exports (which has been growing at a resilient pace of an average of 5% per year since 2009) enabling export-focused Chinese capital goods companies and foreign companies invested in China to boost both their size and scale of investments within the country.

Citi economists discuss the impacts and strategies for Germany and China later in this note.

Figure 12. Key Components of the Factory of the Future: Software Markets typically Growing High-Single Digits vs. Low-Single Digit for Traditional Products

Key Markets for the Factory of the Future	Market Size	Next 5-year Growth (CAGR)	Market Size and Outlook
Factory Automation	$80bn	6-7%	Estimates vary substantially depending on market definition. One estimate puts the market at $80 billion with the addressable market expected to grow 6-7% per year over the long-term. (2019)
Robots	$16bn	14%	IFR estimates robot market at $16.2 billion (2017)
Warehouse Automation	$29bn	5%	One player estimates the market size at $29 billion and see about 5% growth between 2017-2022E (2018)
Vertical Software for Manufacturing Markets	$21bn	0.5%	
PLM (Product Lifecycle Management) Software	$12bn	6%	One player estimated the PLM software market size was $12 billion in 2018.
Automated Data Capture	$5-7bn	~3-5%	MMH states the top 20 players in the ADC market with a combined market size of $5 billion, and technology research firm VDC estimates the market to grow at about a 4% growth compound annual growth rate (CAGR) until 2021.
EDA (Electronic Design Automation) Software	$8bn	~9%	
Machine Vision	$3.5bn	High Single Digit	Cognex views its addressable market as $3.5 billion with high single digit potential (2019)
Industrial Sensors	$16bn	~6%	
IoT Application Enablement Platforms	> $1bn	~30% CAGR	Estimates vary depending on market definition, where we see forecasts range between $5-$10 billion by 2024-25
Industrial IoT/VR/AR Software	$2bn	~40% CAGR	

Source: Citi Research, IFR, ABB, Honeywell, MMH, Appsruntheworld, Dassault Systemes, Cognex, Grandview research, Market Watch

Robotics-Enabled Customized Manufacturing

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The rapid progress in computing over the past 50 years has made it indispensable. Computing has already transformed the way we work, we live, and we play: just imagine a day without the Web and all that it enables; a day without diagnostic medical imaging; a day without GPS; a day without digital media; a day without electronic commerce. The digitization of practically everything coupled with advanced robotics promises a future with democratized use of machines and wide-spread customization. For years, robots have supported human activity in difficult, dangerous, and dirty tasks. Increasingly more capable robots that are able to adapt, learn, and interact with humans and other machines at semantic levels will create new jobs, improve the quality of existing jobs, and buy us time. Advances in cognitive machines will allow us to move beyond using machines as simple tools toward human-machine partnership for improving all aspects of our lives. This requires that robots become more customizable, smarter, and easier to interact with. People and robots will have to come closer together to understand each other and to communicate effectively. The objective is not to replace humans but to create more intelligent tools for physical work in the form of adaptive robots and to find ways that allow humans and robots to collaborate more effectively. Robots are better than humans at crunching numbers and at physical tasks such as lifting things and moving with great precision, but humans are better than robots at reasoning.

The field of robotics aims to create the science and applications of autonomy by asking the questions: How do we design and control autonomous machines, how do we interact with these machines, and how do we use these machines? Current research on the algorithmic and device-level aspects of robots has demonstrated robotic devices that can locomote, manipulate, and interact with people and their environment in unique ways. These advances are possible because of recent progress in developing robot bodies and brains. The bodies of robots are coupled to the computation that comprises their brains and their intelligence and capabilities are a result of this coupling. Today's robots can do basic locomotion on the ground, in air, and in water. They can recognize objects, map new environments, perform pick-and-place operations, learn to improve control, imitate simple human motions, acquire new knowledge, and even act as coordinated teams in simple manipulation domains and in complex games like soccer.

At the root of these advances are several disruptive exponentials that impact disk storage, the scale and performance of the Internet, wireless communication, tools to support design and manufacturing, and power and efficiency of electronics. Also declining are hardware costs, for example the cost of a Universal Robot UR10 arm is approximately 80% lower than a typical industrial robot and estimates of cost of operation for advanced robots is as low as $4/hour.

The next step for robotics is the leap from personal computers to personal robots, leading to a world where robots exist pervasively and work side-by-side with humans. Over the past 50 years robotics made great strides. However, new robot capabilities need to be developed and existing capabilities need to be improved to create a world in which robots and humans can work together.

- Robot bodies should be easily integrated into our living environments.
- Robots should be safe to be around.

- Robots should take commands from human users easily.
- Robots should be functionally capable.
- Robots should engage humans to help mitigate error states and task uncertainties.

Meeting these challenges will bring robots closer to our vision of pervasive robotics. Current research directions in robotics push the envelope on each of these directions, aiming for better solutions to robot movement and ability to manipulation objects, increased ability for robots to figure things out, deeper machine vision, and more flexible coordination and cooperation between machines and also between machines and humans.

However, today's robots are still quite limited in what they can ‘figure out'' because their computations and operations are fairly carefully specified. While we have robot platforms that can move in agile ways and manipulate objects, developing new robot bodies is a lengthy progress. Today, the computation, mobility, and manipulation capabilities of robots, mechatronic devices, fixtures, and most other specialized hardware tools (computational and physical) are tightly coupled to the hardware of the system. Since robot architectures are fixed and difficult to extend, the capabilities of each robot are limited by its architecture. Fabricating new robots, add-on robotic modules, fixtures, or specialized tools to extend capabilities is not a real option, as the process of design, fabrication, assembly, and programming is long and cumbersome. However, new developments in computation design and computational fabrication of machines will bridge this gap, by providing fast ways to create custom machines and processes.

The promise for the future is a world where robots are as common as cars and phones. This is a big challenge for robotics, but its scope is not unlike the challenge of pervasive computing that was formulated about 25 years ago. Today we can say that computing is indeed pervasive, it has become a utility, and is available anywhere, anytime. Robotic technologies have the potential to join writing and computing to become a pervasive aspect of everyday life’s fabric. Just like the App Store has democratized access to computation, because for every computational task there is an app (or the potential of an app), the potential of democratizing physical tasks is equally profound.

Manufacturing will be greatly impacted by several emerging technologies in robotics, artificial intelligence, and machine learning. Today, robots have enabled mass fabrication. Tomorrow, they will enable a world of customized production where computational design and fabrication processes will support rapid manufacturing.

We already have robots working alongside people on factory floors, primarily performing repetitive tasks. In order for the robots to take on a greater variety of tasks, we need to develop a better way for them to interact with people. Humans and machines don’t speak the same language. Imagine telling your automated car, ‘park in the shady spot under the tree’. The machine inside the vehicle needs to look at its image of the surrounding area and find the right spot. It needs to understand the words ‘tree’ and ‘shade’, and translate them into bits and bytes. It needs to figure out that you mean the tree on the right, and not the one on the other side of the street. This is really hard. Now, consider all the specialized language needed in a variety of manufacturing contexts, as well as the sheer number of possibilities, and you can begin to see why building these robots will be challenging.

Advances in Natural Language Processing (NLP) will allow us to build robots capable of taking on a much wider variety of tasks, serving as specialized tools with some degree of autonomy, working side by side with people. There will be robots that know where things are, how to put things together, how to interact with people, how to transport parts from one place to the other, and even how to organize an assembly line. These robots will form teams with people, and your average manufacturing employee will be able to talk with these robots, and partner with them to perform tasks. They will be able to reconfigure assembly lines quickly, and create tools that allow one-of-a-kind designs. Working together, they will enable a new era of customized production that happens in factories across town instead of across the ocean.

Demand for customization is rising. People want products designed to meet their specific needs and preferences. Soon, anyone will be able to use templates to create novel product designs for clothing or book covers or even the chairs in their house. For example, the right color shoes, or the perfect size and firmness couch could be customized at the time of placing the order, without paying the extraordinary prices that make this level of customization impossible for most people today. These products will be fabricated locally using advances in production and 3D printing. Rather than a world of fixed products created offshore, this is a world where everything exists in design or cyber space, where the customer creates the product they really want, and that product ends up being produced locally due to new advances in robotics and fabrication processes. Advances won't stop there. Eventually, robots won't just be producing items of any shape and size; they will become them. Imagine the ability to program matter to change shape or even become invisible. It sounds like the stuff of science fiction, but eventually we will be able to program robots to change acoustics and move in 'stealth' mode so that they can't be detected by most machines.

By teaming machine learning, robot systems, and people together, the world of manufacturing could be reshaped to get people more involved in production, where product templates get designed by specialists, customized by people at home, and fabricated locally. This means a whole approach to production and jobs we cannot begin to imagine. It could mean smaller factories, located closer to population centers, making fewer generic standardized goods and more customized products. Even better, people won't have to understand how the robots work in order to use them. The job market will be democratized, as will the ability to purchase the products they produce.

The emerging computational design and fabrication tools have tremendous potential to disrupt manufacturing. Right now we have to design new robots and tooling in a custom way and it takes years. For this reason automation in manufacturing is lagging. Today the car industry automates approximately 80% of their assembly because they have repeatable and high-volume processes. In contrast only around10% of the assembly processes for electronics such as cell phones are automated. This is because the products are highly customized, have a short life cycle, and are produced in low volumes. The opportunity is to use computation to automate the design and fabrication of specialized tooling and robots that eliminate the fixed points of traditional manufacturing; in other words the technologies that will enable the rapid creation of one robot for any task. A challenge here is to develop the technologies to automatically design, fabricate, and program robots from an intuitive description of the task that non-expert users could specify. By enabling on-demand creation of robots, we can begin to imagine manufacturing lines that can support highly customized products. Configuring an assembly line requires tooling and processes. When the product changes, workers will have access to tools, which can rapidly reconfigure the assembly line.

Imagine the worker providing the new specifications to a computation engine connected to 3D and 4D printing computing technologies that are capable to update and fabricate the required new robots and tooling. The workers will still be in control of the machines, but their focus will be on control and coordination rather than hard physical labor. This could reshape the world of manufacturing by enabling rapid customization. The workers will be in charge of the operations of the factory, and the customers will have the flexibility to customize their product at home prior to purchasing it.

Two technologies that are enabling the next generation of safe and adaptive robots for human-centered manufacturing address computational design and fabrication of soft robots and origami robots.

A robot is classified as hard or soft on the basis of the compliance of its underlying materials.[1] Conventionally, engineers have employed rigid materials to fabricate precise, predictable robotic systems, which are easily modeled as rigid members connected at discrete joints. Natural systems, however, often match or exceed the performance of robotic systems with deformable bodies. Cephalopods, for example, achieve amazing feats of manipulation and locomotion without a skeleton; even vertebrates like humans achieve dynamic gaits by storing elastic energy in their compliant bones and soft tissues. Inspired by nature, engineers have begun to explore the design and control of soft-bodied robots composed of compliant materials. 'Soft' refers to the body of the robot. Soft materials are the key enablers for creating soft robot bodies. While Young's Modulus is only defined for homogeneous, prismatic bars that are subject to axial loading and small deformations, it is nonetheless a useful measure of the rigidity of materials used in the fabrication of robotic systems.[2] Materials traditionally used in robotics (e.g., metals, hard plastics), have moduli on the order of 109–1012 Pa, whereas natural organisms are often composed of materials (e.g., skin, muscle tissue) with moduli on the order of 104–109 Pa (i.e. orders of magnitude lower than their engineered counterparts). We define soft robots as systems capable of autonomous behavior that are primarily composed of materials with moduli in the range of the moduli of soft biological materials. Advantages of using materials with compliance similar to soft biological materials include a significant reduction in the harm that could be inadvertently caused by robotic systems (as has been demonstrated for rigid robots with compliant joints), increasing their potential for interaction with humans. Compliant materials also adapt more readily to various objects, simplifying tasks like grasping and can also lead to improved mobility over soft substrates.

Origami robots redefine how we make and use robots.[3] Traditionally, robots have been complex systems consisting of many parts (e.g. rigid members, actuators, sensors, microprocessors), requiring significant human development effort and expertise in multiple disciplines to design, build, and control. Conventional fabrication of robots is a serial assembly process where the addition of design elements increases the complexity of fabricating and controlling the robot. Folding is a means of decoupling design complexity from fabrication complexity. It enables creating new 3-D structures from planar sheets that can be made from a wide range of materials (e.g., plastics, metal, paper, rice paper, sausage casing, etc.) by manipulating the planar sheet intuitively.

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[1] Daniela Rus and Mike Tolley, Design, Fabrication, and Control of Soft Robots, Nature 521 (7553) 2015.

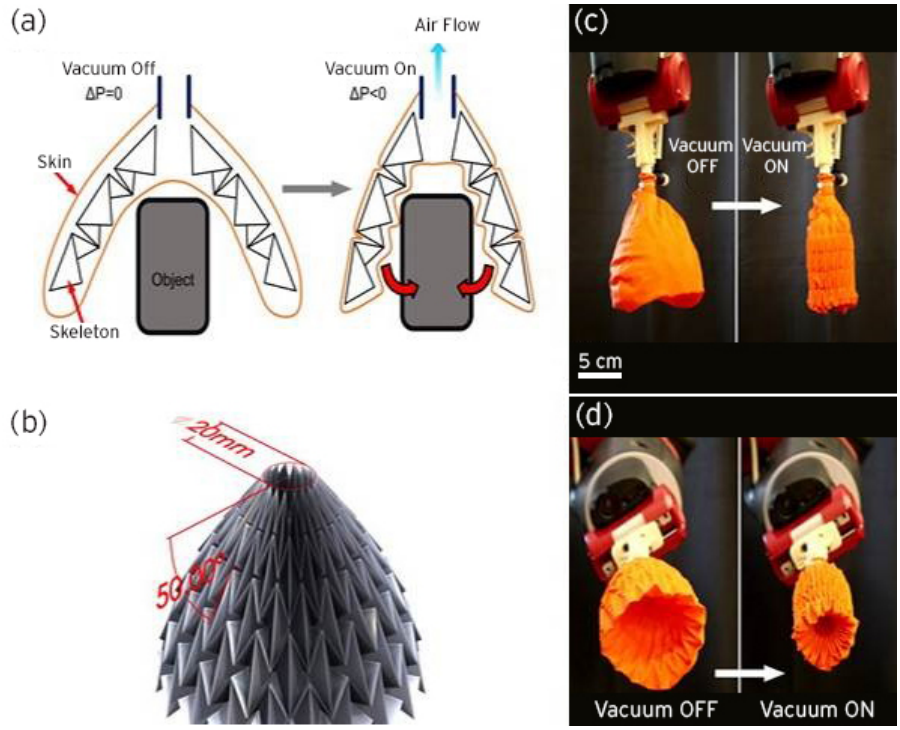
[2] Majidi, C. Soft robotics: A perspective–current trends and prospects for the future. Soft Robotics 1, 5–11 (2013).

[3] Daniela Rus and Mike Tolley, Design Fabrication and Control of Origami Robots, Nature Reviews Materials 3 (6), 101, 2018.

When these techniques are leveraged for robot manufacturing, the results are fast to produce and require little manual assembly. Advances in flexible electronics, where circuitry can be laid out directly on robot bodies themselves, allow actuators and sensors to be placed correctly without additional wires. As a result, fully functional origami robots can be customized and printed as needed within hours, or even potentially, since they are all made of sheets anyway, refolded into new robots on-site.

The first industrial robot called the Unimate was introduced in 1961. The robot was invented to do industrial pick and place operations. By 2020 the number of industrial robots is projected to be around 31 million. These industrial robots are masterpieces of engineering that can do much more than people can. Yet these robots remain isolated from people on factory floors because they are large heavy and dangerous. By comparison organisms in nature are soft safe compliant and much more dexterous and intelligent. Soft-bodied systems like the octopus can move with greater agility, they can bend and twist continuously and compliantly and have the potential to execute tasks that require dexterity and strength. Systems like the elephant trunk are able to exhibit delicacy. An elephant is able to pick up a banana from a child and yet the elephant trunk can move with strength to whip a challenger. These examples inspire us to rethink what is a robot and how we use robots. While the past 60 years have defined the field of industrial robots, and empowered hard bodied robots to execute complex assembly tasks in constrained industrial settings — the next 60 years will be ushering in robots in human-centric environments and a time with robots working side by side with people on the factory floor or at home. While the industrial robots of the past 60 years have mostly been inspired by the human form — the next stage will be soft robots inspired by the animal kingdom with its form diversity and by our own built environments, with broader applications potential. The new robots will be made from a wonder range of materials that go beyond the current use of metals and hard plastics, to include silicone, paper, and even food compounds. Soft robots and origami robots are first steps toward a future of customized manufacturing where machines and people work side by side.

Figure 13. Example of Vacuum Suction Cup



Source: Citi Research: Shuguang Li and Jason Dorfman, CSAIL MIT arch

Digital Manufacturing

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Design, production, and service have to be digitally-driven. We discuss one key component of this, the Industrial Internet of Things (IIoT), in a later section, but the digitization of the manufacturing process is much broader. To this end, companies often talk of three 'digital twins' for manufactured products — a virtual version in design, in production, and in use. Key themes here include the data from connected devices — the IIoT — and the convergence of software and hardware. Digitization becomes a key enabler of distributed manufacturing, with 'digital twin' designs sent to and produced in fully automated factories around the globe.

The 'digital twin' mirrors the physical product through design, production, and in operation

The concept of the 'digital twin' is now commonplace at manufacturing and automation companies. One corporate commented that "*A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart's performance characteristics. Digital twins are used throughout the product lifecycle to simulate, predict, and optimize the product and production system before investing in physical prototypes and assets.*"

Digital twins are used for:

- **Product design:** CAD (computer-aided design) has been established since the 1960's, although the concept of a 'digital twin' for a product is usually wider than this, referring to the precise configuration of specific identifiable product in the field (not just the electronic design for that model of product). Simulation and production planning during the design stage also help optimize the next production stage. One industrial player estimates that time to market for aircraft has been reduced from six years to 2.5 years due to the digitization process. With the proliferation of software-as-a-service into all markets, web-based CAD products, leveraging centralized cloud compute and storage, are bringing these products down to the smallest of manufacturers and other participants in the product value-chain.

- **Production:** Some production technologies already fit naturally with digital product design — including CNCs (Computer Numerical Control used in machine tools) and 3D printing, although the increased penetration of automation (including robotics) is a natural synergy of having a 'digital twin' of the product from the design stage. For the manufacturing process overall, simulation, training, and optimization of production are all enabled by this 'digital twin'.

- **Performance:** The IIoT is a massive enabler of creating digital representations of products in use in the field, used for diagnostics, performance measurement, benchmarking, simulation, and more.

Digital twins can lead to lower costs for manufacturers due to shorter times to market, a cheaper iterative design process, production lines that can be optimized concurrently with product design, and designs that can be continuously improved to reflect real world operational feedback.

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A Real Life Example – Aerospace

An area where advancements in 'digital twins' have had a profound impact is in Aerospace — a major aerospace OEM stated this helped them achieve a 40% improvement in first-time quality of parts and systems across commercial and military aircraft.

There are three different stages where digital twins are used in Aerospace:

- **Product:** Design, simulate, and test products digitally, such as aircraft nose electronics (radome) and landing gear mechanics before an aircraft is certified as fit to fly.
- **Production: Plan:** Simulate, predict, and optimize production processes for different parts of the aircraft, such as production of a wing. As previously stated, one industrial player estimates that time to market for aircraft has been reduced from six years to 2.5 years due to the digitization process.
- **Performance:** Simulating performance such as the impact on landing gear from turbulence, or to get a sense of when aerospace engines will require maintenance and/or repair and more accurately determine the life of structural components.

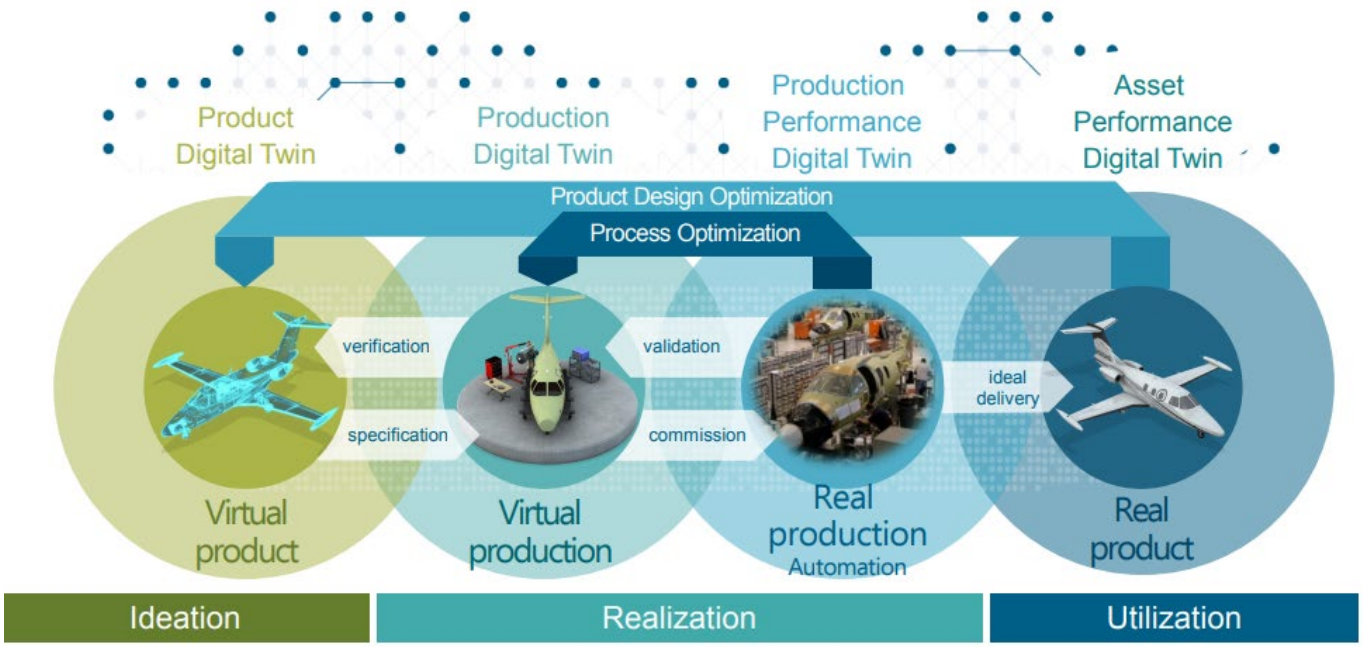
Developments in 'digital twins' have had a particularly big impact for the aerospace engine manufacturers in:

1. **Design**, given an engine's complexity and the high cost of using the 'trial and error' approach or finding a significant fault at the testing phase, particularly as any design changes may require re-certification,
2. **Tracking performance** and forming simulations for early warnings and predictions of maintenance/aftermarket requirements using inputs such as weather, performance, and operations — including identifying which parts are going to be problematic. This takes out a lot of the fixed costs associated with maintenance by (a) allowing engine aftermarket companies to arrange for pre-emptive maintenance to avoid expensive failures, and (b) allows companies to pre-emptively design a solution or upgraded part which they can use in place of the existing part. This is particularly important for engine manufacturers given the increasing number of long-term service agreements (LTSA), i.e. the manufacturers take on the cost burden on repairs.

A British engineering company stated that prior to the developments in 'digital twins' they would typically have significantly damaged or destroyed several engines (30-40 engines in the case for the AE3007) in the design and testing phase of a new engine (each engine costs tens of millions of pounds to produce). This compares to current design and testing of the 'Advance3' demonstrator engine, where the company has produced one core which has been operational in tests (with no engines destroyed).

One of the more challenging performance tests for engines is to gauge the impact when one of the fan blades breaks during a flight and whether the engine would stay in its casing. Previously, this test was conducted by revving up the engine and then igniting a small explosive charge on one of the blades. Testing this instead on a digital twin allows the company and other engine manufacturers to predict how the engine will behave, increasing the probability of the engine passing the real test the first time, saving hundreds of millions in costs.

Figure 14. The Three Different Stages Where 'Digital Twins' Are Used in Aerospace



Source: Siemens eAircraft

Digital in Design

Product Lifecycle Management, or PLM, involves the management of the entire lifecycle of a product from its inception to disposal. The lifecycle includes 3D design, process simulation, model testing and analysis, digital manufacturing, and operations management. PLM is typically a suite of software applications focused around the design, data management, and manufacturing specifications for products. CAD (computer-aided design) is probably the best known, but PLM software also includes programs that perform simulations, and translate designs into manufacturing specifications.

- **CAD (computer-aided design):** Computer-aided design software, or CAD, allows the user to design the product on the screen to build a true-to-scale model that can be the input into the manufacturing process. The majority of these tools enable design in 3D, which has significantly improved their usefulness. Also, lightweight / SaaS-based products have democratized the adoption of these tools.

- **CAE (computer-aided engineering) software:** CAE software enables the simulation of various aspects of the PLM process. This includes FEA (Finite element analysis; the stress test of the product), CFD (Computational fluid dynamics; managing heat and fluid flows), product/process optimization (testing if the process or product functions with maximum efficiency), motion analysis, data management, post-processing visualization, etc. The virtually unlimited compute power in hyper-scale clouds has significantly improved the extensiveness of the simulation process, in an efficient manner.

- **PDM (product data management) software:** PDM software is used for managing and publishing product data (or 'version control'), which includes technical specifications, manufacturing and development specifications, and raw materials of the product. The software itself enables the user to track down data, provides tools to organize the data, and control them. A cloud-connected PDM offering can help to automatically search inventories of raw materials and also integrate into the procurement process to ramp manufacturing scale.

- **CAM (computer-aided manufacturing) software:** CAM software refers to software that uses numerical control applications that drive CNC (computer numerical control) machine tools for manufacturing parts. Used together with CAD and CAE and PDM software, CAM software serves to optimize the manufacturing process in the industrial automation process.

One industry player estimates the PLM software market to be around $12 billion (this includes CAD, Simulation, Product Data Management, and Digital Manufacturing).

Advances in software, namely published application program interfaces and SaaS, have enabled '360 degree' linkage — the more seamless integration of packaged and custom-built software. There has also been significant innovation by new entrants and specifically eCommerce in consumer-facing markets, such that there is a higher expectation of tight linkages between front-office marketing, shopping, ordering, and even customer support with back-office manufacturing. This has forced the manufacturing process to be more responsive as the front office software market has grown much faster than the more mature manufacturing software (ERP +) market. We see a battle looming for strategic relevance between software that is closer to the customer (customer relationship management (CRM)) and software that is closer to the product process (enterprise resource planning (ERP), manufacturing control).

Digital in Production

Connecting the Factory

Factories have been digital in many ways for decades — PLCs, or programmable logic controllers, were introduced in the 1960s, and are commonplace for directing the activity of plant on the factory floor. CNCs, or computer numerical controls, used for programmable metal cutting, were also developed in the late 1950s. While there are some manufacturing methods that are inherently digital (see 3D printing below), the digitization of manufacturing means all processes are tracked digitally. We discuss robotics separately in more detail later in the report, and highlight several key advantages of connectivity:

- **Digital tracking:** Digitally tracking products through the supply chain, factory, and delivery by embedding products with RFID for example. 5G connectivity throughout the plant. Cognex estimates the Machine Vision market at around $3.5 billion, with 2D vision ($1.1bn) and ID Factory automation ($900m) the largest segments within that market. Cognex, a player in the industrial machine vision space, says the largest opportunity for its machine vision is in manufacturing.

- **'360 degree' linkage:** This full digital linkage to suppliers and customers allows more bespoke ordering, and substantially increases efficiency. Digitally-enabled factories allow direct linkage to customers for customizable products (the 'batch of one'). A 2016 Harvard Business School study looked at Nike's quest for mass-production of customizable shoes — much easier with digital instructions passing from customer to factory. Equally for suppliers, the digital instruction resulting from that customer order through to the component order fulfils the vision of '360 degree' linkage, and the demand-driven supply chain.

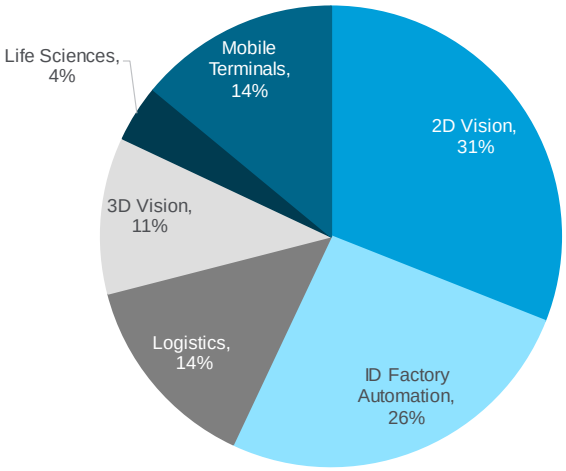
- **3D printing / additive manufacturing:** 3D printing enables manufacturing of highly customized products to the end user, and this particular application can be utilizable in segments that require high levels of customization by nature. Examples would be in medical devices (where patients require customized medical solutions) making customized braces, bioprinting for organ transplants, and drug testing etc. However, there are still challenges imposed for further applications; nano-scale computer parts, like processors, are difficult to manufacture this way because of the challenges of combining electronic components with others made from multiple different materials. A solution to this could potentially be a further advanced '4D printing', which can adjust the process to accommodate environmental changes, such as heat and humidity. This could be useful in clothes or footwear, for example, as well as in healthcare products, such as implants designed to change in the human body. Although 3D printing is potentially highly disruptive to conventional processes and supply chains, it is still a nascent technology with applications still largely confined to the automotive, aerospace and medical sectors. Rapid growth is expected over the next decade as more opportunities emerge and innovation in this technology brings it closer to the mass market.

Figure 15. 3D Printing Offers Potential Opportunity to Mitigate Modern Supply Chain Challenges

#	Supply Chain Challenge	3D Printing Benefit
1	Parts are expensive to manufacture under traditional methods	Stabilize costs & minimize price per unit
2	Manufacturing processes can suffer from long lead times	On-demand production helps minimize lead times
3	Inventory holding costs can be onerous	Facilitates just-in-time & on-demand printing/ production
4	Concentration of supply from one manufacturer	Reduces concentration risk associated with suppliers
5	Difficulty in becoming truly global	Parts can be made where & when required, even in remote locations
6	Import/export fees & tariffs can be punitively high	Helps minimize/ eliminate import & export fees
7	Low functionality of existing parts	Facilitates design of new parts, products & repairs

Source: CBRE, Citi Research

Figure 16. Machine Vision Market by Segment



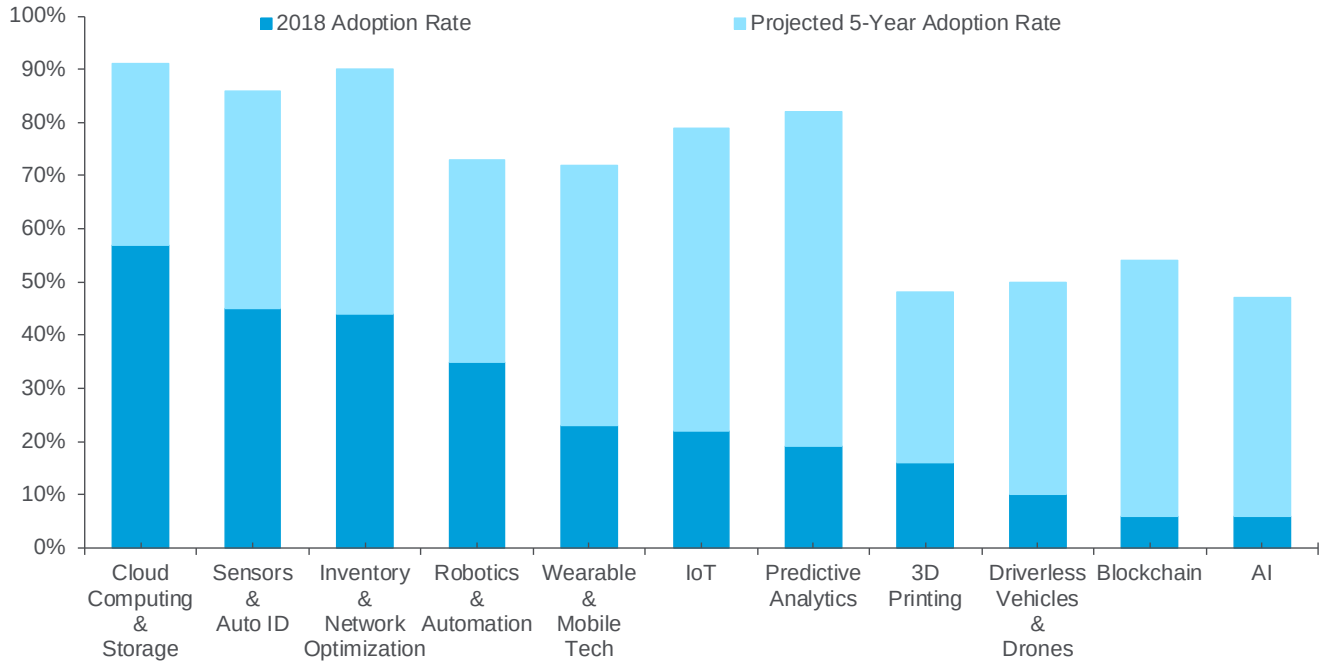
Source: Citi Research, Cognex

Digital in Performance

The IIoT is a massive enabler of creating digital representations of products in use in the field, used for diagnostics, performance measurement, benchmarking, simulation, and more. Gathering data on every component in the factory (on throughput, efficiency, and more) enables an optimization and benchmarking of processes that was not possible beforehand.

We discuss the IIoT in more detail later in the report

Figure 17. Adoption Rate of Innovative Technologies in Supply Chain, In Use Today



Source: MHI, Citi Research

Blockchain as an Enabler of Distributed Manufacturing

Blockchain adoption in industrial companies remains very early stage, largely contained in the corporate R&D function, or in some cases early-stage equity investments in related start-ups. Blockchain is clearly being considered though as a potential disruptive force — according to a survey by Cognizant, a digital consultancy, manufacturing and logistics is the industry that is most considering using open blockchain, ahead of banking, retail and other sectors.

- Initial areas of exploration include supply chain, product certification, and smart contract execution. We don't expect industrial companies to see a notable impacts to earnings in the near term, although as many companies look to broaden their industrial software and data offerings, blockchain could be one technology used, especially in areas like supply chain management and energy (electricity) management, and as such may begin to show up in R&D budgets.

- As supply chains have lengthened and companies increasingly outsource, problems like counterfeit products and a need to prove provenance of products for CSR reporting has become more important. The purpose of blockchain would be to record the supply chain history of a product in blockchain, with the intent to increase / improve supply chain security for manufacturers. We'd say concrete developments in supply chain applications for manufacturing companies are very limited at this stage.

Figure 18. How Manufacturing Companies Use Blockchain

	Blockchain in Manufacturing
Supplier Contracts	Supplier contracts through block-chain can formalized the procure-to-pay process, meaning payment is automated and rules based. This becomes increasingly important as supply chains become fragmented
Traceability	According to a Cap Gemini survey, >80% of organizations cite traceability as of the top three drivers of block-chain investment.

Source: Citi Research

Industrial Software

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Three are a number of trends in the software market both developing alongside and contributing to the evolution of the 'Factory of the Future'. We see significant advances in areas that can be categorized a combination of enhancing the buyer experience and driving back-end efficiency. In many cases, these two drivers are inter-related. Historically, buyer demands have run out ahead of a supplier's ability to fulfill. An obvious example is shorter manufacturing lead times, however other examples are numerous, many of which we will discuss below.

Consumer Technology Forces Yet Again Are Driving Innovation in the Factory

The software underpinnings supporting the Factory of the Future are not unique to the manufacturing industry. Most have roots in consumer technology, like modern software integration technology, hyperscale cloud computing, optimized user interfaces, and big data analytic technologies. It is largely the marrying of these technologies with domain expertise in various industries, which is transforming the software that controls the manufacturing process and marrying it with 'front-office' software that is the gateway to the customer. While this may seem like an obvious progression, there has been a fundamental rearranging of the software stack that supports manufacturing, which has varied in its pace of adoption across various industries. The result has been an 'outside-in' flow of software integration — starting with the software purchase and integrating back to the manufacturing control side. This is a change from the 'inside-out' orientation that started in the mid-1990s as enterprise resource planning (ERP) systems went mainstream. While consistent market numbers to track this are not available, it is worth noting that in the 2000s, the ERP market (back-office) was the largest of the application software markets. While this is still true today, we note the 'front-office' market has clearly seen the most significant growth rates over the last several years, both in terms of rate of growth of scaled companies as well as new company formation and the volume of venture capital funding. CRM revenue is now >50% the size of markets leaders such as SAP after having been founded in 2000 during the heady days of ERP deployments.

The Purchase and Ordering Process Has Fundamentally Changed in the Era of eCommerce

As eCommerce and even business-to-business (B2B) versions of eCommerce grow in terms of share (currently 10% of U.S. retail), it is fundamentally changing the purchase and ordering process. There are now clear user expectations for immediate and accurate inventory as well as fulfillment times and terms. This also comes with proactive notification of changes in the supply chain. The ability to provide this information and ultimately fulfill demand relies on real-time integration from the front-office into the back office. We note this trend has resumed the consolidation effort between these two markets that languished in the mid-2000s.

While business-to-consumer (B2C) eCommerce is the showcase example, the transformation of the purchasing and ordering process extends to the front-office supply chain where there are wholesalers, dealers, channel partners, parts, and after-market services partners.

The process continues even more upstream from eCommerce, as digital marketing, salesforce automation, and customer service software is able to detect needs and predict future demand that can be fed into the manufacturing process.

With all of these functions increasingly tied together (i.e., a successfully resolved customer service episode is a market event), the consolidation towards a small number of front-office suites is inevitable. We believe with CRM having all but consolidated the needed front-office capabilities, it is on the offense integrating into the back-office to take the strategic high-ground (the back-office 'plugs into' its integration technology, not vice-versa).

Procurement and Supply Chain Optimized with Software

Supply chains have been digitized, to some degree, for many years. Much of this has been through proprietary, manufacturer-driven networks and these structures will likely remain in place for some time. Leading the way has been the procurement and supply chain of so-called 'indirect' materials that facilitate business — from purchasing office supplies and catered lunches to even health insurance. The 'network' concept has prevailed here, whereby there is an onboarding and supplier certification process and then direct bidding and matching of bids. This has even extended to contract labor where the employer is looking for a well-defined, arguably commodity skill-set. Manufacturing raw materials have been slow to move in this direction, largely because the data required to match bidders with suppliers is locked up in proprietary networks powered by decades-old electronic data interchange (EDI) technology. Modern replacements for EDI are emerging, albeit slowly, to increase the flexibility of supply chains.

This supply chain modernization extends out of raw material procurement and into the post-production logistics and alignment with the above mentioned purchasing and ordering system. Enabled by software, the post-production supply chain is also being modernized. This ranges from 'omnichannel' inventory management to 'shipping as a service'. This flexible post-production supply chain helps drive customer-driven flexibility back into more flexible manufacturing and a more flexible raw material supply chain we discussed earlier.

Aftermarket Services Opportunity Powered by Software

The last development in manufacturing powered by software that is worth diving into is the expanded market for aftermarket services. Manufacturers have long offered repair services and even operational managed services to customers. Advances in software, connectivity, and sensor technology have significantly enhanced this opportunity. Instrumented products based on high density sensors and connected over LTE (and soon 5G) networks have allowed real-time monitoring of equipment. A service call can be informed with real operational data from a piece of running equipment, enabling a repair person to have the right parts on site and be able to 'pre-diagnose' root cause. The improved employee productivity that is gained results in higher margins and also improves service outcomes for the customer. Advanced analytics and machine learning can be put to work on data in a managed services scenario and significantly boost the value of these already high-margin offerings.

Factory Automation and IoT within Design Software: Big Opportunity but Still Early

The Factory of the Future is a big theme we see benefitting companies in the PLM, CAD, and simulation categories. In the section that follows, we discuss the interplay between the relatively new connected Industrial IoT platforms (and the associated AR/VR components) with the traditional PLM/CAD and simulation products which have been on the market for decades. Simulation is an important piece of an IoT platform, and an area we see as difficult to 'get right' given the complexity of physics.

While the industrial IoT software market is forecast to have significant growth potential (e.g., $1.7 billion today across IoT/AR/VR growing to $10 billion by 2023), we would caution it's still early and highlight that much of the future market growth (like any new software market) depends on customers continuing to expand beyond basic use cases today with continued high return on investment. Use cases today primarily span across monitoring and operational intelligence, although market growth estimates factor in these evolving to much more strategic initiatives (i.e., digital twin, connected factory through IoT). We also note the emergence of some mixed signals recently, which could simply be normal growing pains, but nonetheless an area we believe should be monitored given the early stages of the market and relatively high growth expectations.

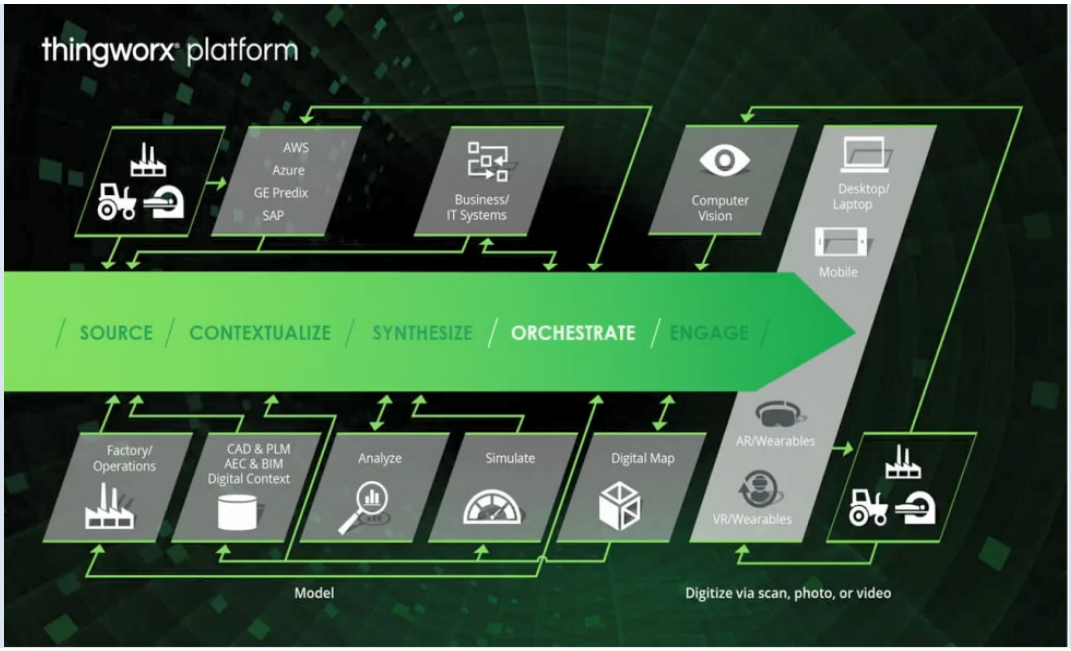
PLM and CAD Businesses Are Important Foundations of IoT

Traditional PLM and 3D CAD are used by manufacturing and industrial companies across the world. PLM refers to technology that enables organizations to design, store, measure, and track various physical product attributes throughout their lifecycle — from creation to retirement. In some ways, a PLM system can be thought of as an ERP system, in that it serves a single source of truth for all things product related (much like an ERP is the 'back office' single source of truth). PML and 3D CAD are complementary products as their tight integration can capture important changes in design and maintain a single system of record.

The ThingWork Platform: An Example of IIoT Components

As discussed in earlier sections of the report, Industrial IoT platforms typically contain several key features/processes that can enable the notion of a connected factory. To better illustrate the various components we highlight the ThingWorx platform. The ThingWorx platform was acquired in December 2013 as a standalone service but four more deals by the parent company — buying Axeda in July 2014 for device management, Coldlight for analytics in May 2015, Kepware in December 2015 for edge data collection and processing, and Vuforia in November of 2013 for Augmented Reality — led to functionalities being folded into the core platform. Figure 19 below illustrates the various components of an IoT platform (in this case ThingWorx):

Figure 19. The ThingWorx Platform

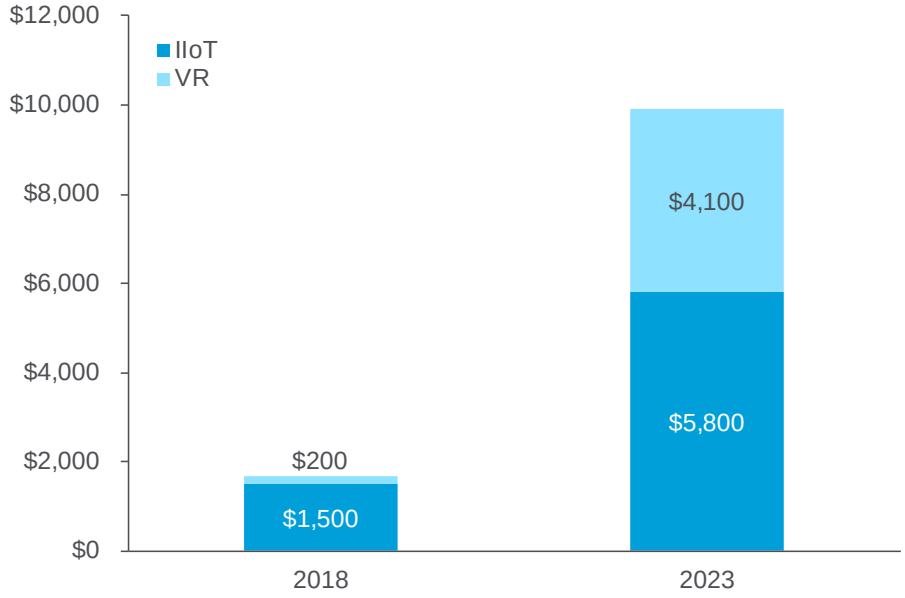


Source: Citi Research, ThingWorx

Robust Market Forecasts for IoT

Industry research from IoT Analytics puts the software industrial IoT market at $1.7 billion in 2018 growing to $10 billion by 2023. This includes both the contribution from IoT and AR/VR.

Figure 20. The IIoT Market is Set to Grow ($ millions)



Source: IoT Analytics, Citi Research

Although Not Without Signs of Caution

While clearly this is strong growth forecast (+42% compound annual growth, CAGR), we note that more recently we've seen some signs of caution in the market. In June 2019, industry research firm Gartner published a Magic Quadrant report on the Industrial IoT market, approaching the overall market with some caution by choosing not to place any vendors in the typical 'Challengers' or 'Leaders' quadrant. The lack of leaders or challengers is uncommon and could reflect: (1) the early stage of the opportunity; and/or (2) uncertainty around market size and potential concerns around use cases generating high enough return on investment.

Use Cases: Operational Intelligence and Monitoring are Big Use Cases

Some of the early IoT use cases revolve around operational intelligence for manufacturing. This enables manufactures to gain complete visibility of their industrial operations and have the tooling to monitor key efficiency metrics to drive improved processes. Monitoring is done across individual machines, for things like downtime and visibility into the broader factory. Ultimately, monitoring and better visibility into factory operations can enable more prescriptive use cases like predictive maintenance and remote monitoring/remote service, which can save organizations costs by minimizing downtime.

Digital Twins and Continuous Service Models Aare Enabled by PLM, 3D CAD, and IoT

While operational intelligence and monitoring are arguably easier initial use cases, much of the excitement centers around the idea of a digital twin and continuous service models. These markets are still very early stage, and while there are a number of competitive platforms in the IoT space, there are few that have the PLM/CAD foundation. This is an important distinction as IoT platforms will need to leverage core PLM and 3D CAD systems for key product/design information which can be synthesized with newer IoT data to provide real-time feedback and predictions to drive better outcomes.

Industrial companies often paint the picture of a connected future where capital equipment will be delivered in a cloud-like 'as-a-service' model with uptime or efficiency as the new units of cost. The combination of a PLM and 3D CAD offering is likely to be viewed as a key component of an equipment service model. PLM would be necessary to enable what many industrial manufacturing companies are referring to as a 'digital twin' to couple with each physical asset. The 'digital twin' will be able to incorporate IoT data to assist with maintenance and provide a feedback loop for future development.

The combination can also enable a more efficient approach for continuous service models. Equipment manufacturers would be able to remotely access devices in the field to analyze, diagnose, and potentially remedy their product.

VR Factory Automation Use Cases Help Increase Efficiency and Lower Cost

Virtual reality (VR) serves a critical piece to the connected factory. The Factory of the Future will undergo significant retooling and computerization, which will require extensive amounts of new workforce training and automation which can be improved through technology such as virtual reality. VR technology can augment or in some cases replace formal training processes and lengthy user manuals through an immersive and interactive experience. This can have the effect of dramatically lowering costs and increasing equipment and labor utilization.

Simulation is a key part of IoT / digital twin

Part of the digital twin trends involves incorporating real-time simulation into product design where product designers can gain real-time feedback and insights on how products respond and optimize the product design on the fly.

End-to-End Platform Could Deliver Definite Competitive Advantage

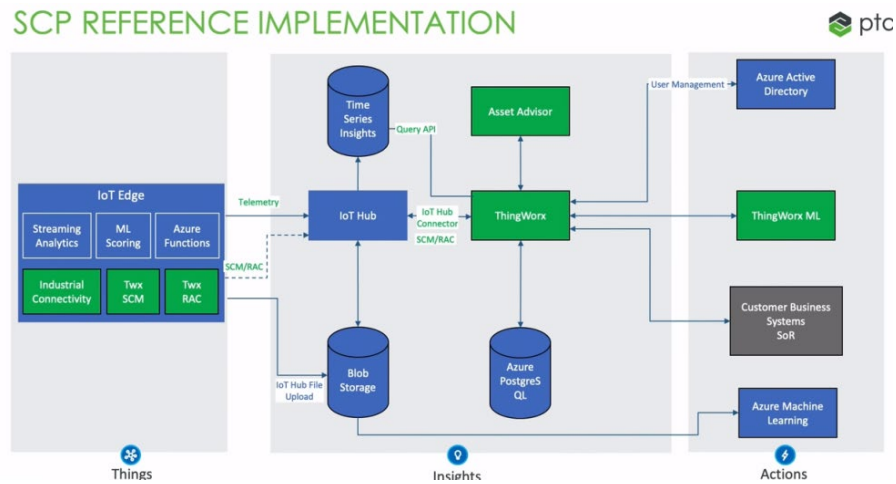
Software companies have developed platforms that are end-to-end solutions for their clients providing value at the modeling layer with design tools along with integrating big data science at the experience level capturing customer information plus the addition of reliability to additive manufacturing designs through the use of simulation.

While these platforms are seen as the more advanced PLM solution and represent ambitious attempts to come up with an end-to-end platform, we understand that most major software customers are still using a mix of solutions owing to some challenges in implementation as the platform matures. However, there has been uptick with traction in big clients and we believe that success in consolidating on a single end-to-end solution platform could lead to further traction.

Partnerships Are Critical in IoT

Different sets of companies bring unique sets of expertize towards IoT platforms, leading to partnerships between industrial and technology companies. In IT infrastructure, scale and technical (rather than industrial) expertise matter, while for edge devices, domain specific industrial-know and installed bases matter more. One key area where we are seeing examples of both partnerships and competition, however, is in industrial software.

Figure 21. The SCP Reference Implementation



Source: PTC

Germany: The Idea of 'Industrie 4.0'

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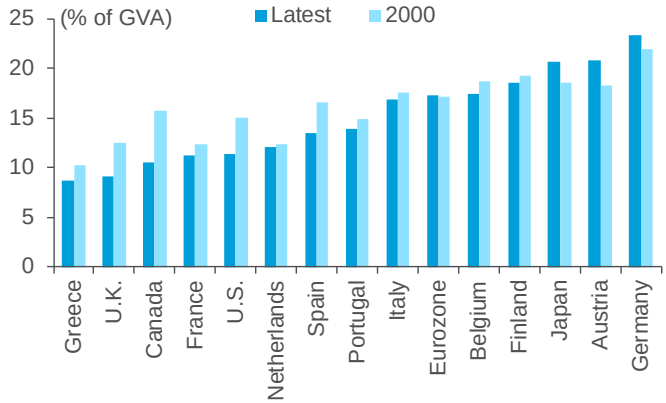
Germany's manufacturing prowess has an almost mythical status in and outside Germany. In Germany, much of the country's economic, trade, foreign, and fiscal policy is geared towards defending its competitiveness. Outside Germany, many blame this competitiveness for global imbalances and see it as a risk to economic, financial, and political stability. Undoubtedly, Germany still has one of the largest manufacturing industries among advanced economies. Government and industry want to make that size matter. 'Industrie 4.0' and the government's Industrial Strategy 2030 respond to shifting challenges.

Germany remains a global manufacturing hub

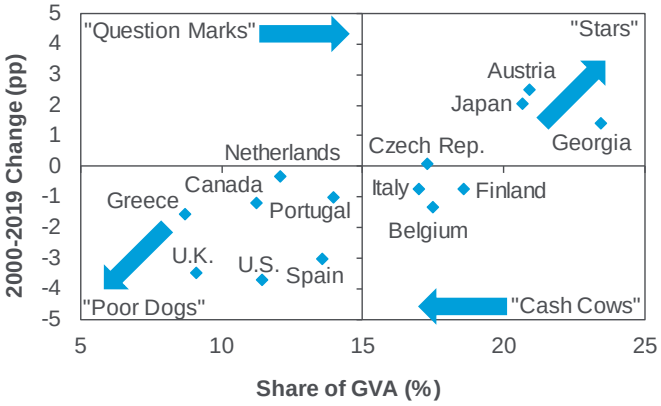
More than in any other major advanced economy, Germany's manufacturing sector still dominates the economy. In 2018, manufacturing accounted for 24% of total gross value added (GVA), the highest among the G7 countries ahead of Japan (20%), and Italy (17%), see Figure 22. In the U.S., the U.K., Canada, and France the share is only between 9-12%. Manufacturing directly accounts for 20% of German employment and 85% of private R&D investment. German companies are among the world leaders in sectors such as metals, chemicals, automotive, optical devices, medical devices, 'Greentech', defense, aerospace, and 3D-printing, according to the federal economy ministry.

Figure 22. Selected Advanced Economies: Share of Manufacturing in GVA (%), 2000 and 2018



Sources: Eurostat, CAO, StatCan, BEA and Citi Research

Figure 23. Selected AEs: Manufacturing GVA Share and Change in Share (%, pp), 2000-2018



Sources: Eurostat, CAO, StatCan, BEA and Citi Research

Germany is pulling away from advanced economy rivals

Strength in manufacturing is self-reinforcing. Not only is Germany's share of manufacturing in the economy the highest among large advanced economies, it is also growing faster than almost anywhere. Approximating a Boston Consulting Group (BCG) style matrix of growth versus market share (Figure 23), we illustrate that Germany (alongside Austria and Japan) devotes ever more resources to manufacturing, making it a 'star' sector of the economy. In Italy, Belgium, and Finland, manufacturing is still large but declining ('Cash Cows' in terms of the BCG matrix). All the other advanced economies have 'Poor Dog' manufacturing sectors: manufacturing is relatively small compared to the overall economy and shrinking (in relative terms). As these economies divert resources away from manufacturing, the sector loses its competitive edge there.

… but globalization and digitalization keep challenging

Our BCG-style matrix does not tell the full story, of course. Advanced economies no longer dominate global manufacturing, and digitalization means the border between manufacturing and services is increasingly blurred. High labor costs, planning rules, environmental regulations or energy costs, but also disruptive innovations constantly threaten German manufacturing competitiveness. For example, from the mid-1990s, more and more economies in Eastern Europe and Asia with lower labor costs and looser regulation have successfully challenged the traditional manufacturing hubs. Germany lost its leadership in sectors such as consumer and communication electronics as well as carbon materials. More recently, advances in digitalization threaten the control of production processes as U.S. and Chinese companies are dominating much of the digital platform market.

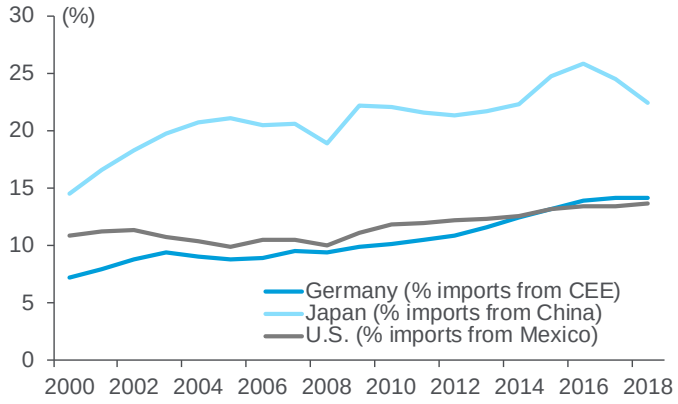
German manufacturers eventually embraced globalization

German manufacturers embraced the previous wave of globalization eventually by extending supply chains cross border to Emerging Markets on its doorstep in Central and Eastern Europe (CEE). Their share in German imports more than doubled from the early 2000s onwards (see Figure 24). In comparison, China's share in Japan's imports has only grown by a quarter (admittedly from higher starting levels) while Mexico's share in U.S. imports has more or less stagnated over this period. German manufacturers have built a supply chain network which other economies have struggled to compete with.

German companies are more exposed to the EM cycle than other Advanced Economies

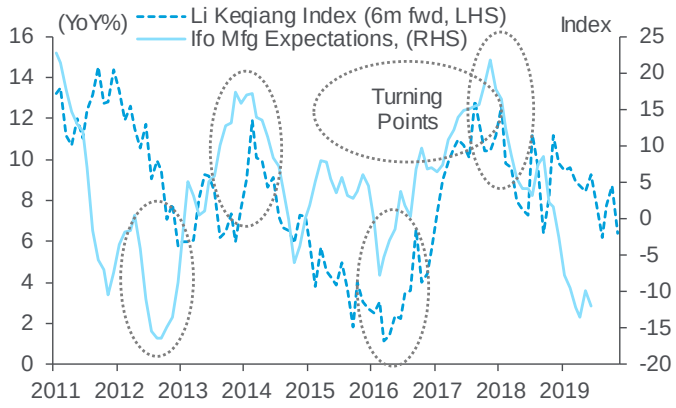
The process of relocating production to CEE and Asia was late and painful, but the cost and scale advantages built by establishing cross-border supply chains allowed Germany to get a much greater exposure to fast-growing emerging markets in CEE and emerging Asia than its European rivals. At the same time, Germany's economy has become ever more dependent on the Emerging Market cycle, as evidenced by the tight leading relationship between Chinese growth (measured by the Li Keqiang Index which tracks bank loans, electricity consumption, and railway freight volumes) and Germany's Ifo Manufacturing Expectations index (see Figure 25). In the current climate of trade tensions, that is not necessarily an advantage anymore.

Figure 24. Germany, U.S., Japan: Import Share from Emerging Markets in Proximity (% of Total Imports), 2000-2019



Sources: IMF DOTS and Citi Research

Figure 25. Germany, China: Li Keqiang Index (YY %) and Ifo Manufacturing Expectations (% Balance), 2011-2019



Sources: Ifo, Bloomberg ad Citi Research

Can German companies respond to digitalization in the same way they did to the Emerging Market challenge? The government and business associations are trying to organize this adjustment process in a more effective way than the largely decentralized, drawn-out, and painful adjustment process in the 1990s and early 2000s. The belief is that by creating a whole manufacturing digitalization ecosystem, this challenge will not just be overcome but turned into a competitive advantage. The vast size and diversity of German manufacturing provides ample data and applications for digitalization if all involved parties work together. This is how the Industrie 4.0 platform was born in 2011, in the middle of the European sovereign debt crisis.

Industrie 4.0 is a cooperation platform for business, associations, research, regulators and government

Under the overall leadership of the Economy Ministry, currently headed by Peter Altmaier, Industrie 4.0 is essentially an attempt by the government and industry in Germany to create an all-encompassing platform on which all relevant parties can cooperate to hasten the evolution of digitally-supported production processes in Germany. Aiming to be able to optimize processes to allow efficient production of innovative bespoke products to lot size one (i.e., a small quantity ('one') of goods ordered for delivery on a specific date or manufactured in a single production run), Industrie 4.0 involves technologies such as artificial intelligence and robotics. On the Industrie 4.0 platform, technical working groups develop, for example, standards and norms, training programs or application scenarios, and assess network security, and the legal framework. Government, business federations, trade unions, or scientific bodies set the agenda and act as multipliers. And the platform directly affects the market by acting as a catalyst for industrial consortia and international standardization initiatives.

Platform has successfully entered industry vocabulary

The initiative, planned over 10-15 years, is based on the German government's High-Tech 2020 Strategy, launched in 2011, and aimed as a "*strategic measure to consolidate German technological leadership in mechanical engineering*". The moniker 'Industry 4.0' has become the widely-adopted label for next generation manufacturing, referring to the fourth industrial revolution (after the steam engine in the 18th century, the advent of the assembly line in the 19th century, and the introduction of automation technology in the 1970s). Since the launch of Industry 4.0 at the Hannover Trade Fair in 2011, we have seen an increasing number of companies define their strategies around the concept.

Mixed record of success

At the macro level, we see limited evidence that Industrie 4.0 has made a difference, so far. German manufacturers are among the heaviest users of robots in the world, with 309 robots per 10,000 industrial workers in 2017 according to the International Federation of Robotics, ahead of Japan (303) and behind only South Korea (631), but intensity has only risen marginally since 2015, when there were 301 robots per 10,000 industrial workers. There is little evidence that the heavy use of robots has been beneficial for the level or growth in productivity (see Figure 26). The share of students in mathematics, IT, natural sciences, and technology (MINT subjects) in Germany has been constant at 38% between 2015 and 2018. We note the World Economic Forum in its Global Competitiveness Report 2018 saw Germany as the economy with the highest innovation capability. At the same time, WEF also reported Germany slipping in the rankings for some technology-related indicators. For example, Germany ranked 38th for mobile broadband subscriptions in 2015, but only 53rd in 2018.

Germany's economy is even more tied to China than before, it seems

In the meantime, manufacturing has gone through a series of cycles (see Figure 27). The recovery from the sovereign debt crisis was cut short by a series of shocks to the Emerging Market growth model, starting with foreign exchange turbulences in the wake of the 2013 taper tantrums, the 2014 Russia/Ukraine crisis, and the 2015 oil price collapse. It was not until China heavily stimulated its economy in 2015/16 that manufacturing experienced a boom of which Germany was a major beneficiary. That boom proved short-lived as well. When Chinese authorities saw a chance to reign in the excesses of their countries growth model and moved to contain shadow banking and environmental pollution, German manufacturing experienced a slowdown as well, which got worse due to escalating U.S. trade aggression and idiosyncratic issues such as the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) changeover in the car industry and bottle necks in the labor market.

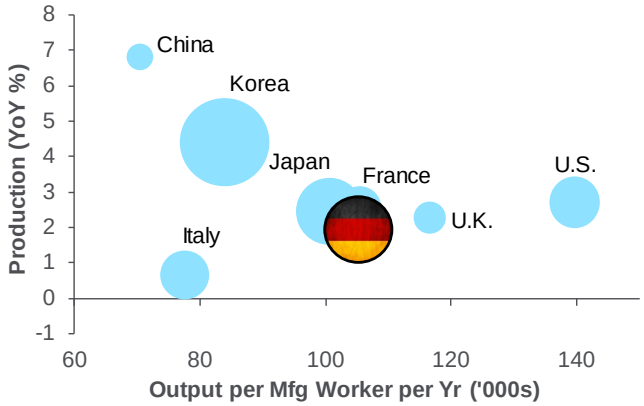
As challenges are shifting ever faster, government is adopting Industrial Strategy 2030

In response to new state-backed initiatives such as Made in China 2025 or America First and with German manufacturing falling into a (mostly cyclical) crisis, the German government has responded with a new, more robust plan called "Industrial Strategy 2030". With this, the government will play a more protective role for businesses, defending Germany's industrial and technological sovereignty and capacity as well as end-to-end value chains. The government will encourage and coordinate their defense against takeover attempts in key industries and is committed to fostering national and European champions which see eye-to-eye with their U.S. and Chinese counterparts. This can go all the way to the government effectively nationalizing key assets with a new acquisition facility.

New Industrial Strategy 2030 causing controversy

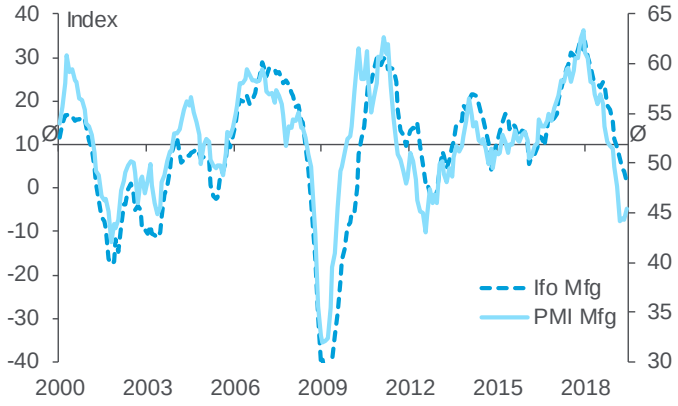
Industrial Strategy 2030 is causing controversy. Influential economists like Christoph Schmidt, head of Germany's Economic Council (see Spiegel) criticize the prospect of government intervention to prevent foreign players from entering German and European markets and the creation of national champions. The business federation BDI has warned that Germany and the EU should protect European markets against exploitation, but strengthen rules-based global trade simultaneously. In a recent paper on China, the BDI acknowledged that hopes for Chinese economic and political convergence were misplaced and 'systemic competition' had to be accepted[4]. Its advice was to tighten state-aid rule and use public procurement to do that, for example, within the WTO framework.

Figure 26. Productivity (Levels $'000's and Growth, YoY %), Use of Industrial Robots (Per 10k Industrial Workers), 2017



Source: OECD, International Federation of Robotics, Haver, Citi Research

Figure 27. Germany: Ifo Manufacturing Business Climate (% Balance) and PMI Manufacturing (50 = Neutral), 2000-2019



Sources: Markit, Ifo, Citi Research

[4] BDI (January 2019) "Partner and Systemic Competitor – How do we deal with China's state-controlled economy?"

Although Germany's manufacturing looks cyclically weak and structurally challenged at the moment, it remains one of the largest among advanced economies. That and its global reach allow it more than other countries to achieve a scale that fosters cross-sectoral innovations such as the digitalization of production processes. Industrie 4.0 was and is an attempt to deepen the existing cooperation between business, research, regulation, and government, with mixed success so far. With challenges apparently growing, the government has stepped up its interventions to protect German manufacturing, but seems to be increasingly treading a fine line between welcome support to foster innovation and harmful picking of winners and market intervention.

Where Is the Factory of the Future Given Uncertainty on Trade & Tariffs?

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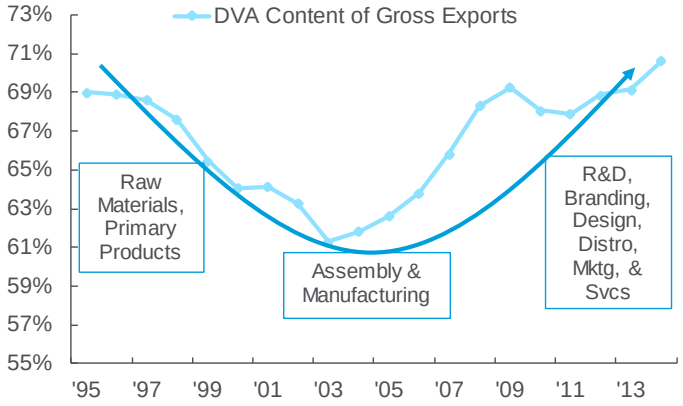
It is increasingly unlikely that US-China tensions, which have morphed from trade issues to geopolitical ones, will have a meaningful resolution anytime soon. Even if we get some interim deal that averts further escalation or may even ratchet down tariffs, technological and geopolitical rivalry between the two largest economies will likely be here to stay. Thus, trade tensions can easily flare up again in the future, and can come in other forms — tariffs have become particularly prevalent, with the U.S. expanding their scope of usage — from what issues constitute a 'national security' threat (e.g., steel imports from Canada; Mexican illegal immigration) to unfair trade policies (e.g., Section 301), which may now expand to the use of undervalued currencies. The U.S. has also utilized the 'entity list' which is tantamount to export controls (most famously in the case of Huawei), investment and other regulatory restrictions, imposing sanctions and secondary sanctions to individuals and entities brought about by U.S. security and foreign policy interest (e.g. Iran), or even possibly involving the Magnitsky Act for human rights violations

The merging of geopolitics and trade policy will be highly disconcerting for multinationals operating across borders to take advantage of cost-based comparative advantage, as they now need to reorganize based on minimizing geopolitically-driven policy risks. Tariffs are costly and disruptive, but outright supply bans on critical components, such as what ZTE endured in Spring of 2018 (though later reversed) and now befalling Huawei with its inclusion in the U.S. entity list, we think can be far more damaging.[5] This will lead to two phenomena.

First, China will even more aggressively want to reduce their reliance on critical components, especially from 'unreliable' partners, and intensify efforts to innovate and localize. There is already evidence of China's track record in industrial upgrading. China will likely lean on their sizeable domestic market, alongside other potential markets among allies (possibly in the "Belt and Road" sphere) to achieve scale and resources for China to achieve this, though this will neither come quickly nor easily, and will likely be curtailed by U.S. policies and risks of resource misallocation. While the 'Made in 2025' program may have been de-emphasized publicly, we think the tenets of achieving higher domestic share targets in critical industries will still resonate and likely intensify due to U.S.-China tensions

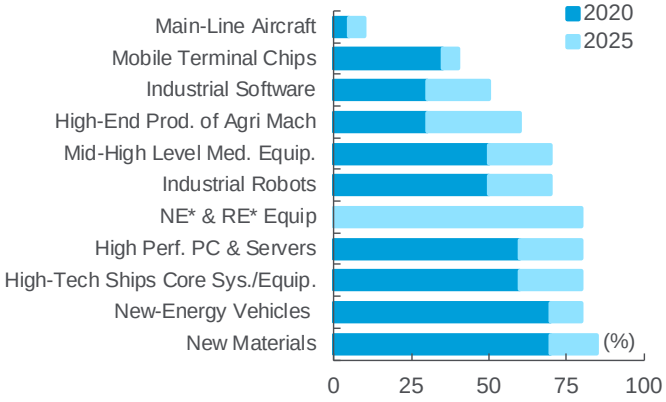
[5] See U.S. Dept of Commerce announced the addition of Huawei on the Entity List https://www.commerce.gov/news/press-releases/2019/05/department-commerce-announces-addition-huawei-technologies-co-ltd

Figure 28. Domestic Value Added (DVA) Share of China's Total Exports



Source: OECD, Citi Research

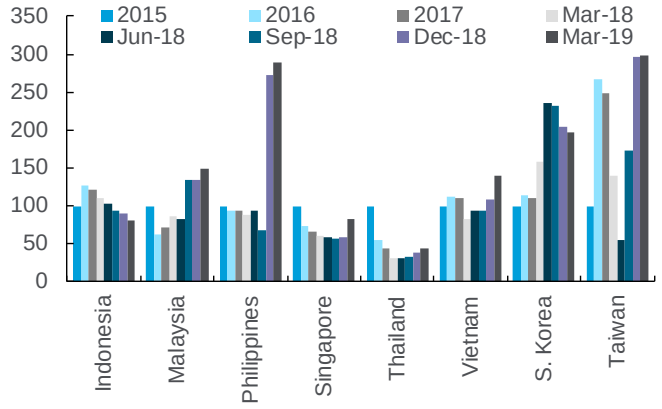
Figure 29. Domestic Market Share Targets for Selected Products



Note: *New Energy(NE) & Renewable Energy (RE)
Source: U.S. Chamber of Commerce citing Expert Commission for the Construction of a Manufacturing Superpower

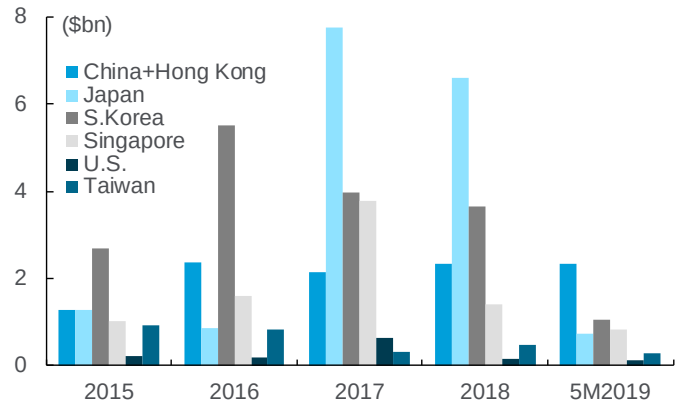
Second, it will also mean that multinationals will need to reduce the concentration risk on their operations away from China, and diversify supply chains to other jurisdictions which will face less policy risks from the U.S. For example, in joint survey of member companies over May 16-20, 2019 by the American Chamber of Commerce in both Shanghai and China, almost 41% of respondents are considering or have relocated manufacturing facilities outside of China, versus only 18% of their respondents having indicated the same in an earlier joint survey (Aug29-Sep 5, 2018). Of course, even non-American companies including those from China itself servicing U.S. markets, and Korea, Taiwan and Japan who are very exposed to tech-sensitive sectors, will also want to diversify (and a to a large extent, many companies already have). ASEAN tops the surveys of corporate relocation plans led by Vietnam, but other economies like the Philippines and Malaysia, and Taiwan are seeing increased investment approvals. Relocation will come at significant costs and efficiency losses that will likely undermine profitability, but will create relative winners and losers geographically at the expense of China.

Figure 30. Select Asia: FDI Approvals in Secondary Industries (2015=100), 4Q Rollin Sum



Note: March 2019 data for Malaysia, Philippines, and Singapore not yet available.
Source: CEIC, Citi Research

Figure 31. Vietnam: FDI Approvals by Major Economies



Source: CEIC Citi Research

If factories can be 'distributed' due to digital design and 3D printing etc., what does that mean for supply chains?

Geopolitical forces alongside technological advancements can accelerate the desire to localize or re-shore production closer to the end market. The rise of digital capabilities in the production process (e.g., research, design, 3D printing, testing etc.) has allowed more parts of 'factory production' to shift online. Thus, instead of raw materials and inputs assembled in large factories to produce identical products in massive scale (i.e., minimizing unit costs via economies of scale) and then distributed to the end users, the rise of 'distributed manufacturing' allows fabrication and mass customization of products in closer proximity of its end-market, helping improve the utilization of local materials, customize products to better suit the customer, shorten lead times, maximize flexibility, and minimize waste.[6] The rapid improvement and increased deployment of industrial robotics with expanded applications, combined with artificial intelligence and advanced computing, will also mean that labor costs in the operational and assembly process of manufacturing becomes increasingly less important.

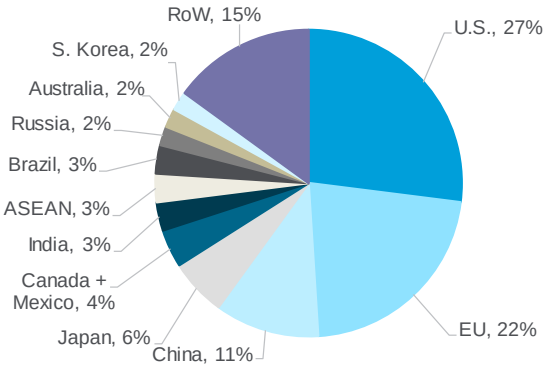
These developments have the potential to significantly upend the nature of supply chains and shift the distribution of value added across economies and companies. Labor cost arbitrage becomes a less important decision factor to production location than proximity to end markets coupled with the right skills. The latter will require a mix, including more strategic and problem solving skills when it comes to logistic and supply chain managers, more technical skills when it comes to those that supervise local manufacturing production, and more social and creative skills in general, that make them less susceptible to automation and digitization.

If end markets become an increasingly important decision factor, then one could argue that more and more manufacturing value addition will agglomerate towards the larger end-consumer markets, led by the US, China, Japan, and Germany. Amid so much attention over the loss of U.S. manufacturing jobs to other economies (e.g., China, Mexico) that became a core part of economic policy of President Trump's administration, we have seen very limited signs of a reshoring trend in the U.S. in recent years, based on the latest AT Kearney Reshoring Index, which measures the percentage change in the U.S manufacturing import ratio, defined as the quotient of the import of manufactured goods from 14 Asian economies divided by the U.S. domestic gross output of manufactured goods. Even their assessment of media press coverage of U.S. reshoring cases remains very low.

This still lack of reshoring in some developed nations suggest there is still sufficient scope for labor-intensive manufacturing processes that are not easily and cost-efficiently automated (thus, U.S. companies are more likely to relocate from China to Vietnam than back to the U.S.), and the investments and technical adoption of companies to refit themselves significantly through a distributed manufacturing set up has not quite happened yet, and we are still in the early stage of this emerging factory reorganization process.

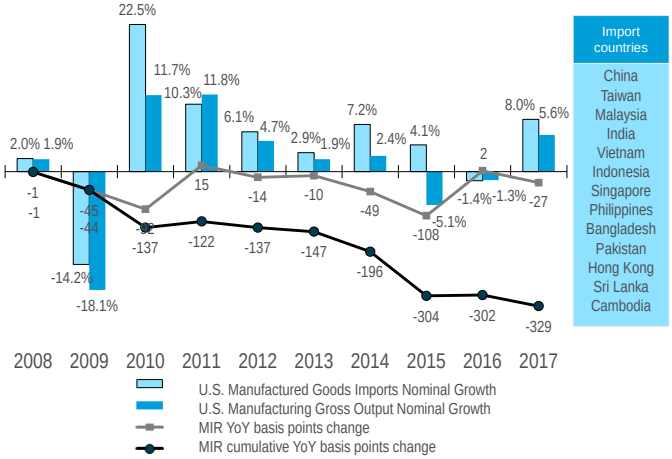
[6] AT Kearney. Reshoring in Reverse Again. https://www.atkearney.com/operations-performance-transformation/us-reshoring-index

Figure 32. Geographical Distribution of the Global Consumer Market



Source: World Bank, Haver, Citi Research

Figure 33. U.S. Manufactured Goods Imports and Gross Domestic Output (YoY Nominal Growth)



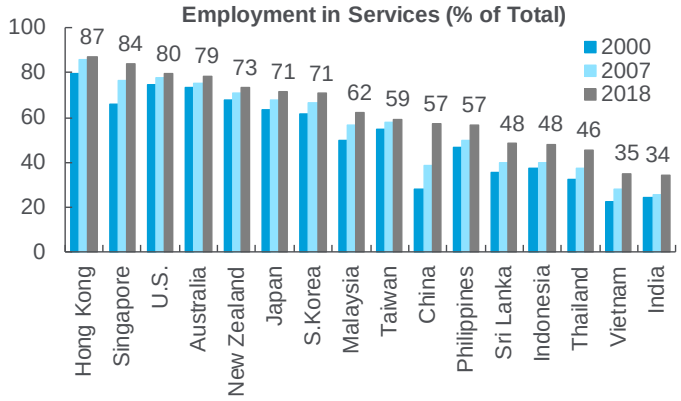
Note: MIR Is Manufacturing Import Ratio
Source: AT Kearney using data from US ITC and BEA.

What is the impact of 100% factory automation on global labor markets?

The loss of jobs in the manufacturing sector would mean more job creation would have to be absorbed by the services sector. The only jobs likely to be left in manufacturing are those that are highly skilled and related to collaborating with machines, supervising the automation process, and big data analytics that can be used for problem solving and developing technology-based solutions. Indeed, the services sector share of employment has been rising globally, including in the manufacturing-centric Asia led by China. It will be hard to imagine that the world labor markets will shift back to agriculture which itself has been increasingly mechanized.

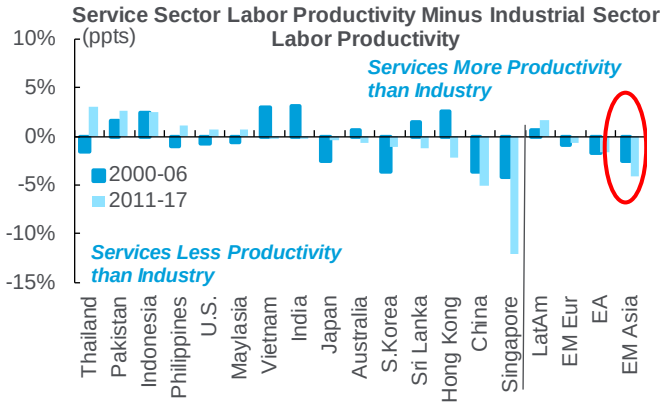
The challenge is to what extent the services sector can generate high productivity jobs which can sustain rising income gains in the same way manufacturing jobs have historically been a well-worn path for economic development and per capita income converge with richer nations. The prognosis for this does not look encouraging. The services sector — encompassing everything outside of agriculture and industry — is historically characterized by lower labor productivity growth than manufacturing sector. One explanation for this is the services sector is associated with less intensive use of technology, is regarded as less tradeable, and captures underemployment and informality. Moreover, economies that are seeing the fastest growth in services sector demand like China are also among the most restrictive/protective of its services sector vis-à-vis the rest of the world, and thus, may also be constraining productivity gains.

Figure 34. Services Sector Employment Share Has Risen Rapidly



Source: ILO, Citi Research

Figure 35. Services Sector Productivity Growth Is Often Lower than Industry (Mostly Manufacturing) Sector Labor Productivity Growth



Source: WDI, Haver, Citi Research

But one could argue that technological advancements, especially in digitization, are likely making many types of services jobs more tradeable and scalable, boosting their productivity growth. However, both artificial intelligence and robotic process automation will also mean that some services jobs, like manufacturing, will also be vulnerable to significant dislocations and obsolescence. Highly-skilled services jobs, especially in cost competitive locations, may win out over white collar service related jobs in richer nations, exacerbating the job polarization we are already seeing in the last few decades in the developed world. However, over time, digitization allows not only the tradability of the services sector, but may also mean low-cost scalability of tradability of skills, which could mean it is skills disparity that may matter more than labor costs, and the displacement of less skilled workers may not just be a developed nation phenomenon, but may hit developing economies as well. This would mean job polarization will also migrate to the developing world, which unfortunately has much weaker social safety nets than richer nations to withstand the pressures that arise from weak growth and rising inequality. Thus, we could see either less business friendly policies or fiscal populism risk becoming more of the norm or intensify, which have both economics, social, and geopolitical consequences.

Figure 36. While the 'Made in 2025' Program May Have Been De-emphasized Publicly, We Think the Tenets of Achieving Higher Domestic Share Targets in Critical Infrastructure Will Still Resonate and Likely Intensify Due to U.S.-China Tensions

Key Sector	Details	Comments / Progress	Global Sectors Impacted
New Information Technology	Involves (1) development of integrated circuits and special equipment; (2) enhancement of intellectual property cores and relevant design tools; (3) mastering of high-density packaging and 3D micro-assembly technology; (4) comprehensive breakthrough to 5G technology through new computing methods and development of relevant core technologies; (5) promotion of core ICT equipment system development; (6) development of operating systems and industrial software; and (8)) development of self-control platform software and high-end industrial applications for key areas	The 'Internet plus' policy and 'cyber power strategy' detailed at the NPC in March have not as yet provided further detail on the strategy for industrial software development	Industrial software companies
Numerical Control Tools & Robotics	In numerical control tools, (1) develop sophisticated, high-speed, high-efficiency numerical control machine tools and relevant manufacturing systems and (2) focus on the development of key components such as motors and bearings for accelerated industrial production. In robotics, increase 'Made-in-China' robotics market share to >50% by 2020, and reach 800,000 units of operational stock of industrial robots by 2020. Boost 'smart manufacturing', while making breakthroughs in the application of key parts and high-end products	CRIA (China Robot Industry Alliance) estimates that domestic robot shipments were ~22k in 2015, with a total domestic market share of ~30%	Numerical control tools Motors & Generators
New Materials	Including high-performance structural materials, functional polymer materials, special inorganic non-metallic materials, and advanced composite materials		
Aerospace Equipment	In aviation equipment, (1) accelerated development of large aircrafts; (2) seek international collaboration for development of heavy helicopters; (3) develop regional aircrafts, helicopters and unmanned aerial vehicles; (4) develop advanced airborne equipment and systems to form a completely independent aviation industry chain In aerospace equipment, (1) develop new generation of carrier rockets and heavy carriers; (2) accelerate civil space infrastructure; (3) develop new satellite and other space platforms; and (4) promote manned spaceflight and lunar exploration project through aerospace technology transfer and space technology applications	Military spending targeted to increase 7.6% in 2016, slowest pace in six years	
Ocean Engineering Equipment & High-Tech Ships	(1) Development of deep-sea exploration; (2) development and utilization of offshore resources through relevant equipment; (3) development and engineering of large floating structures such as deep-water workstations; (4) establish marine equipment testing procedures and identification of equipment capabilities for improvement of marine resource development; (5) development of cruise ship design and manufacturing; and (6) enhance competitiveness of domestically produced LNG vessels and other high-tech ships		
Railway Equipment	Overseas sales of domestic rail equipment to reach >30% by 2020. Focus on development of high-speed multiple units, heavy-duty electric locomotives, inter-city electric multiple units (EMU), medium- and low-speed magnetic levitation products. Includes related parts and accessories	CRC issued tenders in July 2015 for domestically designed high speed trains, in order to get around export restrictions under existing license agreements with foreign partners on current train designs	
Energy Saving & New Energy Vehicles	(1) home brand Electric Vehicles and plug-in hybrids to exceed one million units by 2020 and account for >70% domestic sales, and 3m units and 80% share by 2025; (2) 80% domestic share of key systems on power batteries; (3) overseas sales to reach 10% of total for electric vehicles, and (4) to master unmanned driving by 2025		
Power Equipment	Estimated $280bn investment for smart-grid construction by 2020. Promotion of renewable energy equipment, storage devices, CPE (consumer premise equipment) development etc.		
Biological Medicine & Medical Devices	(1) Develop the ability to innovate and improve the level of medical equipment industry; (2) focus on the development of imaging equipment, medical robots, and other high-performance diagnostic equipment, mobile telemedicine and other medical products; (3) achieve biological 3D printing; and (4) induce pluripotent stem cell breakthrough and application of new technologies		
Agricultural Machinery	Accelerate the development of large tractors and compound working tools, efficient large combine harvesters and other agricultural equipment, and high-end critical core components		

Source: Citi Research

Sustainable Production and the Circular Economy

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- The trends discussed herein involve increasingly advanced manufacturing processes and will have significant impacts on company practice and profitability. However, they will also have a number of effects on companies' ability to support the Sustainable Development Goals (SDGs) and maintain their social licenses.
- Advanced manufacturing operations have a better chance of reducing resource intensity and undertaking circular production.
- On the flip side however, there are significant implications for employment as a consequence of automation.
- In some senses this means advanced manufacturing operations risk being good for economic growth and profitability, but also a force for increasing economic inequality.
- From an ESG perspective we are interested to see the extent to which individual companies are able to use their advanced manufacturing capacities to improve their resource footprints and use, while also continuing to maintain their social license to operate, potentially by giving consideration to SDG 8.

Divergence in Stakeholder Outcomes

Technological innovation increases productivity and is widely considered a key driver for economic growth and improvements in living standards. However, as the pace of technological change has accelerated, the beneficiaries of that change are concentrating. In this section we look at the SRI/ESG perspectives of the Factory of the Future through the United National SDGs. In short, the SDGs represent 17 social priorities against which the parties to the UN are targeting a certain level of achievement by 2030. As with many activities, advanced manufacturing affects many SDGs indirectly, including Water (SDG 6), Climate Change (SDG13), and Terrestrial and Marine Resource Use (SDGs 14 and 15). However, the Factory of the Future lies directly in the crosshairs of two SDGs in particular: Responsible Production (SDG12) and Decent Work & Economic Growth (SDG8).

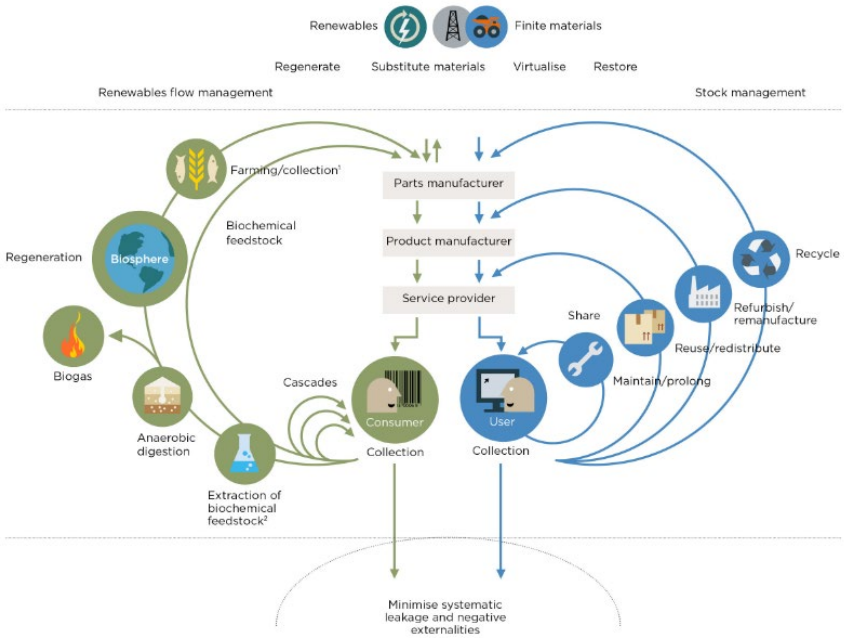
The Factory of the Future Will Likely Underpin the Circular Economy

The potential for achieving a more circular economy presents a major opportunity for the Factory of the Future. What is a completely circular economy? One in which all waste products are productively reused, and as such there is no absolute waste burden. Although a completely circular economy is both very challenging and also unlikely in the near term, movements towards a circular economy are needed. Advanced and digital manufacturing technologies can assist in providing better circularity within supply chains, not in the least because of their position early in the supply chain. The European Commission 'Horizon 2020' policy objectives comment that "*the circular economy starts at the very beginning of a product's lifecycle — smart product design and production processes to save resources, avoid inefficient waste management and create new business opportunities*." Advanced manufacturing processes are likely to assist in improved design and production, allowing materials, energy, and resources to be more completely reused. This needs to occur not only within one manufacturing stream, but across streams, with the ability to pass on used materials to others for their benefit.

Technologies such as additive manufacturing part of the circular economy puzzle: Although it is hard to forecast exactly how impactful the rollout of advanced manufacturing will be, we think it is likely to reduce the resource footprints of firms and increase their ability to use resources in a circular fashion. For example, multiple studies believe additive manufacturing (i.e., 3D printing) will be a primary enabler of a more circular economy, given its ability to help companies and customers to print products on demand using fewer resources.

Policymaking related to the circular economy has already begun reshaping firms' priorities. In 2018, China and the EU signed a landmark agreement to align policies supporting the transition to a more sustainable economy. Given the scale of the two economies, the possibility of a systemic shift towards a regenerative economy is increasingly likely.

Figure 37. The Circular Economy



Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business & Environment

Figure 38. Countries Introducing Circular Economy Initiatives, 2016

Source: Chatham House, 2016

Firms appear to reduce their resource footprints as they improve manufacturing sophistication. Firms who have invested in new factories are often focused on improving the efficiency, while lowering waste and resource use with the installation of increasingly advanced manufacturing processes. Daimler is a good example with its development of 'Factory 56'. The company intends to cut CO_2 emissions at the new factory by 75% as compared to its existing production facility, including through having a CO_2 neutral energy supply. It will focus on reducing by-products and waste and intends to create more durable products with replaceable parts. Siemens, the largest industrial manufacturing company in Europe, is focused on decarbonizing, citing the technologies in its environmental portfolio enabling its customers to reduce their CO_2 emissions by 609mn metric tons, the equivalent of 75% of Germany's annual emissions.[7] Samsung is another good example of a company using automation to reduce their resource use. In 2017, it automated water usage in its manufacturing process, enabling it to cut its daily water use by 63,000 tons by reusing water for different processes.[8]

A drive to efficiency may mean that as manufacturing becomes more advanced it also becomes less resource intensive. Analysis by McKinsey, as part of a study with the Ellen MacArthur Foundation found material cost savings worth up to $630 billion per year by 2025 in EU manufacturing sectors by increasing resource productivity.[9] In the U.S., a study found benefits of 250-350mn metric tons of CO_2 equivalent and $2 trillion in annual US revenues could be generated from circular manufacturing.[10] These points suggest that a move towards more circular manufacturing is likely to reduce costs for manufacturers.

[7] Siemens Sustainability Report (2018).
[8] Siemens Sustainability Report (2017).
[9] Ellen MacArthur Foundation and McKinsey Center for Business and Environment (2015), Growth Within: A Circular Economy Vision for a Competitive Europe.
[10] Closed Loop Partners (2017), Capital Landscape for Investment in Circular Supply Chains.

Advanced manufacturing is also likely to help companies increase the circularity of their resource use: Advanced manufacturing will enable firms to reduce resource consumption and lower their impact on the environment by reusing wasted materials to manufacture new products. Renault Group is an example of a company improving productivity and circularity through advanced manufacturing, while lowering its resource footprint. Its strategy includes remanufacturing engine parts, creating a 'second life' for electric batteries, and increasing the 'short-loop' recycling of raw materials. It resulted in 36% of the total mass of a new vehicle now being made from recycled materials.[11]

Given the evidence, we are optimistic the Factory of the Future is likely to play a role in achieving more circular, less resource intensive economies. With supporting policy, firms have opportunities to reduce their resource footprints as they improve manufacturing sophistication.

Factory of the Future's Impact on Decent Work & Economic Growth

Resource use is not the only site of interaction between advanced manufacturing and the UN SDGs: However, resource intensity and recycling are not the only avenues through which advanced manufacturing is likely to impact the SDGs. Along with reduced resource use often comes reduced labor intensity, and as advanced manufacturing becomes more common this second impact will need to be managed by companies.

Social license to operate is often related to employment: The social license to operate, which is the legitimacy and trust required to gain and maintain the support of local stakeholders, revolves around the notion of shared value. Corporations are given license to operate privately and collect profit, on the unspoken proviso that these activities are a more efficient way of providing the society with what it needs (services, goods, and distributed wealth). Corporations have always dedicated both capital and innovation to improving productivity and generating greater profit. In manufacturing industries these productivity benefits have often replaced human capital to some extent. In the future, these replacements may accelerate, and could lead to firms which employ very little human capital. In this context, we find ourselves curious as to whether a firm's social license to operate will be questioned if it doesn't require human capital.

Relationship Between Labor and Automation

The relationship between labor and automation has been debated for several centuries. The Luddites (in 1811), John Maynard Keynes (in the 1930s) and Martin Ford (2015) have in common the prediction that as machines are increasingly used to staff production, fewer people will be necessary.

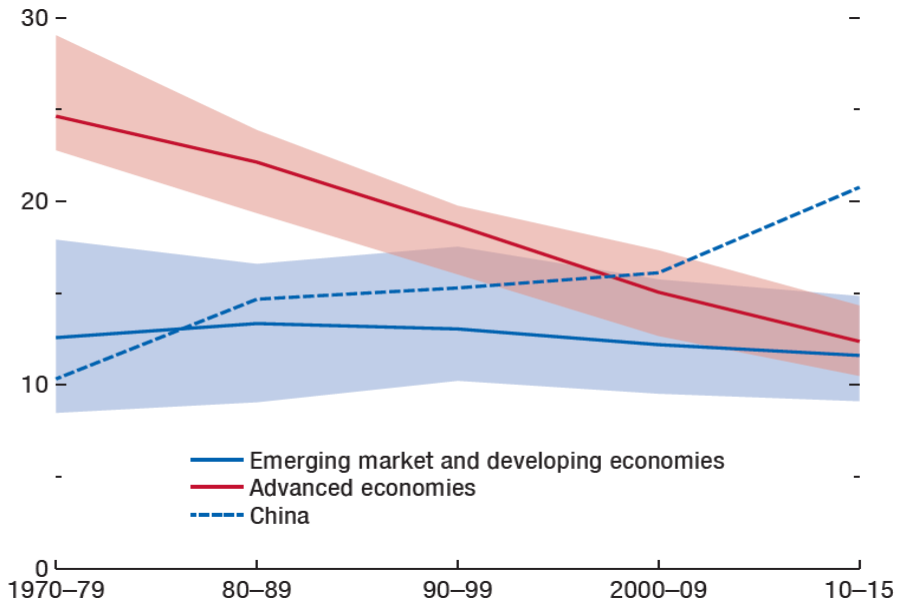
The debate remains and economists continue to produce varying results on the potential impact on employment. In 2013, a report by Oxford University (Frey & Osborne) estimated 47% of U.S. jobs were at risk of automation by 2030. Frey noted that although automation may not be immediately problematic at a national level, sub-national changes in job availability might be quite impactful. A more recent study by the OECD suggested that automation would replace tasks but not whole jobs, finding only 9% of jobs were entirely at risk. It concluded that automation and digitization was unlikely to destroy a large number of jobs, although the greatest impact will be felt for low-qualified workers.

[11] Ellen MacArthur Foundation Case Study, 2017.

For better or for worse, automation will replace human capital in some sectors, and the opportunity for productivity gains is greatest in the manufacturing sector. With goods traded on international markets there is increased competition to drive firms to constantly improve production and lower costs.

Manufacturing employment is constant in share, but not geography: The share of manufacturing jobs in global employment has been remarkably stable over nearly five decades. The sector employs about the same share of the world workforce now— about one in seven workers—as it did in the 1970s.[12] However, as evident in the figure below, there has been a country mix shift as China and other Asian countries have taken share.

Figure 39. Share of Manufacturing Jobs in Global Employment (1970-2015)



Source: International Monetary Fund, 2018

Regional Manufacturing Concentration Raises Inequality Risks

Will the Factory of the Future replace human labor and lead to lower employment? Historically, new technologies have not only transformed regions, industries and companies, but also cities. Given the potential for automating manufacturing particularly and the regional nature of manufacturing, there continues to be a strong risk of regional employment impacts. This raises questions about the possibility of exacerbating regional inequality, and the impacts of this on the social license of firms.

A good historical example of the regional nature of employment impacts is Detroit, which has seen its population shrink from 1.85 million in 1950 to 670K in 2017 as car manufacturers introduced robots and began opening factories in other areas. The high concentration of the population in manufacturing without sufficient skills to adapt to job losses created a widespread deterioration in the standard of living.

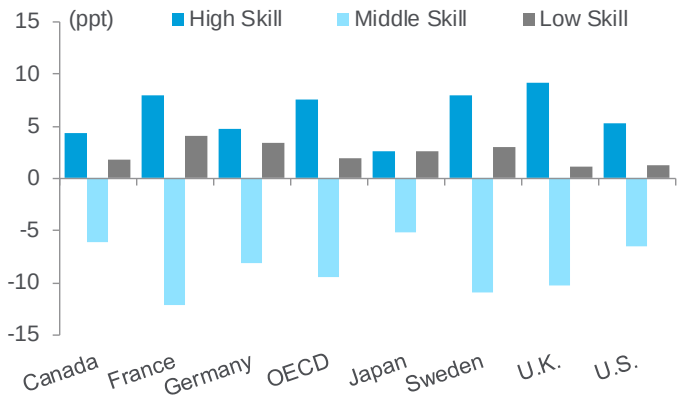
[12] International Monetary Fund (2018), Manufacturing Jobs: Implications for productivity and inequality.

Given the increasing concentration of manufacturing today (i.e., China or South East Asia), there is concern that when the cost of automation falls below low-skilled human labor, a more severe shock is possible. Increased automation in low-wage countries (which have traditionally attracted manufacturing firms) could lead to the loss of their cost advantage and potentially their gateway to achieving rapid economic growth by shifting workers to factory jobs.

This impact could be particularly relevant for the achievement of the SDGs, which are focused on improving sustainable development outcomes particularly in economies presently having low levels of development. Manufacturing employment has historically been a key development route for emerging economies, and as advanced manufacturing becomes increasingly tractable, this route may become far more tenuous.

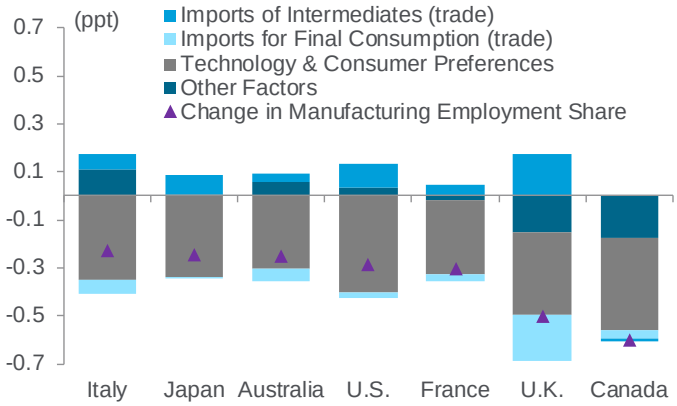
A hollowing of the middle-class in advanced economies is already happening: Over the last 20 years, the decline in the share of manufacturing jobs, particularly in advanced economies, has caused a 'hollowing out' of the middle class. Acemoglu and Restrepo (2017) argue that trade and technology have already altered the manufacturing sector in the U.S. by lowering the demand for labor, especially for the middle-skill group.

Figure 40. Hollowing of the Middle Class, 1995-2015



Note: OECD is the unweighted average of 24 economies. For Japan 1995-2010.
Source: OECD Employment Outlook 2016, European Union Labor Force Survey, Labor Force Surveys for Canada, Japan, and the U.S., and OECD calculation.

Figure 41. Factors Explaining Decline in Manufacturing Jobs, 1990-2008



Note: Decomposition based on regression estimation. Each factor is based on the change over the period.
Source: OECD Economic Outlook, June 2017, STAN database and OECD calculation.

Do firms have a role to play in alleviating the adverse consequences of joblessness and job transitions for the worker? There is evidence to show that companies are aware and considering their own responsibility on labor impacts. Some companies focus on 'digital, flexible, green', with the flexible nature of the factory focusing on the employee and adopting flexible working conditions and using automation where it is practical and economically useful. Others note they have cut back on automation to create a better working environment for employees.

Are the responsibilities different for developing automation and adopting automation? It is worth noting that the providers of advanced manufacturing technology are less likely to face social license risks from their own workforces. It is of course the purchasers of advanced manufacturing goods and services who face this risk. This highlights that automation will impact companies social license to operate in different ways, depending on their position in the supply chain.

In light of this, we remain cautious of the impacts of displacement from automation in the traditional manufacturing sectors, specifically those in developing countries with greater inequality risk and less developed educational structures.

Watch for companies using advanced manufacturing to support responsible production, with an eye to managing labor impacts: The trends discussed herein involve increasingly advanced manufacturing processes and will have significant impacts on company practice and profitability. However, we have seen that they will also have a number of effects on companies' ability to support the Sustainable Development Goals (SDGs) and maintain their social licenses. Advanced manufacturing operations have a better chance of reducing resource intensity and undertaking circular production, but on the flip side present significant implications for employment as a consequence of automation. In some senses this means that advanced manufacturing operations risk being both good for economic growth and profitability, and also a force for increasing economic inequality. From an ESG perspective we are interested to see the extent to which individual companies are able to use their advanced manufacturing capacities to improve their resource footprints and use, while also continuing to maintain their social license to operate, potentially by giving consideration to SDG 8.

Figure 42. United Nations Metrics & Indicators for Sustainable Development Goal 12

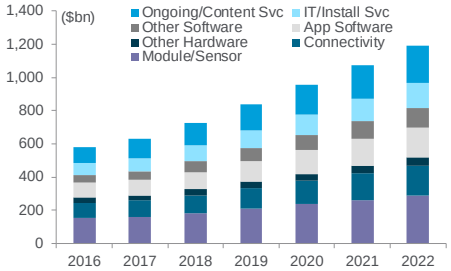
Targets	Indicators
12.1 Implement the 10-year framework of programs on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries	12.1.1 Number of countries with sustainable consumption and production (SCP) national action plans or SCP mainstreamed as a priority or a target into national policies
12.2 By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1 Material footprint, material footprint per capita, and material footprint per GDP 12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	12.3.1 Global food loss index
12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	12.4.1 Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement 12.4.2 Hazardous waste generated per capita and proportion of hazardous waste treated, by type of treatment
12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1 National recycling rate, tons of material recycled
12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle	12.6.1 Number of companies publishing sustainability reports
12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities	12.7.1 Number of countries implementing sustainable public procurement policies and action plans
12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	12.8.1 Extent to which (1) global citizenship education and (2) education for sustainable development (including climate change education) are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment
12.A Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production	12.A.1 Amount of support to developing countries on research and development for sustainable consumption and production and environmentally sound technologies
12.B Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products	12.B.1 Number of sustainable tourism strategies or policies and implemented action plans with agreed monitoring and evaluation tools
12.C Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities	12.C.1 Amount of fossil-fuel subsidies per unit of GDP (production and consumption) and as a proportion of total national expenditure on fossil fuels

Source: UN (2018), Global Indicator Framework for the Sustainable Development Goals and Target of the 2030 Agenda for Sustainable Development, Citi Research

The Industrial Internet of Things (IIoT)

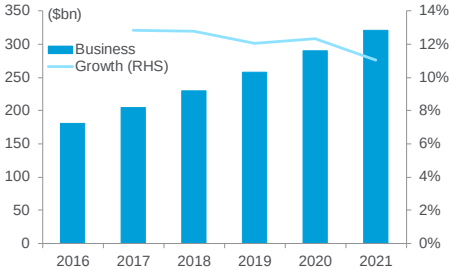
The Industrial Internet of Things (IIoT) broadly refers to the enabling of connectivity and gathering of data from all kinds of industrial devices, then used in a wide range of applications including monitoring, predicting, benchmarking, predictive maintenance, remote servicing, and more. While IIoT applications go beyond factories (in transportation and energy markets for example), we see the IIoT as a key enabler of the factory of the future. The idea of networked industrial devices is not new — Ethernet-enabled plant control systems were launched in the 1980s, and networked plant automation became the norm throughout the 1990s. The Industrial Internet however has become possible through the ability to deploy vast numbers of remote IP-enabled data gathering points on industrial equipment, with cloud computing enabling the storage of the vast amount of data then generated.

Figure 43. Global IoT Market Forecast



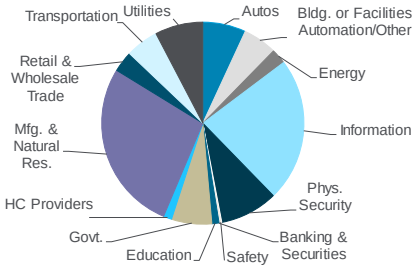
Source: IDC

Figure 44. Industrial IoT Electronic Hardware



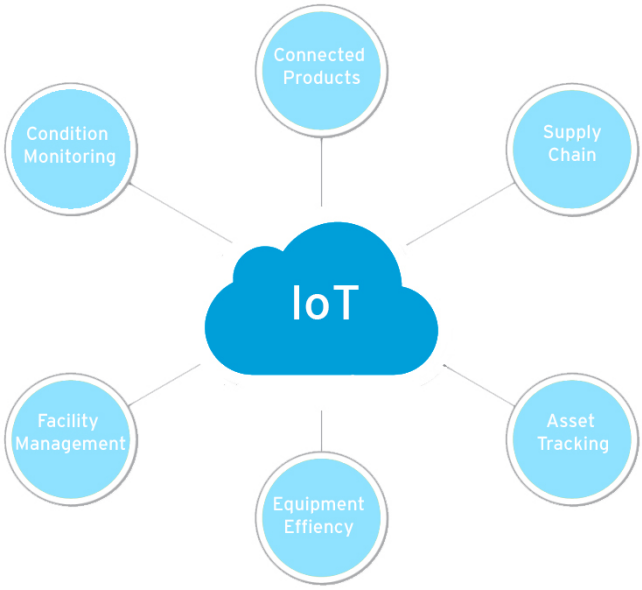
Source: Gartner

Figure 45. 2019 Industrial IoT Device Market



Source: Gartner

Figure 46. The IIoT Can be the Heart of the Factory of the Future



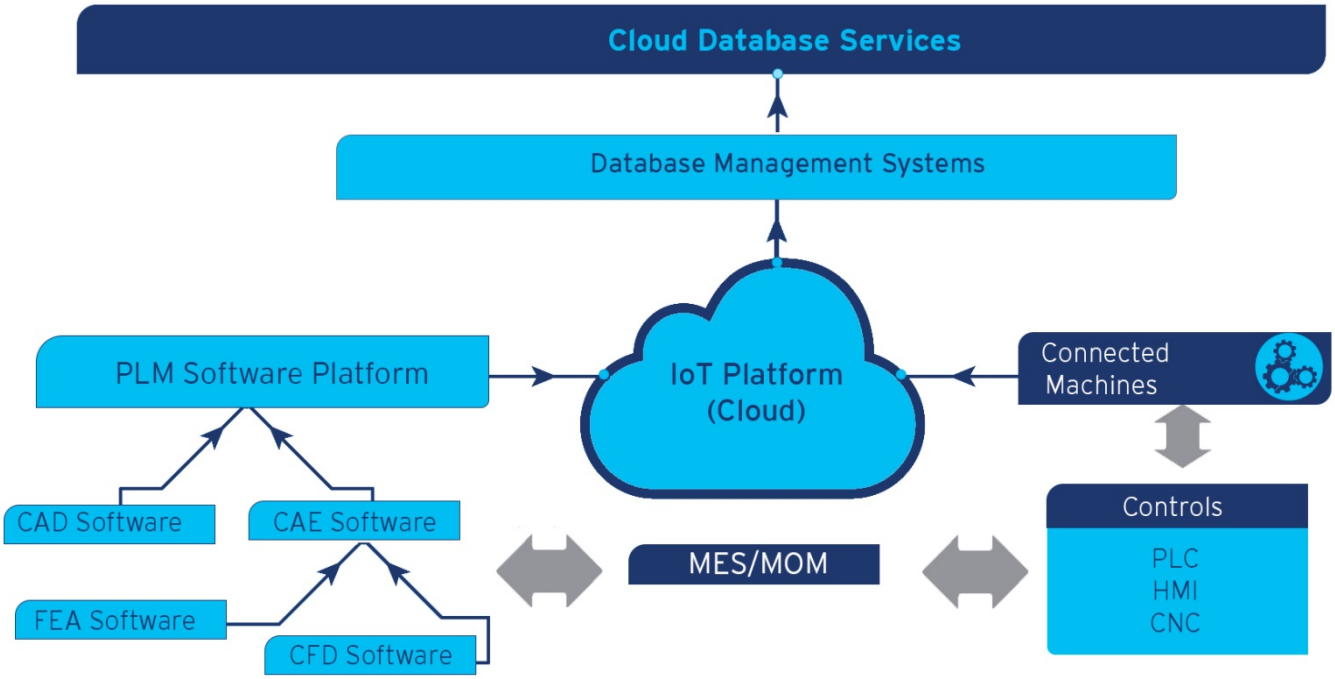
Source: Citi Research

A Convergence in Definitions

"No industry has seen the benefits of IoT more than manufacturing" -- Microsoft

When the IIoT concept was first born, there was a boom in industry consortia to define standards, although this has seen some consolidation. In the U.S., the Industrial Internet Consortium, founded in 2014 by five companies and now has more than 200 member companies. In 2019, the consortium merged with OpenFog, a consortium focused on the IoT standards for edge/decentralized applications, and it has also "deepened its relationship" with Plattform Industrie 4.0, the German government-sponsored platform also linking up recently.

Figure 47.The Beginners Guide to Industrial Software



Source: Citi Research

IIoT Platforms

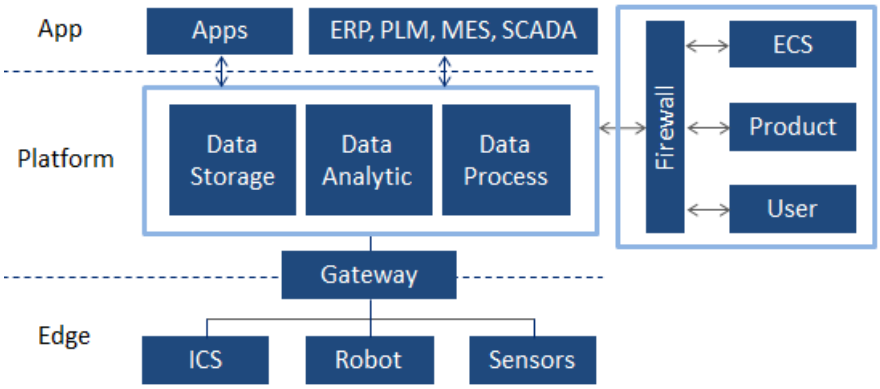
Many companies use the term IIoT 'platform' in slightly different ways (including to blur the distinction with industrial cloud offerings), but PTC's definition that IoT platforms are suites of software components that allow the deployment of applications for '*monitoring, managing and controlling connected devices*' seems to be broadly accepted — these are commonly referred to as 'IoT Application Enablement Platforms', and we can think of them like an app-store for industry, with applications that offer remote condition monitoring, predictive maintenance and so forth. We note that there are other broader definitions (see Figure 48) and estimates of addressable markets can vary enormously depending on how broadly the market is defined.

Figure 48. What is an IoT Platform?

Name	Description
IoT Application Enablement Platforms	Infrastructure for application hosting, development and lifecycle management, with apps designed for monitoring, managing and controlling connected devices
Connectivity / M2M platforms	Connection of devices to internet of things either through cloud or using telecom networks
IaaS backends	Cloud hosting space and processing
Hardware-specific software platforms	Proprietary platforms
Consumer/Enterprise software extensions	Products integrated onto existing enterprise software applications

Source: Cisco, PTC, IoT Analytics, Citi Research

Figure 49. Industrial IoT Architecture

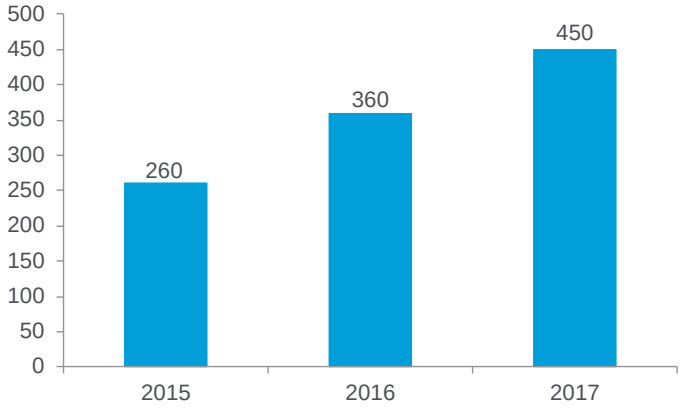


Source: MIIT, Citi Research

So How Many IoT Platforms Are There?

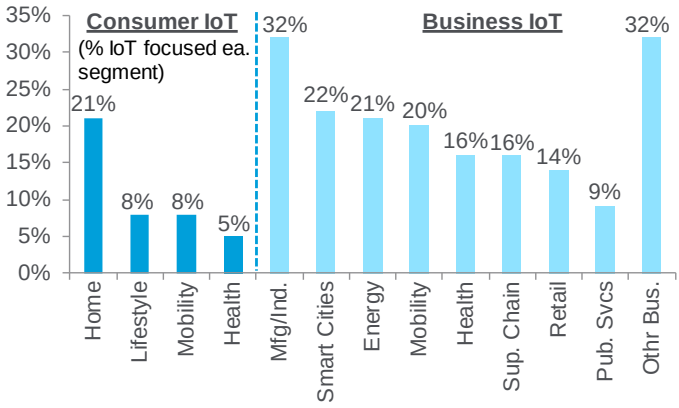
German IoT market research firm IoT Analytics estimated roughly 450 IoT platforms were in the market in 2017, a 25% surge from the year before (360 platforms in 2016). Most of the IoT platforms are now for the purpose of manufacturing / industrial, although smart homes are still take up a good portion of focus.

Figure 50. IoT Platform Companies



Source: IoT Analytics, Citi Research

Figure 51. Most IoT Platforms Focus on Manufacturing/ Industrial



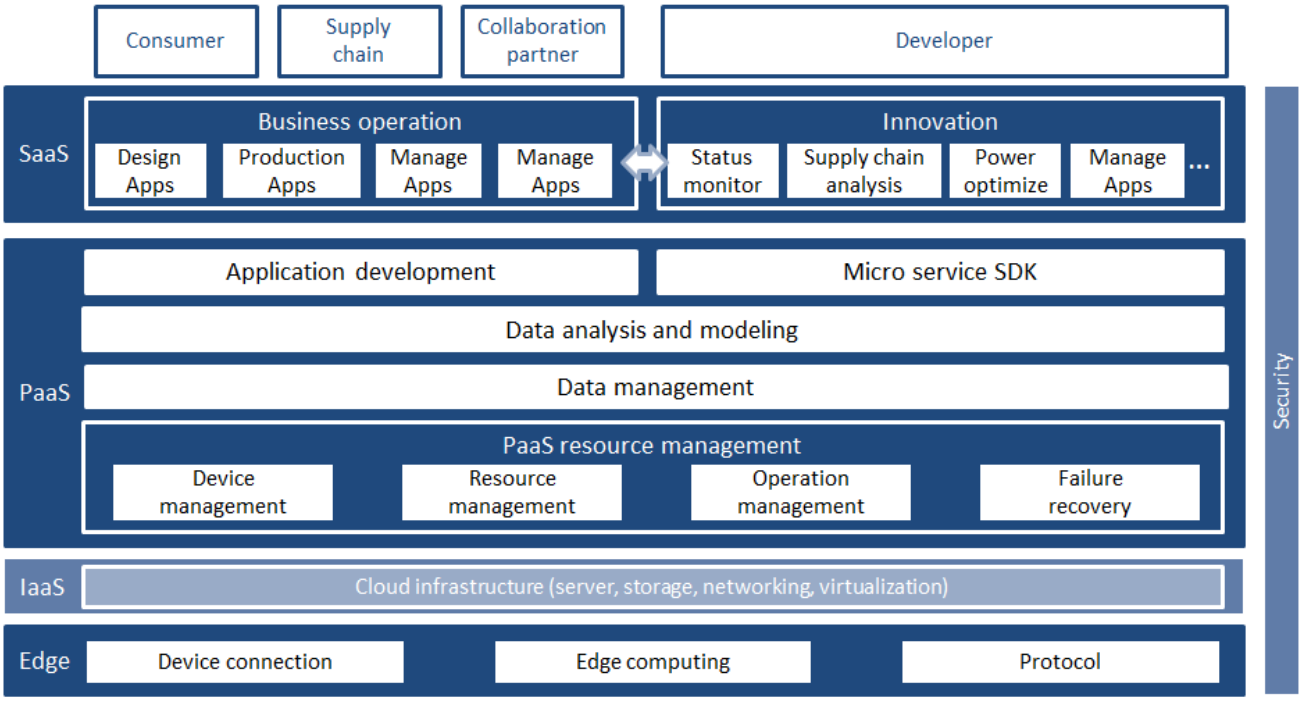
Source: IoT Analytics, Citi Research

The incorporation of IoT in the automation process requires industrial players to process more data than ever before, and this has led them to turn to the cloud platform for connecting physical devices to big-data platforms. Cloud computing distilled down to its simplest definition is off-site data storage, retrieval, and manipulation. Utilizing cloud eliminates the need for manufacturers to maintain their own data centers, while at the same time enabling the incorporation of the software expertise necessary in processing the vast amounts of data generated through 'smart' factories. In regards to this strategy, we are seeing various partnerships being formed between industrial players, software companies, and cloud providers.

IoT Analytics estimated in January 2017 there were over 450 IoT platform providers — this is the equivalent of having >450 distinct app stores. Not all of these are industrial, but many are. Not all will be needed and we think the network effects from scale and an early launch will be differentiators.

- **Industrial installed base and domain expertise matter:** Industrial software platforms benefit enormously from 'equipment on the ground' — controllers, sensors, motors, and other industrial devices well positioned to collect data in order to optimize equipment and streamline processes. These connected products are arguably the largest barriers to entry to new entrants.
- **New applications open up several new competitive debates:** Pricing models, the use of open source software, and data ownership and security are amongst the key themes.

Figure 52. Industrial IoT System Architecture



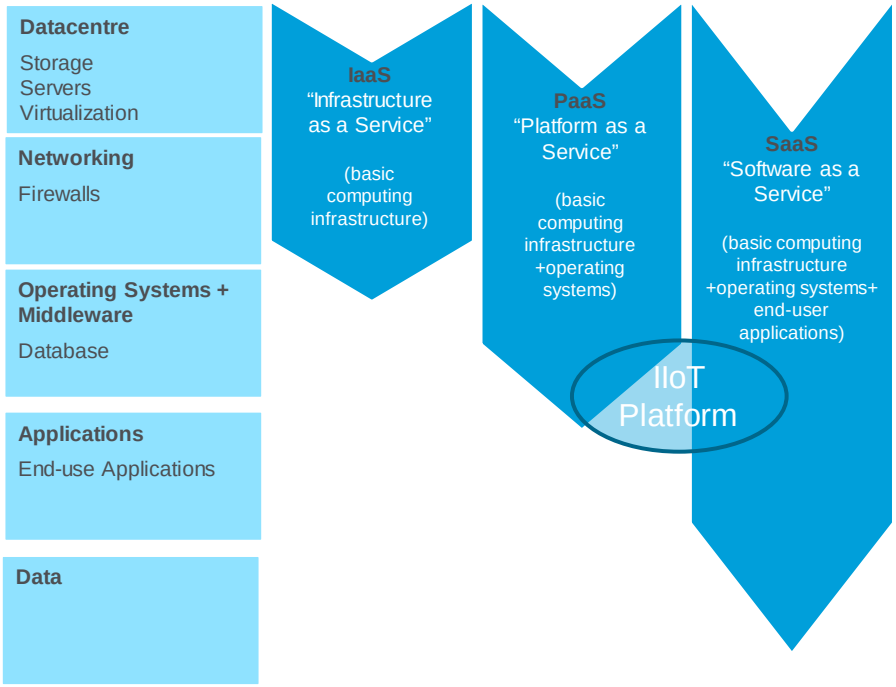
Source: MIIT, Citi Research

IaaS, PaaS, and SaaS…Where Does IIoT Fit?

Cloud computing services are often categorized into three types – IaaS (Infrastructure as a Service), PaaS (Platform as a Service), and Saas (Software as a Service). We'd argue that IIoT platforms span the last two. IIoT platforms use PaaS from vendors but are also themselves application platforms.

- **IaaS – Infrastructure as a Service:** In this "bare bones" example, the vendor provides the IT infrastructure only as a service, including servers, storage, local area networks etc., and avoids the need for the user to manage physical datacenters, or to manage storage capacity since usage can be ramped up and down in real time. Companies can deploy their own software, operating systems, databases etc. to the infrastructure provided by the IaaS.
- **PaaS – Platform as a Service:** As above, but includes computing platforms (operating systems, web servers, databases) to allow users to focus on applications only, and the end customer still manages and "owns" their own software applications.
- **SaaS – Software as a Service:** Infrastructure, platform, and applications are all provided by the vendor. CRM is a commonly used SaaS, and we note that some industrial vertical software companies already provide SaaS in areas like PLM and similar software.

Figure 53. IIoT Platforms Use Vendor PaaS Solutions But Are Still In Themselves Application Platforms to Support End-user Own Applications



Source: Citi Research

Applications

IIoT platforms are not end-use applications in their own right. Think of these platforms as both aggregators of data, and as "industrial app stores" that enable software providers (or even single users), to cheaply produce and easily distribute

quite specific software applications to analyze this data. A niche “app” for monitoring a highly specialized low volume piece of industrial equipment, for example, is enabled by the use of such platforms.

Edge Devices on the Factory Floor

The convergence of “operations technology” and “information technology” is seen most noticeably in edge devices.

In industrial terms ‘edge’ devices are decentralized pieces of industrial product that can gather the data — whether robots in the factories, or equipment in the field. Edge devices have historically been controlled by ‘operations technology’, or ‘OT’ — often using close programming languages specific to one hardware manufacturer. Adding control, sensor, and measurement devices allows even older equipment to become part of the IIoT.

The IIoT platform requires a connection between IT and OT hardware, but since some legacy industrial equipment cannot be connected through IP (internet protocol) technology, a hardware controller needs to be added to translate to the IIoT network. Many legacy control products (like PLCs) will not have had Ethernet or wireless connectivity installed at the time of manufacture despite being ‘digital’, and a lot of legacy industrial equipment (motors, pumps etc.) will not have had digital capabilities at all. In these cases, new edge devices are needed to connect legacy assets.

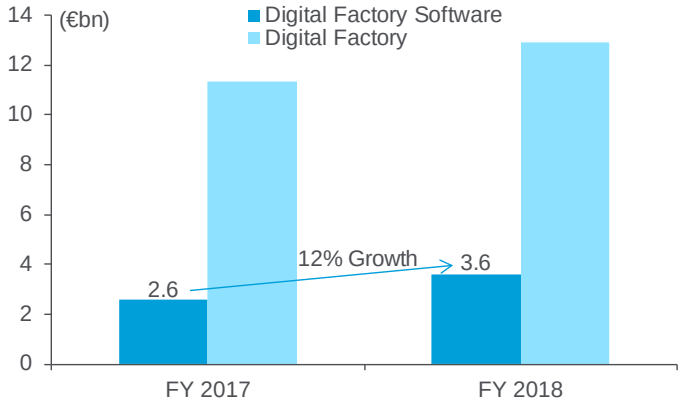
According to a Gartner estimate, 25% of on-site industrial assets will be connected by closed-loop fully automated systems using IIoT by 2023.

The Convergence of Software and Hardware Companies?

We see industrial companies and software companies collaborating rather than competing in enterprise applications – although there is an overlap when it comes to "vertical" software

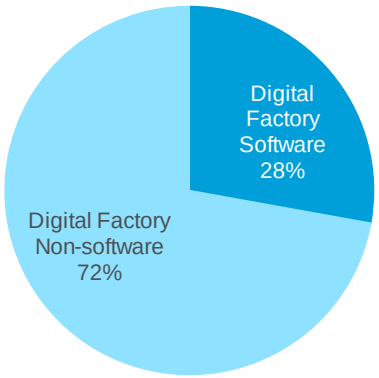
Many industrial products have had software embedded in them for control purposes for decades. The idea of the convergence between IT and industrial markets is not new although the type of software — enterprise-wide for IT companies and domain-specific (and often hardware-specific) for industrial companies — has meant that the overlaps have been relatively limited in the past. Of the 'vertical' software markets that are domain- and end-market-specific, discrete manufacturing is the largest — although much of this is largely embedded in industrial products like PLCs (Programmable Logic Controllers) and CNCs (Computer Numerical Controls).

Figure 54. Software Growth Outpaces Overall Digital Factory Growth



Source: Citi Research, Company data. Note: Figures in €bn

Figure 55. Software Is Now Close to 30% in Digital Factory

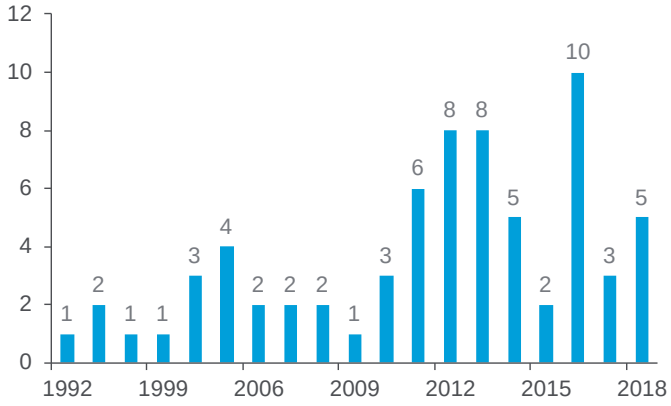


Source: Citi Research, Company data. Note: Based on FY2018 Figures

Information Technology (IT) and Operations Technology (OT) have their roots in very different parts of the organization. IT has traditionally focused on enterprise-wide software and information, and is often business-model-agnostic (like ERP systems) while OT has historically centered around the software used to control and automate specific hardware on the factory floor.

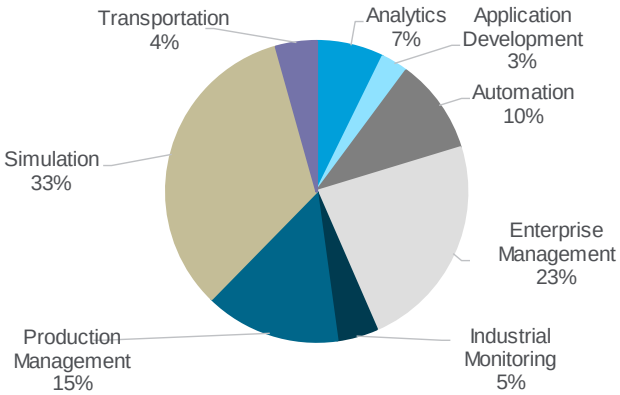
While OT has therefore historically been designed for specific industrial products and processes, often on a standalone basis, this has been changing over time. Industrial applications are already increasingly connected to IT infrastructure with the adoption of IP (internet protocol) connectivity, a trend that will only accelerate through increasingly connected devices and a desire to aggregate data. The use of IP connectivity on more and more industrial devices arguably is the biggest reason for the increasingly blurred distinction between IT and OT.

Figure 56. Software Acquisitions by Industrial Companies (1992-2019)



Source: Citi Research

Figure 57. Software Acquisitions by Business Type



Source: Citi Research

Managing Cyber Risk in Manufacturing

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This section summarizes the manufacturing impact from the Citi GPS report "Managing Cyber Risk with Human Intelligence", May 2019, linked here.

The cyber threat to manufacturing is significant due to the latent power of industry control systems. An attack which can bypass the safety systems of production lines and furnaces may exploit latent fuel sources to create a devastating attack. Because of its complexity, it is difficult to estimate the number of vulnerabilities present in industrial systems, and therefore to present a solution based on the realities of potential compromise.

With the further digitization of industry control systems and significant portions of critical national infrastructure, governments and industry leaders must accept that vulnerabilities will become an inherent part of vital systems. More investment in security testing is required to resolve issues before they arise, and to safeguard users and companies in the event that an unseen vulnerability is leveraged against them.

Attacks that bypass the safety systems of an industrial plant could exploit latent fuel sources with devastating effects

The cyber threat to manufacturing is significant due to the latent power of industrial control systems used in the production of high-powered machinery, computing, foodstuffs, and building materials. An attack which can bypass the safety systems of production lines and furnaces may exploit latent fuel sources to create devastating attacks. In 2014, a cyber attack against a German steel mill was the first attack to cause confirmed physical damage since 2007's Stuxnet.[13] Using social engineering and spear phishing emails, attackers were able to gain access to the mill's office network, which was connected to the industrial control system, and use the system to compromise production and cause a furnace blast and massive damage to the facility.

Attackers could also introduce long-term threat to the industry by altering manufacturing processes

Significant, too, is the long-term threat of cyber to the industry. Sophisticated attackers may be able to introduce faults into manufacturing materials, which would either render tons of product unusable, or potentially introduce new dangers into goods that are made with compromised material. In an extreme variant of this scenario, generations of aerospace parts, building materials, or automobiles may be made deliberately faulty, with little way to trace the error.

The rate of cyber attacks against the manufacturing sector is growing, limiting investment in digital methodologies. A 2018 study by EEF and AIG with the Royal United Service Institute (RUSI) reported that half of surveyed manufacturers had been victims of cyber crime or a cyber attack, and that a further 40% of companies did not feel that they had adequate access to the information needed to assess their cyber risk.[14] A report from 2017 cites manufacturing as the third most attacked sector after Government and finance.[15]

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[13] Zetter, K. (2015), A Cyberattack Has Caused Confirmed Physical Damage for the Second Time Ever. *Wired*. January 8. https://www.wired.com/2015/01/german-steel-mill-hack-destruction/.
[14] Cyber Security for Manufacturing'. 2018. EEF, AIG and RUSI. https://www.eef.org.uk/resources-and-knowledge/research-and-intelligence/industry-reports/cyber-security-for-manufacturers.
[15] IBM X-Force Threat Intelligence Index'. 2018. November 23. https://www.ibm.com/security/data-breach/threat-intelligence.

The majority of these attacks have affected head offices and other services rather than industrial facilities. Manufacturing companies are also vulnerable to distributed denial-of-services (DDoS), malware, and ransomware attacks, which may lead to business interruption, lost production time, and slow communications with suppliers and vendors.

How Many Vulnerabilities Are There?

Estimating the number of vulnerabilities present in industrial systems is difficult and tracking vulnerabilities is an inexact science

It is difficult to estimate the number of vulnerabilities present in industrial systems, and thus to present a solution to the realities of potential compromise. Exploitable vulnerabilities can exist in hardware, software, network protocols, and programming languages such as Java, and can be present on both local and remote, or isolated or connected systems. Products and updates are rarely interrogated for an accurate count for new avenues of compromise, and, as in the case of WannaCry, patches and updates which reconcile pre-existing vulnerabilities may be difficult to roll out systematically and universally. If a programming language contains an exploitable fault, that fault is replicated across any code written in that language.

The number of vulnerabilities in digital and industrial products may be limited or infinite. Although vendors have a responsibility to adequately assess their products for user safety, compromises will inevitably be missed when economic demands and available knowledge limit the time spent to do so. As new technologies arrive with embedded system flaws, protocols may introduce additional faults which can be compromised, which are subsequently grandfathered in. As the cyber economy continues to grow and business becomes ever more reliant on digitization, vulnerabilities known and unknown will only proliferate further.

Vulnerability tracking is an inexact science and is subject to selection bias. Numbers published fluctuate heavily, between 5,000 and 15,000 per year. Companies that are able or willing to fund penetration testing or vulnerability research, or offer rewards for independent security testing, will see more exploits found and patched. There is little incentive for individual security experts to probe vital technologies for flaws on spec, however, for fear of punishment or being ignored by the technology's vendor, and thus many flaws will not be found.

Vulnerabilities which are found can be registered to databases, but there is no central standard hub for vulnerability data and oversight can be lacking. Naming schemes for exploits differ across industries and between security analysts, so lists undoubtedly contain duplicates.

As more vulnerabilities are registered, more money will be invested in security testing

Generally speaking, the number of vulnerabilities registered in a year will correlate with the amount of money invested in security testing. In 2014, the CERT Coordination Center automated the testing of more than 1 million mobile phone apps for SSL encryption, returning insight on 23,000 vulnerabilities in a year, all from a single test. This spike in registered vulnerabilities indicates that more vulnerabilities are found with dedicated security analysis. As the profession develops, more vulnerabilities will be found, though this is unlikely to ever accurately reflect the total number of vulnerabilities actually latent in the landscape. In the meantime, malicious actors will also be looking for and selling unregistered exploits through back channels. These vulnerabilities may be leveraged for significant damage or disruption, but may not become known or addressed until after they are used for malicious means.

As industrial control systems for critical national infrastructure increasingly become digitized, vulnerabilities will continue to increase

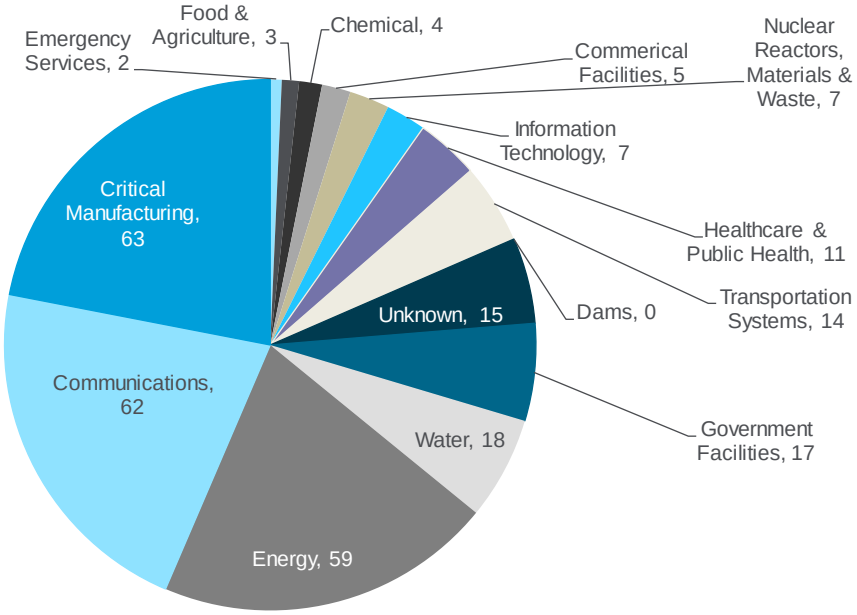
With the further digitization of industrial control systems and significant portions of critical national infrastructure, governments and industry leaders must accept that vulnerabilities will become an inherent part of vital systems. More investment in security testing is required to resolve issues before they arise, and to safeguard users and companies in the event that an unseen vulnerability is leveraged against them.

Figure 58. Catalog of Major ICS Cyber Events from 1999 through 2017 With Primary Consequence or Harm

Date	Event Name	Detailed Description	Actors	Motivation	Methodology	Outcome
April 1999	Russian gas supplier	A Trojan was delivered to a company insider who opened it deliberately. The control system was under direct control of the attackers for a number of hours.	Targeted Attack & Insider	Sabotage & Ransom	Trojan & Insider	Unauthorized Access
July 1999	Bellingham	Over 250,000 gallons of gasoline leaked into nearby creeks and caught fire. Large amount of property damage, three deaths and eight others injured. During the incident the control system was unresponsive and records/logs were missing from devices.	Accident	Unknown	Accidental	Physical Damage and Bodily Injury
Feb & April 2000	Maroochy Shire	A recently fired civic employee sabotaged radio communications and released 800,000 gallons of raw sewage into parks, rivers, and the grounds of a hotel.	Insider Attack	Sabotage	Radio man-in-the-middle	Physical Damage
May 2001	California	A hacking incident at CASO lasted two weeks, but did not cause any damage	External Attack	Unknown and Contained	Deliberate	Thwarted
August 2005	U.S. Auto OEM	Thirteen U.S. OEM auto manufacturing plants were taken offline for about an hour by an Internet worm. This resulted in an estimated $14 million in downtime costs.	Unknown	Spyware Installation	Zotob Worm and MS05-039 Plug-n-Play	Infection
Jan 2008	Kingsnorth	Attacker broke into the Kingsnorth power station which caused a 500MW turbine to make an emergency shutdown.	Targeted Threat Actor	Sabotage	Physical Penetration	Environmental Protest
Nov 2008	Offshore Oil Co	A recently fired employee disarmed safety alarms on three offshore oil platforms.	Insider Attack	Disgruntled Employee	Disabling alarm systems	Revenge & Sabotage
June 2009 to 2010	Stuxnet	Malicious code targeted ICS at an Iranian nuclear plant.	Virus, Unknown Presumed Nation State	Sabotage	Destroying centrifuges and thwarting uranium enrichment	Revenge & Sabotage
2010 to Aug 2014	Dragonfly/Havex/ Energetic Bear campaign	A campaign against defense, aviation, & energy companies	RAT, Espionage	Unknown	Malware infection and remote access	Malware Clean-up
August 2012	Shamoon/Wiper	A Saudi Arabian oil company had over 30,000 workstations knocked out	Unknown, presumed Hacking group, RAT	Mischief	Wiping 30000 machines of their data	Unknown
2013	Bowman Avenue Dam	Iranian hackers breached the control system of a small dam outside New York City but were not able to remotely control the sluice gate	Targeted Attack	Revenge/ Sabotage	Penetration of computer systems via cellular modem	Thwarted, significant political attention paid to advancing cyber teams by foreign nations
April 2013	California Power Station	Snipers fired at a California substation, knocking out 17 transformers.	Unknown	Unknown	Destruction of substation oil tanks	Unknown
December 2014	German Steel Mill	Experienced hackers used a spear phishing campaign to gain access firstly to the corporate and then to the wider plant control network.	Unknown, presumed hacking group	Unknown	Compromised plant control network, causing system components to fail	Physical Damage
December 2015	Ukrainian Blackout	Three energy companies were taken offline, causing an 8-hour blackout which affected 225,000. Malware was found in the substations.	Presumed Nation State	Unknown	Infection of vulnerable power substations	Unknown
November 2016	BMS Attack	A sustained DDoS attack against a vulnerable building management system (BMS) caused internal heating to shut down for 24 hours in two apartment buildings in eastern Finland during sub-zero temperatures	Unknown	Unknown	Sustained denial of service attacks caused system to restart every few minutes	Firewall Installed
December 2016	Ukranian power outage	A second attack on Ukraine's power distributor left Kiev and the surrounding area without power for several hours during the night of 17-18 December	Suspected APT	Unknown	Targeted CRASHOVERIDE malware attack	Unknown
May 2017	WannaCrypt/ WannaCry	A strain of ransomware affected 300,000 computers in 150 countries, demanding $300/ affected computer to release files. An activated kill-switch stopped the malware from spreading further.	Suspected North Korean APT, Lazarus Group	Unknown; the malware did not accrue sufficient funds to suggest financial gain.	ETERNALBLUE and DOUBLEPULSAR exploits as released by ShadowBrokers in April 2017	Killswitch activated
June-July 2017	NotPetya	A second attack utilizing ShadowBrokers exploits affected 12,500 machines in 64 countries. The attack presented as a ransomware but functioned as a diskwiper Trojan.	Presumed Nation State	Unknown	ETERNALBLUE ShadowBrokers' exploit	Malware Clean up and Patch roll out
June-August 2017	Triton/TRISIS	An infection of malware on a Saudi Arabia petrochemical plant caused several outages over the course of several months. The malware affected Triconex safety systems, potentially causing physical damage.	Presumed Nation State	Unknown, likely field testing	Malware Infection and Remote Access	Malware Clean up and System Repair

Source: Citi GPS: Managing Cyber Risk With Human Intelligence, May 2019

Figure 59. Industrial Control System Cyber Incidents by Sector as Reported to the U.S. National Cybersecurity and Communications Integration Centre for 2016



Source: Centre for Risk Studies, Incident Response Pie Charts (YIR 2016 Addendum)

Key Vulnerabilities in Operational Technology

Aging operational technology (OT) in critical national infrastructure (CNI) and their reliance on software patching for security increases the risk of cyber attack

Most OT systems used in CNI were designed and installed at a time when cyber risk was either not known or not considered. Such systems are typically difficult and expensive to replace and therefore software updates and patches are the simplest path to providing a measure of security. The major trend vulnerabilities existing in OT systems and industrial control systems (ICS) have their roots chiefly in both unsecured technology and matters of human judgment:[16]

- **Industrial control system lifetime versus IT system lifetime:** Operational engineering systems are generally designed to last five times longer than the underlying IT systems.[17]

- **Testing costs:** The security of many commercially successful off-the-shelf products has steadily improved over time due to mutually beneficial security testing by independent security professionals. The popularity of a product, such as a smartphone or a virtual assistant, and its level of availability may inspire a penetration tester to interrogate that product for system weaknesses, leading to a growth in the tester's reputation and a boon for the product vendor.

[16] The following trend analysis was submitted by the Cambridge Centre for Risk Studies as written evidence on November 19, 2018 to 'Cyber Security of the U.K.'s Critical National Infrastructure – Joint Committee on the National Security Strategy – House of Commons'.

[17] SecurityZap (2015). Vulnerabilities in Industrial Control Systems – SCADA. Security Zap.

The reverse is true of OT equipment, however, as widely-used systems rarely have any brand recognition outside of industrial engineering circles and equipment is expensive or cumbersome for a researcher to acquire for testing purposes. Many OT products are therefore under-examined because there is too little incentive for independent security testing.

- **Poor patching cadence:** Given the complexities of technology, it is challenging to patch operating systems and software to ensure the functionality of the entire system. A study by the Zero Day Initiative determined that in 2016, it took 143 days for human machine interface vulnerabilities to have a patch released by the vendor.[18] Both patching cadence standards within an organization and regular patch releases from vendors are susceptible to long delays and installation issues. Many times, organizations lack a complete inventory of all systems, including their various software 'subcomponents'. This is commonplace in an IT environment, but the OT environments have not matured in this way. Additionally, OT systems have not generally been managed in a way to accommodate downtime due to patching.

- **Poor password security and unencrypted protocols:** The recent Mirai botnet came about as a result of IoT devices being sold with easily hackable passwords and using unencrypted protocols.[19] Although the Mirai botnet cyber attack was not related to ICS, it highlights several security issues imbedded in it. Default passwords on installed ICS devices are not regularly changed. This situation is gradually improving as industries become more conscious of it, but many older systems still in use are vulnerable to cyber attack.

- **Third-party vendor access:** Outside vendors are often employed to aid in various engineering support activities, from system improvement to training. This poses a further risk should the vendor (or the client organization) not adhere to a rigorous cyber security culture.

- **Enterprise management systems:** In order to enable real-time monitoring of production processes, a corporate office will have an uptime/downtime and production count reporting system. These systems are a potential entry point for attackers who are trying to pivot from a corporate environment into the control system.

- **Network architecture:** The use of firewalls, intrusion detection systems, and user privileges can increase or decrease an OT system security depending on the method of deployment. Additionally, many of the systems employed in manufacturing processes are not IP-based and don't have the interfaces that make it easy to communicate with or extract data from. The security products that are able to interface with these systems are more specialized and still developing into the mainstream. Publicly-held ForeScout made a recent acquisition here and we've seen significant venture capital investment in this market.

- **Potential for physical damage:** It is possible to cause physical effects, even damaging expensive and equipment which is difficult to reach or replace, by exploiting OT systems.

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[18] Gorenc, B., & Fritz Sands. 2017. 'Hacker Machine Interface: The State of SCADA HMI Vulnerabilities' Trend Micro Zero Day Initiative Team.

[19] Fruhlinger, J. (2018). The Mirai Botnet Explained: How IoT Devices Almost Brought Down the Internet'. CSO Online. March 9.

Inside Robotics

Robotics remains the poster child for the "Factory of the Future", even though they are just one component. Arguably they are often seen as the driving force behind replacing human labor

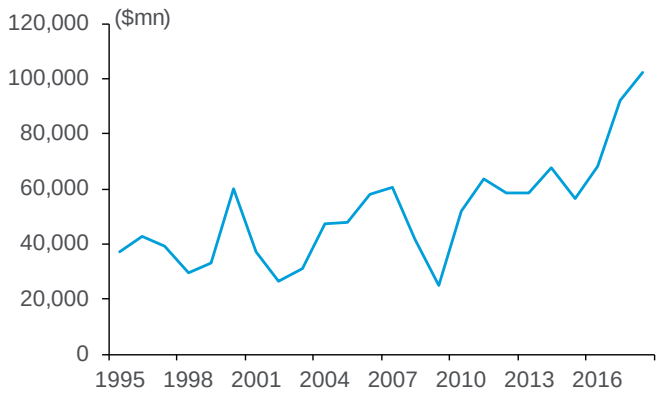
Industrial robots have their roots in the automotive industry, first adopted by General Motors in the 1950s. Even now, close to half of all industrial robots sold are for the automotive industry, including for both chassis and powertrain assembly, with electronics & technology hardware the second largest end market.

Industry conjecture 2-3 years ago suggested that the 'sub $10k cobot' was coming, but this was the first year we'd seen so many — cobots priced at <€10k (or even less than €5k in some cases) are now on show at the event, although the higher price points of established suppliers (at up to $35k) include end use application software. The use of these cheaper cobots using open standards (like ROS) looks so far confined to development and academic applications, rather than in production applications. From fewer than five cobot players 3-4 years ago, there are now >50 cobot suppliers globally, including >20 from China, although the scaling back of government grants is expected to drive some consolidation in the China market. Competition in cobots is not yet significantly driven by the established industrial robot suppliers with Universal Robots noting their biggest source of competition is still 'customers who choose not to automate'.

Even as robot penetration increases, the cyclicality of these key end markets means it is unlikely that robotic growth will be immune from the ups and downs of the cycle. In automotive, ABB recently commented it saw end market demand for robotics remaining at a high levels, as the complexity of multiple power trains (combustion engine, hybrid, electric) offset lower unit production growth; more complex chassis structures (incorporating aluminum and carbon fiber as well as steel) also makes joining and welding more complex. In electronics and tech hardware assembly, smartphone assembly in China has seen growth slow recently.

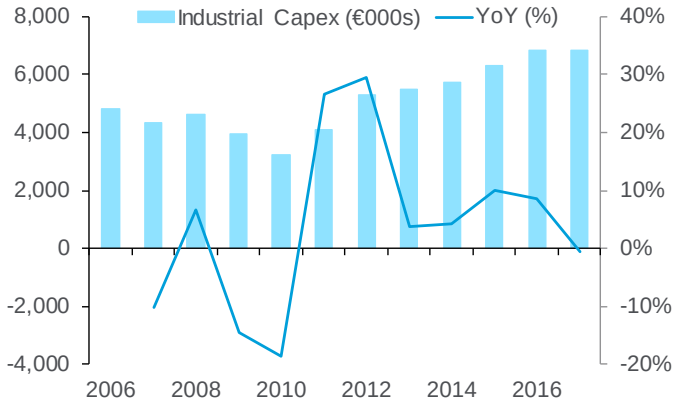
Logistics, food & beverage, and other emerging areas for robotics have not yet been large enough markets to offset this cyclical weakness seen in 2018.

Figure 60. Semiconductor Capex Cycle



Source: Citi Research

Figure 61. Auto Capex Cycle

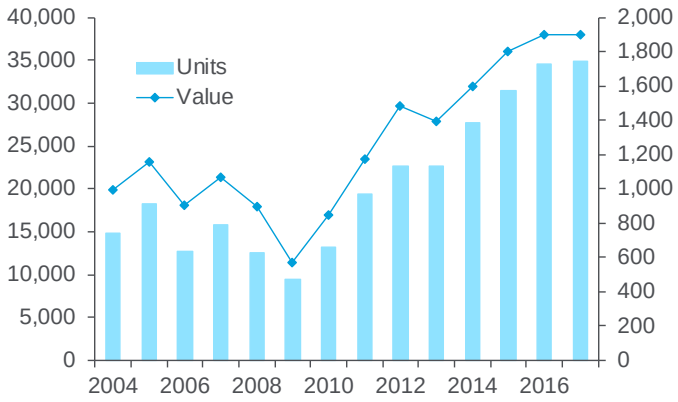


Source: Citi Research

Robotics Market

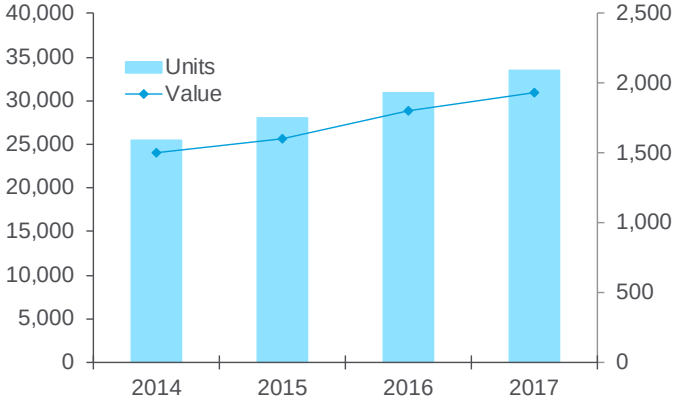
The Robotics Industry Association, or RIA, is the U.S. robotics industry body (counterparts include JARA in Japan and IFR globally). Recently due to the increased importance of vision & imaging / motion control, RIA put out data on these categories as well as robotics orders and shipments.

Figure 62. North American Robotics Orders ($mn)



Source: RIA, Citi Research

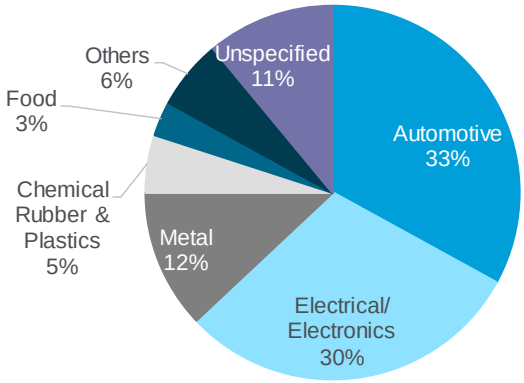
Figure 63. North America Robotics Shipment ($mn)



Source: RIA, Citi Research Note: 2018 Shipment value not available.

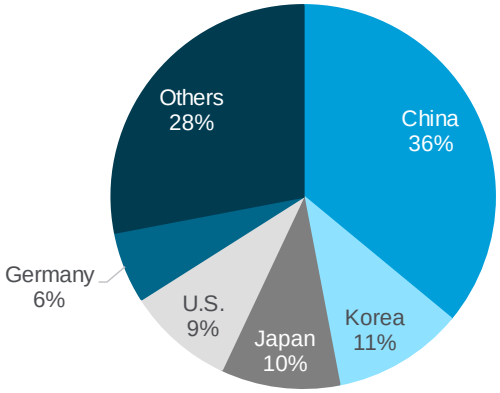
The International Federation of Robotics (IFR) is the global association for the robotics industry, and generally releases statistics annually. According to their latest release (2017 data), Automotive is still the largest end market although their proportion has been on the relative decline (38% in 2015 to 33% in 2017), and China has been clearly outgrowing the market and now stands as the dominant #1 market share in global robotics.

Figure 64. End Market Split by Industry (2017)



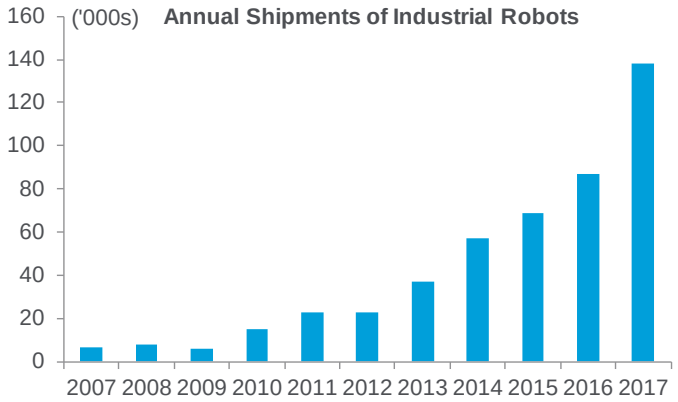
Source: IFR, Citi Research

Figure 65. End Market Split by Country (2017)



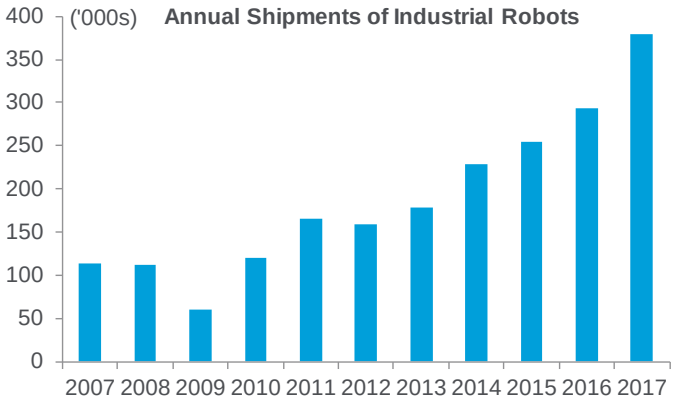
Source: IFR, Citi Research

Figure 66. While the Robotics Markets is Growing Steadily Globally...



Note: Figures in '000 units of industrial robots shipments globally.
Source: IFR, Citi Research

Figure 67. ...China's Growth is Clearly Outpacing Global Growth



Note: Figures in '000 units of industrial robots shipments in China
Source: IFR, Citi Research

IFR estimates global shipments of robots to show around a 14% CAGR within the next three years, with the growth mostly coming from Asia (by far the largest market for industrial robotics). China is expected to increase its dominance with almost a 50% market share by 2021.

Figure 68. Estimated Annual Shipments of Multipurpose Industrial Robots in Selected Countries

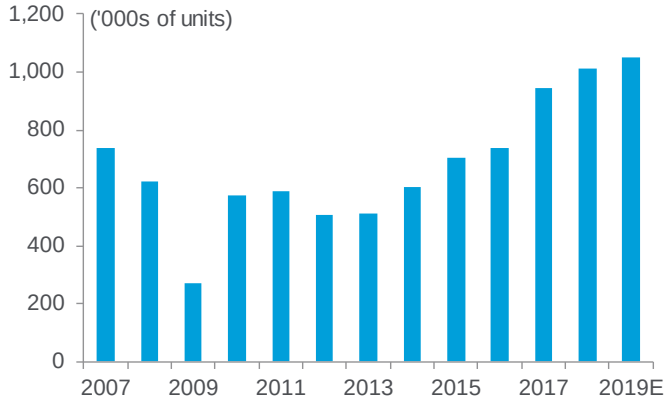
(in # of units)	2016	2017	2018E	2019E	2020E	2021E	CAGR '18-21
Americas	41,295	46,118	44,300	48,900	55,600	63,500	*12.8%*
North America	39,671	43,529	43,000	47,500	54,000	61,500	*12.7%*
- United States	31,404	33,192	35,000	37,500	41,000	46,000	*9.5%*
- Canada	2,334	4,003	3,500	4,000	5,500	6,500	*22.9%*
- Mexico	5,933	6,334	4,500	6,000	7,500	9,000	*26.0%*
Brazil	1,207	961	900	900	1,000	1,200	*10.1%*
Rest of South America	394	300	400	500	600	800	*26.0%*
Other Americas	23	1,328					
Asia/Australia	190,542	261,826	298,150	351,250	405,400	462,600	*15.8%*
China	87,000	137,920	165,000	210,000	250,000	290,000	*20.7%*
India	2,627	3,412	4,500	5,000	6,000	7,500	*18.6%*
Japan	38,586	45,566	54,000	56,000	59,000	64,000	*5.8%*
Korea	41,373	39,732	41,000	42,000	44,500	46,000	*3.9%*
Taiwan	7,569	10,904	13,000	14,000	17,000	20,000	*15.4%*
Thailand	2,646	3,386	4,000	5,000	6,000	7,000	*20.5%*
Vietnam	1,618	8,252	2,500	3,000	4,500	7,000	*40.9%*
Other Asia / Australia	9,123	12,654	14,150	16,250	18,400	21,100	*14.2%*
Europe	56,078	66,259	70,950	75,250	82,500	93,600	*9.7%*
Central/Eastern Europe	7,758	10,538	13,500	16,500	19,750	24,300	*21.6%*
France	4,232	4,897	5,200	5,600	6,000	6,500	*7.7%*
Germany	20,074	21,404	22,500	23,500	25,000	26,000	*4.9%*
Italy	6,465	7,713	9,000	9,000	9,500	10,500	*5.3%*
Spain	3,919	4,180	4,700	4,600	5,100	6,500	*11.4%*
United Kingdom	1,787	2,334	2,400	2,200	2,300	2,600	*2.7%*
Rest of Europe	11,706	12,133	12,850	13,300	14,350	16,600	*8.9%*
Europe unspecified	137	3,060	800	550	500	600	*-9.1%*
Africa	879	451	500	600	700	800	*17.0%*
Unspecified	5,553	6,681	7,100	8,000	8,800	9,500	10.2%
Total	294,347	381,335	421,000	484,000	553,000	630,000	*14.4%*

Source: IFR, National Associations, Citi Research

JARA

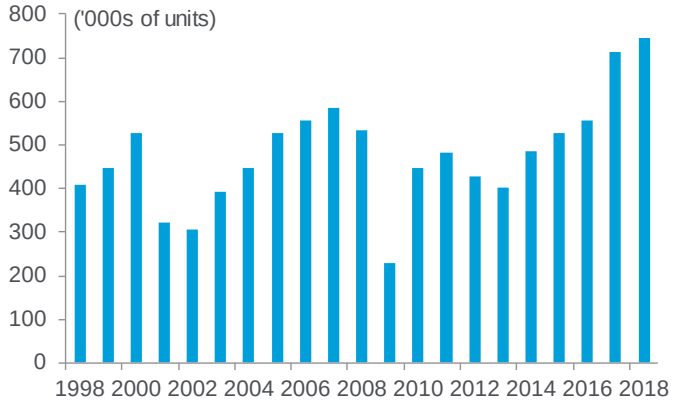
The Japan Robot Association (JARA) released its latest forecasts in late January of 2019. They forecast a 4% increase in industry-wide orders in 2019 (including non-members), which is the slowest rate of growth since 2013 and a marked slowdown from 28% growth in 2017 and 7% growth in 2018. On a regional basis, the main source of lower growth is China, and JARA highlights the negative impact of trade friction between the U.S. and China on spending plans at local manufacturers. However, given rising wages and a gradual decline in the working population, JARA is confident that the secular trend of automation remains in place. In our view, another reason for the slowdown is weakness in the smartphone value chain, and this is crucial as chip mounters exports make up around 40% of the value of Japan's total robot exports.

Figure 69. JARA Robotics Orders including 2019E Forecast



Source: JARA, Citi Research.

Figure 70. JARA Robotics Total Shipments



Source: JARA, Citi Research.

Is Innovation Always Profitable?

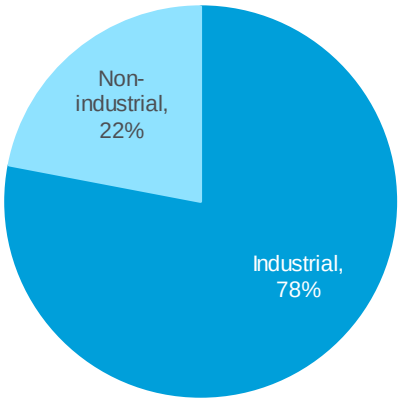
Rethink Robotics, one of the pioneers in the high growth collaborative robot market space, closed its doors in late 2018. The company was deemed to be one of the first to venture into this segment, although sales falling short of expectations ultimately led the company to close. Rethink was not the only one to shut its doors last year; two social robotics companies, Jibo (the creators of the world's first 'social robots') and Bosch-backed Mayfield Robotics (creators of 'Kuri') also closed its doors after failing to create meaningful sales in the market.

The subsequent closures of these companies prove that despite the prospects of growth in the underlying market, robotics companies may not necessarily materialize into profitable ones.

Logistics / Food Other Non-auto Growth Areas

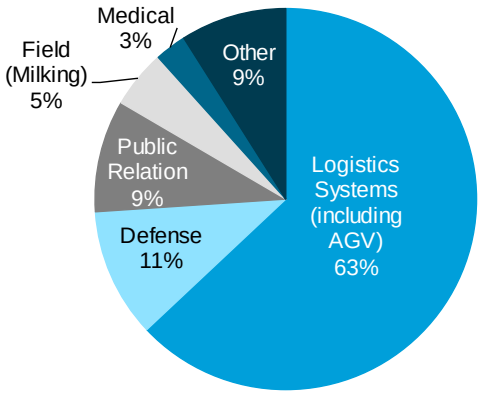
The non-industrial robotics segment is relatively a smaller part of the overall robotics industry, although it is showing a much faster growth rate (84% growth YoY in 2017 vs 29% for industrial robots). The majority of this segment is in logistics (including AGVs), where >90% are used for non-manufacturing applications.

Figure 71. Non-industrial Robotics Is Still the Smaller Segment



Source: IFR, Citi Research. Note: Based on unit figures

Figure 72. Non-Industrial Robotics by Type



Source: IFR, Citi Research. Note: Based on unit figures

A U.S. Perspective

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Factory of the Future, viewed broadly, encompasses a number of efforts that, individually and collectively are aimed at the singular effort of driving increasing productivity — both within OEMs own operations and for their customers. Digitization of industrial assets, analysis of the data captured from these assets, and operational optimization enabled by this digitization and analysis are key aspects of the Factory of the Future, but not the sole drivers. Advanced manufacturing including increasing deployment of robotics, broader application of automation, and new manufacturing technologies such as additive are also key enablers of the Factory of the Future over time. Given these multiple facets that come into play to ultimately achieve the Factory of the Future, partnering is an increasingly important competency — those who are most successful at driving toward the Factory of the Future will likely do so by partnering with others through various forms — joint ventures, M&A, strategic alliances, etc.

With many (if not most) U.S. Multi-Industrials highlighting current and future plans that incorporate at least some of these components as part of their long-term strategy, we view Factory of the Future as an evolutionary process that, while still in its relatively early days, is starting to impact results for our U.S. Multi-Industrials and could, over time contribute to accelerated topline and earnings growth and potentially help support lower volatility of outcomes.

Key Themes for U.S. Multi-Industrials

For U.S. Multi-Industrials that are able to adapt/transition as the Factory of the Future takes shape, the key themes noted above — digitization, analysis & operational optimization, advanced manufacturing, and partnering — represent complex challenges that, if successfully addressed, could support long-term topline and earnings growth opportunities across the industrial landscape.

Digitization, Analysis & Optimization: Physical assets — both the 'tools' of production within the factory footprint and more broadly, the equipment that multi-Industrials sell to their customers — are becoming increasingly digitized over time. Digitization and a growing ability to capture data related to the operating characteristics of equipment in turn can increase the knowledge base of how assets are performing. Digitization is not an entirely new trend — large capital assets such as gas turbines and aircraft engines for instance, are examples of physical assets from which meaningful data has long been captured and used to help drive improving performance. What is changing is that (1) we are seeing more and more physical assets being digitized over time and (2) growing technology capabilities such as more powerful artificial intelligence, digital twins, and augmented reality are broadening the scope of the opportunity to use digitization to optimize performance.

We see a growing trend toward digitizing 'all' physical assets: Formerly purely mechanical products are evolving, to include a digital component that allows for more 'real-time' data capture and monitoring. With increasing digitization of physical assets, we are seeing, in some instances, accelerated product innovation as newly 'smart' assets are introduced and increasingly adopted by customers. We've seen, for instance, a proliferation of digitally enabled Fire & Security as well as HVAC/Buildings Controls products and services that deliver quantifiable performance improvements versus prior generation products. As such, these digitally enabled products and services seem to be a tailwind to growth for OEM providers as previously relatively untapped digital opportunities are increasingly monetized overtime.

At the same time that we are seeing a proliferation of 'connected' assets, continued technological innovation is evolving the boundaries of what is possible to do with these assets — digital enablement, while important and increasingly common, is just the beginning step in driving improved productivity from physical assets; how the data is captured and used is critical to achieving the desired outcome of improved productivity. With the growing digitization of physical assets, we increasingly see OEMs as focused on understanding how best to use the data generated from these physical assets to drive improving outcomes for themselves and for customers. Through the use of technologies discussed throughout this report such as artificial intelligence, digital twins, and augmented reality, the potential usefulness of digitized assets continues to increase over time. Hardware-software convergence is a growing theme as we've seen examples of how, for instance, through the use of artificial intelligence and digital twins, many industrial companies increasingly have the ability to drive improving uptime/reliability for their customers. Our sense though is that adoption of these tools — while growing rapidly — remains in the relatively early stages as analysis and optimization tools and services evolve and as business models shift to address the changing manufacturing landscape.

Advanced Manufacturing: In addition to the digitization of physical assets that we discussed above, a continued evolution of manufacturing tools and techniques is another crucial facet of the Factory of the Future. Factory automation is not new – Rockwell Automation, for instance, has roots dating to 1903. Industrial robotics similarly is a field that has been evolving for 50+ years since the introduction of the first industrial robot in 1961. What is changing now for both — as noted elsewhere in this report — is that the same rise in computing power and capabilities that supports the digitization of an ever expanding pool of physical assets is contributing to rapid advancements in automation and robotics capabilities.

U.S. Multi-Industrials companies have not historically been large suppliers of industrial robots per se; however several do have a significant presence in industrial automation end markets. For companies who have meaningful exposure to industrial automation, the advancement and potentially accelerating adoption of robotic technologies means these companies will have to continue to develop their own robotic capabilities as well as work closely with robotics suppliers to adapt their automation products to be capable of integrating and working seamlessly with a broader scale of more advanced and capable robots over time.

Beyond automation and robotics, additive manufacturing is an important emerging technology that is poised to have a meaningful impact in the context of the Factory of the Future. Additive manufacturing (sometimes referred to as '3D printing') is the process of depositing layer upon layer of material to create three-dimensional objects — in contrast to traditional subtractive manufacturing methods such as milling, machining, etc. The potential benefits of additive manufacturing are multi-fold: additive allows for more rapid proto-typing than traditional methods; allows for greater customization and more complex designs than can be achieved by traditional methods; and supports waste reduction through more precise usage of materials. We consider the technology still largely nascent, but rapidly advancing — investment has continued in advancing additive manufacturing capabilities and increasingly incorporating additive manufacturing into aspect of the production of jet engines. Other aerospace suppliers are examining potential additive manufacturing-driven solutions to help ameliorate limited supply chain capacity for certain inputs.

Partnering: With Factory of the Future encompassing a broad range of changes across the industrial value chain, we view it as unlikely that any single entity has or will have the capabilities to fully achieve (either for itself or for its customers) the full promise of the Factory of the Future with a stand-alone approach. As such, we view the ability to effectively partner with outside entities as an important factor in successfully transitioning to the Factory of the Future, with such partnership likely to come in many forms.

We note that partnerships are likely to come in many forms – software and technology-related M&A that broadens Multi-Industrials' capabilities to deliver the Factory of the Future is a form of "partnering", as are initiatives through which the company makes venture capital investments to accelerate its exposure to disruptive emerging technologies across a broad range of industrial applications such as analytics and machine-learning for IIoT.

Potential Outcomes: Accelerating Growth & Profitability; Lower Volatility

With the development of and transition to the Factory of the Future well underway, we view U.S. Multi-Industrials broadly as positioned to benefit from an evolving industrial landscape. As digitization of physical assets continues and optimization of those assets to drive improving productivity accelerates, we see opportunity for U.S. Multis to both improve their own operating performance and to drive improving outcomes for customers.

Factory of the Future, for Multi-Industrials best able to capitalize on the opportunity, holds the potential to support both improved operations internally, as well as commercial opportunities that could help accelerate growth. We note too that, given the software oriented nature of many components of Factory of the Future, we view digital-related offerings as likely accretive to operating margin (although we do note the risk of potential price competition in a 'land-grab' as companies compete to establish themselves as leaders in various domains within the broader Factory of the Future landscape).

Finally, while we caution that industrial companies remain subject to the impacts of exposure to cyclical end markets and broader macro-economic volatility, we do think the growing digital/service related opportunities associated with delivering the Factory of the Future could, over time, help to dampen the cyclicality of U.S. Multi-Industrials who are able to 'win' in the digital-industrial space. It's a little early, we think, to gauge who amongst U.S. Multi-Industrials will truly have the capacity to sustainably build and monetize software-oriented business models that succeed over the long-term, while also managing and growing a broader industrial portfolio. But, to the extent that they are able to offer productivity gains to customers and, through subscription and/or service models that drive recurring revenue, monetize that value delivered, Multis could, over-time, be positioned to dampen some of the volatility that they have historically experienced.

A China Perspective

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China Automation Market May Revive

We think the major downstream industries of automation include automotive, consumer electronics (i.e., smartphone) and home appliances (i.e., air-con), which together should contribute >60% of total demand. However, shipment data for the first quarter of 2019 of the three industries were sluggish. In particular, China automotive shipment declined 11% YoY in; China smartphone shipments declined 10% YoY; and China air-con shipment (incl. export) edged up by 1% YoY.

Therefore, we believe the U.S.-China trade war has been having a widespread impact on the investment decisions of general manufacturers in China since the second half of 2018, coupled with the down-cycle of consumer electronics (e.g., slower new smartphone model launch), which were the two major downstream demand sources for China automation.

According to our channel checks and comments from Chinese corporates power their first quarter 2019, the order trend has been improving from March/April and most companies were expecting to see sequential growth ahead. However, the domestic sentiment on the recent trade war had a sudden turnaround since early May and the new order trend deteriorated. Although China and the U.S. are back at the table for negotiations, we think the market will maintain a cautious view before any substantial agreement is reached. Above all, we forecast the China automation market will return to a growth trajectory from 2020 and most likely deliver a booming year, mainly fueled by another round of capital expenditure upcycle of both general manufacturing industries and consumer electronics.

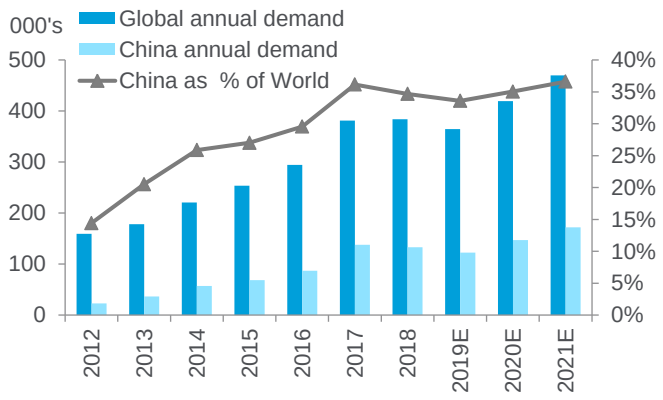
The China Robot Market Trend

Robots are a representative product to China automation, or the capital expenditure (capex) by factory.

China robot shipments have been greatly outperforming the global market over the past few years. According to IFR, China robot shipments surged 59% YoY to 138k units in 2017, enhancing its leading position with 36% of global shipments (from 30% in 2016). A slowdown in domestic manufacturing activities plus tension in the global trade environment in 2018-2019 has been a drag on the pace of robot shipments in China, which for the first time declined ~3% in 2018 and is forecasted to drop another ~8% in 2019. However, China robot shipments are estimated to return to their growth trajectory from 2020 and register 20% and 17% YoY growth in 2020 and 2021, to 172k units shipment in 2021, remaining the largest global market with ~37% market share estimated in 2021.

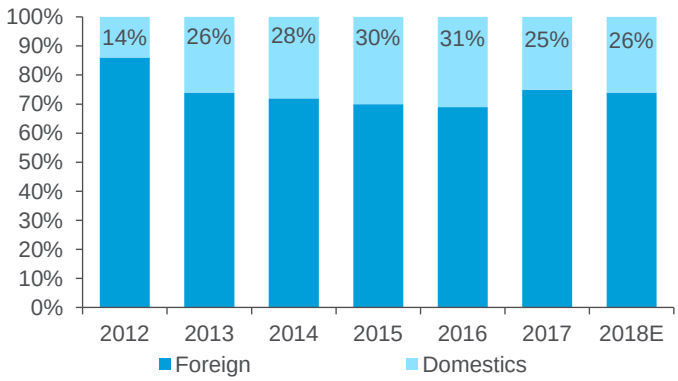
Noticeably, in 2017, Chinese robot makers sold ~35k units in the domestic market, up 29% YoY, indicating a market share loss (of up to 25%) for the first time in recent years, according to CRIA (the China Robot Industry Alliance). We think the reversed trend could be attributed to: (1) leading global robot makers localized their production in China and thus became more competitive in terms of pricing and established direct market access to China domestic customers; 2) China's robot downstream industries had been experiencing an upgrading trend, resonated by the upcycle in capex in the automotive, consumer electronics, and home appliance sectors in 2017; and 3) some Chinese robot makers which focused on low-end market, shut down and left the market as they had been loss-making.

Figure 73. China Robot Demand as % of Global Has Been On the Rise



Source: Gongkong, Citi Research

Figure 74. China Domestic Brand Robot Shipment Market Share Retreated in 2017



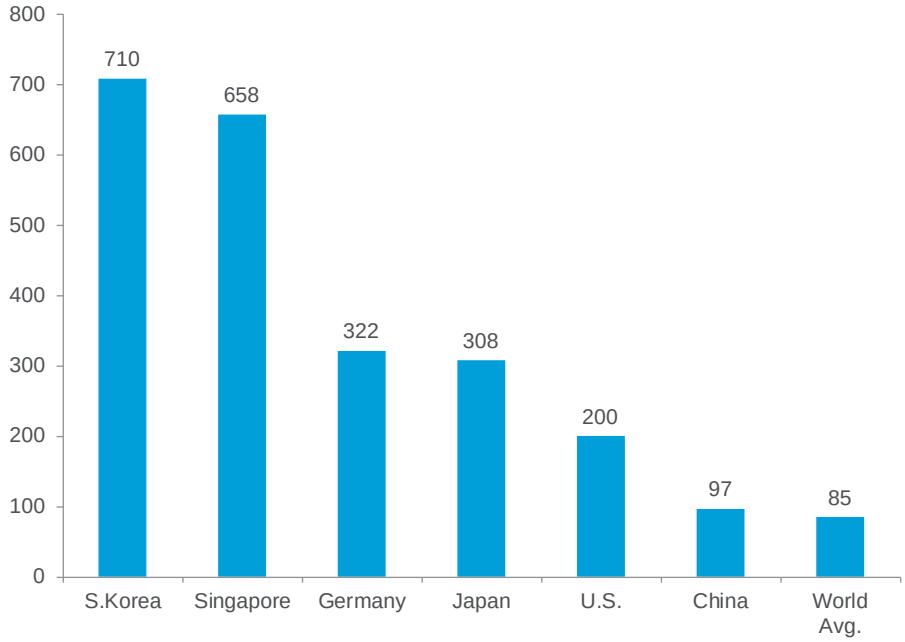
Source: Gongkong, Citi Research

It is estimated that there are over 7,000 Chinese companies are engaged in automation or the robot business. Although China's robot market is still dominated by the four global leading players, the remaining market which is shared by Chinese players is very fragmented and competitive. We expect market consolidation will continue in the foreseeable future.

Huge Potential from Robot Density Improvement in China

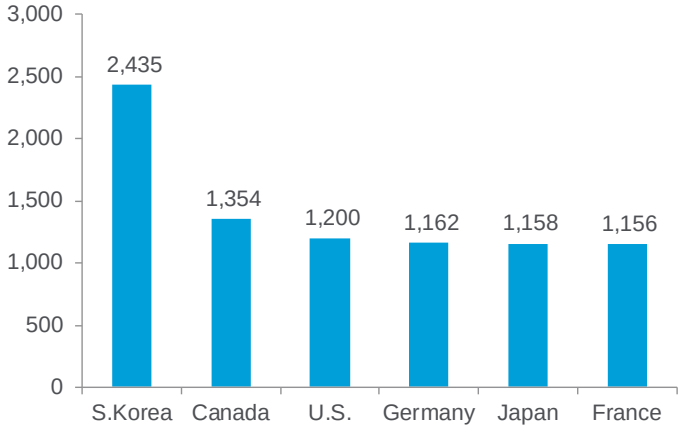
The average global robot density elevated to 85 units/10k employees in 2017 versus 74/69 units/10k employees in 2016/15. The Republic of Korea has the highest robot density (710 units/10k employees), followed by Singapore, Germany, and Japan. China's robot density reached 97 units/10k in 2017 vs. 68/49 units/10k employees in 2016/15), surpassing the world average for the first time. Comparing with the robot density level of global leading countries, we believe there is still huge potential for China's robot density to improve. Further, the automotive continues to enjoy the highest robot penetration. Projects aimed at manufacturing batteries for hybrid and electric cars might be the major reason. That said, the robot density in the general industry (all industries excluding automotive) is still comparatively low, which could see faster growth ahead.

Figure 75. Industrial Robot Density by Country, Overall



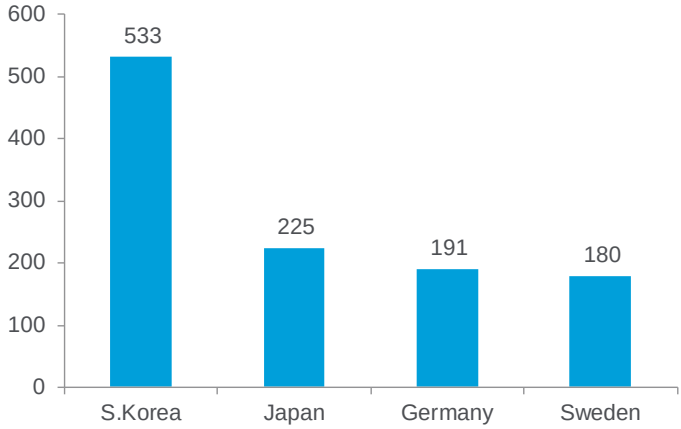
Source: IFR, Citi Research

Figure 76. Industrial Robot Density by Country (2017), Auto



Source: IFR, Citi Research

Figure 77. Industrial Robot Density by Country (2017), General



Source: IFR, Citi Research

Government's Supportive Policies

The Chinese government attaches great importance to the development of intelligent manufacturing, robots, and core components, with support from both macro policy and industrial policy.

Earlier in 2015, the China government formally proposed the 'Made in China 2025' strategy. China's State Council pledged to boost the implementation of the 'Made in China 2025' strategy, alongside an 'Internet Plus' plan, based on innovation, smart technology, the mobile Internet, cloud computing, big data, and the Internet of Things. The strategy targets to upgrade China's manufacturing sector, with the aim of shifting from 'a big manufacturing country' to 'a powerful manufacturing country'.

Further, informationization and industrialization will be unified and priority will be given to the development of ten particular fields. We believe there are three areas target Factory of Future areas, including (1) information technology; (2) high-end numerical control machine and automaton; and 3) new materials.

In particular, the Chinese government regards ‘high-end CNC machine tools and robots’ as one of the key areas for vigorous promotion in order to achieve the industrialization and application of industrial robots and meet the urgent needs of China's manufacturing transformation and upgrading.

A Japanese Perspective

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Lights-out manufacturing with robots doing everything from bin picking, assembly, machine tending, inspection, and packing would seem to a good starting point when considering the concept of the Factory of the Future. This concept would encompass robot collaboration and newly designed robots with hollow arm structures, which reduce the need for external cables and wiring, so helping to reduce footprint. Moreover, at the warehouse / distribution center, most of the picking and movement would be done by mobile robots. In theory, the role of human labor on the factory floor could be limited to performing maintenance and repair on the robots although in future as a result of the advancement of machine learning these kinds of jobs could also disappear. Factory

While not necessarily an inaccurate picture of the factory of the future, the image described above is still a rather conceptual one. Japanese factory automation companies like many Japanese companies that are good at hardware, the company struggle when it tries to explain how to monetize this concept and how it is different from other IoT platforms. When it comes to the Factory of the Future we have little doubt that Japanese factory automation companies will remain competitive in the manufacture of robots, discrete components, material handling systems etc., but we worry about their limited presence on the software side of this business relative to North American and European companies.

Given its long manufacturing history (especially in autos and electronics) we do not doubt that Japanese companies will remain key hardware suppliers for the Factory of the Future whether it is located in Japan, China, Vietnam, or wherever but we worry that they will miss out on some of the more value-added processes, and also on some of the faster growing segments. For example, where are the leading Japanese companies in PLM (product lifecycle management)? Defined as a solution that offers a systematic approach to managing the sequence of changes a product undergoes from design, creation through to retirement / disposal, PLM may not be a new idea but the main suppliers of these systems are outside of Japan.

Separately, at the Automate / Promat trade show in Chicago in April 2019 there were around fifty suppliers of AMRs (autonomous mobile robots) and AGVs (automated guideway vehicles). While there are a number of real world examples in Japan from our perspective, the standout name in Chicago was a company whose new collaborative robot can transport up to 1,000kg with the ability to attach different modules like bins, lifts or collaborative robot arms, and is aimed at replacing traditional pallet lifters. From a Japanese perspective, it is good to see some companies involved on the hardware side but, as before, we do worry that a lot of the development of SLAM (simultaneous localization and mapping) algorithms appears to be done by U.S. universities and corporations. Again, Japan seems to be lagging on the software side. Perhaps this is a function of the focus of the education system and as such there may be no short-term easy fix.

Connectors and Sensors Enabling IIoT with Industrial Automation

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Adopting industry automation to increase productivity and lower manufacturing cost has been the trend in Technology Supply Chain for several years. However the recent increased flexibility to more easily reprogram the automation process has enabled this trend to accelerate. One example is the evolution in technology for wafer and semiconductor chip manufacturing sector which has now evolved to a 'lights-out' manufacturing environment wherein a factory is fully operated by machines and robotics without the need of humans on-site. The development of automation significantly increased semiconductor fabrication productivity and compares to traditional manual operating mode whereby humans previously touched and moved wafers through the manufacturing produces, which is less precise and also involved toxic working environment to human beings. Additional examples include the production of smart electronics using automated injection molding with the help of vision systems mounted robots which can more precisely determine the placement, shape, and density accuracy of components (metal and plastic), and inspect faster than a human can in quality control for insert mounded parts. In addition, evolving automation manufacturing processes enable Electronic Manufacturing Services (EMS) companies to provide tailored designing capability in both high volume low mix (i.e., consumer electronics such as smart phones or TVs) and low volume high mix (i.e., hospital and doctor medical devices) products and create value for customers.

Historically EMS companies have utilized labor arbitrage (moving production to low labor cost area) to increase profitability and outsourcing penetration. We believe this trend will continue for low mix high volume products, particularly in consumer electronics and commoditized enterprise hardware (routers, switches, etc). However, we expect manufacturing companies to increase local-to-local supply chain solutions in high value products which require faster time to market, customized design, as well as high standard of quality control. This area is where industrial automation could play increasingly important role. There are three elements that we believe will be critical for industrial automation

- **Digitization of manufacturing process:** Automating manufacturing process requires transforming analog signals to digital signals so that people can monitor and adjust their manufacturing based on real time data. The digitization requires large amount of sensors and connectors installed to capture and transmit signals to central control system.

- **Data consistency for quality control:** With less humans involved in the manufacturing process, automated manufacturing systems need to monitor every step in the process for quality control purposes. Data consistency is an additional step to digitization as data collected from different process has to be translated and analyzed to increase the transparency of each production step and enable timely diagnoses and adjustment.

- **Predictability for optimization:** We think the ultimate goal of industrial automation is process optimization in throughput, inventory management, and product design. This requires big data analysis with the data collected from on-prem equipment. To enable the optimization, operational technology and information technology teams have to work together as data needs to be accurately collected and transmitted from edge (equipment) to central computing system/cloud and then sent back to edge with optimized feedbacks.

Using Virtual Reality for Training and Augmented Reality to Increase Efficiency

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Companies are improving operational efficiency thanks to technological developments in virtual reality (VR) and augmented reality (AR). These technologies are being used for training and operations support in areas such as factory operations, instrument reading and inspection, surgical procedures, driving and aircraft piloting, and situational assessments.

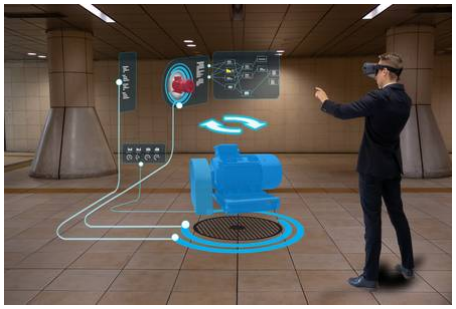
VR enables workers to experience the actual conditions of working in factories and the like before they actually start work via images reproduced using headsets in a virtual space. This can be used for training and orientation, to make workers familiar with actual processes, and to give them usual experience in incidents and discoveries ahead of time.

AR involves wearing headsets in the form of glasses and goggles during factory processes to display computer graphics overlaid on the actual field of view. Computer graphics are superimposed on actual instrument panels, workplaces, and machines etc., to provide a range of supplementary explanations and instructions via text and data to workers. Similarly, AR can enable preparatory inspection and training via simulations, and in some cases can be easier to use and more effective than VR.

Figure 78. Training Using VR

Source: 123RF, Citi Research

Figure 79. Training Using AR



Source: 123RF, Citi Research

Figure 80. Workplace Leveraging AR

Source: 123RF, Citi Research

Specific example of AR and VR used in training

In familiar environments, VR and AR can be used on production lines and in logistics sorting, and in more extreme environments they could be used in the cleanup of nuclear reactors that have suffered meltdowns, both for training of workers ahead of time and to monitor operational processes. To date, training has used photographs and diagrams, or videos and models.

We think the use of VR in industry will now become and established trend. This should improve training quality and reduce the time required for training, as well as cutting the costs for training providers and operations managers. VR can also be used for safety training in environments that cannot be tested ahead of time, including for huge areas such as outer space and tiny spaces such as within the human body, as well as in situations in which reference images and local experience are not available.

AR will also enable effective training ahead of time. The main difference between AR and VR is that AR can display objects and information superimposed on actual spaces, enabling testing and checking operations directly related to actual things and the background. In our view, VR is better suited to major operations and training that require considerable time, while AR is more appropriate for small-scale checking operations in short time periods. AR is also simpler in that in addition to headsets, it can reproduce images on monitors or use smartphones in place of headsets.

Figure 81. Examples of VR Used in Training

Source: 123RF, Citi Research

Figure 82. Examples of AR Used in Training

Source: Toshiba, Citi Research

Specific example of assistance in the workplace

AR can be used to add supplementary (or indeed important and effective) information to objects or the operating environment in factories and other worksites involving processing, assembly, transport, and inspection etc. It can be used to check whether the accurate number of components have been installed in the correct places and whether the product shape and operation is correct by superimposing graphics displays. By displaying arrows that essentially float in space, AR can be used to indicate the correct destination for items as well as the spaces from which components and materials must be retrieved, enabling workers to understand tasks more rapidly and more accurately. When inspecting products or viewing, reading, and recording instrument panels, workers can use arrows directed by their own eye movements as well as displaying data, explanations, and text in space to improve operational efficiency and accuracy.

Figure 83. Example of Usages to Assist in the Workplace

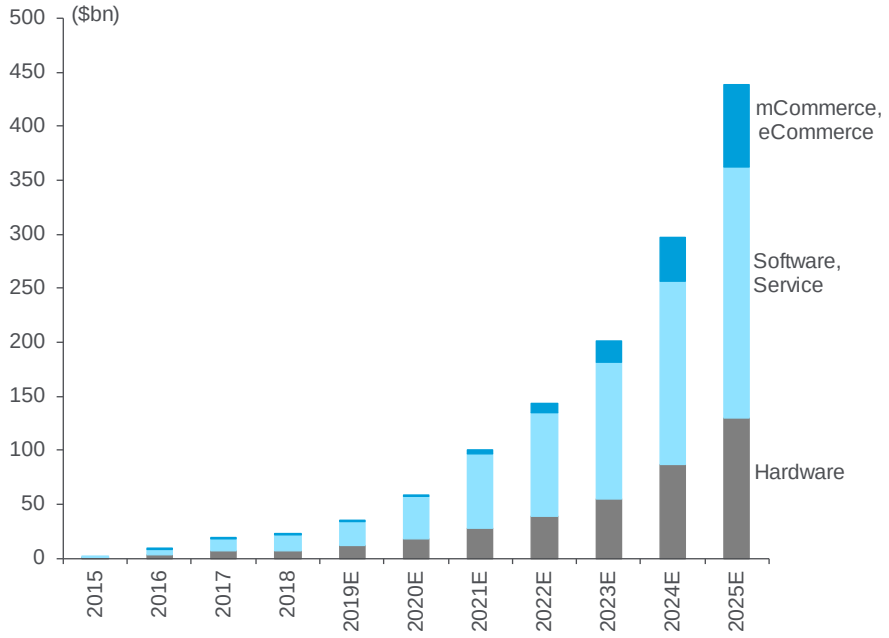
Source: Shutterstock

VR and AR market size

At this point there is a broad range of VR/AR market size forecasts, but a large number of companies are already involved in the VR and AR market, which has grown to $22 billion. We forecast a compound annual growth rate of 57% for the industry to $438 billion in 2025. The VR/AR hardware market at $130 billion in 2025 would equate to the current market for display panels ($125 billion in 2017) and memory chips ($168 billion in 2018), and would constitute a major market domain among technology sector applications.

We expect the consumer market to remain the largest for VR and AR in the near term, as applications spread to include gaming, new amusement park attractions, music and sport appreciation and watching, and real estate and apparel marketing. Business applications such as operational support and training make up a smaller market than consumer applications at this time, and growth is more modest. However, we see the business application as representing a bigger potential market over the longer term, and advances in hardware and software should reduce the physical burden and the economic burden of its use. As people become more familiar with AR and VR, psychological barriers should also weaken, leading to a broadening in the business application to include familiar uses. At that time, we would expect business application to become the primary driver of the VR and AR market.

Figure 84. VR and AR Market Scale



Source: Citi Research

VR and AR breakdown

The VR and AR market can be roughly categorized into hardware such as headsets, controllers and sensors, base software, and a range of software applications used for individual services.

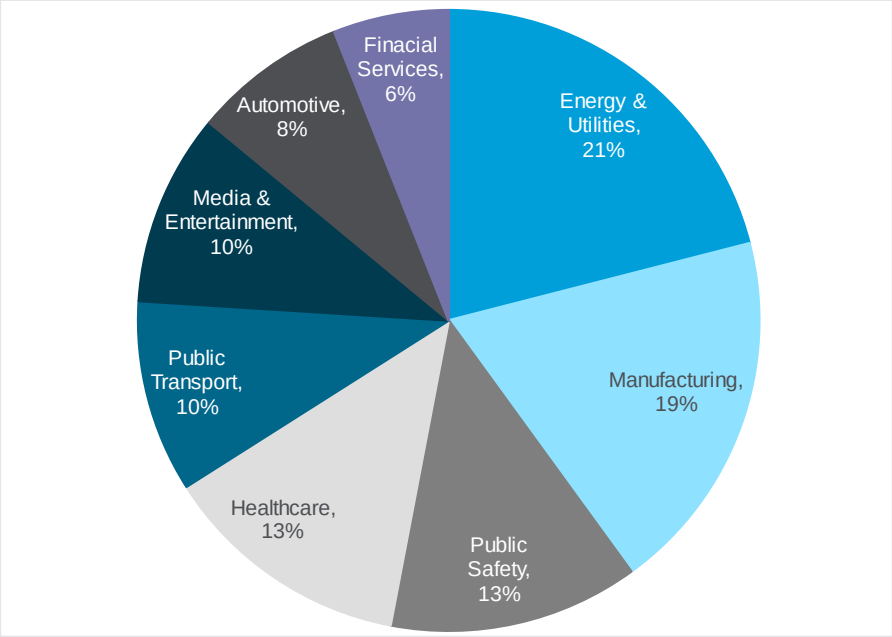
The necessary platforms and tools for VR center on hardware such as headsets, controllers and sensors; service application software including those for games, entertainment, business, healthcare and education; communications and service platforms; and input/output systems for 3D imaging and surround-sound engines as well as 360-degree imaging.

The same type of headset is mainstream for both AR and VR, but glasses-type headsets which do not impinge on the user's field of view are also available. Another major driver of growth in of AR is smartphones. AR hardware also includes a broad range of input/output devices including displays and smartphones, so users can experience and consume information that is harvested by input devices by reproducing it on headsets and displays in real time. Similarly to VR, software includes a broad range of application genres, and there is a large group of providers particularly for the business application for use in factories and the like. As with VR, big companies are the main players in platforms and tools.

5G as an IIoT Enabler

Manufacturers are increasingly focused on how devices on the factory floor will communicate, with security, latency, and reliability of machine-to-machine communication all key. Wired Ethernet, including the industry standard PROFINET is commonplace today, but the proliferation of connected equipment means hard wired connections (especially the cabling) can become unwieldy and expensive, and can make factory reconfiguration challenging. Wireless communication is not without challenges; Murata, a manufacturer of electronic components comments that in the past "*in nearly all indoor and outdoor settings, industrial and factory equipment produces electromagnetic and RF [radio frequency] interference that wreaks havoc on wireless performance*". Qualcomm identifies "*high reliability with low latency in challenging RF environments*" as a key requirement for the IoT.

Figure 85. 5G-enabled Digitalization Revenues for ICT1 Players in 2026

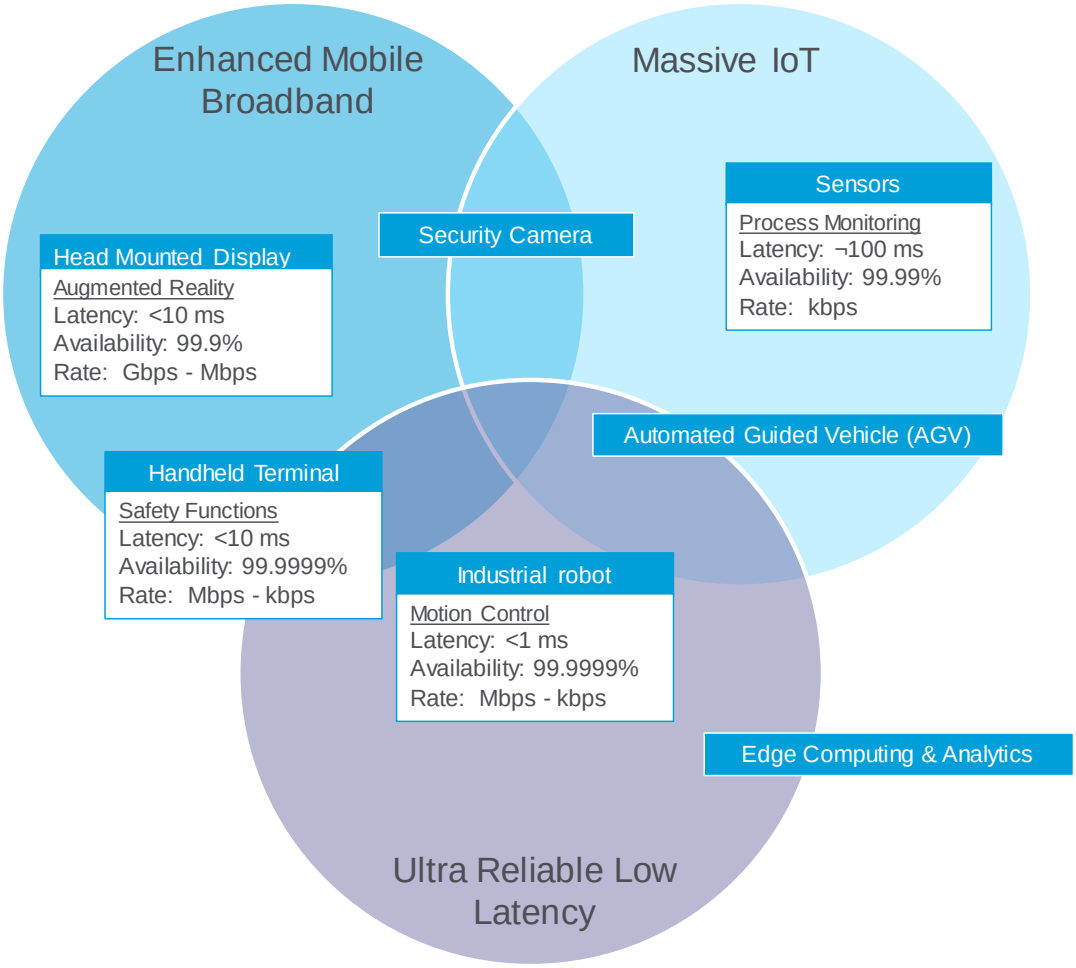


Source: Bosch, Ericsson & Arthur D. Little (2017)

5G, the fifth generation cellular wireless technology, looks set to address these issues with lower higher bandwidth, lower latency, and better security.

Manufacturers are increasingly seeing 5G as a key enabler (or indeed necessity) to enable the IIoT in factories. According to Audi, 5G *"…has many network characteristics that are essential for Industry 4.0 with increasingly flexible and complex production processes. It allows for faster data throughput rates and more network capacities, as well as promising highly secure availability. Moreover, ultra-low latency ensures fast response times between equipment in the factory system."*

Figure 86. How 5G Will Transform Industrial IoT



Source: Qualcomm, Citi Research

According to a study by Bosch and consultancy Arthur D. Little, manufacturing represents the second largest potential market of 5G-enabled revenues for the Information & Communications Technology (ICT) industry, second only to Energy & Utilities. The study estimates a total market size of $1,233 billion by 2026. Bosch believes the manufacturing end market is hugely appealing for 5G given the much more controlled environment as compared to other potential industrial applications such as vehicle-vehicle communication for autonomous vehicles, or even hostile and remote facilities in the energy industry.

Figure 87. Key Applications for 5G on the Factory Floor

Factory Application	Use Case
Motion Control	Motion control is the closed loop control of rotating machinery, such as a machine tool (drills, lathes etc.). Most motion control applications today use proprietary Ethernet standards like PROFINET and EtherCAT
Control to Control	Communication between industrial control devices like PLCs (programmable logic controllers). Again this is currently often done with proprietary Ethernet standards
Mobile Control Panels	Panels used for configuring, monitoring, controlling, and maintaining machines
Augmented Reality	The ACIA expects AR to play a key role the monitoring of processes and production flows, the delivery of step-by-step instructions for specific tasks (such as manual assembly), or the delivery of ad-hoc support from a remote expert
Mobile Robots	Mobile robots like AGVs (Automated Guided Vehicles) are by definition not fixed, and need to communicate with other machinery included conveyors, cranes etc.
Massive Wireless Sensor Networks	Distributed sensors recording temperature, pressure, humidity, CO_2, and sound monitor the manufacturing environment
Plant Asset Management	While more pertinent for equipment in the field, factory equipment can also be enabled for asset management (the extraction of date for predictive maintenance) and other uses

Source: ACIA, Citi Research

While the adoption of 5G offers huge potential as a key enabler of the Factory of the Future, there are some key parameters that will need to be met. 5G offers improvements in all of these relative to earlier technologies:

- **Reliability:** The ACIA estimates 99.999% reliability for data packets.
- **Ultra-low latency:** Latency is the time lag to transmit the data. According to Gemalto, 5G aims to reach high speed (1 Gbps), low power, and low latency (1ms or less) goals in order to be deployed in IoT applications.
- **Device synchronization:** Synchronization allows data to be transmitted without losing any information, with all transmitted signals synchronized to a common source. 5G networks will have tighter network synchronization than any preceding technology. In mobile networks, poor synchronization can lead to problems like missed call handovers; a dropped call is frustrating for a user, but intolerable for a fully automated factory.

Operator Models and Non-public Networks

Private 5G factory networks, as opposed to PLMNS (Public Land Mobile Networks), provide a dedicated network for use by the industrial owner(s), as opposed to relying on traditional telco operators. According to Reuters, the German regulator is due to allocate regional 5G licenses, and several industrial companies including have expressed interest. This does not seem to be a global trend — France appears not to be following the German model, with Minister of Economy and Finance Agnes Pannier-Runacher commenting there would be no allocation of 5G spectrum for 'private' spectrums, rather it is being auctioned to telecom operators.

We do think however that since data connectivity will become a key enabler, closer collaboration could be seen between industrial automation providers and telecom equipment players.

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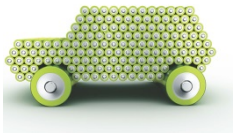

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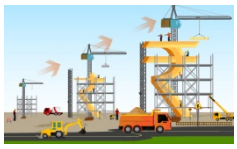

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