OXFORD ECONOMICS





HOW ROBOTS CHANGE THE WORLD

WHAT AUTOMATION REALLY MEANS FOR JOBS AND PRODUCTIVITY

JUNE 2019

TABLE OF CONTENTS

Fieldwork Robotics trialling a robot raspberry harvesting system on a British farm, 2019.

FOREWORD: THE SHAPE OF THINGS TO COME

Adrian Cooper
CEO and Chief Economist
Oxford Economics

The robotics revolution is rapidly accelerating, as fast-paced technological advances in automation, engineering, energy storage, artificial intelligence, and machine learning converge. The result will transform the capabilities of robots and their ability to take over tasks once carried out by humans.

The number of robots in use worldwide multiplied three-fold over the past two decades, to 2.25 million. Trends suggest the global stock of robots will multiply even faster in the next 20 years, reaching as many as 20 million by 2030, with 14 million in China alone. The implications are immense, and the emerging challenges for governments and policy-makers are equally daunting in their scale.

The rise of the robots will boost productivity and economic growth. It will lead, too, to the creation of new jobs in yet-to-exist industries, in a process of 'creative destruction.' But existing business models across many sectors will be seriously disrupted. And tens of millions of existing jobs will be lost, with human workers displaced by robots at an increasing rate as robots become steadily more sophisticated.

For both people and businesses, the effects of these job losses will vary greatly across countries and regions, with a disproportionate toll on lower-skilled workers and on poorer local economies. In many places, the impact will aggravate social and economic stresses from unemployment and income inequality in times when increasing political polarisation is already a worrying trend.

At Oxford Economics our mission is to help our clients better understand an ever-more complex and fast-changing world economy, in all its dimensions—and how to successfully operate in it. Our clients look to us to explain the forces shaping their economic environment, help them anticipate the future, and plan for its uncertainties.

That is why we brought together a team of our economists, econometricians, modellers and technology experts from across our worldwide network of over 250 analysts to conduct an extensive research study to analyse the robotics phenomenon. We are pleased to share our findings not only with our clients but with all who want to understand the implications of one of the most profound shifts the world economy will experience this century.

EXECUTIVE SUMMARY

20m

Number of manufacturing jobs that could be displaced by industrial robots by 2030—8.5% of the global manufacturing workforce.

Over the past decade, a robotics revolution has captured the world's imagination. As their capabilities expand, so does the rate at which industries purchase and install these increasingly intelligent machines. Since 2010, the global stock of industrial robots has more than doubled—and innovations in engineering and machine learning portend an accelerated adoption of robots in service sector occupations over the next five years.

This report sheds new light on both the current impact of robots on manufacturing jobs around the world and the potential for robots to transform the much larger (but as-yet far less automated) global services sector. To evaluate the implications of this ongoing robot revolution, we have brought together the combined expertise of Oxford Economics' economists, econometricians, modellers, and subject-matter experts.

The rise of robots has already had a profound effect on industrial employment around the world: today, approximately one of every three new manufacturing robots is being installed in China, the world's great workshop. Our econometric modelling finds that on average each newly installed robot displaces 1.6 manufacturing workers.[1] By 2030, we estimate that as many as 20 million additional manufacturing jobs worldwide could be displaced due to robotization.[2]

Lower-income regions are more at risk

This great displacement will not be evenly distributed around the world, or within countries. Our research shows that the negative effects of robotization are disproportionately felt in the lower-income regions of the globe's major economies—on average, a new robot displaces nearly twice as many jobs in lower-income regions compared with higher-income regions of the same country.[3] At a time of worldwide concern about growing levels of economic inequality and political polarisation, this finding has important social and political implications.

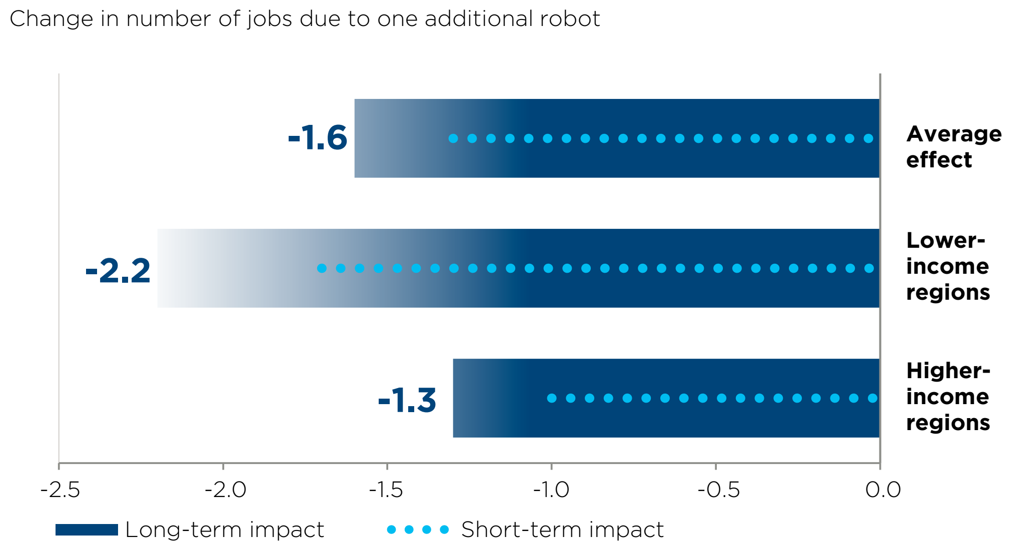
Given the stakes, policy-makers need an early warning system to help them mitigate the risks of automation on employment. As part of this study, we have developed a Robot Vulnerability Index that ranks every region of seven developed economies in terms of how susceptible their respective workforces are to the installation of industrial robots (see page 25).

[1] This finding is based on an analysis of a large, regional panel-dataset of robot stock, and other labour market indicators, over a 11 year timeframe, for 24 EU countries (minus Croatia, Cyprus, Luxembourg and Malta), along with Norway, the United States, Japan, and South Korea.
[2] Countries included in this estimate account for more than 90% of industrial robot installations: EU 28, US, Japan, South Korea, Australia, China, Taiwan, Thailand, Mexico, India, Canada, Singapore, Brazil, Turkey, Malaysia. We assume the rate of robot installations in manufacturing up to 2030 follows the latest projections by the International Federation of Robotics, and we also account for long-term depreciation of existing robot stock.
[3] Throughout this report, higher- and lower-income regions are defined as those with average household income levels above and below the national average, respectively.

In many cases, our Index highlights that the most vulnerable regions are somewhat removed from the wealthier districts of their home countries—such as Cumbria in the UK, Franche-Comté in France, and the high desert of Eastern Oregon in the US. These rural regions often include towns or cities with strong manufacturing heritages that play a surprisingly large part in the regional economy. In contrast, regions that surround knowledge-intensive cities, such as Toulouse and Grenoble in France, or Munich and Stuttgart in Germany, typically show much lower levels of vulnerability to the rise of the robots. This is also true of capital cities such as London, Paris, Seoul, and Tokyo.

Our research shows the negative effects of robotization are disproportionately felt in the lower-income regions of major economies.

Fig.1: Job losses from robots hit lower-income regions harder[4]



Source: Oxford Economics

[4] Our modelling differentiates between a "short-term" effect, within the year of a robot installation, and a longer-term effect that builds over 10 to 15 years.

As the pace of robotics adoption quickens, policy-makers will be faced with a dilemma: while robots enable growth, they exacerbate income inequality.

The $5 trillion robotics dividend

While regional impacts vary, fears about permanent global job destruction generated by robots appear somewhat exaggerated. Our study shows that the current wave of robotization tends to boost productivity and economic growth, generating new employment opportunities at a rate comparable to the pace of job destruction. We estimate that a 1% increase in the stock of robots per worker in the manufacturing sector leads to 0.1% boost to output per worker across the wider workforce.

These increases are large enough to drive meaningful growth. Using Oxford Economics' Global Economic Model (GEM), we calculated how changes in the rate of installation of industrial robots could affect the global economy. Overall, we found that a faster adoption of robots has a positive impact on both short- and medium-term growth. For example, boosting robot installations to 30% above the baseline forecast by 2030 would lead to an estimated 5.3% boost in global GDP that year. This equates to adding an extra $4.9 trillion per year to the global economy by 2030 (in today's prices)—equivalent to an economy greater than the projected size of Germany's.

The future of service robots

Robots are steadily gaining traction in specific segments of the service economy, from baggage handling in airports to loading inventory in warehouses. In this report, we assess the likely impact (and timeframe) of service robot roll-outs in five key sectors: healthcare, retail, hospitality, transport, and construction and farming. For the purposes of this study we are considering robots only as physical machines, and not including the already-popular service-industry software like robotic process automation (RPA) that can speak, hear, read, conduct transactions, automate processes, and so on.

One key consideration for anticipating the pace of robot deployment in service industries is the environment in which these robots may be asked to operate—in particular, the extent to which service jobs include repetitive functions. Jobs like warehouse work are in imminent danger, while other jobs in less structured environments will likely be carried out by humans for decades to come.

It will be difficult for machines to replace humans in service sector occupations that demand compassion, creativity, and social intelligence. Physical therapists, dog trainers, and social workers are likely to remain secure in their jobs, for instance, even if truckers and warehouse workers see the future of their jobs jeopardised.

It will be difficult for machines to replace humans in service sector occupations that demand compassion, creativity, and social intelligence.

Policy implications

As the pace of robotics adoption quickens, policy-makers will be faced with a dilemma: while robots enable growth, they exacerbate income inequality. Automation will continue to drive regional polarisation in many of the world's advanced economies, unevenly distributing the benefits and costs across the population. This trend will intensify as the impact of automation on jobs spreads from manufacturing to the services sector, making questions about how to deal with displaced workers increasingly critical.

The challenges will be daunting. Our analysis of the job moves of more than 35,000 US individuals over the course of their careers shows that more than half the workers who left production jobs in the past two decades were absorbed into just three occupational categories: transport, construction and maintenance, and office and administration work. Ominously, our analysis found that these three occupational areas are among the most vulnerable to automation over the next decade. These findings, however, should not lead policy-makers and other stakeholders to seek to frustrate the adoption of robot technology. Instead the challenge should be to distribute the robotics dividend more evenly by helping vulnerable workers prepare for and adapt to the upheaval it will bring. Policy-makers, business leaders, technology companies, educators, and workers all have a role to play. We conclude the report with a framework for action for each of these groups to navigate the challenges and opportunities that robotization will bring.

Robots are on the rise as never before. Preparing for and responding to the social impacts of automation will be a defining challenge of the next decade.

A vision of human-free production in Italy.


ICE CREAM
5 M

INTRODUCTION

Over the past decade, the global stock of industrial robots has risen dramatically, and is projected to grow even faster in the next 10 years, led by China's record pace of installation. The robotics industry has experienced exponential investment growth, upending decades-long trends of gradual and steady expansion. A convergence of innovations in digital technologies (e.g., artificial intelligence and machine learning) along with advances in robotics engineering and energy storage, is dramatically transforming the capabilities of robots. New breeds of "cobots"—small, highly mobile, and dextrous machines that can readily collaborate with humans—are entering the manufacturing and logistics arenas, and can be easily "trained" to work with humans to optimise productivity.

This era of automation presents significant opportunities for businesses to boost productivity. But there will be winners and losers in the labour market as these opportunities are seized. Millions of workers around the world, across all sectors of the economy, will see many of the functions they were once paid to perform handled instead by new technology. Millions more will see the nature of their jobs altered significantly as they are required to master new skills to collaborate with intelligent machines. In autumn 2018, Andy Haldane, the Bank of England's chief economist, warned the disruption caused by the automation of cognitive skills could have "as wrenching and lengthy [an] impact on the jobs market" as Britain's industrial revolution.[5] He urged policy-makers to learn the "lessons of history," with governments stepping up to train workers for the new world of work while providing a welfare state to cushion the blow from technological change.

This era of automation presents significant opportunities for businesses to boost productivity. But there will be winners and losers in the labour market.

To shed new light on the future impacts of automation, Oxford Economics combined the expertise of its economists, econometricians, modellers, and other subject-matter experts around the world. Our analysis begins by modelling the latest and best data for industrial robot installations in all manufacturing sectors around the world. These are credible, longitudinal datasets from which we draw fresh insights regarding the impact of robots on employment and productivity in different countries, and in the higher- and lower-income regions within those countries.

Building on these insights, we then assess the future impact of increased robotization on global service sectors—an area where rates of robot adoption have been much lower than in manufacturing to date, but which employs a much greater proportion of the global workforce. Around three-quarters of workers across advanced economies earn their wages from service labour.

This multi-disciplinary approach enables us to construct a set of questions for policy-makers about the impact of increased robotization—as well as other processes of automation—on economies and societies around the world. Greater understanding of these issues will be key to making the most of robot-driven gains in the future while supporting and protecting those who stand to lose out from this era of dramatic technological change.

[5] Haldane warns AI threatens lengthy widespread unemployment' (Financial Times, 20/08/2018).

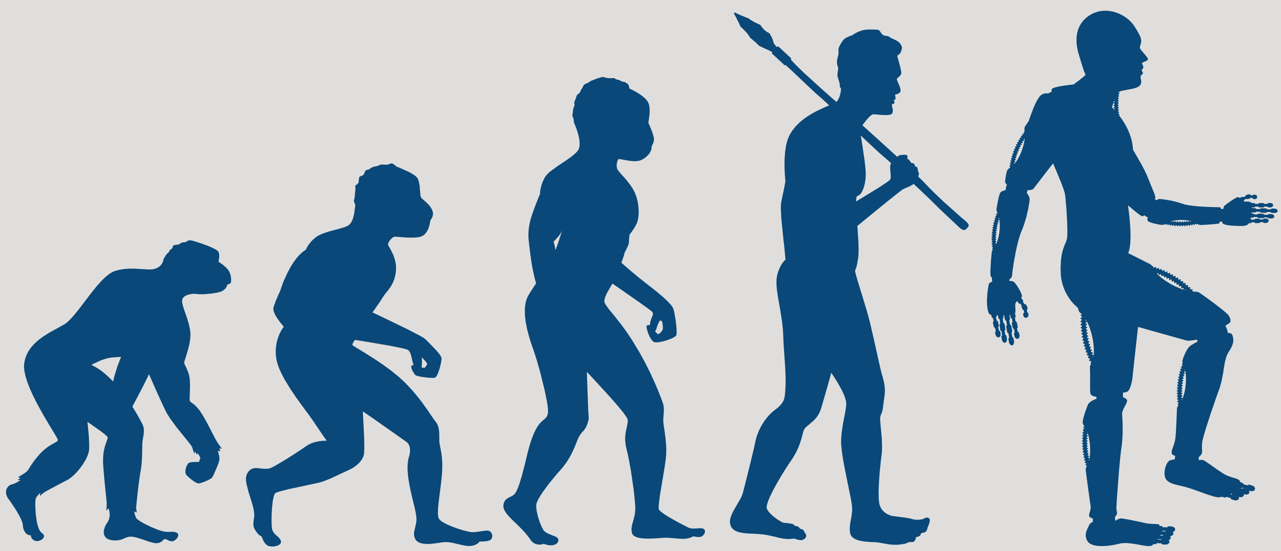
WHAT IS OUR DEFINITION OF A ROBOT?

The quantitative modelling aspects of this study are focused on industrial robots used in all types of manufacturing around the world. These automatically controlled, reprogrammable machines are typically used for a host of physical activities in production, such as processing materials (laser cutting, mechanical grinding), assembling and disassembling, precision welding, painting, and handling a wide range of operations for measurement, inspection, packaging, bending, and casting. These robots can be fixed installations or mobile, and the latest versions are increasingly powered by artificial intelligence, so they are "smart" and responsive to their surroundings.

Manufacturing accounted for more than 86% of the world's operational stock of industrial robots at the end of 2016, according to the International Federation of Robotics.[6] Automation has long been a critical component of manufacturing, particularly in the automotive industry, which in 2016 accounted for more than 43% of the total operational stock of industrial robots in global manufacturing. The industry is at the leading edge of robotic applications.

The quantitative analysis in this report is focused on physical machines for which rich, longitudinal data exists. We do not incorporate into this aspect of the analysis the growing role of disembodied software applications sometimes referred to as robots or bots, including programmes used in call centres and in RPA.

Based on robust data, our analysis of the manufacturing sector offers the best perspective to date on the impact of robots on employment and productivity levels. But the story will continue to unfold as manufacturing itself undergoes rapid technological change. In recent years, new, collaborative categories of AI- and cloud-enabled robots have emerged that seamlessly bridge the gap between skilled manual assembly and automated production. These "cobots" create new opportunities for automation—even on short, mixed production runs that require both high levels of precision (at which robots excel), and sophisticated vision, handling, and creativity (where human workers continue to add great value).



[6] International Federation of Robotics (2017) "World Robotics: Industrial robots"

WHAT DRIVES THE ROBOT RISE?

Since 2010, the global stock of robots in industry has more than doubled: as many robots were installed in the past four years as over the eight previous. During this period, the centre of gravity in the world's robot stock has shifted towards new manufacturers, mainly in China, Korea, and Taiwan but also India, Brazil, and Poland.

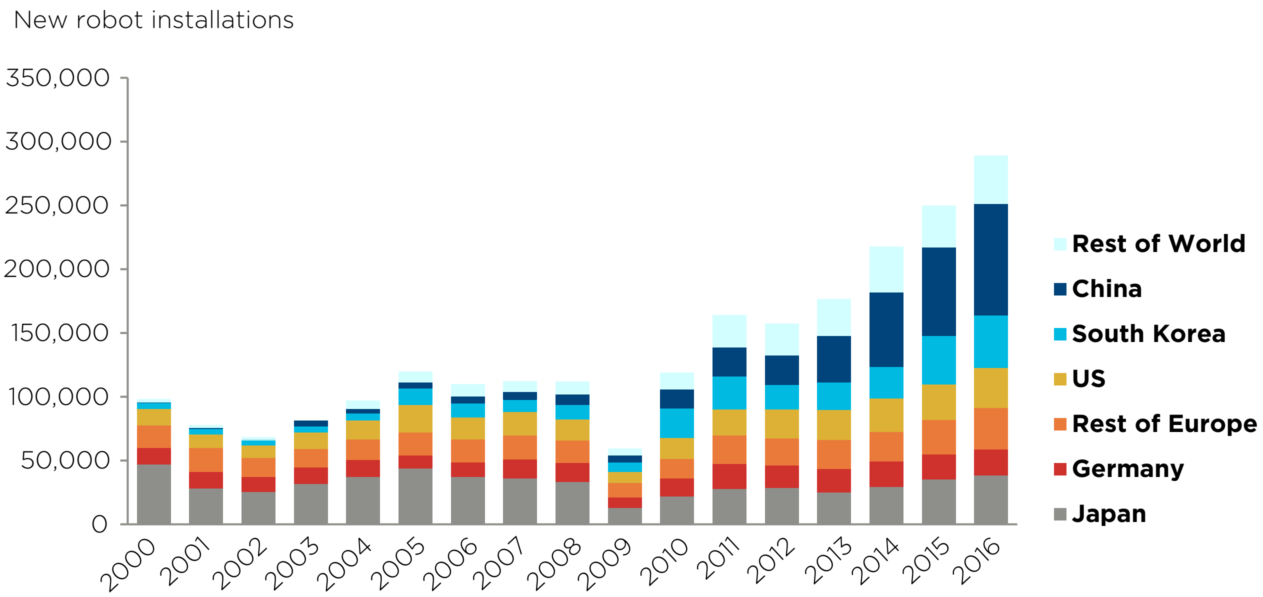
Approximately every third robot worldwide is now installed in China, which accounts for around one-fifth of the world's total stock of robots—up from just 0.1% in 2000 (see Fig. 2). In 2017, China expanded its lead as the world's largest market for industrial robots, accounting for 36% of global sales, up from 30% in 2016. If this trajectory of investment continues, by 2030 China could have as many as 14 million industrial robots in use, dwarfing the rest of the world's stock of industrial robots as it reinforces its position as the world's primary manufacturing hub.

In contrast, though it has grown by around 370,000 units since 2000, the combined robot inventory of the US and Europe has fallen to under 40% of the global share from its peak of close to 50% in 2009. And Japan—formerly the world leader in automation—has reduced its active stock of robots by around 100,000 units since the start of the millennium, in line with a rebalancing of its economy away from manufacturing and the migration of many production facilities offshore, especially to China.

20%

Proportion of the world's robot stock located in China. Approximately every third robot is now installed there.

Fig. 2: Robot installations by country, 2000 to 2016[7]

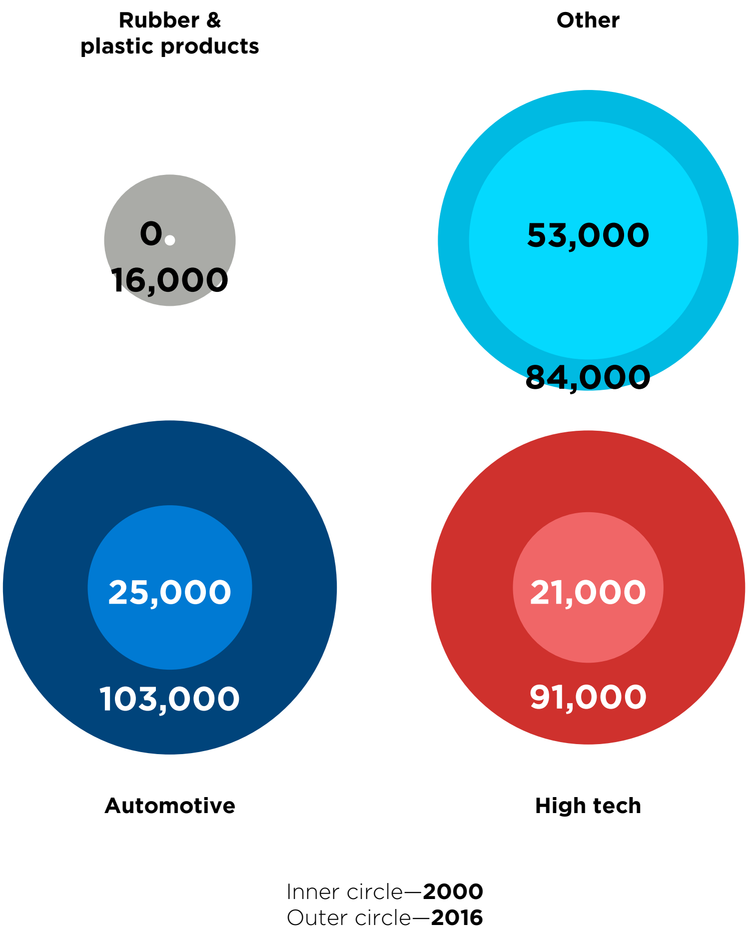


Source: IFR

[7] Note: US data include immaterial robot installation numbers for Mexico and Canada prior to 2010

The automotive sector has long been the predominant user of robots: innovations in autonomous and electric vehicle manufacturing requires increasingly sophisticated production chains, and this has sparked demand for new, more powerful, and intelligent machines to build them. However, other manufacturing industries are now taking a more prominent role in robot use. For example, the share of new robot installations in high tech manufacturing[8] grew to 31% in 2016, from 21% in 2000, reflecting rapid growth both in the sector and in the integration of robots into production. Robots have also been increasingly introduced into the production of rubber and plastics, and are slowly finding their way into the food and beverage manufacturing industry (see Fig. 3).

Fig. 3: New industrial robot installations across the world by usage, 2000 vs. 2016



Numbers refer to global robot installations in each sector for that year. Source: Oxford Economics

[8] High tech manufacturing is defined as electronic devices, semiconductors, LCDs, LEDs, computer equipment, telecommunication equipment, medical equipment, and electrical appliances

THREE REASONS FOR THE ROBOT SURGE

Our analysis of the use of industrial robots across the manufacturing sector identifies three main drivers behind this new pace of adoption: price, innovative applications, and consumer demand.

Trend #1: Robots are becoming cheaper than humans

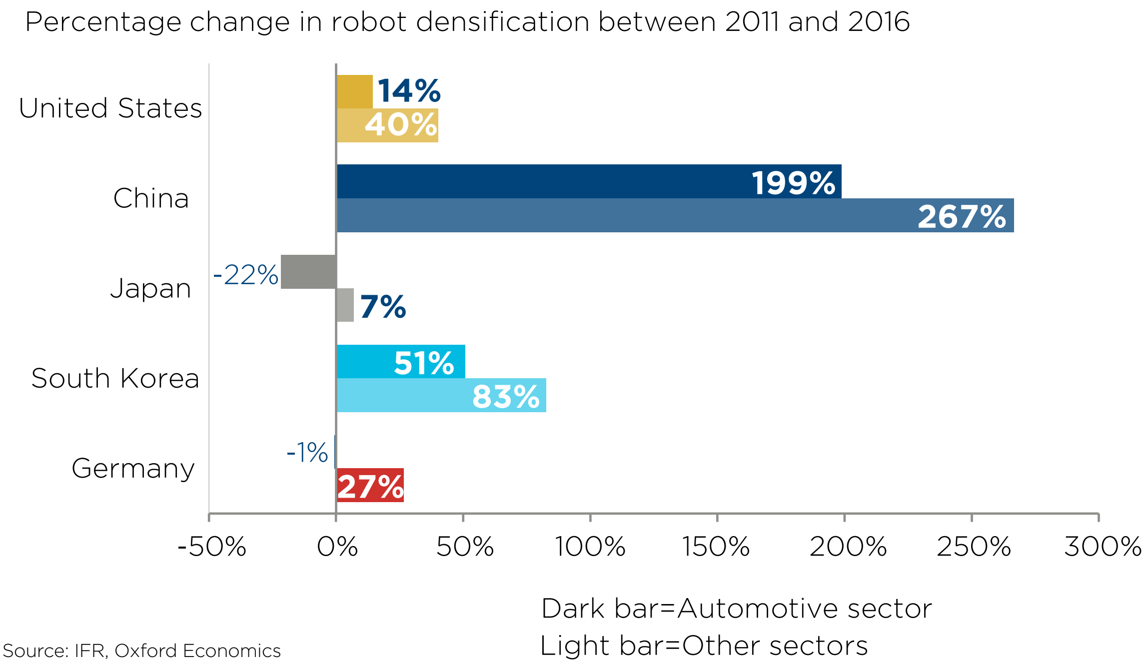
The rapid expansion in robot installations is driven in part by the plummeting real costs of the machines. As with other advanced technologies, exponential growth in the processing power of microchips, extended battery lives, and the benefits of ever-larger, smarter networks have all dramatically increased the per-unit value of many technological components, while the average unit price of a robot fell by 11% between 2011 and 2016.[9]

Rising labour costs in major manufacturing economies also contribute to increasingly attractive pricing dynamics. In China, for example, unit labour costs in manufacturing have increased by more than 65% since 2008. Wage rates have also been rising consistently in Korea, Japan, the US, and Germany, in part due to the ageing of the population in these countries.

Trend #2: Robots are rapidly becoming more capable

As robot technologies improve, they are being used in ever-more sophisticated processes, in more varied contexts, and can be installed more rapidly. Innovations have made today's robots smaller, more sensitive to their environments, and more collaborative. Thanks to AI, they can learn from their experiences and make decisions informed by data from a network of other robots. These developments have helped propel robot adoption in sectors beyond the automotive industry (see Fig. 4).

Fig. 4: Robot adoption growing faster outside the automotive sector



Source: IFR, Oxford Economics

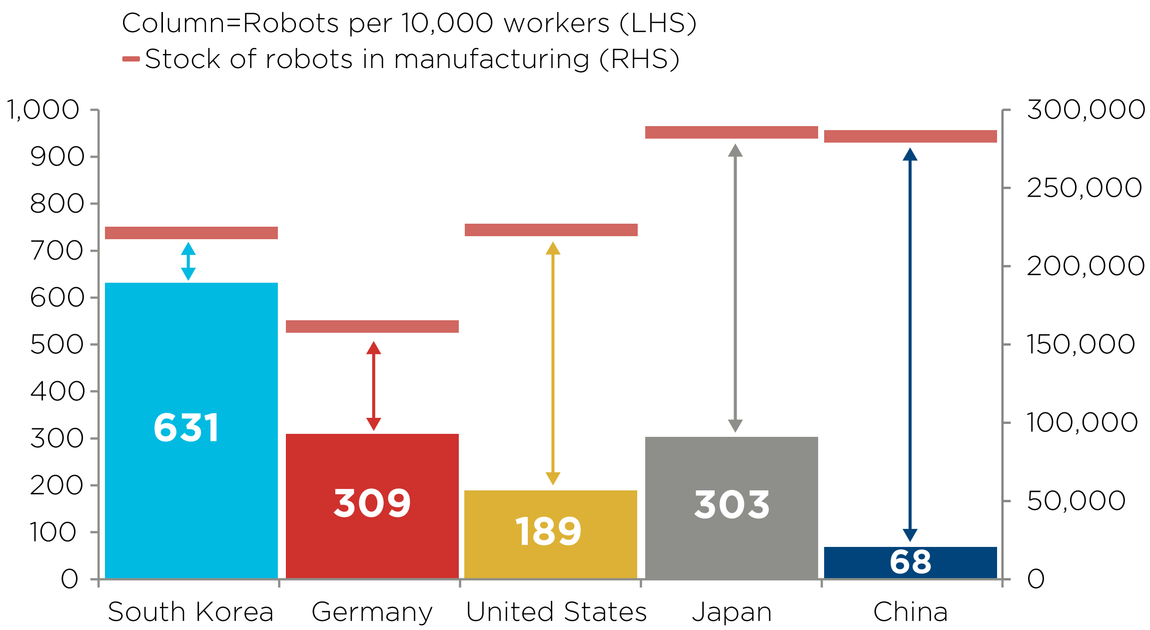
[9] Figures may be subject to upward bias by a trend in robot sales toward smaller installations

Trend #3: Demand for manufactured goods is rising, and China is investing in robots to position itself as the global manufacturing leader

Much of the growth in robot stock over the past decade can be attributed to rising demand for manufactured goods. China is at the heart of this change: it has become the world's largest automotive manufacturing site, and a major producer of consumer electronic devices, batteries, and semi-conductors—all highly robot-intensive manufacturing sectors. This trend is set to continue, as China is still only at the beginning of its automation journey. Despite its rapidly growing inventory, China only uses 68 robots per 10,000 workers in general manufacturing, compared with 303 per 10,000 in Japan, and 631 per 10,000 in South Korea. The imbalance between stock and density is shown in Fig 5. Large sections of China's workforce are still engaged in manual processes, meaning vast potential remains for further robotization of its manufacturing sector—moreso than in any other country.

With government policies aimed at expanding the use of electric vehicles (which will require large-scale battery production), and the establishment of high-tech manufacturing, we expect China will likely continue its acceleration in robot investments for the next decade. By 2030, if the investment in industrial robots continues to grow at its current trajectory, China will have close to eight million industrial robots in use, as its robot density approaches levels comparable with the average across the European Union.[10]

Fig. 5: Chinese scope for catch-up in robot density (2016)



Source: IFR, Oxford Economics

[10] 2030 projections based on short-term International Federation of Robotics forecasts, controlling for longer-term stock depreciation.

THE IMPACT OF ROBOTS ON MANUFACTURING JOBS

Throughout history, the geographical imbalance between the positive and negative effects of automation has had significant economic, social and political implications.

While China leads the way in robot investment, many other major manufacturing economies have also rapidly expanded their use of industrial robots in recent years. We quantified the impact of this global rise in industrial robot inventory on manufacturing employment since 2000. We also forecast the number of manufacturing jobs that could be lost to robotization around the world by 2030, and the distribution of potential changes across higher- and lower-income regions within countries.

It's important to note that despite the rising pace of robotics investment and installation, popular fears that robots will create huge swathes of unemployment around the world are somewhat misplaced. This is because the value created by robots across the economy more than offsets their disruptive impact on employment. Manufacturers automate their production processes to boost productivity.

This creates a "displacement effect" on manufacturing jobs, since the new technology can perform a worker's job more cost-effectively for a given standard of quality. It also reduces unit-production costs that, in a competitive market, translate into lower prices and effectively raises the real spending power of consumers. Therefore, the same robots that displace jobs in manufacturing also create employment across the wider economy. We explore this positive economic impact in greater detail on page 35.

At a regional or local level, however, the impact on jobs varies greatly. Since most manufactured goods are highly tradable (because they are cheap to transport and have a long shelf life), the households that benefit from cheaper goods are widely dispersed. By contrast, the communities most reliant on manufacturing jobs—and thus most affected by the introduction of new technology—are typically much more concentrated. Throughout history, this geographical imbalance between the positive and negative effects of automation has had significant economic, social, and political implications. We developed an econometric model to quantify the impact on manufacturing jobs in each country's higher- and lower-income regions.

GLOBAL IMPACTS

Since 2004, each new industrial robot installed in the manufacturing sector displaced an average of 1.6 workers from their jobs. The full impact takes time to materialise, however. Within the first year of a robot's installation, roughly 1.3 workers are displaced, on average, from their job; this extends to 1.6 workers over subsequent years.

This finding is consistent with other evidence from industry as it adopts automation: the true productivity gains can take several years to materialise as workers receive appropriate training, and as firms understand how best to reorganise their production processes and business models to exploit the benefits of the new technology at scale.

A NOTE ABOUT OUR ECONOMETRIC MODELLING

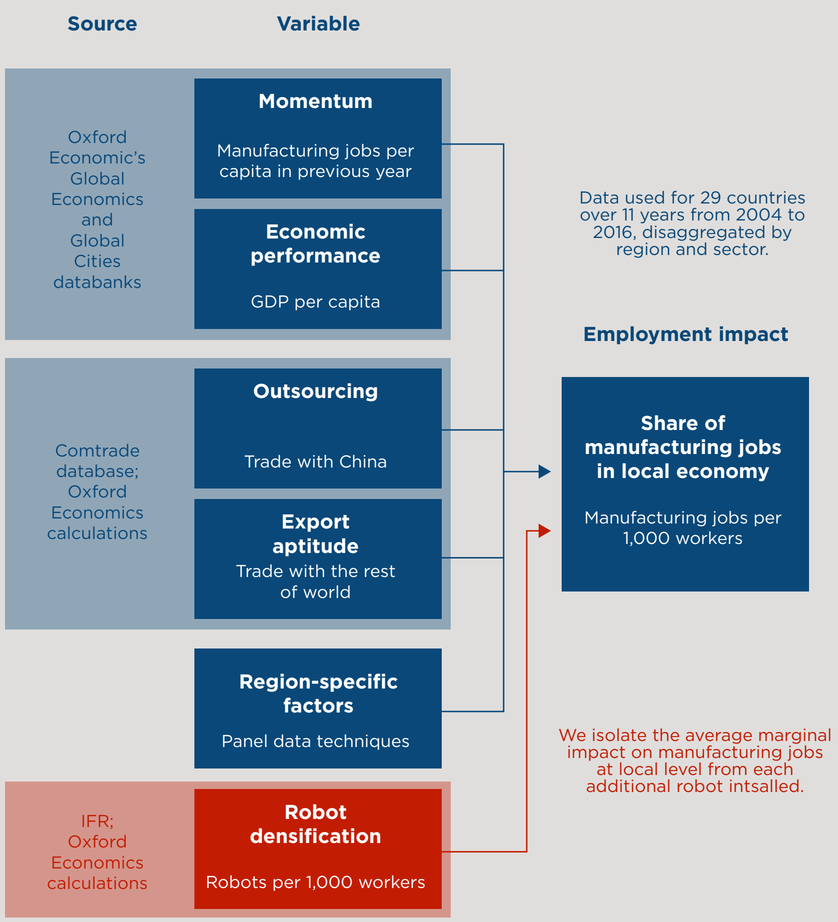
Our study presents our econometric analysis of the link between robot installations and manufacturing job losses at both the national level and for regions within specific countries. Our model focuses on 29 manufacturing-intensive countries using 11 years of data, offering unprecedented levels of detail about the past and future impacts of robotization on manufacturing jobs around the world.

In addition to providing absolute figures, we have calculated the marginal impact of each additional robot installation on manufacturing jobs across the countries studied. Our modelling establishes how this impact compares between lower- and higher-income regions within a country (defined as regions with average household income levels above and below the national average).

Drawing on data from the International Federation of Robotics (IFR), an industry trade group, we investigated the ways in which the installation of additional industrial robots affected local manufacturing employment in Japan, the European Union, the United States, South Korea, and Australia.[11] By constructing a large, regional panel dataset of robot stock alongside other labour market indicators over an 11-year timeframe, we were able to isolate the impact of robotization versus other strong influences on local labour markets—these include changes in real wages, shifts in global trade patterns, and other unobservable regional and industry-related factors.

See Appendix for a full explanation of this methodology.

Fig. 6: Our econometric modelling framework



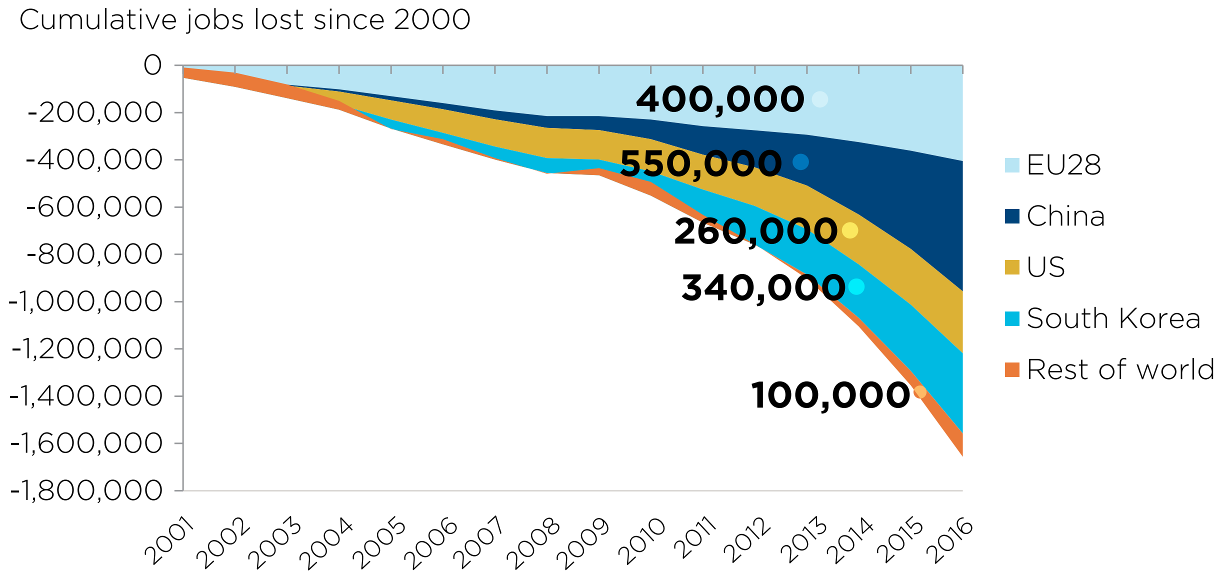
[11] Despite its prominence in global manufacturing, China was omitted from our econometric modelling exercise due to a lack of data in other important modelling variables.

We also calculated the total amount of manufacturing jobs lost to robotization throughout the world since the turn of the century,[12] considering factors such as redundancies caused by off-shoring and the globalisation of supply chains. In all, we estimate that around 1.7 million manufacturing jobs have been wiped out since 2000 due to the global rise of industrial robots. Fig. 7 illustrates the impact by country: in the US, we estimate that more than 260,000 jobs have been lost to robots (around 2% of today's manufacturing workforce), while in the European Union, robots have taken the place of 1.5% of the current manufacturing workforce (some 400,000 jobs). In China, as many as 550,000 manufacturing jobs have been displaced by robotization since 2000, equivalent to around 1% of its current manufacturing workforce.

Assuming robot investments continue at their current pace, many millions of additional manufacturing jobs are likely to be displaced by robots by 2030. While considerable uncertainties exist around the rate of adoption of new technologies, it is possible to estimate the likely impact of robotization in the coming years.

We have projected the growth in the active robot stock across major manufacturing economies to 2030, based on the IFR's three-year growth projections for new robot installations and including the need to replace some robots over time as they deteriorate. On this basis, we expect almost 20 million manufacturing jobs to disappear around the world because of robotic automation (see Fig. 8). Put differently, if current trends hold, the global manufacturing workforce would be 8.5% larger by 2030 if robots were not remaking the market.[13]

Fig. 7: Cumulative jobs losses implied by automation since 2000



Source: Oxford Economics

[12] Global estimate based on more than 90% of known global industrial robot installations, according to the International Federation of Robotics.
[13] Manufacturing employment projections from Oxford Economics' Global Industry model.

Installing one extra industrial robot in a lower-income region leads to almost twice as many manufacturing job losses as in higher-income regions.

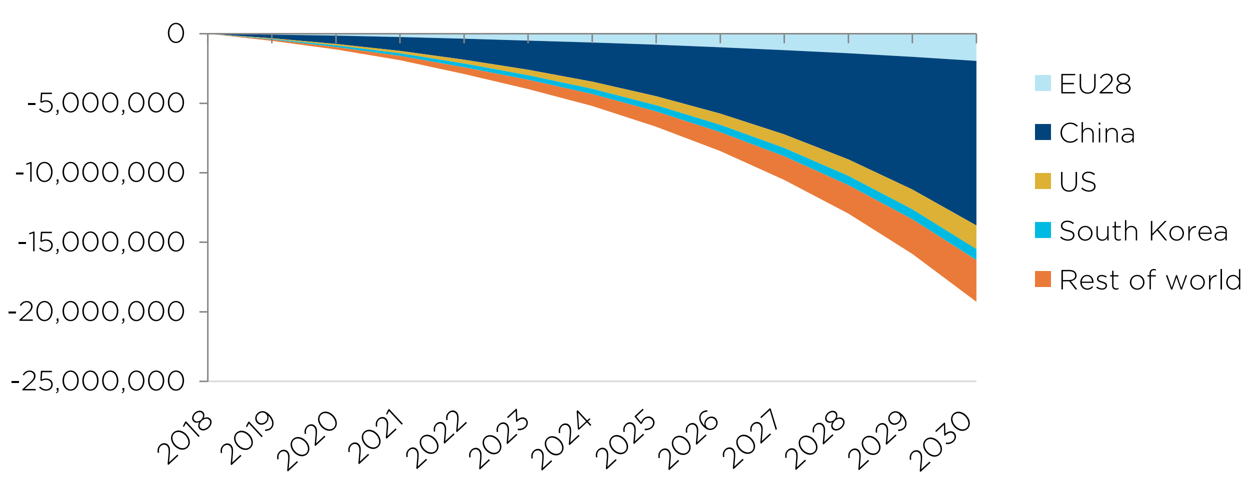
REGIONAL IMPACTS HIT HARDER IN LOWER-INCOME AREAS

Our modelling also allows us to look at the impact of automation on different regions within each country. These regional differences offer important social and political implications for policy-makers.

Our analysis shows that installing one extra industrial robot in a lower-income region leads to almost twice as many manufacturing job losses as in higher-income regions (see Fig. 9). This finding is based on an analysis of our 29 sample countries, distinguishing between regions whose average household income levels are either above or below the national average. It also controls for regionally-specific labour market shocks and underlying employment trends.

Why do these regional differences occur? They are not driven by the relative size of the manufacturing sector—manufacturing accounts for roughly the same share of economic activity and employment in both lower- and higher-income regions in our sample, and our model controls for sector size. But there are structural differences in the composition of employment in manufacturing that influence the impact robots have.

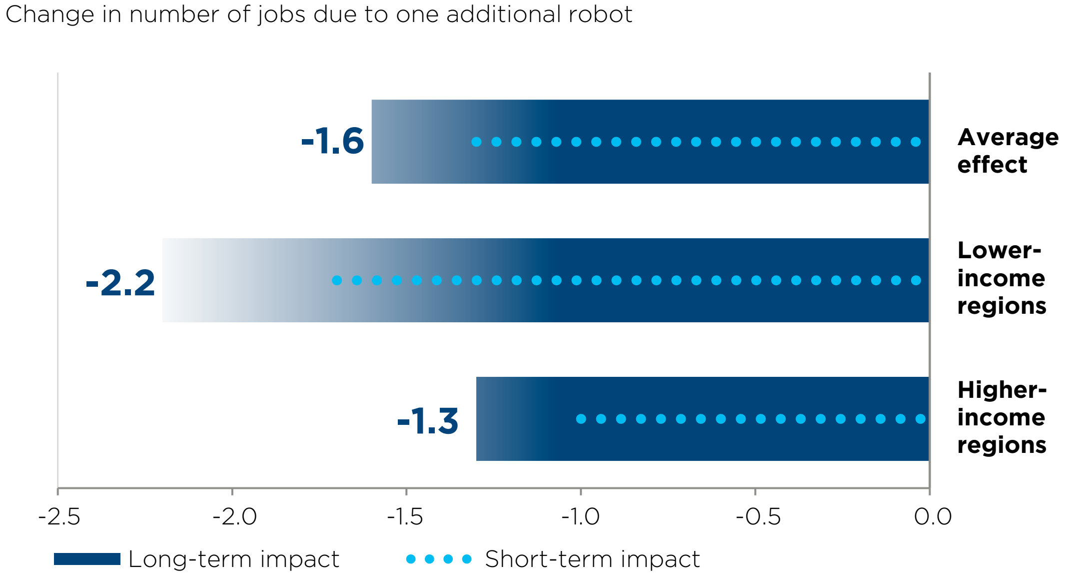
Fig. 8: Projected cumulative jobs losses by automation, up to 2030[14]



Source: Oxford Economics

[14] Projections for 'Rest of World' include countries covering more than 99% of the estimated global total.

Fig. 9: Manufacturing job losses skew towards lower-income regions



Source: Oxford Economics

Manufacturing workers in lower-income areas tend to have lower skill levels and are therefore more vulnerable to automation. There is typically a difference in the number of robots per manufacturing worker between higher- and lower-income regions, indicating that those in lower-income regions are, on average, less productive. Data from the UK Labour Force Survey, for example, shows that manufacturing workers in lower-income regions of the UK are more likely to work in lower-skilled occupations—elementary workers and machine operatives account for around one-third of the workforce in lower income regions, compared with 22% in higher-income regions. In contrast, a significantly higher proportion of managers and professionals in the manufacturing industry are in higher-income regions.

This vulnerability has evolved over time. In the past, lower-income areas competed with more expensive cities and regions for manufacturing investment, with the lure of lower unit costs of production. This competitive edge was a consequence of relying on a lower-paid, less-productive workforce to carry out lower-skilled jobs. In the new era of automation, the occupational mix in lower income areas means those same manufacturers face the biggest opportunities for efficiency savings. The functions their employees carry out are—on balance—easier to automate. These efficiency gains can be realised by laying off staff, or by moving the firm to a new, more productive (and likely more automated) site. Either way, the manufacturing workers in those regions are at risk.

Moreover, the regions of a country most likely to shed manufacturing workers will not benefit equally from the "robotics dividend" —the new jobs created from the productivity boost that feed into the wider economy. Instead, increased industrial automation will tend to exacerbate the regional inequalities that already exist within advanced economies.

THE ROBOT VULNERABILITY INDEX

It is vital for policy-makers to understand how an uneven distribution of robotics will affect different parts of their country. We have developed a Robot Vulnerability Index to help identify which regions within our chosen economies (the US, Germany, UK, France, Japan, South Korea, and Australia) will be hardest hit by the ongoing automation of the manufacturing sector.

Our index produces a vulnerability score for each sub-national region[15], comprised of three equally weighted indicators:

- Local dependence on manufacturing employment—defined as the manufacturing share of total employment in the region.
- Future readiness of local industry—characterised by a region's current intensity of robot use in manufacturing, controlling for the type of manufacturing activity undertaken, and measured relative to international competitors.
- Productivity of the local manufacturing workforce—measured relative to the national average.

The index is thus designed to highlight regions that are economically dependent on a less productive (or lower-skilled) manufacturing industry and do not currently use many robots, since these areas are at highest risk of economic upheaval in the years ahead. Mapping the vulnerability to robot adoption across all regions of these five advanced economies revealed some common patterns, which can be summarised in three key trends.

Our Robot Vulnerability Index shows that specific regions that are at highest risk of labour disruption—but also reveals some common patterns across regions.

TREND #1: EXISTING INEQUALITIES WILL INTENSIFY

Successful economic performance at the regional level in advanced economies is usually inversely correlated with robot vulnerability. In the UK, France, and Germany, those regions that have performed best in recent years (in terms of overall GDP growth) are the least exposed to future robot automation, and vice versa.

This means the regional inequalities that exist within countries, such as England's north-south divide, could be exacerbated by the rise of the robots. This trend has important implications for policy design in advanced economies pursuing international competitiveness through automation.

[15] Sub-national regions correspond to European NUTS 2, US States, Japanese prefectures, Australian states, and South Korean districts.

The pockets of workers most vulnerable to automation can often be found in rural areas.

TREND #2: MANY MAJOR CITIES ARE SAFE (FOR NOW)

Our analysis shows that major cities are often safe havens for workers in the face of robot led job displacement. Diversified economies depend less on manufacturing jobs, and higher labour costs mean manufacturers located there are already highly productive and tend to employ more highly skilled workers. London, Paris, Seoul, Sydney and Tokyo are all examples.

But manufacturing-intensive cities (including many in South Korea) face a more uncertain future. Cities with large populations that are more dependent on the manufacturing sector for employment but lag their industry peers in robot intensity and labour productivity are vulnerable to disruption. Fierce competition will ultimately lead these city-based industries to pursue further automation or risk losing out to more productive competition elsewhere. Either way, additional job displacement of current manufacturing workers is likely.

TREND #3: RURAL REGIONS MASK HIDDEN VULNERABILITIES

The pockets of workers most vulnerable to automation can often be found in rural areas. Despite relatively sparse populations, these regional economies are frequently grounded to isolated towns with more manufacturing-intensive industrial structures on which the wider region depends. This is especially problematic when manufacturing in these towns is characterised by traditional, labour-intensive techniques, low levels of productivity, and dated manufacturing processes.

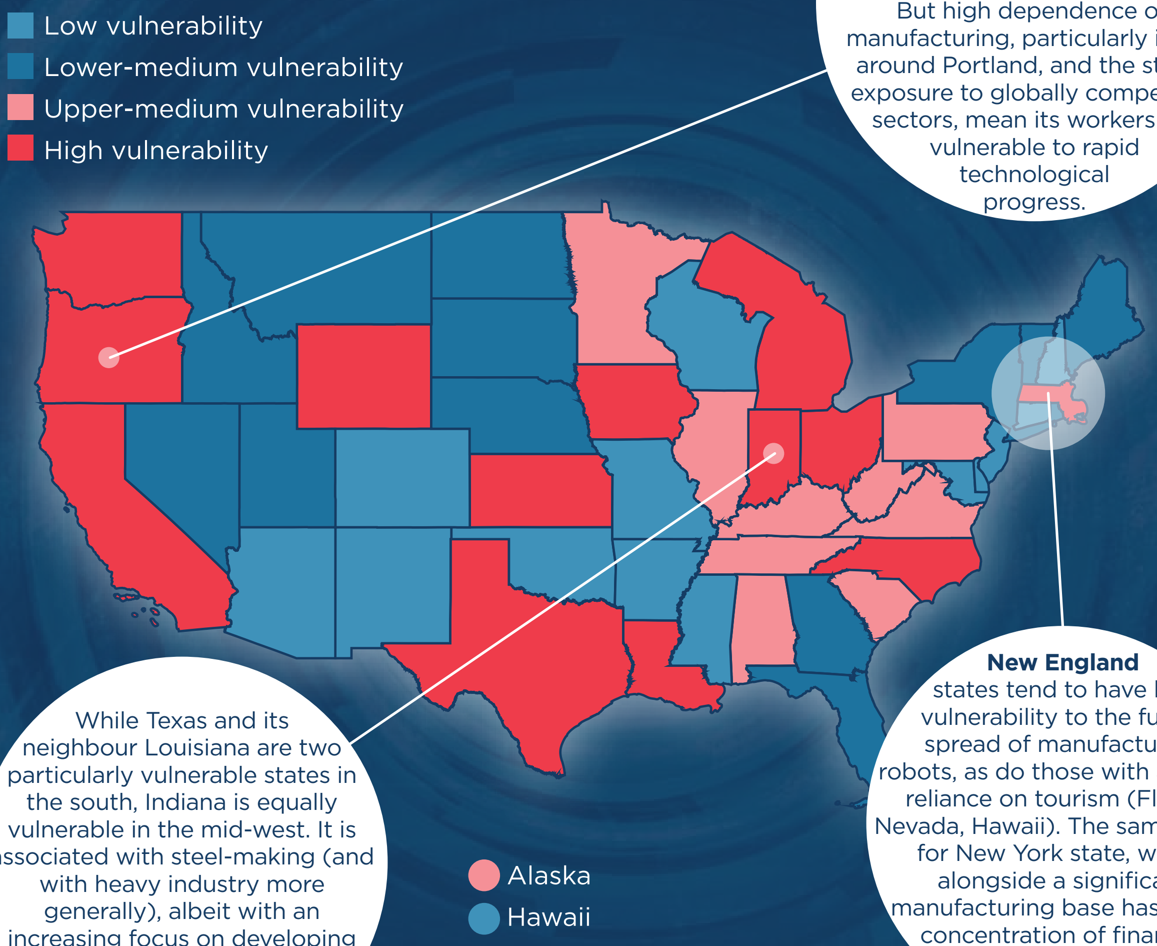
In many countries, such regions have often been left behind as metropolitan centres prospered, and those dynamics have generated political polarisation. This highlights the importance of taking policy action to cushion the likely impact of robotization in these vulnerable areas.

Country-by-country analysis

Over the next seven pages, we illustrate each local region's relative vulnerability to future manufacturing automation, according to our Robot Vulnerability Index. Each map is colour-coded from "high vulnerability" to "low vulnerability" regions (relative to the rest of that country) and includes commentary on some of the most striking geographical results.

[1] Xxxxxx

UNITED STATES



Oregon is the most vulnerable state in the US to a future acceleration in robot installations. The state has had success in transitioning out of traditional sectors into the production of high-tech components. But high dependence on manufacturing, particularly in and around Portland, and the state's exposure to globally competitive sectors, mean its workers are vulnerable to rapid technological progress.

While Texas and its neighbour Louisiana are two particularly vulnerable states in the south, Indiana is equally vulnerable in the mid-west. It is associated with steel-making (and with heavy industry more generally), albeit with an increasing focus on developing the growth of its higher-value, knowledge-based industries.

New England states tend to have low vulnerability to the future spread of manufacturing robots, as do those with a higher reliance on tourism (Florida, Nevada, Hawaii). The same is true for New York state, which, alongside a significant manufacturing base has a high concentration of financial and business services.

Most vulnerable states

State:	Index Score:
Oregon	0.58
Louisiana	0.58
Texas	0.50
Indiana	0.46
North Carolina	0.46

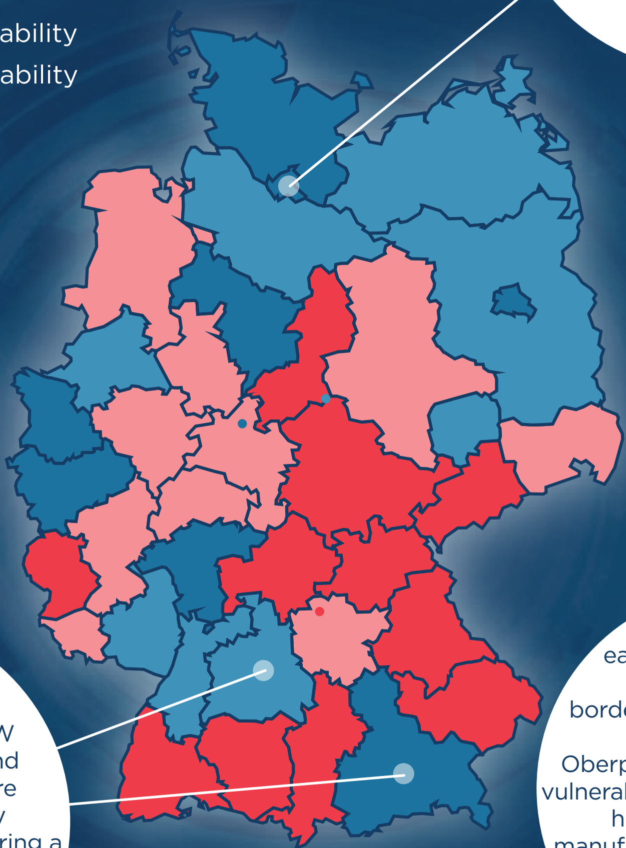
Least vulnerable states

State:	Index Score:
Hawaii	0.17
District of Columbia (DC)	0.18
Nevada	0.25
Florida	0.25
Vermont	0.26

GERMANY

Germany's least-vulnerable region is Hamburg. It has a low level of dependence on manufacturing jobs, and what manufacturing it does have is typically advanced and highly productive, with cutting-edge levels of automation.

- Low vulnerability
- Lower-medium vulnerability
- Upper-medium vulnerability
- High vulnerability



The home regions of BMW and Mercedes—Bavaria and Stuttgart, respectively—are examples of future-ready production ecosystems, featuring a highly skilled, highly productive workforce.

A cluster of four eastern regions close to the Czech border—Chemnitz, Thüringen, Oberfranken, and Oberpfalz—look to be the most vulnerable to robotization. All have high concentrations of manufacturing employment, and (typically) low levels of productivity—particularly **Chemnitz** and **Thüringen.**

Most vulnerable regions

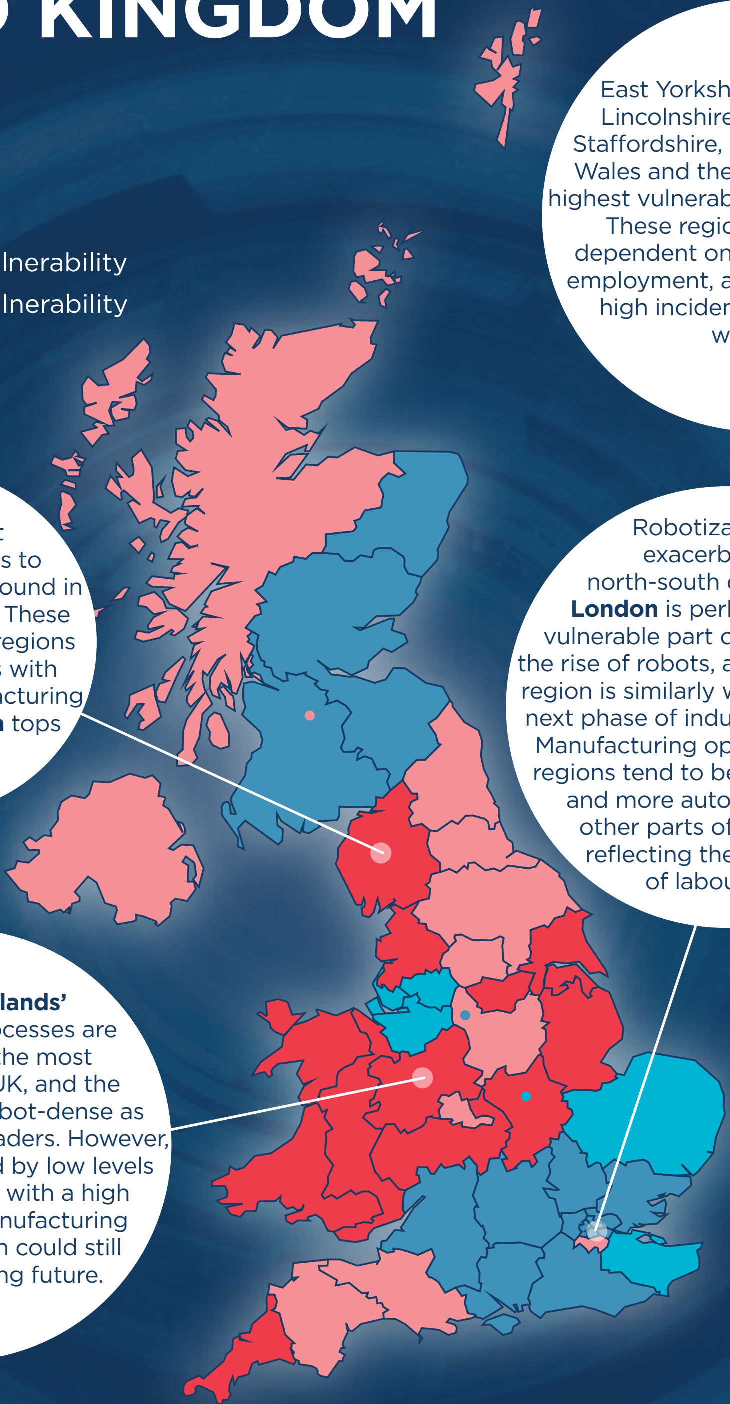
Region:	Index Score:
Chemnitz	0.56
Thüringen	0.49
Oberfranken	0.49
Oberpfalz	0.47
Freiburg	0.46

Least vulnerable regions

Region:	Index Score:
Hamburg	0.06
Darmstadt	0.13
Oberbayern	0.17
Köln	0.19
Berlin	0.20

UNITED KINGDOM

- Low vulnerability
- Lower-medium vulnerability
- Upper-medium vulnerability
- High vulnerability



East Yorkshire and Northern Lincolnshire, Shropshire and Staffordshire, Cumbria, and West Wales and the Valleys exhibit the highest vulnerability scores in the UK. These regions are relatively dependent on manufacturing for employment, and have a relatively high incidence of low-skilled workers.

The UK's most vulnerable regions to robotization can be found in its more rural areas. These sparsely populated regions may contain towns with concentrated manufacturing industries. **Cumbria** tops our UK Index.

Robotization will exacerbate the north-south divide. **Inner London** is perhaps the least vulnerable part of the country to the rise of robots, and the South East region is similarly well-placed for the next phase of industrial automation. Manufacturing operations in these regions tend to be more advanced and more automated than in other parts of the country, reflecting the higher cost of labour here.

The **West Midlands'** manufacturing processes are already among the most automated in the UK, and the region is nearly as robot-dense as international market leaders. However, it is also characterised by low levels of productivity, and with a high dependence on manufacturing employment, which could still imply a challenging future.

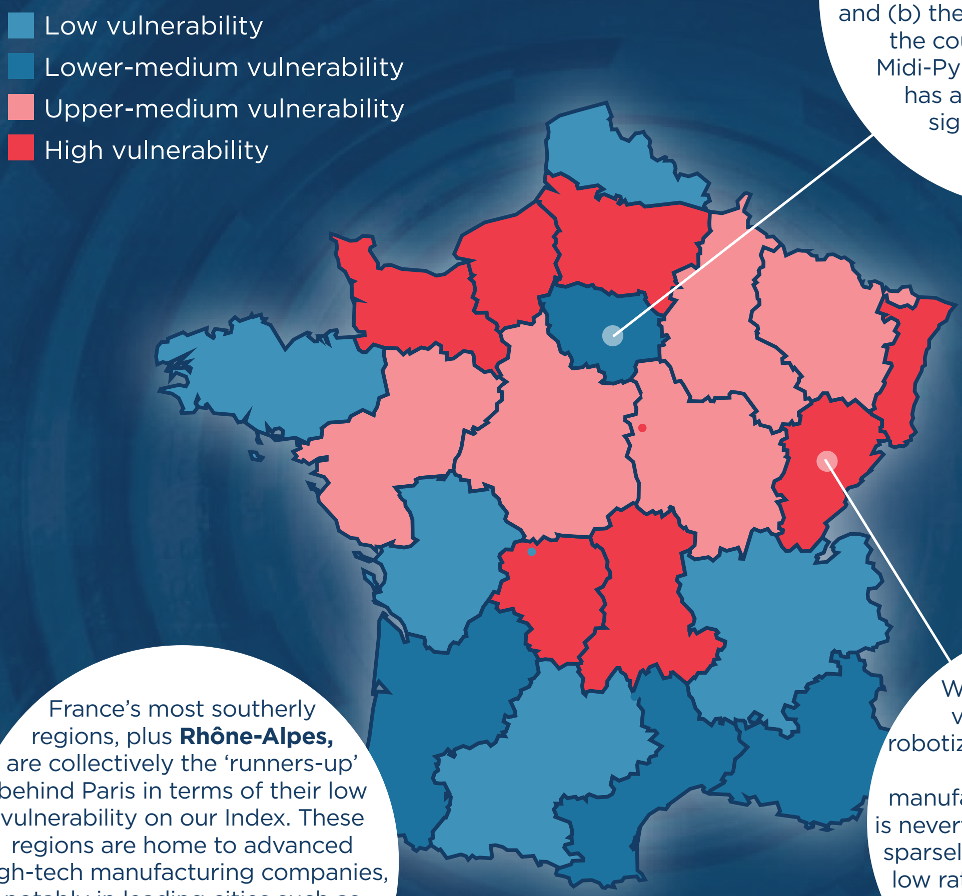
Most vulnerable regions

Region:	Index Score:
Cumbria	0.59
East Yorkshire & North Lincolnshire	0.59
Shropshire & Staffordshire	0.58
West Wales & the Valleys	0.56
Lincolnshire	0.54

Least vulnerable regions

Region:	Index Score:
Inner London (East)	0.15
Inner London (West)	0.17
Outer London (West & NW)	0.20
Berks, Bucks & Oxfordshire	0.25
Surrey, East & West Sussex	0.28

FRANCE



The **Île-de-France,** centred on Paris, is France's least-vulnerable region. It is least dependent on manufacturing jobs, and what manufacturing activity it does have is (a) highly productive and (b) the most robot-intensive in the country, alongside the Midi-Pyrenees. This means it has already undertaken significant levels of automation

We find that the most vulnerable region to robotization is **Franche-Comté.** France's most manufacturing-intensive region is nevertheless relatively rural and sparsely populated. Its relatively low rate of robotization means there could be high levels of automation coming.

France's most southerly regions, plus **Rhône-Alpes,** are collectively the 'runners-up' behind Paris in terms of their low vulnerability on our Index. These regions are home to advanced high-tech manufacturing companies, notably in leading cities such as **Toulouse** (home to Airbus, among others) and **Grenoble,** and thus benefit from a future-ready, highly skilled workforce.

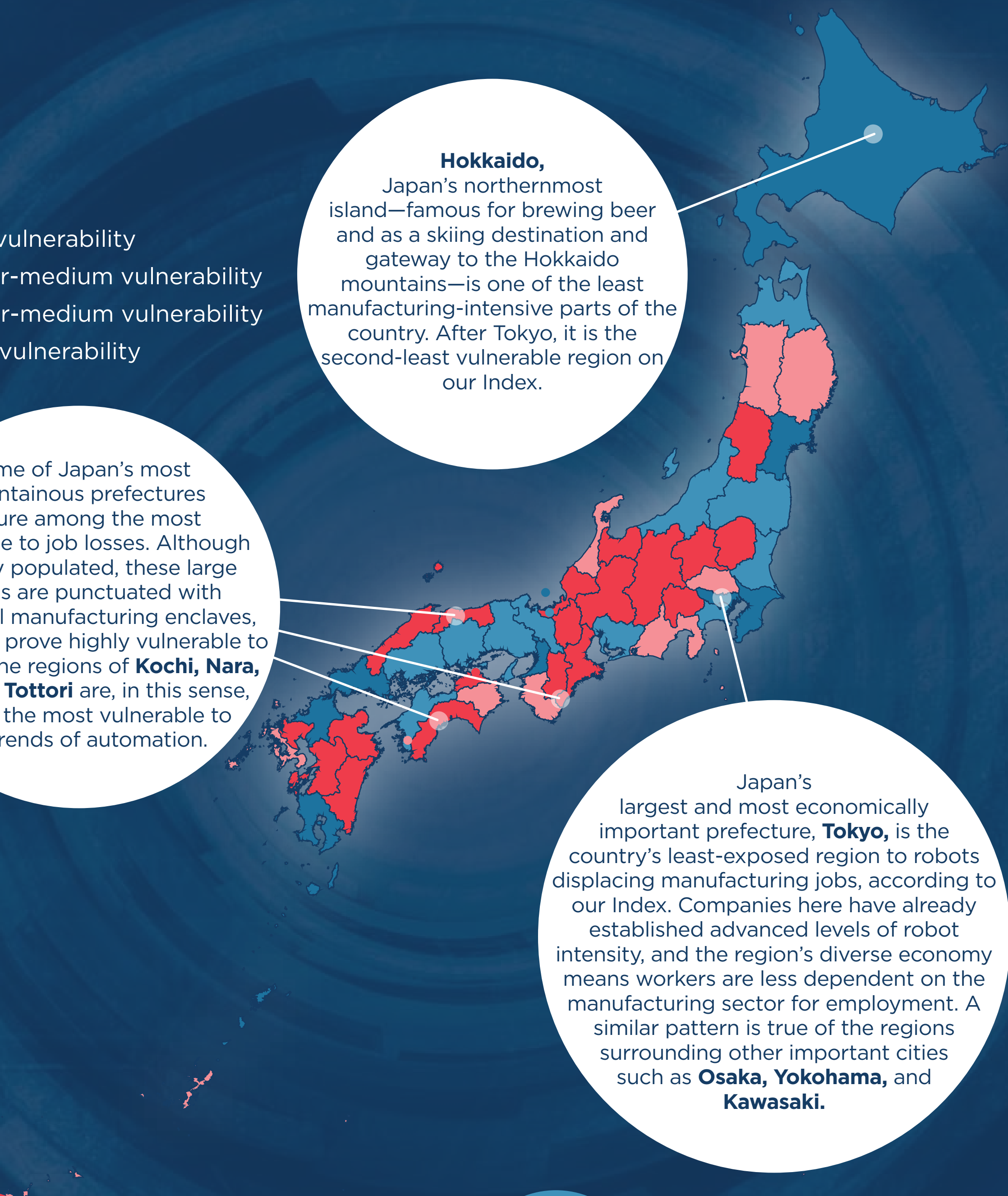
Most vulnerable regions

Region:	Index Score:
Franche-Comté	0.61
Basse-Normandie	0.51
Picardie	0.51
Limousin	0.51
Auvergne	0.49

Least vulnerable regions

Region:	Index Score:
Île de France	0.03
Provence-Alpes-Côte d'Azur	0.26
Languedoc-Roussillon	0.30
Aquitaine	0.35
Midi-Pyrénées	0.36

JAPAN



- Low vulnerability
- Lower-medium vulnerability
- Upper-medium vulnerability
- High vulnerability

Hokkaido, Japan's northernmost island—famous for brewing beer and as a skiing destination and gateway to the Hokkaido mountains—is one of the least manufacturing-intensive parts of the country. After Tokyo, it is the second-least vulnerable region on our Index.

Some of Japan's most mountainous prefectures feature among the most vulnerable to job losses. Although sparsely populated, these large regions are punctuated with traditional manufacturing enclaves, which may prove highly vulnerable to change. The regions of **Kochi, Nara,** and rural **Tottori** are, in this sense, among the most vulnerable to the trends of automation.

Japan's largest and most economically important prefecture, **Tokyo,** is the country's least-exposed region to robots displacing manufacturing jobs, according to our Index. Companies here have already established advanced levels of robot intensity, and the region's diverse economy means workers are less dependent on the manufacturing sector for employment. A similar pattern is true of the regions surrounding other important cities such as **Osaka, Yokohama,** and **Kawasaki.**

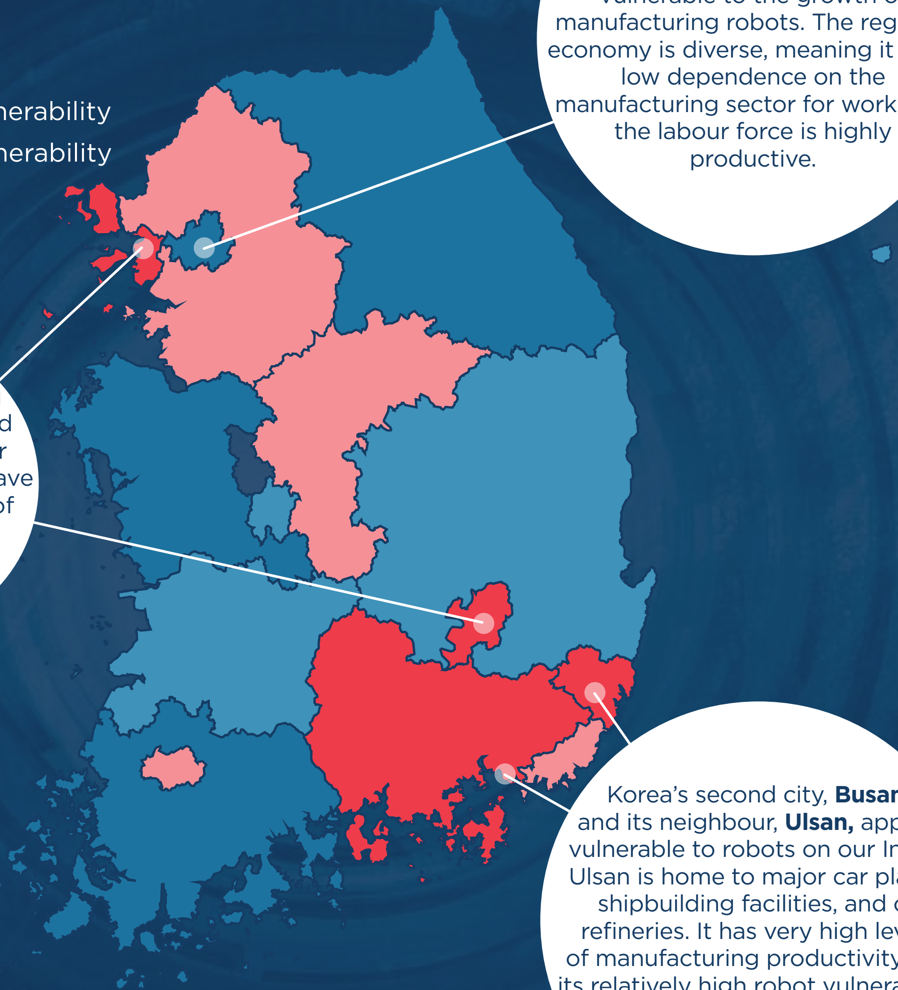
Most vulnerable regions

Region:	Index Score:
Tottori	0.54
Kochi	0.51
Nara	0.49
Shiga	0.49
Saga	0.48

Least vulnerable regions

Region:	Index Score:
Tokyo	0.09
Hokkaido	0.20
Osaka	0.25
Fukuoka	0.28
Miyagi	0.28

SOUTH KOREA



Workers in South Korea's largest city, **Seoul,** are the country's least vulnerable to the growth of manufacturing robots. The regional economy is diverse, meaning it has a low dependence on the manufacturing sector for work, and the labour force is highly productive.

Incheon and **Daegu** are the most exposed regions. These major manufacturing hubs have relatively low levels of manufacturing productivity, so are ripe for change.

Korea's second city, **Busan,** and its neighbour, **Ulsan,** appear vulnerable to robots on our Index. Ulsan is home to major car plants, shipbuilding facilities, and oil refineries. It has very high levels of manufacturing productivity, but its relatively high robot vulnerability score is driven by a remarkable dependence on manufacturing employment.

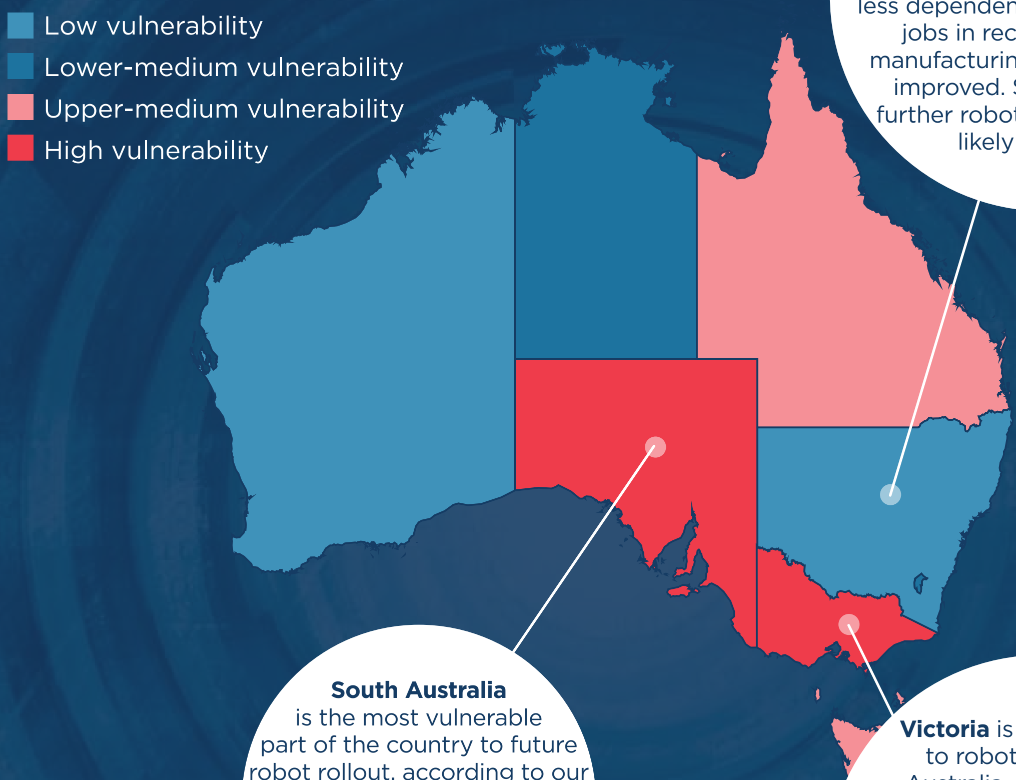
Most vulnerable regions

Region:	Index Score:
Daegu	0.38
Incheon	0.35
Ulsan	0.33
Gyeongnam	0.32
Busan	0.29

Least vulnerable regions

Region:	Index Score:
Seoul	0.11
Jeollanam-do	0.13
Gangwon	0.19
Chungcheongnam-do	0.21
Gyeongbuk	0.23

AUSTRALIA



Australia's most populous state, **New South Wales,** looks rather less vulnerable than either Victoria or South Australia. In this state, the labour market has become less dependent on manufacturing jobs in recent years, while manufacturing productivity has improved. So the impact of further robot densification will likely be muted.

South Australia is the most vulnerable part of the country to future robot rollout, according to our Index. The state is Australia's most manufacturing intensive but has the slowest-growing economy and low levels of manufacturing productivity.

Victoria is less vulnerable to robots than South Australia, and also faster growing. Melbourne and its surrounding area have a diversified manufacturing base, although one that is declining in relative importance as Melbourne's service economy strengthens. Victoria's manufacturing productivity is also higher than that of South Australia.

Regions and territories ranked from most-to-least vulnerable

Region:	Index Score:
South Australia	0.42
Victoria	0.39
Tasmania	0.37
Queensland	0.32
New South Wales	0.28
Western Australia	0.14
Northern Territory	0.06
Australian Capital Territory	0.06

A delivery robot being trialled in London, 2017.

THE ROBOTICS DIVIDEND

Despite the decline of manufacturing jobs over the past decade, it would be simplistic to characterise robotization as only a destroyer of jobs. While certain sets of workers lose their jobs to robots, many in the wider population benefit from a "robotics dividend"—lower prices for manufactured goods, higher real incomes, and stronger tax revenues. This will be particularly important to the lower-income regions we have identified as being most vulnerable to the robot revolution.

Our modelling shows that robots have delivered considerable productivity gains in recent years. We analysed the impact of robot densification on productivity growth in an international sample of countries over 11 years, controlling for factors such as skill levels and other capital investment, across 29 of the world's most advanced economies.[16] We found that a 1% increase in the stock of robots per worker in the manufacturing sector alone leads to a 0.1% boost to output per worker across the wider workforce. This confirms our hypothesis: that by displacing automatable jobs in manufacturing, robots free up many workers to contribute productively elsewhere in the economy, as they meet the demands generated by lower prices for manufactured goods.

To capture the potential implications of the new era of robotics on the global economy, we used Oxford Economics' Global Economic Model (GEM). The GEM covers 80 countries and is the foundation of all Oxford Economics' country, industry, and city forecasts. It enables us to test the sensitivity of macroeconomic outcomes to different rates of investment across many advanced economies around the world. This modelling suggests that the rate of industrial robot adoption over the coming years will have a significant impact on global GDP growth.

The first step in our GEM analysis was to establish a baseline projection for GDP growth consistent with the short-term robot investment trajectories forecast by the International Federation of Robots (IFR) trade group.[17] These trajectories for the US, Europe, and large Asian economies were calibrated against historical growth levels for both robot stock and robot density. Our baseline projections for the growth in robot stock amounted to an annual increase of roughly 5% for China, 3% for the US, 2% for both South Korea and the Eurozone, and 0.7% for Japan.

Next, we explored "high" and "low" scenarios for robotization, relative to the IFR's short-term benchmark. The high scenario assumes that the global stock of industrial robots will accelerate

1%

increase in the stock of robots per worker in the manufacturing sector leads to a 0.1% boost to output per worker across the wider workforce.

30% above baseline projections for 2030. For China's manufacturing sector, this would put its robot density on a par with the levels of robot density that currently exist in Japan and Germany.

By contrast, the low scenario assumes the pace of robot adoption slows, leaving the stock of industrial robots some 30% lower than the baseline by 2030. This would put the robot density of China's manufacturing sector at a level comparable with the current robot density of the US manufacturing sector—a level significantly lower than Japan and Germany. (For more information on how we used the GEM to simulate the impact of different robot adoption rates on the annual GDP performance of key economies around the world, see box on page 37).

[16] The sample size for this model differs to our employment model due to data availability.
[17] The IFR's latest three-year growth projections for new robot installations appear in its publication World Robotics 2017: Industrial Robots.

The jobs displaced by industrial robots will be concentrated in the manufacturing sector—where their uses are most well established.

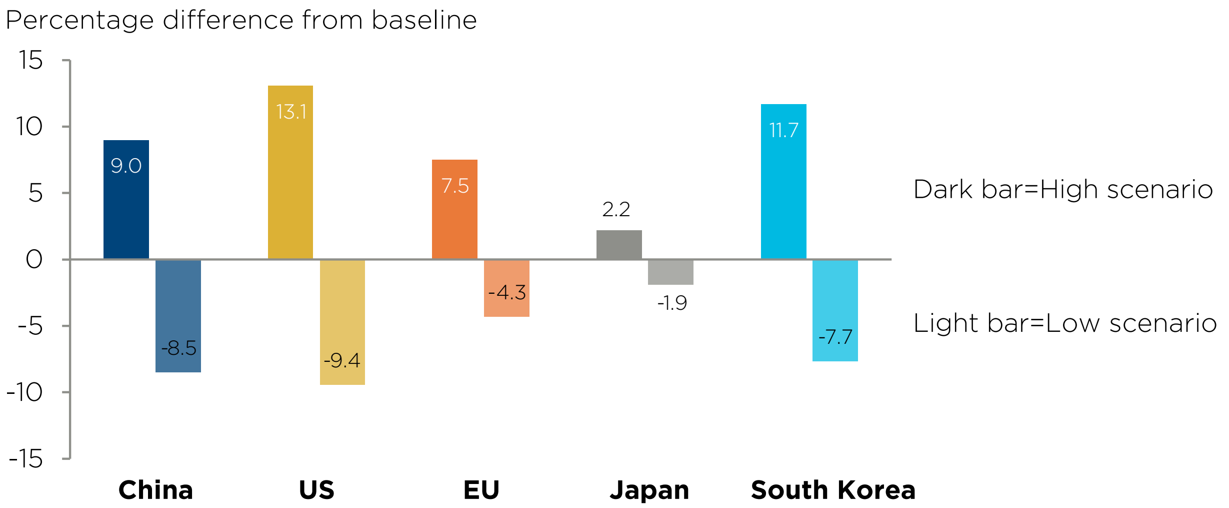
Results of our high and low robotization scenarios

Overall, we find that faster adoption of robots has a positive impact on both short- and medium-term economic growth.

Specifically, the GEM suggests the high adoption scenario would boost global GDP by 5.3% above our baseline GDP growth forecast in 2030. This equates to adding an extra $4.9 trillion to the global economy that year—equivalent to an economy greater than the projected size of Germany's.[18] Under the low adoption scenario, we predict a similarly sized negative impact on the global economy's growth trajectory.

The high-adoption scenario bolsters the productive potential of the economy. We used the GEM to simulate a corresponding increase in the level of business investment and a boost to productivity, both in the manufacturing sector and the wider economy. As Fig. 10 illustrates, a speed-up of robot investment results in significant gains in GDP growth for the world's largest economies. US GDP rises by 13.1% above the baseline projection by 2030. South Korea GDP rises 11.7%, and China experiences a 9% increase. The relative gains and losses for Japan in either scenario are significantly lower than for all other major economies, due in part to a slower rate of robot investment in the baseline forecast, since Japan's manufacturing sector is already heavily robotized.

Fig. 10: Projected impact of different scenarios on annual GDP in 2030



Source: Oxford Economics

[18] Value expressed in 2018 prices and compared with estimated German GDP in 2030.

MODELLING THE ECONOMIC IMPACTS OF ROBOTIZATION

To investigate the implications of different rates of investment in and adoption of industrial robots, we simulated some stylised scenarios for the US, Europe, and large Asian economies using the Oxford Economics Global Economic Model (GEM).

We used the GEM to establish a baseline projection for global growth consistent with the current "benchmark" robot investment trajectories established by the International Federation of Robots (IFR). We then employed the GEM's modelling capabilities to explore two alternative scenarios. We set these "high" and "low" robotization scenarios at 30% above or below the IFR's current benchmark rates of adoption.

In practice, this meant using the GEM to apply three key, robot-related economic "shocks" to our baseline model:

- An increase/decrease in "total factor productivity" (the output achieved by a certain amount of capital and labour inputs) that result from adopting more/fewer robots into industrial practices;
- A rise/fall in business investment, capturing different levels of expenditure on industrial robots;
- A shock to employment, expressing the fact that, to generate a given level of output, fewer/more workers may be required under the high/low scenarios. This adjustment was calibrated with our headline econometric result detailed on page 20 of this report, which found that in our modelled economies, each additional industrial robot ultimately displaces 1.6 manufacturing workers, on average.

Once these initial economic shocks were applied, the GEM used its modelled linkages between business, household, government, and international sectors to derive the overall impacts on the different economies.

RESHAPING THE LABOUR MARKET

The results of our GEM analysis show that jobs are both created and destroyed through the increased use of automation and industrial robots. Specifically, an increase in the rate of robot adoption would significantly affect firms' productivity levels, and hence the size of the economy. This increased wealth is therefore likely to result in job creation that will offset the displacement of local manufacturing employment we have identified.

But while this "robotics dividend" will boost employment across many sectors of the global economy, the jobs displaced by industrial robots will be concentrated in the manufacturing sector—where their uses are most well established. And while some new manufacturing jobs will be created by the robotics dividend, it is unlikely they will equal the number of jobs that could be displaced by automation in that sector—up to 20 million around the world by 2030.

Historically, low- and medium-skilled workers displaced from an increasingly productive manufacturing sector have found opportunities in the service sector. But as robotic technology converges with rapid digital innovations, what can unemployed workers do if robots take on service jobs as well? Next, we explore the new frontier of service robotics, and how this is manifesting itself across the service sectors of the world's largest economies.

ROBOTS ARE COMING TO THE SERVICE SECTOR

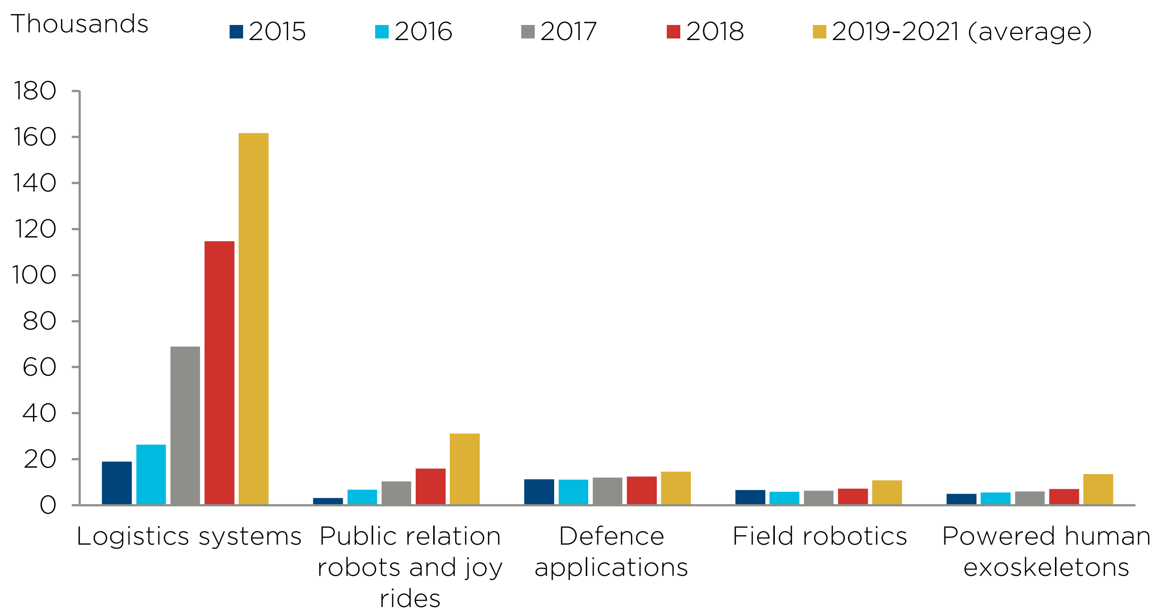
Innovations in AI, machine learning, and computing power suggest a significant acceleration in the adoption of robots across service industries.

While the rise of industrial robots has already reduced manufacturing employment significantly in advanced economies around the world, manufacturing accounts for only a minor share of total employment in these countries. Instead, the vast majority of people work in the sprawling service sector—around three-quarters of all workers, according to the latest Oxford Economics estimates.

To date, the adoption rate for physical robots (as opposed to software-only bots and applications which have already gained wide acceptance in powering robotic process automation) across service industries has been slow, for important reasons. The underlying return on large capital investments can be harder to justify in environments without significant scale. Many aspects of service work can prove difficult to automate.

However, innovations in artificial intelligence, machine learning, and computing power suggest a significant acceleration is coming, particularly in the category of logistics systems—led in part by the global expansion of Amazon and other multinational e-commerce companies (Fig. 11).

Fig. 11: Number of professional service robots distributed, by broad category (top-five most popular)



Source: IFR

Where will automation occur most quickly in the service sector, and which jobs will remain immune to the rise of the robots? As industrial workers displaced by automation seek alternative employment in the services sector—whether as taxi drivers, shop assistants, or hotel porters—will robots and artificial intelligence start to pinch those opportunities as well?

Robots are steadily gaining traction in specific segments of the service economy, from baggage handling in airports to maintaining inventory in warehouses and even bricklaying on construction sites. Guided by sensors, cameras, and machine intelligence, which grow cheaper and more powerful by the year, robots are beginning to stake out their presence in the hospital ward, on the retail sales floor, and in hotels and restaurants.

But how quickly a widespread shift to service robots occurs depends on several factors. While some service jobs may be considered standardised and relatively easy to automate, others demand uniquely human qualities such as social intelligence, imagination, empathy, and other cognitive skills not readily translated into algorithms.

"Yes, Amazon warehouse workers are likely to be replaced by robots in two or three years," says Dr. Kai-fu Lee, an expert on artificial intelligence, founder of Sinovation Ventures, and former senior executive at both Google and Microsoft "But for work that takes place in unstructured environments, I don't anticipate robots fully replacing people. Some more breakthroughs will be required."

In his current role as a venture capitalist and author,[19] Dr. Lee has an interest in promoting AI—which makes his measured view about the subject all the more telling. He notes that an inventory warehouse, like a motorway, represents a relatively defined space where programming rules and sensing technology can help delineate the precise work landscape. "But in a flexible and highly changeable environment, like a room full of people at a cocktail party, the tasks are far more difficult," he says.

AI-powered systems will only prove cost-effective where large economies of scale exist, Dr. Lee says. For example, a robot could likely be employed to vacuum rooms across a hotel chain, because each floor contains rooms that follow only two or three standardised floorplans the robot can recognise. Likewise, hospitals have a series of extensive, standardised procedures, many of which could be passed off to a robot system. To better calculate the potential impact of robotics on service sector employment, it is therefore imperative to differentiate

"For work that takes place in unstructured environments, I don't anticipate robots fully replacing people for another 20 or 30 years."

Dr. Kai-fu-Lee, venture capitalist and author

[19] Kai-Fu Lee, "AI Super-Powers: China, Silicon Valley, and the New World Order" (Houghton Mifflin Harcourt, 2018).

Robot receptionists in Tokyo's Henn Na Hotel in Ginza.

between occupations and tasks to complete certain occupations even in the same sector—and to accurately assess the mix of routine and highly cognitive skills embedded within a specific occupation or job function.

Another key factor is whether scale can be used to offset the added costs associated with deploying robot systems. For example, an autonomous vehicle is far more expensive to build than a conventional car, because of all the cameras, sensors, and software needed. "That car only pays for itself when you can exclude the pay for the driver, and run that vehicle all day long," says Dr. Lee.

To better unravel the impact of robots on a variety of service jobs, we have examined several key sectors.

Healthcare

The healthcare industry in the developed world faces real challenges. Populations are ageing rapidly: the World Health Organization has estimated that by 2020 the number of people aged 60 years and older will outnumber children younger than five—and by 2050 the proportion of the world's population aged over 60 years will nearly double, from 12% to 22%. Many countries face a severe shortage of care workers to assist the elderly and infirm. So it is realistic to expect robots to have a greater impact in assisted living homes, hospitals, and clinics.

Over time, robots will displace personnel in the performance of specific tasks, leaving humans with more time to focus on the compassion, empathy, and emotional intelligence that remains a major component of healthcare. Robots can readily transport blood samples to a lab, or obtain medicines from a dispensary. The potential for robots to be used in controlled hospital environments may be especially compelling, since healthcare in many developed markets faces an acute labour shortage, and few nurses can expect to confront unemployment if robots take over some of their menial tasks. Because the cost of developing and deploying robots is significant, only the largest institutions are likely to introduce them rapidly into a clinical setting, but they may become more commonplace over the next decade.

Robot-assisted surgery (typically in procedures that are minimally invasive) already lets doctors perform complex procedures with more precision and flexibility. The most common robotic system includes a camera arm and mechanical arms connected to surgical instruments, which the surgeon controls while seated at a computer console near the operating table. The console gives the surgeon a high-definition, magnified view of the surgical site. Minimally

According to IFR data, sales of medical robots increased by 49% in 2018 compared with 2017, to total over 4,400 units—totalling an estimated $1.9 billion.

In health and care, unlike other settings, machines would work alongside human beings, not replace them.

invasive surgeries can reduce hospital stays and shorten recovery times.

According to IFR data, sales of medical robots increased by 49% in 2018 compared with 2017, to total over 4,400 units at an estimated $1.9 billion. IFR expects that more than 22,000 units will be sold between now and 2021, a compound annual growth rate of 27%, making medical robots the most valuable of all service robot sectors.

One robot system, the Relay, manufactured by San Jose, California-based Savioke, safely and reliably transports items throughout a hospital, freeing time for pharmacists, lab techs, and other skilled workers to focus on more valuable work and patient care. Able to operate elevators and doors and navigate in busy public corridors, the Relay delivers medicines, blood, lab specimens, snacks, and documents safely and reliably 24 hours a day.

"You don't want nurses spending time doing things that aren't about nursing," says Steve Cousins, CEO of Savioke, which builds the Relay. "Why should a nurse walk down the hall to take a blood sample to the lab, when a robot can do it?" Collaborating with robots not only increases worker satisfaction, he says, it also helps alleviate a chronic nursing shortage.

A report prepared by the Institute for Public Policy Research (IPPR) in the UK largely conforms with Mr. Cousins' view, noting that "in health and care, automation will primarily complement human skills and talents by reducing the burden of administrative tasks. Unlike other settings, machines would work alongside human beings, not replace them, so patients would benefit."[20]

Retail

The US retail sector employs some 16 million workers that include cashiers, salespeople, stock clerks, and customer service representatives. Robots are already displacing human workers in giant warehouses and logistics centres, where online retailers such as Amazon are continuously seeking productivity improvements to reduce costs.

At the leading edge of automation, Amazon keeps finding new ways of getting robots to do work once handled by employees. In 2014, the company began rolling out robots to its warehouses using machines originally developed by Kiva Systems—a company Amazon bought for $775 million seven years ago and renamed Amazon Robotics. Amazon now has more than 100,000 robots in action around the world and plans to add many more. These robots are said to make warehouse work less tedious and physically taxing while also enabling the kinds of efficiency gains that allow a

[20] https://www.ippr.org/news-and-media/press-releases/embrace-full-automation-to-release-time-to-care-in-the-nhs-and-social-care-says-top-surgeon-lord-darzi

customer to order toothpaste after breakfast and receive it before dinner.

The IFR estimates that 69,000 logistics systems (the kind used in retail warehouses) were installed in 2017, an increase of 162% over 2016. Some 90% were installed outside of factories. The value of logistics systems sales reached about $2.4 billion.

Today, robots are also moving steadily to the showroom floor, even if the roles they are being designed to perform are somewhat circumscribed. The Dutch giant retailer Ahold Delhaize is placing 500 robots armed with sophisticated cameras into US grocery stores, to make sure store shelves are stocked and spills are cleaned from the floors. On the sales floor of Saturn appliance stores in Germany, a life-sized robot is likely to greet you heartily and direct to you the specific model of TV you're looking for. And in a BevMo wine and liquor store in Walnut Creek, California, the inventory is likely to be monitored and tracked by a two-wheeled assistant named Norma, who can also lead you to the shelf of chardonnay (see case study).

The job of a checkout cashier is already endangered: Amazon has started opening small, AI-powered, checkout-free supermarkets, where a customer uses her smartphone to pay for the merchandise in her basket.

Likewise, robots can do a better job walking down an aisle and tracking inventory than humans can since they are less easily distracted. "You're not going to see a robot stocking shelves, at least in the near term," says John Wilson, head of research at Cornerstone Capital Group, a New York-based investment advisor. "But technology will bring more efficiency."

CASE STUDY: A ROBOT IN THE WINE SHOP

Christian Bronstein, who works at a BevMo liquor store in Walnut Creek, California says that robots help him do his work better, and do not threaten his long-term prospects.

For the last six months, he's been working alongside a four-foot robot named Norma who "scans shelves for out-of-stocks, directs customers to the right aisle, and tells jokes. Norma makes our job easier," he says.

The robot, manufactured by Fellows Robots in northern California, is an experiment launched by the beverage chain. It features a large touch-screen body, but no arms, and provides support to other workers in the store. "It provides greater efficiency and offers something of a novelty," Mr. Bronstein says. "Naturally, people love it. It's kind of like our soft way into using automation."

A similar Fellows robot, called the LoweBot, was installed as a test in a few big-box hardware stores operated by Lowe's in the US. Customers could ask the LoweBot, by speaking or using a touch screen, where to find items inside the sprawling store. The robot also carries out real-time inventory tracking as it cruises down the aisles and can help store management identify shopping patterns to get a better understanding of which merchandise moves more quickly.

One of Apple's prototype fleet of self-driving vehicles, 2018.

Hospitality

As with hospitals, a major part of the work carried out in hotels and restaurants requires social intelligence and a human touch. But simple, routine tasks are increasingly being passed on to robots.

In the posh Vdara Hotel in Las Vegas, for example, a room service call for fresh towels or a pot of hot coffee is likely to be answered by a robot trundling on wheels. A pair of robots named Fetch and Jett deliver service items to rooms, deliver coffee in the restaurant, and attend to other chores for hotel guests. Guests can touch a tablet computer on the robots to rate their satisfaction with their service.

As underlying robotic capabilities such as vision, speech recognition, and machine learning continue to improve, and costs for these components shrink, the use of service robots in hospitality areas is accelerating. Executives in hotels and other hospitality settings will closely analyse the work component of each occupation and determine which jobs can be more efficiently handled by an AI-powered robot.

The IFR estimates that demand for what it calls "public relations robots" will grow strongly over the next three years. The number of robots used in supermarkets, as guides in museums, or as information providers at convention centres or in hotels is projected to grow from 15,780 units sold in 2018 to about 93,350 by 2021.

Whether these robots will displace a company's existing employees is not always clear-cut, however. Savioke installed the robots in the Vdara Hotel and after a three-month trial, the human workers there voted to keep the robots on staff "because the workers made more money," says Mr. Cousins—the workers knew which room service requests from hotel guests would yield the largest tips, and kept those jobs for themselves. The robots were delegated the most mundane, low-tip chores, like delivering toothpaste or fresh towels. "The workers could do triage to make sure they kept the highest-valued jobs," Mr. Cousins says.

According to Ashleen Bhim, a manager at the Vdara, both workers and guests love interacting with the robots. "We've gotten great reviews from everybody," she says. "I really don't know of any negative feedback."

Robots are also poised to play a greater role in the food service industry, as restaurant owners find the rising cost of labour often outpacing the ability of customers to pay for sit-down food service. In some "limited menu" restaurants, robots may do the cooking: a San Francisco burger shop is using a robot to prepare and grill its patties, but it is too early to say whether this trend will be economically viable. Walmart has also revealed it is testing a kitchen robot assistant (named "Flippy") at its Bentonville, Arkansas. headquarters, to see whether it could be used in its many in-store delis.[21]

At least three US start-ups are also working in Arizona to see whether robot grocery delivery can be made viable. But some early customers have noted that while the robots can get the grocery up the driveway, they cannot get the bags into the kitchen.

Transport

Those who have seen recent auto advertisements on television can be forgiven for thinking that autonomous vehicles (AVs) are already on the road in large numbers. While the massive investment needed to deploy AI to create truly autonomous vehicles has captured a great deal of attention, real progress has been slow—and few if any drivers have been displaced to date.

This could begin to change over the next five years. The Center for Global Policy Solutions estimates that more than four million jobs will likely be lost in a rapid transition to AVs. Occupations such as delivery and heavy-truck drivers, bus drivers, and taxi and chauffeur drivers would be most severely

[21] https://finance.yahoo.com/news/exclusive-walmart-testing-robot-fry-cook-delis-154733360.html

affected. But the impact on workers will largely depend on the pace of the transition.

Anecdotal evidence suggests that AV deployment in large numbers is not likely to be swift. An accident last year in which an autonomous vehicle struck and killed a pedestrian in Arizona served as an alarm bell for regulators, slowing investor enthusiasm. Just as significantly, there are competing views on what the future structure of autonomous transportation might look like. While some believe incumbent automakers will push to develop individually owned autonomous vehicles, others believe the entire transportation infrastructure will be disrupted by networks of "vehicles on demand" in which a rider will summon a vehicle as needed. Developing this kind of network could take years.

Moreover, a shortage of truck drivers already plagues American roadways. A recent report by the American Center for Mobility led by Michigan State University concludes that only a modest number of truck driver jobs, if any, will be displaced by AVs, and that the impact on jobs likely will not be felt until the latter half of the 2020s.

CASE STUDY: ROBOTS ON THE WATER

Autonomous vehicles aren't just for roads any more. Norway's Kongsberg Maritime, a nautical technology company, and Yara, a leading mineral fertiliser company, are building the world's first fully autonomous, battery-operated container vessel. The Yara Birkeland will reduce emissions and improve road safety by removing up to 40,000 truck journeys annually in a densely populated area of Norway. According to Olivier Cadet, executive vice president for products and services at Kongsberg, the vessel will transport fertiliser from Yara's Porsgrunn plant via inland waterways to the deep-sea ports of Larvik and Brevik—a journey of 31 nautical miles.

Yara's goal, Mr. Cadet explains, "is really to reduce emissions and to get trucks off the road." The company wanted a vessel that had zero emissions, but also wanted to reduce the operating costs of the ship as much as possible. A driverless system was really deployed "to justify the project. We really needed the operating cost of the vessel to be as low as possible, and this is when we introduced autonomy," he says.

While the project for Yara is a singular case because the ship will follow a regular path—always within two miles of shore, as opposed to sailing in open waters—Mr. Cadet believes more autonomous features will find their way onto ocean-going container ships as shipping firms continue to seek ways to reduce costs.

Construction and Farming

Developers have struggled to fabricate robots that can be useful in the relatively uncontrolled and free-form environment of a construction site. However, this reality is beginning to change, as engineers "dissect" in granular detail the tasks demanded during construction projects and create machines that use cameras, sensors and spatial awareness to work alongside humans. New kinds of robots have already been built to lay bricks and install sheetrock. These machines are mostly used in well-defined work environments, where robots can carry out mechanical or repetitive tasks more rapidly than humans. In the UK, the first bricklaying robots can place up to 3,000 bricks a day.[22] Robotics are poised to increase production, improve worker safety, and reduce pollution.

In farming, robots are helping to combat a growing labour shortage. On dairy farms, robot milking machines can tend to cows four times a day on average compared with the traditional twice-a-day regimen when humans manage the milking. IFR data shows that a total of 5,386 milking robots were sold in 2017, a 2% increase from the previous year, but estimates more rapid uptake in the next three years, with CAGR of 27%.

In some European countries, up to 30% of cows are milked by robotic machine, while in the US the share is closer to 2%, Mathew Haan, a dairy technology expert at Pennsylvania State University's agriculture extension program, recently told The New York Times. Haan noted that dairy farmers in Europe face higher labour costs and get more generous EU farm subsidies to help pay for the milking robots, which can cost $200,000.

WHERE SERVICE ROBOTS GO FROM HERE

The history of technological change suggests the integration of robots into a variety of service sectors will inexorably gain momentum. But this transition will not take place overnight—which means there is time for employers and workers to anticipate the service occupations that robots and automation may displace, and determine the best ways for robots and humans to collaborate. Expect robots to take on only the most routine aspects of service at first—delivering blood samples for nurses, for example, or frying burgers in a fast-food establishment. Even as the capabilities of machine learning and artificial intelligence rapidly improve, occupations that demand compassion, creativity, and social intelligence will not easily be replaced by machines. Nor will those requiring touch and feel—robots are still bad at moving their fingers, even if they excel at reading X-rays. Because developing robot replacements for humans is expensive and complex, job substitutions are most likely to take place in institutions that serve many people at large scale. A major chain hotel with 500 standard rooms is far more likely to install robotic vacuum cleaners than a chic bed-and-breakfast with only 11 rooms, each with a different floor plan.

As developing robot replacements for humans is expensive and complex, job substitutions are most likely in institutions that serve many people at large scale.

[22] https://www.theconstructionindex.co.uk/news/view/brick-laying-robot-reaches-the-uk

The 'Sophia' robot at a manufacturing Expo in Bangkok, 2018.

HOW TO RESPOND TO THE RISE OF ROBOTS

Historical evidence from the US labour market suggests that manufacturing workers typically turn to service-sector employment when their old production jobs disappear. Analysing the job moves of over 35,000 US workers over the course of their careers (using longitudinal household data dating back to 1995), we find that more than half the workers who left production jobs were absorbed into just three occupational categories: transport; construction and maintenance; and office and administration work (see Fig. 12).

But according to our research, these three occupational categories are among the most vulnerable to automation over the next decade. This highlights the ongoing threat to workers who are at highest risk to automation as the service economy enters its own era of technology-driven job disruption.

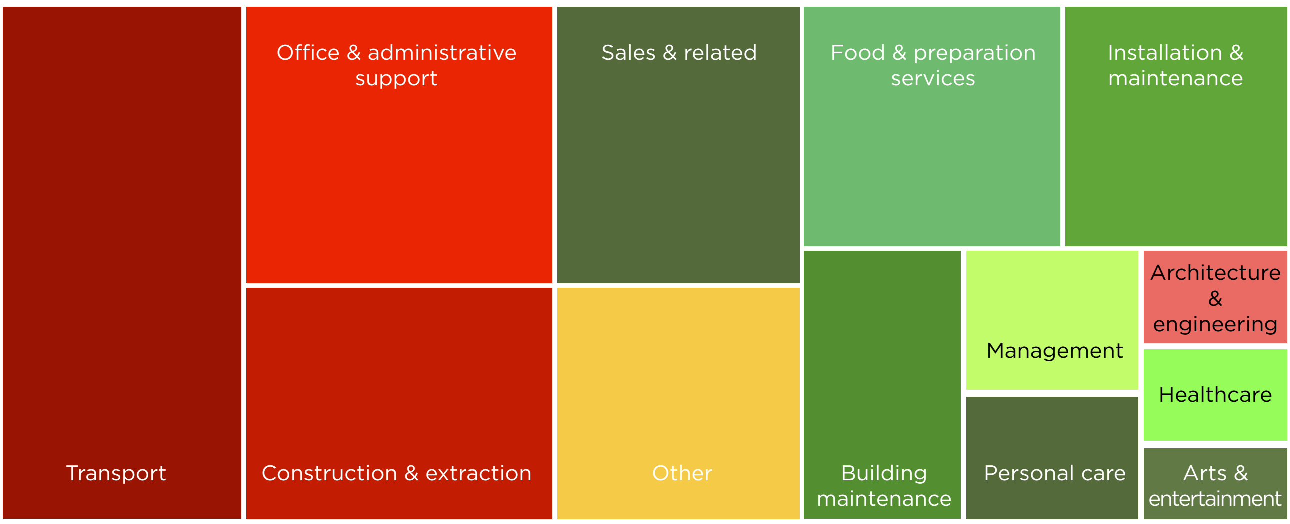
Size represents the category's share of new occupations: red boxes are shrinking occupations; green boxes are growing occupations

At the same time, we have demonstrated how robot investment drives economic growth and creates new jobs across each economy. Policy-makers must anticipate the mix of forces this level of automation will unleash—including job creation as well as job displacement across the economy.

To better understand the skills challenges many workers will need to overcome to adapt to an automated future, Oxford Economics developed a Skills Matching Model in partnership with Cisco (see page 52). This model simulates the more complex dynamics at play when labour markets are disrupted, as organisations fill vacancies with compatible workers, who then leave a vacancy in their previous sector. The model captures the many small moves involved in the labour market's evolution around technological disruption, highlights the new skills the economy now demands, and illustrates how the skills deficit might be best addressed.

Fig. 12: New occupations secured by workers leaving production jobs

Size represents the category's share of new occupations: red boxes are shrinking occupations; green boxes are growing occupations



UNDERSTANDING THE RESKILLING CHALLENGE

The biggest skills shortfalls appear in such skills as negotiation and customer service orientation, where humans typically demonstrate a distinct advantage over robots.

In a 2017 study entitled "The AI Paradox: How Robots Will Make Work More Human", conducted in partnership with Cisco, Oxford Economics produced ground-breaking analysis of the skills challenges facing the US economy. We developed a multi-layered modelling framework to simulate how the nature of occupations and the shape of the labour market might evolve in response to rapid technological change. Our scenario assumptions were informed by a broad panel of technology experts and were used to explore both the displacement of workers from their current jobs—based on the unique task profiles of over 800 occupations—and the productivity gains this implied for businesses.

Our 10-year employment projection suggested a rebalancing of demand for workers across sectors and occupational groups. US employment in transport and warehousing was predicted to shrink by around 9% under our scenario, while new demand drove a net increase in employment in ICT, finance, healthcare, and tourism. We developed the Skills Matching Model to understand how workers might navigate these changes.

The study revealed a range of acute shortages in technical skills among US workers—gaps that must be overcome to realise the productivity gains that new technologies can offer. But paradoxically, as technology becomes more capable, it is in "human skills" that today's workforces are most lacking. The biggest skills shortfalls appear in such skills as negotiation, persuasion, and customer service orientation, which are the skills in which humans typically demonstrate a distinct advantage over robots.

We applied the same modelling framework to a different context in a follow-up study, "Technology and the Future of ASEAN Jobs". We found that 6.6 million jobs across the ASEAN-6 economies could be made redundant by 2028 as a result of new technology adoption. Strikingly, large numbers of agriculture workers were projected to be driven into the service economy as a result, leapfrogging the traditional re-employment route through manufacturing. Furthermore, not only did many vulnerable workers lack the ICT skills needed in a reshaped labour market, but almost 30% of the redundant cohort lacked the "interactive skills" future jobs will require. In addition, more than a quarter lacked necessary "foundational skills" such as continuous learning, reading, and writing. Some skills challenges, such as ICT and technical skills, require formal education and regular refresher courses. Others, such as the softer skills of negotiation, persuasion, and customer service, typically require on-the-job experience, and might be supported by more flexible, virtual training options.

A FRAMEWORK FOR ACTION

In this report, we have outlined both the potential value that robots bring and the real fear that the displacement they cause could exacerbate existing economic inequalities. Robotization poses a fundamental dilemma for policy-makers, who must balance the potential gains of long-term growth with the short-term pain of social dislocation.

Our analysis took a coordinated, evidence-based approach to understand how robots are changing the world. The issues raised will affect many different sections of business and society. The repercussions of robotization are interconnected and complex, but the growth in robotics is inevitable—these challenges must be embraced and addressed. Policy-makers, business leaders, technology companies, educators, and workers all have a role to play. With this in mind, we offer a framework for action so that different stakeholders can seek to navigate the challenges and opportunities that robotization will bring.

Business Leaders

- Do not hesitate to seek technological solutions to your business challenges; the pace of innovation is increasing, and global competition continues to intensify.
- Get buy-in from your workforce when making technology investments. Communicate clearly your intentions regarding robots directly with your workers. Invest in the required training and education programs in parallel to your robotics strategy, to allow workers to anticipate and adapt.
- Recognise that technological changes will disrupt the lives of many workers and take responsibility collectively to help them onto a path towards future opportunities.

"Get buy-in from your workforce when making technology investments."

Educators

- Be cognizant of the shifting demands for skills across the economy. Technology skills are critical, but the economy is evolving in ways that require many non-technical and "soft" skills from workers, too.
- Develop flexible approaches to delivering skills training and education. In addition to keeping formal training curriculums fresh and relevant, this means investing more in "lifelong learning" and "on-the-job training" programmes.
- Invest in closer, more cooperative relations with local industries, to anticipate emerging workforce needs in the local economy based on assessments of sectors that are growing and shrinking as a result of new technology. Anticipate which new skills will be needed for new jobs.
- Share data with local authorities to tailor education and training to local strategic skills priorities and employment programmes. Intensive "boot camp" training is one option to jumpstart vulnerable or displaced workers into new fields of work.

Technology Companies

- Put steps in place to mitigate the job displacement and societal disruptions robots can create, to avoid undermining the consumer market on which businesses depend.
- Collaborate around industry-wide initiatives to invest in human capital—for example committing to share a portion of profits.
- Partner with governments and educational institutions to take responsibility for job retraining and coaching. Recognise the range of skills required in the workforce to optimise the potential of technology and to grow the market.
- Look for technological solutions for the problems robots create.

"Collaborate around industry-wide initiatives to invest in human capital."

Workers

- Audit your own job to better understand the balance between unique, human skills and automatable skills, to compete in the right areas and make your job more "robot proof."
- Adopt a "lifetime learning" mindset. Unlike in previous generations, there are no jobs for life. Retraining and upskilling will become a normal part of the employment landscape.
- Support programs that develop job flexibility, even in unionised work settings, to help develop cooperative job sharing and flexitime.

"Adopt a 'lifetime learning' mindset. There are no jobs for life."

Government Policy-Makers

- Explore and analyse the implications of robotization for the economy, the workplace and the wider society, and adapt policy programmes to the evolving landscape.
- Develop collaborative environments such as science parks, living labs, and other accessible innovation ecosystems to foster skills development for small and medium-sized enterprises.
- Map out the existing skillsets at the local level with labour force surveys and analyse alongside regional business trends and growth strategies, as a basis for strategic planning. Incentivise companies and workers with fiscal benefits to engage in local programs to retrain workers with locally relevant skills.
- Identify the areas most vulnerable to dislocation from the rise of robots and develop aggressive, forward-thinking programs to counteract those effects. Explore all policy options, from infrastructure investments to training initiatives and innovative welfare programmes (such as universal basic income).

APPENDIX: ECONOMETRIC ANALYSIS

LITERATURE REVIEW

To explore the implications of robot densification on manufacturing jobs and economic performance we developed two econometric models, grounded in academic literature. Our methodology built most prominently on four previous studies:

1. Graetz and Michaels (2015)[23] drew on the data from the International Federation of Robotics (IFR) in an industry-country panel specification of 17 countries over the period 1993-2007. The researchers found that an increase in the use of robots per hour worked to boost total factor productivity and average wage levels, and to have a negative impact on hours worked by low-skilled workers, relative to middle- and high-skilled workers.
2. Acemoglu and Restrepo (2017)[24] used the same dataset but restricted their analysis to the period 1990-2007 (partly due to data limitations and partly to avoid the post-2007 crisis period) and explored localised effects of robot densification in the US economy, by exploiting heterogeneity in both local labour distributions across industries and national change in the use of robotics. They found that one additional robot per thousand workers reduces the US employment-to-population ratio by 0.37%, on average.
3. Dauth et al (2017)[25] adopted a similar localised model in the German context with a timelier dataset, from 1994-2017. They found that while industrial robots had a negative impact on employment in the German manufacturing sector, there was a positive and significant spillover effect on jobs in non-manufacturing sectors to offset it.
4. Chiacchio et al (2018)[26] also built on the Acemoglu approach in a study of six EU countries between 1995-2007. They found that one additional robot per 1,000 workers reduced the employment rate by 0.16-0.20 percentage points. They do not find robust and significant results on the impact on wage growth.

DATA

We used data on robot investment (per unit) from the IFR in Japan, the European Union, the United States, South Korea, and Australia. The IFR reports robot stock and investments for 50 countries over the period from 1994 to 2014. It is based on yearly surveys of robot suppliers and captures around 90% of the world market. The information is broken down at the industry level, but data availability differs across countries.

We augmented the IFR dataset with Oxford Economics' data on GDP, GVA by sector, employment by sector, population by 5-year age band, and wages and compensation in total and by sector (where available) from our datasets. We also used data on trade from the COMTRADE database.

We used a sub-national unit of analysis for the modelling exercise, corresponding to European NUTS 2, US Metro areas, Japanese prefectures, Australian states, and South Korean districts. We built a panel dataset for 29 countries (all of EU, plus US, Japan, Australia, Korea) over 11 years within the period (2004-2016), disaggregated by region and sector.

We used a dynamic panel approach (using the Generalised Method of Moments estimator, or GMM) to account for secular trends. The GMM approach allowed us to use internally generated instrumental variables (i.e., using past values as instruments) that helped us establish a causal link between the growth in robot density and employment or productivity.

MODEL SPECIFICATION

The following section describes the two models used in our analysis.

[23] Goerg Graetz, Guy Michaels, "Robots at Work" (CEP Discussion Paper No 1335, 2015)
[24] Daron Acemoglu, Pascual Restrepo, "Robots and Jobs: Evidence from US Labor Markets" (NBER, 2017)
[25] Wolfgang Dauth, et al, "German Robots: The Impact of Industrial Robots on Workers" (CEPR Discussion Paper 12306, 2017)
[26] Francesco Chiacchio, et al, "The impact of industrial robots on EU employment and wages: A local labour market approach" (Bruegel Working Papers, 2018)

MODEL 1: MANUFACTURING EMPLOYMENT

The model specification, as shown below, isolates the impact of robot density (robots per 1,000 workers) on the manufacturing employment-to-population ratio in each region (r) and year (t), having controlled for secular trends (lagged employment to population ratio), economic performance (GDP per capita), globalisation (trade with China, trade with the rest of the world), wage levels (compensation per capita), region-specific factors (using panel data), and other trends/ year-specific events (year dummies).

$$\begin{aligned} &Employment\ (mfg.)\ to\ population\ ratio_{\mathrm{r},t} \\ &\quad = \alpha + \beta_1 Employment\ (mfg.)\ to\ population\ ratio_{r,t-1} + \beta_2 Robots\ density_{\mathrm{r},t} + controls \end{aligned}$$

Our approach embodies one key difference with the existing literature: we use a dynamic panel method exploring year-on-year variations, while previous studies focused on the cumulative change in employment between two distinct years (e.g., Acemoglu between 1990 and 2007). Acemoglu and Restrepo justified this approach as a way of avoiding the potentially confounding effects of the recession post-2007. While this is a valid concern, we mitigated this risk by using more recent years of data (up to and including 2014) and dynamic panel methods. In addition, the cumulative change method would have been inadequate for the period 2004-2014 due to the changes in employment over that period (which declined in the recession years and increased in the subsequent years) and the change in robot stock (which increased consistently over time). By using appropriate control variables, including time dummies, in a dynamic panel setting, our model accounts for the effects of the recession and isolates the impact due to robots.

MODEL 2: LOCAL LABOUR PRODUCTIVITY

The model specification, as shown below, isolates the impact of the log of robot density on the log of GVA per worker in each region and year, having controlled for the pre-existing trend (lagged productivity), globalisation (trade with China), wage levels (compensation per capita), region-specific factors (using panel data), and other trends/year-specific events (year dummies).

$$\begin{aligned} &\ln(GVA\ per\ worker)_{\mathrm{r},t} \\ &\quad = \alpha + \beta_1 \ln\left(GVA\ per\ worker\right)_{r,t-1} + \beta_2 \ln(Robots\ stock)_{\mathrm{r},t} + control \end{aligned}$$

ANALYSING REGIONAL IMPACTS

To test the relative impact of robot densification in higher- and lower-income regions, we categorised regions by average compensation per worker. Those that were higher than the national average over the sample period were labelled higher-income regions; those lower than average were labelled lower-income regions. We used interaction terms (also known as partitioned variables) in the same model specifications as above to identify the relative differences. As a sensitivity check, we tested alternative control variables to establish that the coefficients on the control variables were significant and of the right sign.

ANALYSING SHORT-TERM AND LONG-TERM IMPACTS

To control for the fact that the impact of robotization may take time to impart its full effect on employment and productivity, we used lag variables. This involved investigating the relationship between robot installations in one period, and employment and productivity in subsequent periods, with various degrees of time lag.

ESTIMATOR SELECTION

In order to produce robust estimates, we used various tests to select the most appropriate estimator. We ran the Wooldridge test for autocorrelation[28] to determine the need for a dynamic panel approach. The data was found to be autocorrelated, meaning employment and productivity in current periods might be affected by past trends in the same variables.

We used the Arellano Bond/Blundell Bond estimator ("System GMM") to account for the presence of such "dynamic effects" in the data. This method augments the Arellano–Bond estimation ("difference GMM") by allowing the introduction of more instruments and can dramatically improve the efficiency of the model.[29] Using a dynamic panel model also enables us to identify overall coefficients for explanatory variables, corresponding to the long-term effects as well as contemporaneous ones corresponding to the short-term.

Even where a dynamic model is the preferred specification, it still comes with potential risks. The most prominent risk is omitted variable bias. For example, the growth in ICT services corresponds broadly with the rise in industrial robots but because our unit of analysis is at the regional level, there is insufficient data to control for ICT spend at local levels across the 29-country sample. We attempted to mitigate this risk by using a proxy for local productivity growth (wage growth) and past values of the dependent variable as instruments, which reduces the need to identify all alternative instrumental variables. Instruments in dynamic models also account for serial correlation between past and current values of employment and productivity.

ECONOMETRIC RESULTS

Model 1: Manufacturing employment

The regression output for our three preferred model specifications are presented in Table A1.

1.1 Our preferred model for the average employment impact across all regions.
1.2 Our preferred model to estimate the variable impacts in higher- and lower-income regions.
1.3 Our preferred model to estimate the productivity impact across all regions.

In all three models, the lag dependent variable is low but significant at the 5% level. The coefficients on the dependent variables are significant and of the expected sign in all three models. All three models include year dummies. We have also tried estimating other specifications across all three models but were unable to obtain a satisfactory model.

Table A1: Change in the number of jobs due to one additional robot

	Short-term impact	Long-term impact
1.1 Average across all regions	-1.3	-1.6
1.2 High-skilled regions	-1.0	-1.3
1.3 Low-skilled regions	-1.7	-2.2

The employment model implies that a 1 unit increase in robots per 1,000 workers reduces the average employment ratio by 1.5 in the short run and 2.0 in the long run. The impact is lower for high skilled regions, at 1.2 and higher for low skilled regions, at 2.0.

[27] The Wooldridge test was implemented using the xtserial command in Stata using a specification comprising of dependent and independent variables. We tested for serial correlation in the data using multiple specifications with different independent variables.
[28] The "system GMM" builds a system of two equations—the original equation and the transformed one. The assumption of no correlation between the first differences of instrument variables and fixed effects in system GMM allows for the inclusion of time-invariant regressors, which would disappear in "difference GMM."

We converted this into the average impact of one additional robot on the number of jobs using the average robots per capita ratio across regions. Using these results, we find that a 1-unit increase in robot stock reduces the number of jobs by 1.3 in the short run and 1.6 in the long run across all regions. The impact is lower in high-skilled regions and higher in low-skilled regions. (Table A1)

Model 2: Local labour productivity

Our preferred specification for estimating the productivity impact of robotization implies that a 1% increase in robot stock leads to a 0.1% increase in productivity in the short-term and a 0.3% increase in productivity in the long-term. Due to the range of factors influencing the productivity impact in a long-term timeframe, we use the short-term impact as a basis for our analysis.

COMPARISONS

Table A3 presents a comparison of our results with previous academic literature. All results regarding the employment effect have been converted into the change in number of jobs due to one additional robot. Our results are the same sign but slightly lower than other studies, which find the impact of one robot displaces between 3 to 6 jobs depending on the sector, time period and country covered. Graetz and Michaels (2015) and Dauth et al (2017) also find that an increase in robots increases productivity.

Table A2: Change in productivity (GVA per worker) due to a 1% increase in robots

	Short-term impact	Long-term impact
Average across all regions	0.1%	0.3%

Table A3: Change in the number of jobs due to one additional robot

STUDY	Geography	Time frame	Impact on jobs (of one robot)	Impact on labour productivity
Graetz and Michaels (2015)	17 countries (US, fourteen European countries, South Korea, and Australia)	1993-2007	No effect on total hours worked, but a reduction in hours of low-skilled and middle-skilled workers.	Increase in total factor productivity
Acemoglu and Restrepo (2017)	US	1990-2007	Loss of 3 to 6 jobs.	-
Dauth et al (2017)	Germany	1994-2014	Loss of 2 manufacturing jobs offset by a gain of 2 additional jobs in the service sector.	Increases productivity
Chiacchio et al (2018)	6 EU countries	1995-2007	Loss of 3 jobs.	-

ABOUT OXFORD ECONOMICS

Oxford Economics was founded in 1981 as a commercial venture with Oxford University's business college to provide economic forecasting and modelling to UK companies and financial institutions expanding abroad. Since then, we have become one of the world's foremost independent global advisory firms, providing reports, forecasts and analytical tools on more than 200 countries, 250 industrial sectors, and 7,000 cities and regions. Our best-of-class global economic and industry models and analytical tools give us an unparalleled ability to forecast external market trends and assess their economic, social and business impact.

Headquartered in Oxford, England, with regional centres in London, New York, and Singapore, Oxford Economics has offices across the globe in Belfast, Boston, Cape Town, Chicago, Dubai, Frankfurt, Hong Kong, Houston, Johannesburg, Los Angeles, Melbourne, Mexico City, Milan, Paris, Philadelphia, Sydney, Tokyo, and Toronto. We employ 400 full-time staff, including more than 250 professional economists, industry experts and business editors—one of the largest teams of macroeconomists and thought leadership specialists. Our global team is highly skilled in a full range of research techniques and thought leadership capabilities, from econometric modelling, scenario framing, and economic impact analysis to market surveys, case studies, expert panels, and web analytics.

Oxford Economics is a key adviser to corporate, financial and government decision-makers and thought leaders. Our worldwide client base now comprises over 1,500 international organisations, including leading multinational companies and financial institutions, key government bodies and trade associations, and top universities, consultancies, and think tanks.

June 2019

To discuss the report further, please contact:

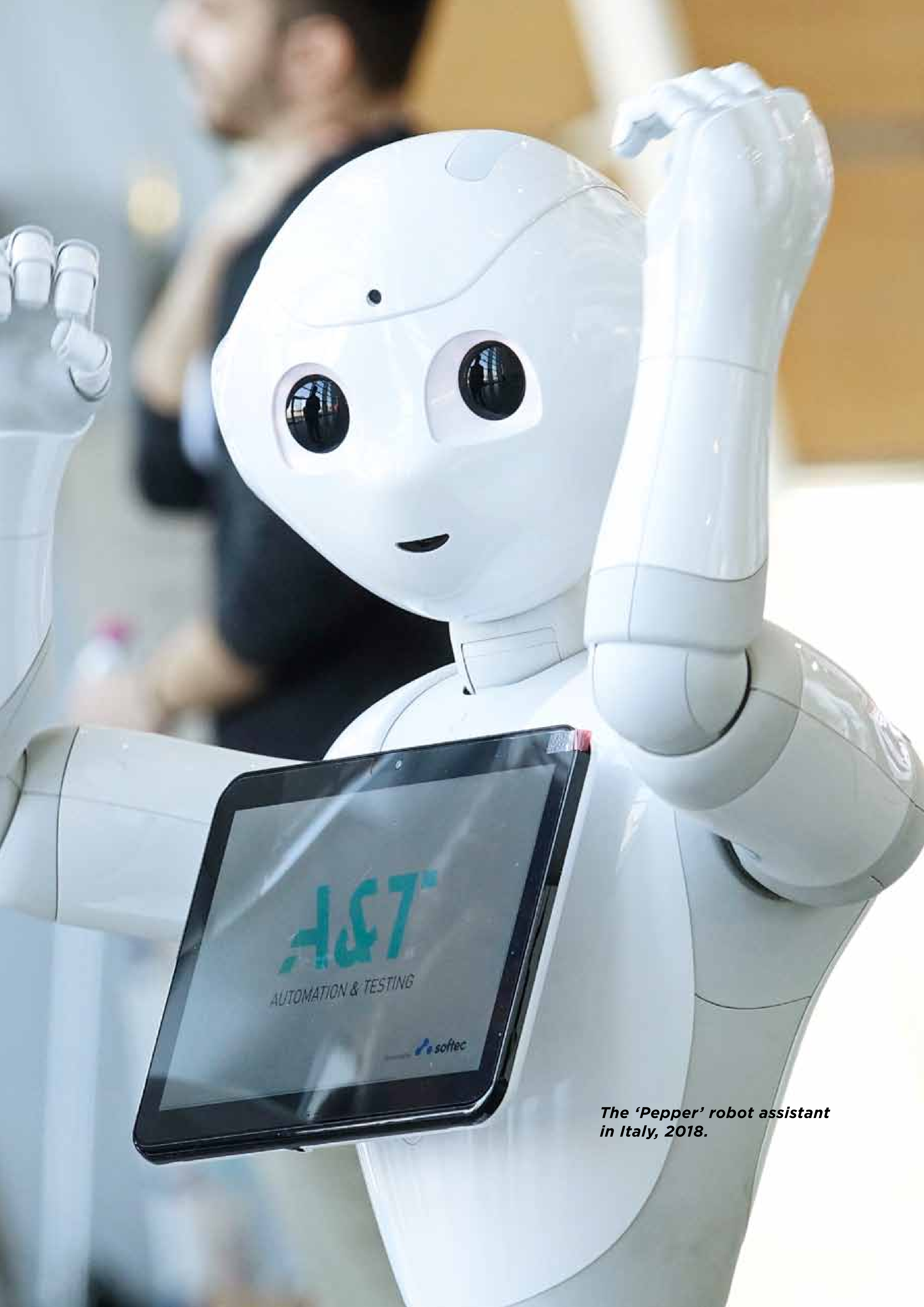
James Lambert:
jlambert@oxfordeconomics.com
Edward Cone:
edcone@oxfordeconomics.com

Oxford Economics,
Broadwall House,
21 Broadwall,
London,
SE1 9PL
UK

Tel: +44 207 803 1400

www.oxfordeconomics.com

The image on page 2 is by Field Robotics, and all other images in this report are by Shutterstock (www.shutterstock.com).



The 'Pepper' robot assistant in Italy, 2018.

Global headquarters
Oxford Economics Ltd
Abbey House
121 St Aldates
Oxford, OX1 1HB
UK
Tel: +44 (0)1865 268900

London
Broadwall House
21 Broadwall
London, SE1 9PL
UK
Tel: +44 (0)203 910 8000

New York
5 Hanover Square, 8th Floor
New York, NY 10004
USA
Tel: +1 (646) 786 1879

Singapore
6 Battery Road
#38-05
Singapore 049909
Tel: +65 6850 0110

Europe, Middle East and Africa

Oxford
London
Belfast
Frankfurt
Paris
Milan
Cape Town
Dubai

Americas

New York
Philadelphia
Mexico City
Boston
Chicago
Los Angeles
Toronto
San Francisco
Houston

Asia Pacific

Singapore
Sydney
Hong Kong
Tokyo

Email:
mailbox@oxfordeconomics.com

Website:
www.oxfordeconomics.com