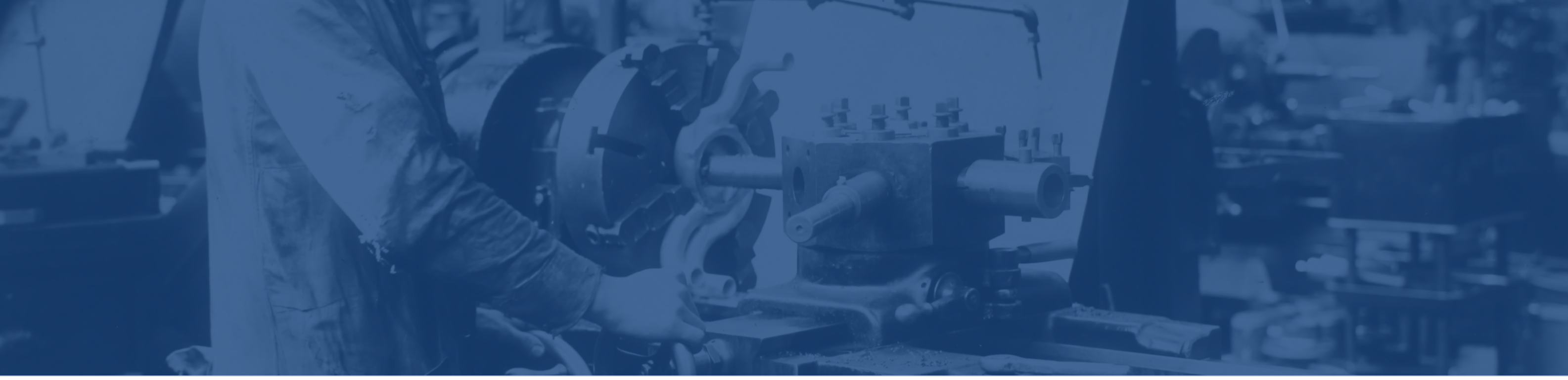



**ABSTRACT**

There is a popular narrative that the rise of automation threatens to displace a large segment of the American workforce. Robots in particular are the object of public concerns about employment. But in most American manufacturing plants—particularly small and medium firms—robots are scarce. Fewer than 10 percent of American manufacturers have any industrial robots. This case study argues that the technology challenge facing American industry is not too many robots, but too few. Multiple factors contribute to low robot adoption, including high integration costs, flexibility and design limitations, and workforce challenges. When firms do adopt robots—whether to fulfill a new contract or attract a new customer—there may be benefits for the workforce as well as the economy as a whole.


---

**Keywords**: robots, automation, manufacturing, workforce


**Suzanne Berger**
John M. Deutch Institute Professor, MIT



**Benjamin Armstrong**
Research Scientist, Industrial Performance Center, MIT


## Learning Objectives

- Understand how predictions and perceptions of industrial automation compare to technology on the factory floor.
- Understand the difference between “bottom up” and “extrapolation” studies on the impact of new technologies.
- Identify what motivates some manufacturing firms to adopt robots, while others do not.
- Consider policy directions for encouraging the benefits of robot automation while also improving workplace conditions and wages for (human) workers.

Automation has been a longstanding source of concern for the public and the government in the United States. In 1955 and again in 1960, the US Congress held hearings on the progress of automation and its consequences. The hearings were supposed to keep Congress “currently informed lest the increasing productivity to be obtained through automation and which is sought and welcomed by all segments of American life carry with it excessive personal hardships or set up adverse forces which will hamper future economic stability and growth.”[1] Walter Reuther, the head of one of America’s largest labor unions—the Congress of Industrial

Organizations (CIO)—was invited to speak. He said of automation, “we are faced with mighty forces whose impact on our economy can be vastly beneficial or vastly harmful, depending on whether we succeed or fail in achieving economic and social progress that will keep pace with changing technology.”[2] Reuther and fellow labor leader George Meaney described technological change as a force for increasing the country’s economic well-being, while also urging government to play a more active role in insuring that gains from automation were fairly distributed.

Public hopes and anxieties about the impact of automation and technological change have coexisted since at least the start of the Industrial Revolution. Economists and journalists writing about robots and jobs nowadays often reach back to the introduction of new machines in factories in the 19th century and to the “Luddities”—farm and factory workers who protested by smashing machines at the workplace. Even before large-scale mechanization of work, governments worried about whether new technologies might lead to unemployment and to political unrest. References to the Luddites have become ways of warning about the political dangers of hostility to machines.[3] Today, as in the past, public sentiments continue to be mixed. In polls from 1970 and 2017, respondents generally approved of new technologies and their benefits for the economy and society.[4] A Pew Research Center survey in 2017 found that more people reported that technology made their work more interesting and increased their opportunities for career advancement. When it came to specific automation technologies like scheduling software and even industrial robots, workers were more likely to say that new technologies have had a positive impact on their jobs. However, in the same poll, 72 percent of US adults reported that they were worried about a “future where robots and computers can do many human jobs.” And 85 perent of respondents said they would favor a policy that limited machines to doing dangerous or unhealthy jobs.[5]

In 2017, these anxieties about a robotic future coincided with waves of headlines about robots eating jobs and self-driving cars and trucks becoming ubiquitous on the road within one to five years. Research contributed to this panic with widely cited academic articles predicting massive job losses.[6] Two Oxford researchers, Carl Benedikt Frey and Michael A. Osborne, published work suggesting that 47 percent of US jobs were at risk within “a decade or two.”[7] But the Frey-Osborne predictions were basically extrapolations, as were others made at the time. Frey and Osborne used 702 occupation classifications from a database maintained by the US Department of Labor (known as the “Occupational Information Network,” or O*NET) and identified tasks within the occupations. They then asked technology experts to judge whether they thought machines could do those tasks now, or would soon be able to do them. Other studies followed in the same methodological vein, including studies by the Organisation for Economic Co-Operation and Development (OECD), which, however, focused on tasks rather than occupations and estimated that far fewer jobs were in jeopardy. McKinsey Research Institute used similar methodologies and estimated about four hundred million jobs worldwide would be lost. These were all basically exercises that extrapolated from an expert’s view of which tasks could now or “soon” be automated to calculations about job loss.

What followed were empirical studies of job losses in factories that already had robotic automation in France, Germany, Netherlands, Canada, and the United States. And here the picture became a lot more complicated. Some large firms with international markets in France employed more workers after robots were introduced while their domestic competitors seemed to lose workers.[8] In Canada, the introduction of robots led to the reduction in the numbers of middle-level managers and an increase in production workers.[9] Large-scale studies in Germany and the Netherlands of changes in the workforce after the introduction of robots also showed increases in some categories of workers, with decreases in other categories. Among firms in the United States, those adopting robots seemed to offer higher wages to production workers, but the addition of robots was associated with fewer jobs overall.[10] Context seems to matter when it comes to the effects of robot adoption—but how it matters we do not yet understand.

## Too Many Robots or Too Few?

Amid growing concerns about automation, Americans also worried about declining manufacturing competitiveness and the stagnation of wages in manufacturing jobs. As researchers, we have been concerned by the puzzle of slow productivity growth in the US economy and that has led us to be especially interested in technology and skills in small and mid-sized manufacturing enterprises (SMEs). (See Figure 1.)[11]

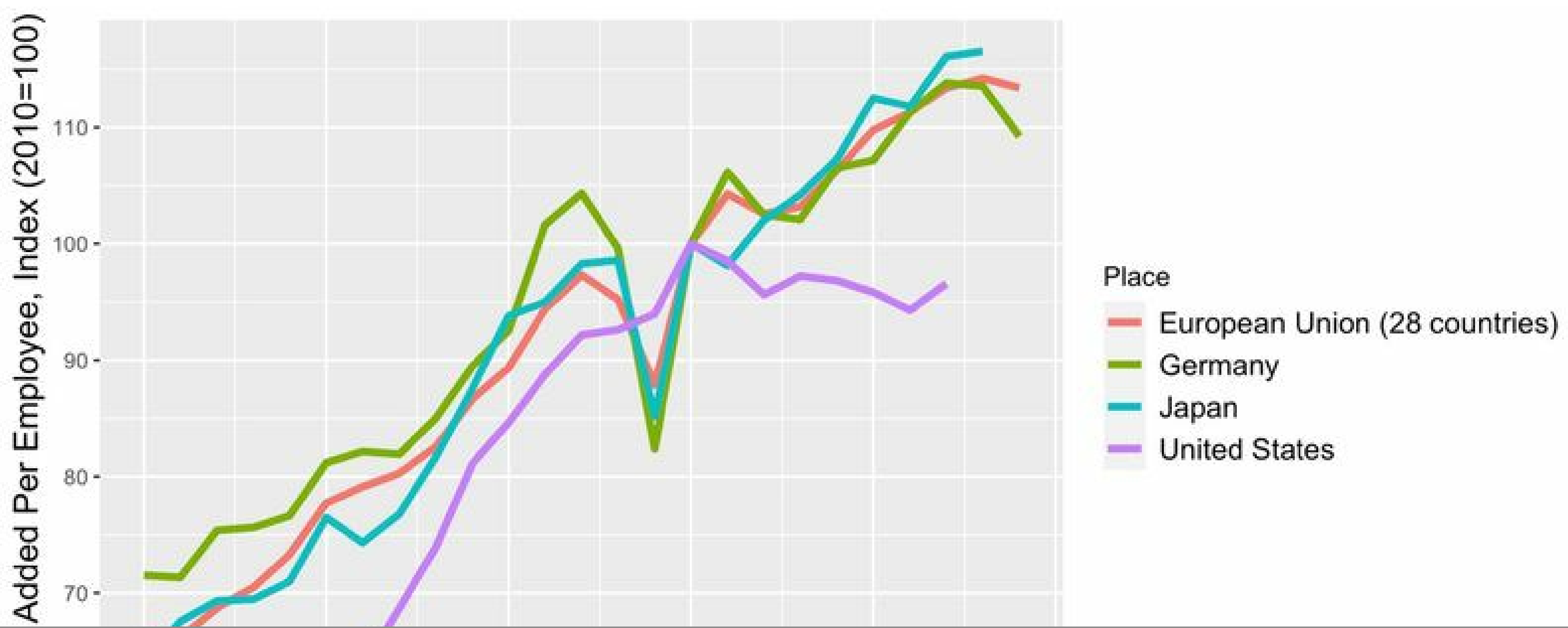



**Figure 1**
Manufacturing productivity in advanced industrial economies.

The gap between the productive performance of these SMEs and that of large manufacturing firms has widened at the same time that economists have shown a concentration of economic activity in the most productive "superstar firms" in a sector.[12] The widening gap between the most productive performers and the rest raise questions about why diffusion of best practices from the most productive firms has been slow, and what public policies might do to accelerate it.

Over the past fifty years, this performance gap between large manufacturing firms and small and mid-sized manufacturing plants has widened. In the early 1970s, the output per worker of large manufacturing establishments—plants with over five hundred workers—was only about 25 percent higher than in plants with fewer than five hundred workers. By 2012, output per employee at plants with more than five hundred workers was 93 percent higher than that at smaller plants. (See Figure 2.)[13] A growing wage gap between large and small plants has mirrored the growing gap in output per worker. (See Figure 3.)[14]

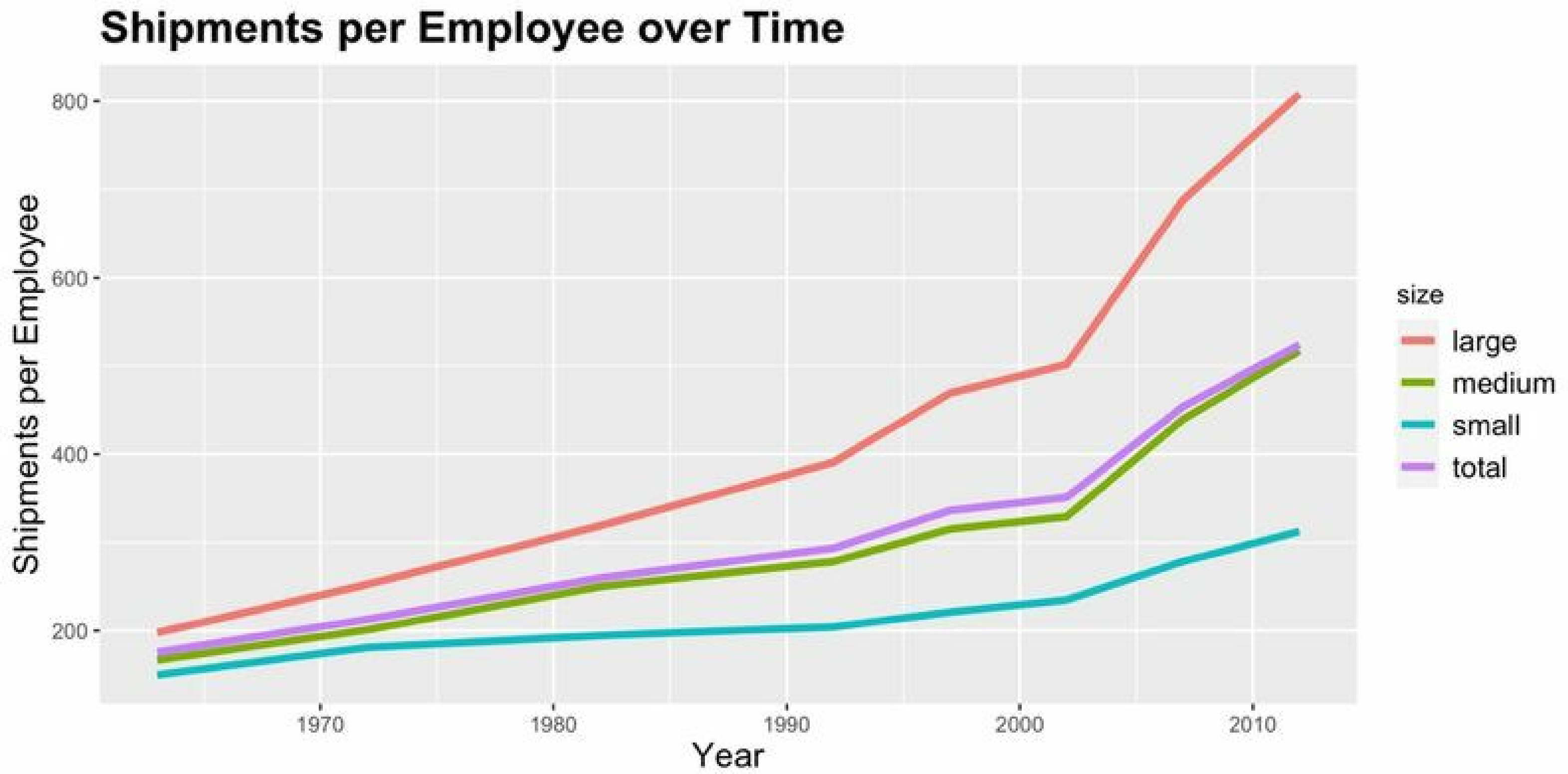



**Figure 2**
Output gap by plant size.

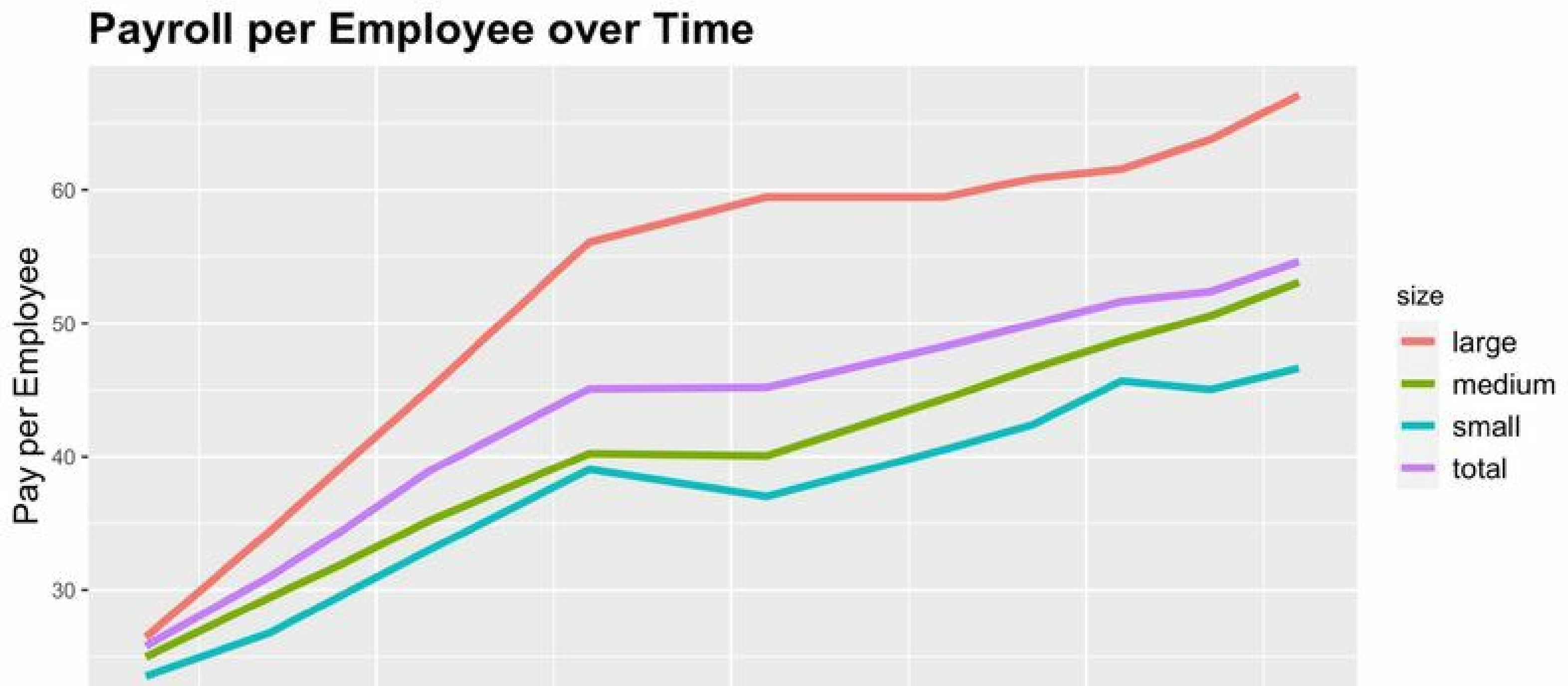



**Figure 3**
Wage gap by plant size.

Trying to explain slow productivity growth in SMEs and what appears to be their worsening relative performance seems a critical step in understanding the future prospects of US manufacturing. Whereas automation anxieties emphasize the risks of too much technology, slow productivity growth suggests that there may not be enough technology for small and medium firms to become more competitive. When, why, and how manufacturing firms acquire new technology, and how they find or train workers with new skills—these issues are central to figuring out why productivity lags in smaller companies.

## Looking for Robots

In seeking to understand the impact of the introduction of robots and other new forms of automation on the number and quality of manufacturing jobs, as well as the performance of manufacturing firms, we turned to a different research approach from one that seeks to match up tasks with the capabilities of machines.[15] It is an approach that starts from the "bottom up"— from the people and the machines already in the plant and from the factory manager's conception of possible options. In order to carry out these "bottom up" studies over the past thirty years, MIT researchers have walked through factories with managers in the United States, Germany, France, Japan, Hong Kong, and China.[16] They have listened to managers explain how they organize production, when and how they decide to buy new equipment, how they hire and train workers, and what they see as promising strategies for their business in the future. In the most recent of these studies, the 2018–2020 MIT Taskforce on Work of the Future, a group of faculty and graduate students again focused on analyzing changes in production from the factory floor up.[17] The methodology aimed at identifying the mechanisms that link the key variables: hiring and training, technology adoption, and productivity.

Our interviews and observations examined the adoption of new production technologies in general and industrial robots in particular. The definition of an industrial robot we used was that of the International Federation of Robotics: an "automatically controlled reprogrammable multipurpose manipulator programmable in 3 or more axes." If a 5-axis CNC (computer numerical control) machine were to be counted as a robot, we would have counted more robots in the plants, since several companies had recently acquired advanced CNC machines. There are good reasons to distinguish CNC machines from robots, our colleagues from an MIT robotics laboratory suggested. Even though a CNC machine can do the same milling as a robot does, a robot can *also* be repurposed for functions like pick-and-place by changing out the end effector.[18] Roboticists think of robots as taking inputs from sensors and making decisions based on those inputs, as well as being flexible enough to perform a variety of tasks that the CNC machine does not do. So in this study we decided to distinguish between purchases of robots and purchases of advanced CNC machines. We also ruled out including automated guided vehicles (AGVs), which are small mobile robots that are used to move parts from station to station across factory floors.[19]

Based on the experts' predictions of the past few years we expected to find many robots on the factory floors. But the majority of the firms that our group visited had none. Many still had manual machines that their grandparents had purchased in the 1940s and 1950s. We observed that the plants with old technology also had low-skill and low-wage workers and high turnover of the workforce. But is it the low skills of the workers that keep the firm from adopting robots, or is it the old technology in the plants and low productivity that make it likely that managers will continue to hire low-skilled workers at low wages? How could we tell? We started to consider what forces were keeping American manufacturers in this low-tech—low-skill—low-wage equilibrium, and how they might break out of it.

We interviewed owners and senior managers in forty-four manufacturing companies in Ohio, Massachusetts, and Arizona, and leaders in twenty-one industrial ecosystem institutions, such as trade associations, community colleges, unions, and Manufacturing Extension Partnership offices. In Germany, we visited eleven companies identified as having world-class advanced manufacturing systems. The US companies ranged from a metal stamping firm whose owner frankly described it as on "the cutting edge of low tech" to a photonics company on the far frontier of new technology. Of the forty-four U.S. companies we visited between 2018 and the outbreak of COVID-19 in 2020, ten are US divisions of large multinational corporations, and thirty-four are small and mid-sized enterprises (SMEs) that employ fewer than five hundred workers. Manufacturers in the latter size category represent 98.4 percent of all manufacturing establishments in the United States, and they employ 43 percent of all manufacturing workers.

The firms we interviewed in 2018–2020 were mainly ones that MIT researchers had interviewed once before, in 2009–2012, in the MIT Production in the Innovation Economy study.[20] The original sample of firms had been drawn from a list of all US manufacturers that had doubled their revenues and increased employment between 2004 and 2008, that is, firms that were reasonably "healthy" on the eve of the 2008–2010 economic and financial crisis.[21] By returning to firms we had visited previously, we hoped to be able to track changes in their technology and workforce profiles. To firms we had visited in 2009–2012, we then added eighteen other companies in the same codes from the North American Industry Classification System (NAICS), namely, metalworking, automotive, and electronics.[22] These new added firms were chosen in close geographic proximity to the original sample.

The key questions we asked in all of our 2018–2020 factory visits were simple ones that we posed in the formal interviews and pursued as we walked with the managers across the plant floor. "Which technologies did you buy over the past five years? Why did you buy them? What new skills did you need to work the new equipment? Where did you find people with those skills? What happened to the people who used to work with the old machine?" We had read the 2017–2018 articles predicting a massive wave of robots replacing workers over a five- to ten-year horizon, so we were surprised to find very few robots anywhere. Surely, if the process of robots replacing workers were to take place over the short period that Frey and Osborne or the publications of the World Economic Forum ("Davos") predicted in

2017, by 2018–2020 we should already have been seeing robots moving into the factories. But they were few and far between.

In the Ohio small and medium-sized manufacturing firms we studied, one mid-sized auto supplier that we had first visited in 2010 had subsequently been purchased by Japanese suppliers, incorporated into Japanese auto supply networks, and then experienced a major growth spurt. That company in 2018 had 105 robots in plants it now managed—and its Ohio workforce had grown from 120 to 260. But in all the other Ohio SMEs we visited, there had been only one robot purchase over the previous five years: a 6-axis welding robot to work on large tubular sections for a naval defense contract. In the Arizona SMEs, there had been three robot acquisitions; in Massachusetts, one.

Indeed, even in the large firms (with over five hundred workers) we visited, robots were scarce.[23] In one large division of a multinational company in Pennsylvania, we learned that there had been robots in the plant in the past. But when demand for the parts they were making with the robots fell off sharply, the job along with the robots was transferred to another division of the company. At the time of our visit, the plant had no robots. They were experimenting with a robot that they hoped to use for vision and quality control. The onslaught of rapidly advancing robots that we had expected to find in the heartland of American manufacturing was nowhere in sight.

Preliminary results of the 2018 first-ever US survey "on the presence of robots" in US manufacturing establishments confirms that the absence of robots in the SMEs we visited is no sampling error, but in fact representative of the overall situation. The Census of Manufacturing survey of robots shows that only 9.5 percent of US manufacturing establishments have at least one robot. Even among plants with more than five hundred employees, fewer than half have robots.[24]

What did we learn about when firms do decide to buy robots or other advanced manufacturing technologies? We had often read that companies buy robots and other new equipment to reduce their workforce. But on the ground we did not find such cases. In fact, in the firms we were visiting for a second time after eight years, all of them (with the exception of one going out of business and a second in fragile shape) were hiring more workers. We interviewed a company that manufactures welding robots and asked what changes they saw in their customers' businesses after the purchase of the robot. They told us that customers buy robots thinking to become more productive, but then discover that the biggest change is greater quality and reliability in their operations. In our own interviews, the most frequent factor driving a purchase was the prospect of a new contract that would require new equipment. A third-generation family firm that started its business making industrial boilers today does about two-thirds of its business on defense contracts. When the navy urged them to use robotic welding, the company bought a 6-axis welding robot. Another firm we visited purchased a new bed mill when they realized the laser mill they had could not produce the volume they needed for a customer with a big project coming up. An Arizona firm that makes analogue load cells that measure force acquired robots for their high-volume products and for automated visual inspection. But the small-volume cells are still made by hand. There's a lot of tacit knowledge involved in making load cells, and as we walked the factory floor, we saw people assembling tiny parts under magnification.

In a few factories, robots were introduced to reduce stressful and boring human labor. Artaic, a small Boston firm that makes customized mosaics, mainly for hotels and restaurants, realized that its competitive advantage was sending out samples rapidly.[25] Owner Ted Acworth had already figured out how to program robots to do the otherwise tedious task of picking and placing individual tiles. But to make samples, workers needed to place tiles in sample squares manually. To make the task easier, Acworth invented a device he calls Whack-a-Tile, basically a monitor with light signals to assist workers in putting the sample together quickly. Each Whack-a-Tile is set up to take best advantage of the individual work styles and hand positions of each employee. Ackworth's company is a modern design firm. But we saw similar reasoning in a very traditional Arizona metalworking job shop. The owner told us that before buying the shop twenty years ago, he had worked on a Boeing assembly line, which he experienced as "boring, brain-dead work that no human being should do."[26] He's planning to retire soon and leave the business to his sons. In the past few years, he has replaced old manual machines with new lathes that can be programmed so that one person can deal with three to five machines. He now plans to buy a robot to feed the machines. With the new machines and a few trained workers, the sons' principal tasks would be to program the machines.

## The Puzzle of the Missing Robots

Why are there so few robots in the small and mid-sized companies that constitute the majority of American manufacturers? Virtually all of the businesses we visited were suppliers, companies that make a diversity of parts for customers who make the final products. The suppliers are high-mix, low-volume manufacturers. Robots today are still relatively inflexible. They are invaluable in auto assembly plants, in which the robots operate consistently on large product runs. These are industrial robots: too powerful and hence too dangerous to work alongside humans. They are located in fenced-in areas that workers do not enter. Collaborative robots (cobots), which are robots that are safe to work alongside humans, still have limited use on factory floors. They are still very difficult to reprogram, so for a business that makes a very diverse product mix involving quite different production phases, it's not economically rational to buy a robot that can do only one operation.

What makes the robot expensive is not just its initial cost, but all the costs of integrating the robot into the factory. Equipment needs to be installed to move the part up to the robot and away from the robot. It's estimated that the purchase price of the robot is only 25 percent of the total cost of integrating it into the production line. Sometimes firms use integrators to help them get the robot working. But many companies worry that the integrators pick up too much of the firm's proprietary knowledge along the way. An Arizona firm told us of the years it spent trying to install a robot by itself. "How long was it until you were able to get real value out it?" we asked. "Seven years." We asked what the problem was. The answer was short: "It took seven years because there was a lot of hubris on our part. We tried to do way too much."[27] Much progress is being made in research labs and robot manufacturers in designing more user-friendly interfaces, and success in that line should eventually make robots more accessible to smaller manufacturers. But even in factories that do have robots and advanced CNC machines and other new technology, we observed that the new machines are simply working alongside old ones. It's common to find equipment purchased in the 1940s by the owner's grandfather still in service. This layering of the new on top of the old makes it difficult to reap the full productivity benefits out of advanced equipment.

The barriers to the introduction of advanced manufacturing equipment are not just technological. A high-mix/low-volume supplier is dependent on customers whose orders vary unpredictably, so heavy investment in equipment for making any particular product is unwise. The owner of Gent Machine Co. in Cleveland, Ohio, repeated to a journalist what he had explained to MIT researchers previously: that even on a large contract he hesitated to buy automation equipment because the contract could disappear overnight. That's exactly what happened to an eight-year-long Tesla contract with Gent for making fasteners that attach battery parts. About Tesla's decision to terminate the contract, Gent's owner said: "That's just how it works."[28] It is how it works in US manufacturing, at least. In Germany and Japan, MIT researchers have observed more collaborative relationships between large firms and their suppliers. Large firms make longer-term commitments to suppliers and share their plans and technical know-how in order to help the smaller firms adjust and advance.

Finally, we needed to consider a frequently heard explanation of the slowness of adoption of advanced manufacturing technologies: that the problem lies in the lack of skills of the manufacturing workforce. In this view, manufacturers are reluctant to invest in new equipment because they cannot find workers with the right skills to work on it. International comparisons highlight the weaknesses of US workforce education relative to the institutions in countries like Germany and Denmark that provide apprenticeships and extensive advanced training and retraining to workers. People blame culture change for the unwillingness of young people to seek out manufacturing jobs. But low entry-level wages and job insecurity can explain much of that reluctance. When parents have watched more than five million manufacturing jobs disappear in their lifetimes, it can be difficult to convince them of a good future in manufacturing for their children. And low-tech jobs are not challenging and attractive to new generations of workers.

## Breaking Out of the Low-Tech—Low-Wage Trap

The scarcity of robots and other automation equipment in most US manufacturing plants shows that robots are not taking over the jobs of most humans. But this is hardly good news for the US economy or for American workers. Without higher rates of investment in advanced manufacturing technology, the country's sluggish productivity growth is not likely to accelerate. Without new technology in manufacturing plants, the wages of workers are not likely to rise. Wages are determined by multiple factors, including labor supply, unionization, and public policies. We observed that firms that invested little in advanced equipment were also unwilling to invest in their employees' skill development. They asked little of their workers beyond coming to work on time. They offered low entry wages and little training beyond shadowing a worker already doing the job for which the new entrant was hired. These firms typically have high turnover rates, since workers have little incentive to stick with such a company.

There are companies that have followed a different track. We encountered them in our research and discovered that they had typically made substantial investments in new equipment—either to improve the quality, speed, and safety of their production process, or to satisfy a big customer, such as the US Department of Defense. When they make investments in technology, manufacturers also frequently invest in training. After all, now they need their workforce to know how to make the best use of new tools. The acquisition of new technology and new skills often goes hand in hand. These observations suggest that in order to break out of a stalemate in which outdated equipment and low-level skills are mutually reinforcing, we need public policies to support both higher levels of capital investment and investment in worker education.[29] There is a road out of our current dilemma. We need to move onto it.

## Discussion Questions

1. What factors might influence manufacturing firms to adopt new technologies like robots? Could government play any role here?

2. How could engineers design new technologies and take into consideration factors that would make for good jobs: more interesting ones, ones with less physical and mental stress, ones that encourage workers to contribute to process improvement?

3. How should a company decide who should be trained to use new technology? Workers? Technicians? Engineers?

4. There have been proposals to tax robots or in some other way limit their use. What do you see as the pros and cons of such restrictions?

5. The authors of the article sugggest at the end that government should play an active role in supporting the introduction of robots and other advanced manufacturing technologies into the workplace. Do you agree? On what grounds could one critique the authors' position?

## Bibliography

Acemoglu, Daron, and Pascual Restrepo. "The Race between Man and Machine: Implications of Technology for Growth, Factor Shares, and Employment." *American Economic Review* 108, no. 6 (2018): 1488–542. https://ide.mit.edu/sites/default/files/publications/aer.20160696.pdf.

Acemoglu, Daron, and Pascual Restrepo. "Robots and Jobs: Evidence from US Labor Markets. *Journal of Political Economy* 128, no. 6 (June 1, 2020): 2188–44. https://doi.org/10.1086/705716.

Aeppel, Timothy. “The Robot Apocalypse Is Hard to Find in America’s Small and Mid-Sized Factories.” Reuters.com, August 2, 2021. https://www.reuters.com/technology/robot-apocalypse-is-hard-find-americas-small-mid-sized-factories-2021-08-02/.

Aghion, Philippe, Céline Antonin, Simon Bunel, and Xavier Jaravel. “What Are the Labor and Product Market Effects of Automation? New Evidence from France.” Unpublished manuscript, December 2021. https://scholar.harvard.edu/files/aghion/files/what_are_the_labor_and_product_market_effects_of_automation_dec_2021.pdf

Armstrong, Benjamin, Suzanne Berger, and William Bonvillian. “Advanced Technology, Advanced Training: A New Policy Agenda for U.S. Manufacturing.” Cambridge, MA: Initiative for Knowledge and Innovation in Manufacturing, February 2021. https://www.ikim.mit.edu/national-manufacturing-workforce-plan.

Arntz, Melanie, Terry Gregory, and Ulrich Zierahn. “The Risk of Automation for Jobs in OECD Countries.” *OECD Social, Employment, and Migration Working Papers* no. 189. Paris: OECD Publishing, 2016. https://doi.org/10.1787/5jlz9h56dvq7-en

Berger, Suzanne, and Richard K. Lester. *Made By Hong Kong*. Hong Kong: Oxford University Press, 1997.

Berger, Suzanne, and the MIT Industrial Performance Center. *How We Compete.* New York: Doubleday, 2005.

Berger, Suzanne, and the MIT Taskforce on Production in the Innovation Economy. *Making in America.* Cambridge, MA: MIT Press, 2013.

Berger, Suzanne. “Manufacturing in America: A View from the Field.” MIT Task Force on the Work of the Future Research Briefs, November 24, 2020. https://workofthefuture.mit.edu/research-post/manufacturing-in-america-a-view-from-the-field/.

Brynjolfsson, Erik, and Andrew McAfee. *The Second Machine Age.* New York: WW Norton, 2014.

Dertouzos, Michael, Robert Solow, and Richard K. Lester. *Made in America.* Cambridge MA: MIT Press, 1989.

Dinlersoz, Emin, and Zoltán Wolf. “Automation, Labor Share, and Productivity: Plant-Level Evidence from U.S. Manufacturing.” US Census Bureau, Center for Economic Studies, Working Paper No. CES 18-39 (September 2018). https://econpapers.repec.org/paper/cenwpaper/18-39.htm.

Dixon, Jay, Bryan Hong, and Lynn Wu. 2020. “The Robot Revolution: Managerial and Employment Consequences for Firms.” NYU Stern School of Business. http://dx.doi.org/10.2139/ssrn.3422581.

Frey, Carl Benedikt, and Michael A. Osborne. “The Future of Employment: How Susceptible Are Jobs to Computerisation?” *Technological Forecasting and Social Change* 114 (2017): 254–80. https://doi.org/10.1016/j.techfore.2016.08.019

Frey, Carl Benedikt. *The Technology Trap.* Princeton, NJ: Princeton University Press, 2019.

Hobsbawm, E. J. “The Machine Breakers.” *Past & Present* 1, no. 1 (February 1952): 57–70. https://doi.org/10.1093/past/1.1.57

Manyika, James, Michael Chui, Mehdi Miremade, Jacques Bughin, Katy George, Paul Willmott, and Martin Dewhurst. *A Future That Works: Automation, Employment, and Productivity*. San Francisco: McKinsey Global Institute, 2017. https://www.mckinsey.com/~/media/mckinsey/featured%20insights/Digital%20Disruption/Harnessing%20automation%20for%20a%20future%20that%20works/MGI-A-future-that-works-Full-report.ashx

Organisation for Economic Co-Operation and Development. “Productivity and ULC by Main Economic Activity (ISIC Rev. 4).” The OECD Productivity Database, 1995–2019. https://stats.oecd.org/Index.aspx?DataSetCode=PDBI_I4.

Owen-Hill, Alex. “What’s the Difference between Robots and CNC Machines?” *RoboDK* (blog), May 29, 2019. https://robodk.com/blog/difference-robots-cnc-machines/.

Reuther, Walter. “Papers.” *Walter P. Reuther Selected Papers*. Edited by Henry M. Christman. Kowloon City, Hong Kong: Eurasia Publishing House, 1961.

Smith, Aaron, and Monica Anderson. “Automation in Everyday Life.” Washington DC: Pew Research Center (October 2017). https://www.pewresearch.org/internet/wp-content/uploads/sites/9/2017/10/PI_2017.10.04_Automation_FINAL.pdf

Staff of US Joint Economic Committee, 86th Congress. *New Views on Automation* (Joint Comm. Print, 1960).

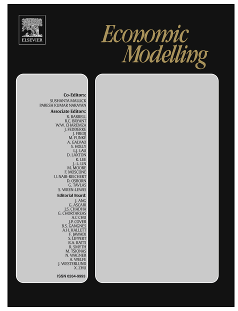
Taviss, Irene. “A Survey of Popular Attitudes toward Technology.” *Technology and Culture* 13, no. 4 (October 1972): 606–21. https://doi.org/10.2307/3102838

Tracy, Spencer L., Jr., *Accelerating Job Creation in America: The Promise of High Impact Companies*. Corporate Research Board, LLC for SBA Contract Number SBAHQ-10-M-0144. www.sba.gov/sites/default/files/files/HighImpactReport.pdf.

US Bureau of the Census. *Annual Survey of Manufactures Industrial Robotic Equipment.* March 11, 2021.

https://www.census.gov/library/publications/2019/econ/2018-asm-robotic-equipment.html.

# Accepted Manuscript




How can robots affect wage inequality?

Clemens Lankisch, Klaus Prettner, Alexia Prskawetz

PII: S0264-9993(18)31062-9

DOI: https://doi.org/10.1016/j.econmod.2018.12.015

Reference: ECMODE 4799

To appear in: *Economic Modelling*

Received Date: 25 July 2018

Revised Date: 5 November 2018

Accepted Date: 30 December 2018

Please cite this article as: Lankisch, C., Prettner, K., Prskawetz, A., How can robots affect wage inequality?, *Economic Modelling* (2019), doi: https://doi.org/10.1016/j.econmod.2018.12.015.

# How can robots affect wage inequality?

Clemens Lankisch[1], Klaus Prettner[2], and Alexia Prskawetz[1,3]*

1) Vienna University of Technology
Institute of Statistics and Mathematical Methods in Economics
Wiedner Hauptstr. 8 – 10, 1040 Vienna, Austria

2) University of Hohenheim
Institute of Economics
Schloss 1d, Osthof-West, 70593 Stuttgart, Germany
email: klaus.prettner@uni-hohenheim.de
Corresponding author

3) Wittgenstein Centre (IIASA, VID, WU),
Vienna Institute of Demography
Welthandelsplatz 2 / level 2, 1020 Vienna, Austria

**Abstract**

We explain the simultaneous presence of i) increasing per capita output, ii) declining real wages of low-skilled workers, and iii) a rising wage premium of higher education within a model of economic growth in the age of automation. The theoretical implications are consistent with the data for the United States since the 1970s. Thus, automation contributes towards our understanding of the driving forces of rising inequality. The immediate policy conclusion is that investments in higher education can help to soften the negative effects of automation.

**JEL classification:** O11, O41, D63.

**Keywords:** Automation, declining real wages of low-skilled workers, income inequality, long-run economic growth, skill premium.

*We would like to thank the editor Sushanta Mallick, two anonymous referees, Ana Abeliansky, Anna Dugan, Emanuel Gasteiger, Niels Geiger, Johannes Schwarzer, and Holger Strulik for valuable comments and suggestions. Declarations of interest: none.

# How can robots affect wage inequality?

**Abstract**

We explain the simultaneous presence of i) increasing per capita output, ii) declining real wages of low-skilled workers, and iii) a rising wage premium of higher education within a model of economic growth in the age of automation. The theoretical implications are consistent with the data for the United States since the 1970s. Thus, automation contributes towards our understanding of the driving forces of rising inequality. The immediate policy conclusion is that investments in higher education can help to soften the negative effects of automation.

**JEL classification:** O11, O41, D63.

**Keywords:** Automation, declining real wages of low-skilled workers, income inequality, long-run economic growth, skill premium.

# 1 Introduction

Despite sustained economic growth in the United States over the past decades, the median real wage stagnated and the real wages of low-skilled workers even declined since the 1970s (De Santis, 2002; Acemoglu and Autor, 2012; Autor, 2014). Over the same time period, the wages of high-skilled workers with a bachelor's degree or higher have grown. Clearly, the overall development of the United States economy has therefore been characterized by a rise in the skill premium, which is the percentage by which workers with a college degree earn more than workers without a college degree (cf. Mallick and Sousa, 2017; Neves et al., 2018). Figure 1 shows the evolution of the real wages of workers with less than a bachelor's degree (solid line, left axis) and the skill premium (dotted line, right axis) from 1970 to 2015. While the real wages of low-skilled workers declined by more than 20 percent over this period, the skill premium almost doubled from slightly above 60 percent to 120 percent.

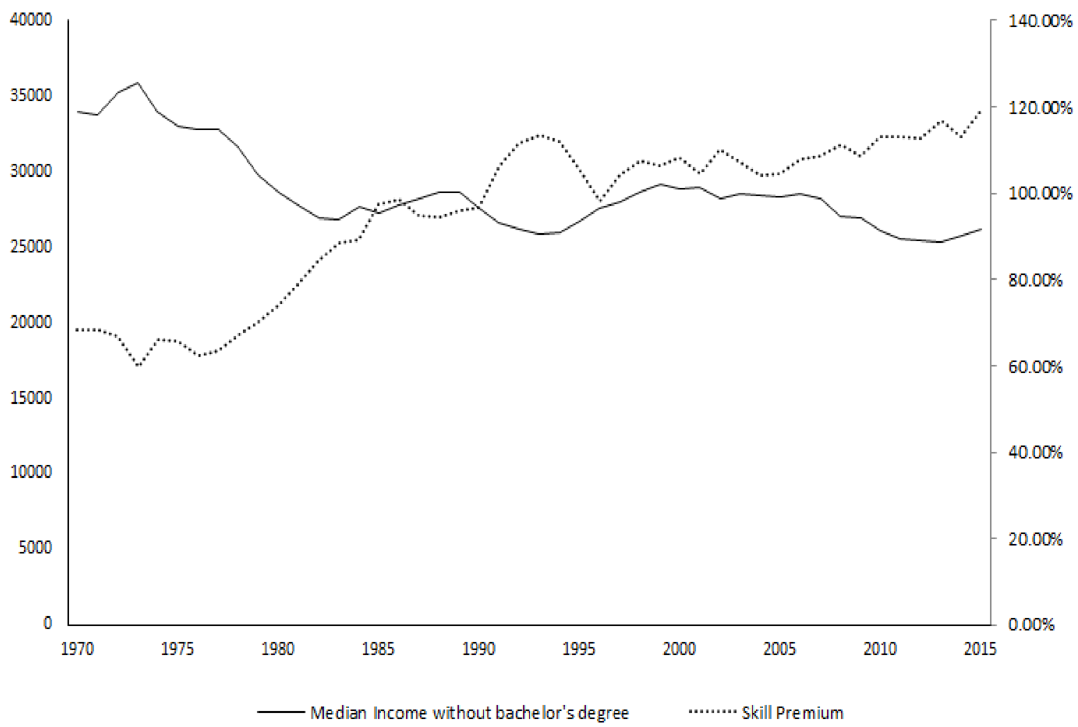



Figure 1: Real wages of workers with less than a bachelor's degree (solid line, left axis) and the skill premium (dotted line, right axis) from 1970 to 2015 in the United States. Source: United States Census Bureau (2017), own calculations.

The rise in wage-related inequality is one of the driving forces behind the rise of overall income inequality since the 1980s (Piketty and Saez, 2003; Atkinson et al., 2011; Piketty, 2014; Milanovic, 2016). A widely accepted and convincing explanation for the rise in the skill premium is skill-biased technological change that disproportionately raised the productivity of high-skilled workers over the past decades (cf. Acemoglu, 1998, 2002; Goldin and Katz, 2008; Autor and Dorn, 2013; Sochirca et al., 2013; Jung et al., 2017; Mallick and Sousa, 2017). According to this explanation, the rise in the number of college-educated workers in the second half of the 20th century has led to a rise in the demand for technologies that suited their skills. The increase in the stock of these technologies – such as computers, programming languages, and software for spreadsheet calculations – has in turn raised the productivity of high-skilled workers. Depending on how difficult it is to substitute high-skilled workers by low-skilled workers in the production process, the increase in the productivity of high-skilled workers has the potential to raise their wages by more than the wages of low-skilled workers. If this is the case, skill-biased technological change widens the wage gap. Moreover, the skill premium does not only apply in case of individual workers but also at the firm level: Matemilola et al. (2013), Nemlioglu and Mallick (2017), and Prettner and Strulik (2018) show empirically that firms with more investments in managerial practices – or with higher managerial skills to start with – perform better.

Other developments – notably international trade and outsourcing – have complemented (and sometimes substituted for) skill-biased technological change in its effect on the wage differential (Autor et al., 2016). The intuition behind the effects of international trade and outsourcing on the dispersion of wages is straightforward. The production of goods that primarily require low-skilled labour input (simple toys, clothes, etc.) can be easily shifted to countries in which labour is abundant and wages are low. Due to decreasing transport costs and globally decreasing tariffs in the 20th century, these goods can ever more cheaply be exported back to the home market. As a result, firms with high demand for low-skilled labour tend to concentrate in low-wage countries. By contrast, the production of goods that require predominantly skilled labour input (sophisticated machinery, airplane engines, etc.), is more difficult to shift abroad. The reason is that high-skilled labour is scarce in low-wage countries. Thus, firms producing high-skill intensive goods concentrate in countries where workers are well-educated and wages are high. This implies, from the perspective of high-wage countries, that globalization leads to a fall in the demand for low-skilled labour and a rise in the demand for high-skilled labour. As a result, the wages of high-skilled workers increase further and the wages of low-skilled workers decrease.

Further explanations for the rise in inequality include the reduction in wealth taxes and top marginal income tax rates since the 1980s, the reduction in the bargaining power of labour unions, and demographic changes such as declining birth rates that lead to a higher concentration of inheritances, or assortative mating, i.e., that nowadays spouses and life partners tend to have a similar level of education, which was not always the case (Piketty and Saez, 2003; Atkinson et al., 2011; Piketty, 2014; Piketty et al., 2014; Milanovic, 2016). In addition, the compensation structure in markets for superstars – where someone with either the skills or the luck to be slightly ahead of others in a certain domain is able to earn a disproportionate share of overall earnings – also contributes to a concentration of high incomes (Rosen, 1981).

In our contribution, we show that there is another aspect that has not yet been credited sufficiently. Over the past decades, automation has made it possible to replace the production factor of low-skilled labour entirely – at least as far as different routine tasks in the production process are concerned. Tasks previously performed by assembly-line workers are now undertaken by industrial robots. By the same token, 3D printing has allowed to reduce the amount of labour input in the production of customized products – such as hearing aids and prostheses. 3D printing is now even used for the construction of entire buildings, which could reduce the need for construction workers substantially (Abeliansky et al., 2015; The Economist, 2017). Currently, self-driving cars and lorries are being developed and tested successfully. This technology has the potential to replace millions of taxi drivers and truckers in the not too distant future.

The crucial difference between automation and the standard formulation of skill-biased technological change is that automation does not raise the marginal productivity of labour but that it renders the production factor labour entirely obsolete for given tasks. For example, a standard computer still has to be operated by a suitably skilled person, whereas the skill of driving taxis becomes technically obsolete once autonomous cars are available. While overall production per worker usually rises with automation[1], the marginal product of labour might not, such that these two different measures of productivity would start to diverge with automation.[2] Further-

[1]This holds for the standard Ramsey- and Solow-type of growth models with automation but might not necessarily be true in an overlapping generations setting (Sachs and Kotlikoff, 2012; Sachs et al., 2015; Benzell et al., 2015; Gasteiger and Prettner, 2017) or in a setting in which structural unemployment arises due to a mismatch between the skill requirements of jobs and the current supply of skills by workers (Restrepo, 2018).

[2]In the context of the US banking industry, Mallick and Ho (2008) show how IT investments can reduce operational costs but, at the same time, reduce profitability. Ceteris paribus and without network externalities, IT expenditures reduce payroll expenses and raise the market share such that profits rise. However, if all banks invest in IT, network effects are created to the extent that market shares might not change, while more intense competition drives down profitability.

more, as compared to standard physical capital in the form of machines, assembly lines, and production halls, a rise in the stock of automation capital does not imply a higher demand for workers. If a firm invests in new machines and assembly lines, it needs workers to operate them. By contrast, if a firm invests in a fleet of self-driving cars or in a production facility that operates with 3D printers instead of workers, this does not raise the demand for labour. Consequently, capital deepening, which is seen as a driver of rising wages in standard macroeconomic models, could lead to a replacement of labour and to lower wages in the age of automation.

To analyse the distributive effects of robots, we incorporate automation capital as a new production factor into an otherwise standard and simple model of capital accumulation with low-skilled and high-skilled workers. Consistent with the stylized facts to date, we assume that low-skilled labour is easier to automate than high-skilled labour.[3] An increase in the stock of automation capital has two effects. First, it allows to substitute for workers and thereby to overcome the diminishing marginal product of labour that constrains growth in the standard Solow (1956) model. Second, the accumulation of automation capital drives a wedge between the wages of high-skilled workers and low-skilled workers and, thus, raises wage inequality. The resulting framework is capable of generating automation-driven long-run growth even in the absence of technological progress and it explains the rise in the skill premium. In addition and in contrast to the model of skill-biased technological change, our framework can explain the reduction in the real wages of low-skilled workers that we have observed over the past decades in the United States.[4]

The central policy implication of our model is to invest in higher education in the face of automation. Doing so would yield a larger share of high-skilled workers in the economy who are not as susceptible to automation as low-skilled workers. Such a strategy could have a dampening effect on the rise in wage inequality if it is driven by automation.

The paper is structured as follows. Section 2 discusses the related literature.

[3]This holds up to now. However, progress in the development of machine learning algorithms has been very fast such that even non-routine, skill-intensive tasks become more and more automatable. Examples are diagnosing diseases and writing novels (Barrie, 2014; Ford, 2015).

[4]Automation capital can be interpreted as a special case of equipment capital in the literature on capital-skill complementarity (Krusell et al., 2000). While Krusell et al. (2000) consider capital equipment and capital structures and assume that high-skilled workers are more difficult to substitute by capital equipment than low-skilled workers, we decompose the production factor of capital equipment into i) the machines and assembly lines the operation of which requires labour and ii) industrial robots and 3D printers that do not need any labour input at all. We show that the naturally arising capital-skill complementarity in this setting explains the contemporaneous presence of long-run economic growth with shrinking wages of low-skilled workers, and, consequently, a rising skill premium.

In Section 3, we present the central elements of our model. In Section 4, we solve for the long-run balanced growth rate and present our main results. We show that the model generates falling wages of low-skilled workers, a rising skill premium, and positive per capita GDP growth with a rising automation level. In Section 5, we conclude and sketch out some scope for further research.

# 2 Related literature

As far as the related literature is concerned, the analysis of automation has received considerable attention most recently. To our knowledge, Steigum (2011) was the first to address the implications of the use of robots in a neoclassical type of growth model along the lines of Ramsey (1928), Cass (1965), and Koopmans (1965). He shows that automation implies the possibility for sustained long-run growth and leads to a declining labour share, which is consistent with the empirical evidence for the United States (Elsby et al., 2013; Karabarbounis and Neiman, 2014; Barkai, 2018).[5] Prettner (2018) analyses the effects of automation in a simpler framework based on Solow (1956). He shows that the results of Steigum (2011) carry over to this setting and quantifies the extent to which automation contributed to the reduction in the labour share of the United States between 1970 and 2010. However, neither of the two contributions by Steigum (2011) and Prettner (2018) allows for the skill-specific heterogeneity of workers and, thus, they cannot analyse the evolution of wage inequality. In addition, Prettner (2018) only considers an exogenous split of overall investment into automation capital and into traditional physical capital, whereas we solve for the endogenous choice that rational investors would make.

Gasteiger and Prettner (2017) show that the implications of automation for long-run economic growth are very different in the canonical overlapping generations framework of Diamond (1965). In the overlapping generations model with automation, the economy always converges to stagnation, even if there is full replacement of labour by automation capital such that aggregate production resembles the properties of an $AK$ growth model. The reason is that households save exclusively out of their first-period wage income in this setting. However, wage income is diminished by automation because workers and robots are perfect substitutes. This reduces the amount of overall investment, which, in turn, reduces economic growth. The corresponding vicious circle implies long-run stagnation of the economy and thereby explains the numerical findings of Sachs and Kotlikoff (2012), Sachs et al. (2015), and

[5] Barkai (2018) shows that the labour income share has been declining and argues that an increase in the market power of firms plays a crucial role in the explanation of this phenomenon.

Benzell et al. (2015), according to which automation can reduce economic growth. While the numerical results of Sachs and Kotlikoff (2012) and Benzell et al. (2015) show that the wages of high-skilled workers and low-skilled workers may diverge with automation, the other articles mentioned so far do not analyse wage-related inequality in the context of automation.

Acemoglu and Restrepo (2016), Hémous and Olsen (2016), and Prettner and Strulik (2017) have proposed frameworks for the analysis of the implications of automation within the R&D-based endogenous growth literature. In Acemoglu and Restrepo (2016) and Hémous and Olsen (2016), R&D investments generate new varieties of tasks (in the former paper) and intermediate products (in the latter paper) that are initially non-automated. Firms can subsequently invest with the purpose to automate the corresponding production. Thus, the wages of low-skilled workers rise with R&D-based innovations and fall with in-house automation. To the extent that R&D-based innovation is encouraged by automation, it could even be the case that the wages of low-skilled workers rise with automation in such a setting. By contrast, the results of Prettner and Strulik (2017) are less benign because new innovations come in the form of the very machines by which the production of goods is automated. As such, automation only raises the wages of high-skilled workers such that wage dispersion and inequality rise with innovation-driven automation.

Our contribution to the literature is that i) we set forth a simple framework of capital-skill complementarity in the age of automation with a straightforward interpretation of automation capital that, in contrast to Sachs and Kotlikoff (2012) and Benzell et al. (2015), allows for the analytical analysis of wage inequality; and ii) our framework can explain the contemporaneous presence of rising per capita GDP, shrinking wages of low-skilled workers, and rising wage inequality as experienced by many economies over the past decades (see Graetz and Michaels, 2015; Acemoglu and Restrepo, 2017; Dauth et al., 2017, for empirical evidence on the role of automation in this context).

# 3 A simple model of automation and wage inequality

Consider an economy that is populated by households who invest a fraction $s$ of their income in either traditional physical capital (machines, assembly lines, production halls, etc.) or in automation capital (industrial robots, 3D printers, autonomous mining equipment, etc.). We abstract from endogenous saving decisions that would mainly complicate the exposition.[6] Time $t$ evolves continuously and the population grows at rate $n$. There are four production factors: low-skilled workers denoted by $L_u$, high-skilled workers denoted by $L_s$, traditional physical capital denoted by $K$, and automation capital denoted by $P$. For simplicity, we do not make a distinction between the population size and the amount of labour such that workforce growth and population growth coincide. Automation capital is a perfect substitute for low-skilled workers (e.g., assembly line workers can easily be substituted by industrial robots) but it is still an imperfect substitute for high-skilled workers (e.g., engineers and managers are still difficult to automate). This implies a natural capital-skill complementarity along the lines of Krusell et al. (2000).

Suppressing time arguments whenever this does not impair the clarity of exposition, the representative firm produces output $Y$ according to the CES production function

$$Y = \left[(1-\beta)L_s^{\gamma} + \beta\left(P + L_u\right)^{\gamma}\right]^{\frac{1-\alpha}{\gamma}} K^{\alpha}, \tag{1}$$

where $\beta \in (0,1)$ is the production weight of low-skilled workers, $\alpha$ is the elasticity of output with respect to traditional physical capital, and $\gamma \in (-\infty, 1]$ determines the substitutability between both types of workers, where workers with different skills are perfect substitutes for $\gamma = 1$ and perfect complements for $\gamma \to -\infty$. In the following analysis, we focus on the empirically relevant range $\gamma \in (0,1)$ for which low-skilled and high-skilled workers are gross substitutes as stressed, for example, by Autor (2002) and Acemoglu (2009).

Traditional physical capital and automation capital are the only saving and investment vehicles in the economy. Denoting the saving rate by $s$, the fraction of investment diverted to the accumulation of traditional capital by $s_K$, and the rate of depreciation by $\delta$, the laws of motion for both types of capital are given by

$$\dot{K} = s_K s Y - \delta K, \tag{2}$$

$$\dot{P} = (1 - s_K) s Y - \delta P. \tag{3}$$

Assuming different rates of depreciation for both types of capital would not change the main qualitative results. Apart from allowing for different types of skills in the economy, we also depart in another crucial way from Prettner (2018) by endogenising $s_K$, i.e., the decision of rational investors of how much to invest in the two different stocks of capital.

[6] See Steigum (2011) for the analysis of the growth effects of automation in a model with endogenous investment but with only one type of labour.

For simplicity, we abstract from endogenous education decisions that would allow individuals to switch from being low-skilled to being high-skilled and we also abstract from exogenous technological progress. For an R&D-based growth model with endogenous technological change, automation, and endogenous skill-upgrading, but with a simpler production structure and only one type of capital, see Prettner and Strulik (2017). Considering general labour-augmenting technological progress in our production function would merely add an additional driver of long-run growth and not change anything in terms of our central results. Considering education decisions would primarily affect the transitional dynamics but not the long-run solution as shown by Prettner and Strulik (2017).

Denoting the size of the workforce by $L = L_u + L_s$, defining the shares of high-skilled and low-skilled workers by $l_s = L_s/(L_s + L_u)$ and $l_u = L_u/(L_s + L_u)$, respectively, and referring to per worker counterparts of aggregate variables with lowercase letters such that $y$ is output per worker, $k$ is traditional capital per worker, and $p$ is automation capital per worker, we obtain per worker output as

$$y = \left[(1-\beta)l_s^\gamma + \beta\,(p + l_u)^\gamma\right]^{\frac{1-\alpha}{\gamma}} k^\alpha. \tag{4}$$

This expression shows that the accumulation of traditional physical capital increases the productivity of both types of labour, whereas automation competes with low-skilled workers directly and with high-skilled workers indirectly depending on the extent to which high-skilled workers can be substituted by low-skilled workers. In essence, automation changes the property of labour in the fundamental sense that labour becomes an accumulable production factor.

Rational investors would only invest in both types of capital if they deliver the same rate of return such that an interior equilibrium with an endogenous split of investment between traditional physical capital and automation capital requires $r_K = r_P$. From the production function (1), it follows that the factor rewards for traditional physical capital and for automation capital are given by, respectively,

$$r_K = \alpha K^{\alpha-1}\left[(1-\beta)L_s^\gamma + \beta\,(L_u + P)^\gamma\right]^{\frac{1-\alpha}{\gamma}}, \tag{5}$$

$$r_P = (1-\alpha)\beta K^\alpha\,(L_u + P)^{\gamma-1}\left[(1-\beta)L_s^\gamma + \beta\,(L_u + P)^\gamma\right]^{\frac{1-\alpha-\gamma}{\gamma}}. \tag{6}$$

Imposing the no-arbitrage condition $r_K = r_P$ allows to derive the equilibrium stock of traditional physical capital depending on automation capital and employment of both types of workers as

$$K = \frac{\alpha \left(L_u + P\right)^{1-\gamma} \left[\beta \left(L_u + P\right)^{\gamma} + (1-\beta) L_s^{\gamma}\right]}{(1-\alpha)\beta}. \tag{7}$$

Clearly, an increase in the number of both types of workers raises the equilibrium capital stock. The reason is that, if labour becomes more abundant, the return on physical capital rises such that investors would choose to raise the stock of traditional physical capital. Since automation capital is a perfect substitute for low-skilled workers, its increase has the same effect on the equilibrium capital stock as an increase in the number of low-skilled workers. Dividing Equation (7) by the number of workers ($L = L_u + L_s$) provides the traditional physical capital stock per worker ($k = K/L$) depending on automation capital per worker ($p = P/L$) and the fraction of skilled and unskilled workers $l_s$ and $l_u$, respectively:

$$k = \frac{\alpha\beta \left(l_u + p\right) + \alpha(1-\beta) l_s^{\gamma} \left(l_u + p\right)^{1-\gamma}}{(1-\alpha)\beta}. \tag{8}$$

Since $l_s$ and $l_u$ are constant because we abstract from endogenous education decisions, the time derivative of capital per worker is given by

$$\dot{k} = \frac{\alpha\beta\dot{p} + \alpha(1-\beta) l_s^{\gamma} (1-\gamma) \left(l_u + p\right)^{-\gamma} \dot{p}}{(1-\alpha)\beta}. \tag{9}$$

Aggregate investment $I = sY$ is used to raise the stocks of both types of capital such that the accumulation equation in per worker terms is given by $\dot{p} + \dot{k} = sy - (n+\delta)(p+k)$, where $n$ is the population growth rate. Plugging Equations (4) and (9) into this expression, the evolution of automation capital per workers follows as

$$\begin{aligned}
\dot{p} = &\left[\frac{(1-\alpha)\beta}{\beta + \alpha(1-\beta) l_s^{\gamma} (1-\gamma) \left(l_u + p\right)^{-\gamma}}\right] \\
&\left\{ s \left[(1-\beta) l_s^{\gamma} + \beta \left(p + l_u\right)^{\gamma}\right]^{\frac{1-\alpha}{\gamma}} \left[\frac{\alpha\beta\dot{p} + \alpha(1-\beta) l_s^{\gamma} (1-\gamma) \left(l_u + p\right)^{-\gamma} \dot{p}}{(1-\alpha)\beta}\right]^{\alpha} - \right. \\
&\left. (n+\delta) \left[p + \frac{\alpha\beta \left(l_u + p\right) + \alpha(1-\beta) l_s^{\gamma} \left(l_u + p\right)^{1-\gamma}}{(1-\alpha)\beta}\right] \right\}.
\end{aligned} \tag{10}$$

As is obvious, this expression cannot be solved explicitly for $\dot{p}$ during the transition period in which $p$ is still very low. We therefore follow the standard practice in the economic growth literature and focus on the long-run asymptotic solution to derive our central analytical results.

# 4 Results

If the saving rate $s$ is low, the economy converges to a steady state in which the per capita stocks of both types of capital are positive but do not grow such that the economy stagnates as in the standard Solow (1956) model without technological progress. However, there is the more interesting case of a long-run balanced growth path along which the economy grows at a constant rate, despite the absence of technological progress. Along this balanced growth path of the economy, $p \to \infty$ such that the following asymptotic approximations hold

$$k = \frac{\alpha\beta\,(l_u + p) + \alpha(1-\beta)l_s^\gamma\,(l_u+p)^{\,1-\gamma}}{(1-\alpha)\beta} \approx \frac{\alpha p}{1-\alpha} \Rightarrow k^\alpha \approx \left(\frac{\alpha}{1-\alpha}\right)^\alpha p^\alpha, \tag{11}$$

$$(1-\beta)l_s^\gamma + \beta\,(p+l_u)^\gamma \approx \beta p^\gamma, \tag{12}$$

$$\left[(1-\beta)l_s^\gamma + \beta\,(p+l_u)^\gamma\right]^{\frac{1-\alpha}{\gamma}} \approx \beta^{\frac{1-\alpha}{\gamma}} p^{1-\alpha}, \tag{13}$$

$$\frac{(1-\alpha)\beta}{\beta + \alpha(1-\beta)l_s^\gamma(1-\gamma)\,(l_u+p)^{\,-\gamma}} \approx 1-\alpha. \tag{14}$$

In Appendix A we use these approximations and the evolution of automation capital per worker (10) to derive the following constant asymptotic growth rate $g$ for automation capital per worker

$$g = s \cdot \beta^{\frac{1-\alpha}{\gamma}} \cdot \alpha^\alpha (1-\alpha)^{1-\alpha} - (n+\delta). \tag{15}$$

Furthermore, using the asymptotic approximations $k = \alpha/(1-\alpha)p$ and $\dot{k} = [\alpha/(1-\alpha)]\dot{p}$ in the long run, it follows that the balanced growth path involves $\dot{k}/k = \dot{p}/p$. Finally, Equation (4) implies that per capita output also grows at rate $g$ because

$$\begin{aligned} ln(y) &= \frac{1}{\gamma}(1-\alpha)\cdot ln\left[(1-\beta)l_s^\gamma + \beta\,(p+l_u)^\gamma\right] + \alpha\cdot ln(k) \\ &\approx \frac{1}{\gamma}(1-\alpha)\cdot ln\left(\beta p^\gamma\right) + \alpha \cdot ln(k) \\ \Rightarrow \frac{\mathrm{d}ln(y)}{\mathrm{d}t} &= g_y = (1-\alpha)g_p + \alpha g_k = g. \end{aligned} \tag{16}$$

Altogether, the economy therefore exhibits a long-run balanced growth rate $g$ that is positive as long as

$$s \cdot \beta^{\frac{1-\alpha}{\gamma}} \cdot \alpha^\alpha(1-\alpha)^{1-\alpha} > (n+\delta).$$

If this inequality is not fulfilled, the economy converges to the standard steady state of the Solow (1956) model without technological progress in which the economy stagnates. From this, our first central result follows immediately.

**Proposition 1.** *Consider our variant of the Solow (1956) model with high-skilled workers, low-skilled workers, and the possibility of full automation of the tasks performed by low-skilled workers and imperfect automation of the tasks performed by high-skilled workers. In this setting, there exists a balanced growth path with positive long-run economic growth at the rate $g$ given by Equation (15). This growth rate increases with the saving rate ($s$) and with the substitutability between low-skilled and high-skilled workers ($\gamma$), whereas it decreases with the rates of population growth ($n$) and depreciation ($\delta$).*

*Proof.* The proposition follows immediately from inspecting Equation (15) and noting that $\beta < 1$ such that an increase in $\gamma$ raises the first term in this expression. $\square$

The results in Proposition 1 generalize the results of Prettner (2018) to a model with i) two different types of workers that have different levels of skills, where low-skilled labour is easier to substitute by automation than high-skilled labour and ii) an endogenous share of investment that is diverted to traditional physical capital. The intuition for the finding of perpetual growth in the absence of technological progress is that automation turns labour into an accumulable production factor, which prevents the marginal product of traditional physical capital from declining.

As far as the dependence of the long-run growth rate on the parameters is concerned, i) a rise in the saving rate raises economic growth because it implies that both types of capital accumulate at a faster rate if households divert a larger fraction of their income to saving, ii) a rise in the population growth rate leads to faster dilution of both types of capital and thereby reduces economic growth, and iii) faster depreciation reduces the accumulation of both types of capital and thereby also reduces economic growth.

In addition, the substitutability between low-skilled and high-skilled workers plays a crucial role. The easier it is to substitute between the two types of workers, the easier it is for automation capital to raise the amount of *effective* labour in the economy, i.e., the easier it is to turn the whole composite labour input in production into an accumulable production factor. Consequently, the better low-skilled workers and high-skilled workers can be substituted, the stronger is the growth effect of automation.

Next, we focus on the distributive effects of automation and state our second central result.

**Proposition 2.** *Consider our variant of the Solow (1956) model with high-skilled workers, low-skilled workers, and the possibility of full automation of the tasks per-*

*formed by low-skilled workers and imperfect automation of the tasks performed by high-skilled workers. In this setting, the accumulation of automation capital leads to*

*i) decreasing wages of low-skilled workers,*

*ii) decreasing wages of high-skilled workers if low-skilled workers and high-skilled workers are easy to substitute,*

*iii) an increasing skill premium.*

*Proof.* Assuming perfect competition, the wages of high-skilled workers ($w_s$) and the wages of low-skilled workers ($w_u$) are

$$w_s = (1-\alpha)\frac{Y}{L_s^{1-\gamma}}\frac{1-\beta}{(1-\beta)L_s^\gamma + \beta\,(P+L_u)^\gamma}, \tag{17}$$

$$w_u = (1-\alpha)\frac{Y}{(P+L_u)^{1-\gamma}}\frac{\beta}{(1-\beta)L_s^\gamma + \beta\,(P+L_u)^\gamma}. \tag{18}$$

The effect of an increase in the stock of automation capital on the wages of low-skilled workers is given by

$$\frac{\partial w_u}{\partial P} = \frac{(1-\alpha)\beta Y}{(P+L_u)^{2-\gamma}} \frac{\{(1-\alpha-\gamma)\beta\,(P+L_u)^\gamma - (1-\gamma)\left[(1-\beta)L_s^\gamma + \beta\,(P+L_u)^\gamma\right]\}}{\left[(1-\beta)L_s^\gamma + \beta\,(P+L_u)^\gamma\right]^2}. \tag{19}$$

Since $(1-\alpha-\gamma)\beta\,(P+L_u)^\gamma < (1-\gamma)\beta\,(P+L_u)^\gamma$ and we focus on the case of $\gamma \in (0,1)$ in which the two types of workers are gross substitutes, the numerator of the second term is always negative and so is the whole derivative. Thus, the accumulation of automation capital reduces the wages of low-skilled workers. This proves part i) of the proposition.

The effect of an increase in the stock of automation capital on the wages of high-skilled workers is:

$$\frac{\partial w_s}{\partial P} = $$

$$= (1-\alpha)Y\frac{(1-\beta)\beta L_s^\gamma}{L_s(P+L_u)^{1-\gamma}}\frac{1-\alpha-\gamma}{\left[(1-\beta)L_s^\gamma + \beta\,(P+L_u)^\gamma\right]^2} = \begin{cases} \geq 0 & \text{for} \quad 1-\alpha \geq \gamma, \\ < 0 & \text{for} \quad 1-\alpha < \gamma. \end{cases} \tag{20}$$

The influence of automation on the wages of high-skilled workers is therefore ambiguous and depends on the substitutability between both types of labour. If $\gamma$ is high and substitution is easy, an increase in the use of robots even reduces the wages of high-skilled workers. The reverse holds true for a low $\gamma$. This proves part ii) of the proposition.

The skill premium is defined as the ratio of the wages of high-skilled workers to the wages of low-skilled workers and amounts to

$$\frac{w_s}{w_u} = \frac{1-\beta}{\beta}\left(\frac{P+L_u}{L_s}\right)^{1-\gamma}. \tag{21}$$

As long as $\gamma \in (0,1)$, which is the empirically relevant case of imperfect substitution between the two types of skills, an increase in the stock of automation capital $P$ raises the skill premium. This proves part iii) of the proposition. $\square$

The intuition for part i) is that competition by automation reduces the wages of workers whose tasks can easily be performed by machines. However, and this is shown in part ii) of the proposition, also the wages of high-skilled workers could be negatively affected by automation if low-skilled workers and automation capital can easily be used as a substitute for high-skilled workers. Since the wages of high-skilled workers either increase with the extent of automation – or at least decrease by less than the wages of high-skilled workers – this implies a rising skill premium, i.e., it implies part iii) of Proposition 2.

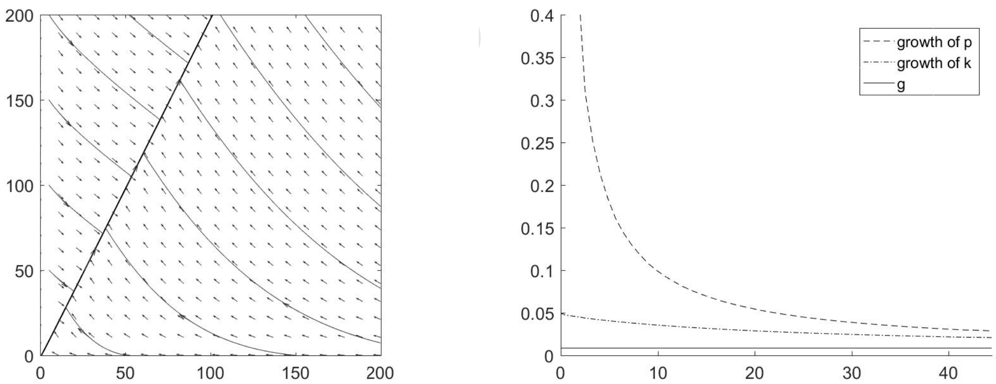



Figure 2: Phase diagram of the evolution of $k$ and $p$ (left) and growth rates of $k$ and $p$ during the transition to the asymptotic growth rate $g$ (right).

Up to now, we considered the asymptotic analytical results of the model for the long-run balanced growth path. Next we illustrate the transitional dynamics of the model for situations in which the long-run relation between $k$ and $p$ is not yet close to the steady state. In addition, we use the numerical illustrations to show how well the model can explain i) the growth of per capita GDP that we observed in the

United States over the past 40 years and ii) the evolution of the skill premium over the same time period.

The left diagram in Figure 2 displays the phase diagram of the model for the parameter values in Table 1. We observe that, irrespective of the initial levels of $k$ and $p$, there is convergence to the long-run solution as depicted by the solid line that starts at the origin. Altogether, there is long-run growth of $k$ and $p$. This is also illustrated in the right diagram, which displays the growth rates of $k$ and $p$ that converge to the asymptotic long-run solution $g$.

Table 1: Parameter values for simulation

| Parameter | Value | Justification |
|---|---|---|
| $s$ | 21% | Average long-run value in the US (Grossmann et al., 2013) |
| $n$ | 0.9% | Average population growth rate in the US (World Bank, 2016) |
| $\delta$ | 4% | Standard value in the literature (Grossmann et al., 2013) |
| $\alpha$ | 0.33 | Standard Value in the literature (Grossmann et al., 2013) |
| $\beta$ | 0.5 | Normalized for illustrative purposes |
| $\gamma$ | 0.7 | To fit the per capita growth rate and the skill premium |
| $l_s$ | 23% | Average long-run share in the US |

In the left diagram in Figure 3, we depict the scaled evolution of per capita GDP as observed in the United States (dashed line) versus the predictions of the model (solid line). In the right diagram in Figure 3, we do the same for the skill premium. Altogether, we observe that the model is able to replicate the evolution of per capita GDP and the skill premium reasonably well. However, we overestimate growth in per capita GDP and in the skill premium slightly. Considering that the model is a very stylized depiction of the economy that abstracts from many features of actually existing economies (e.g., endogenous responses in the education decisions of individuals), this is not surprising.

To summarize, our results show that automation leads to rising per capita GDP and rising wage inequality. This development is in line with the data for the United States since the 1970s as presented in Acemoglu and Autor (2012) and Autor (2014) and as illustrated in Figures 1 and 3. Thus, automation is likely to be an important aspect that deserves more attention when explaining the past three decades of economic development.

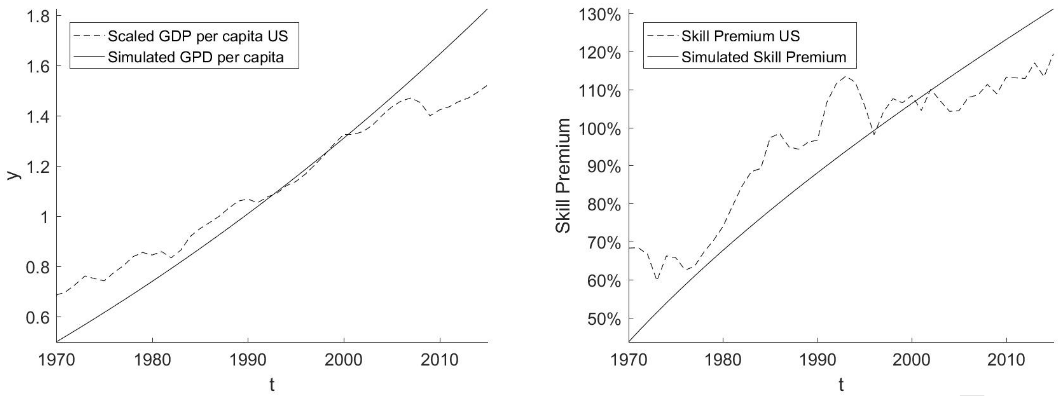



Figure 3: Per capita GDP of the model solution versus scaled per capita GDP in the United States for the period 1970 to 2010 (left) and model solution for the skill premium versus the skill premium in the United States for the period 1970 to 2010 (right).

# 5 Conclusions

We analyse the effects of automation in a model with low-skilled and high-skilled workers in which low-skilled workers are easier to automate than high-skilled workers. We show that i) there is the possibility for perpetual economic growth despite the absence of technological progress, ii) automation decreases the real wages of low-skilled workers and has the potential to even decrease the wages of high-skilled workers, iii) automation raises the skill premium. All three results are consistent with the experience of the United States over the past decades and help to explain why the less well-educated did not benefit from economic growth. As such, automation is an important aspect in the explanation of the evolution of income inequality.

A central policy implication of our model is to invest in higher education in the face of automation. Doing so has the potential to raise the share of high-skilled workers in the economy. Since they are not as susceptible to automation as low-skilled workers, such an education policy could dampen the effect of automation on wage inequality and allow a larger part of the population to benefit from the gains due to automation-driven economic growth.

For future research, it would be interesting to include skill-biased technological change, globalization, and automation within a single framework to quantify the relative importance of the different mechanisms. Clearly, such a project would not be analytically tractable and rather constitute a large-scale simulation study that is beyond the scope of the present paper.

# Appendix

## A Derivation of the steady-state results

The factor rewards for physical capital and automation capital pin down to

$$r_K = \alpha K^{\alpha-1} \left[\beta \left(L_u + P\right)^{\gamma} + (1-\beta) L_s^{\gamma}\right]^{\frac{1-\alpha}{\gamma}}, \tag{22}$$

$$r_P = (1-\alpha)\beta K^{\alpha} \left(L_u + P\right)^{\gamma-1} \left[\beta \left(L_u + P\right)^{\gamma} + (1-\beta) L_s^{\gamma}\right]^{\frac{1-\alpha-\gamma}{\gamma}}. \tag{23}$$

The no-arbitrage condition states that $r_K = r_P$ such that, after solving for $K$, we arrive at

$$K = \frac{\alpha \left(L_u + P\right)^{1-\gamma} \left[\beta \left(L_u + P\right)^{\gamma} + (1-\beta) L_s^{\gamma}\right]}{(1-\alpha)\beta}. \tag{24}$$

Dividing by $L = L_u + L_s$ yields

$$\frac{K}{L} = k = \frac{\alpha \left(l_u + p\right)^{1-\gamma} \left[\beta \left(l_u + p\right)^{\gamma} + (1-\beta) l_s^{\gamma}\right]}{(1-\alpha)\beta} \tag{25}$$

$$= \frac{\alpha\beta \left(l_u + p\right) + \alpha(1-\beta) l_s^{\gamma} \left(l_u + p\right)^{1-\gamma}}{(1-\alpha)\beta}. \tag{26}$$

Taking the derivative with respect to time under the assumption that $l_s$ and $l_u$ are constant, we arrive at

$$\dot{k} = \frac{\alpha\beta\dot{p} + \alpha(1-\beta) l_s^{\gamma} (1-\gamma) \left(l_u + p\right)^{-\gamma} \dot{p}}{(1-\alpha)\beta}. \tag{27}$$

Investment $I = sY$ is split into capital and robots such that we have

$$\dot{p} + \dot{k} = sy - (n+\delta)(p+k) \tag{28}$$

in per worker terms. Plugging (27) into this expression yields

$$\begin{aligned}
&\dot{p}+\frac{\alpha\beta\dot{p}+\alpha(1-\beta)l_s^\gamma(1-\gamma)\left(l_u+p\right)^{-\gamma}\dot{p}}{(1-\alpha)\beta} \\
&=\dot{p}\left(1+\frac{\alpha\beta+\alpha(1-\beta)l_s^\gamma(1-\gamma)\left(l_u+p\right)^{-\gamma}}{(1-\alpha)\beta}\right) \\
&=\dot{p}\left(\frac{(1-\alpha)\beta}{(1-\alpha)\beta}+\frac{\alpha\beta+\alpha(1-\beta)l_s^\gamma(1-\gamma)\left(l_u+p\right)^{-\gamma}}{(1-\alpha)\beta}\right) \\
&=\dot{p}\underbrace{\left(\frac{\beta+\alpha(1-\beta)l_s^\gamma(1-\gamma)\left(l_u+p\right)^{-\gamma}}{(1-\alpha)\beta}\right)}_{c(p)} \\
&\overset{(28)}{=} sy-(n+\delta)(p+k) \\
\Leftrightarrow \dot{p} &= \frac{1}{c(p)}\left[sy-(n+\delta)(p+k)\right] \\
&\overset{(8)}{=} \frac{1}{c(p)}\left[sy-(n+\delta)\left(p+\frac{\alpha\beta\left(l_u+p\right)+\alpha(1-\beta)l_s^\gamma\left(l_u+p\right)^{1-\gamma}}{(1-\alpha)\beta}\right)\right].
\end{aligned}$$

Plugging in $y$ yields

$$\dot{p}=\frac{1}{c(p)}\left[s\left[(1-\beta)l_s^\gamma+\beta\left(p+l_u\right)^\gamma\right]^{\frac{1-\alpha}{\gamma}}k^\alpha-(n+\delta)\left(p+\frac{\alpha\beta\left(l_u+p\right)+\alpha(1-\beta)l_s^\gamma\left(l_u+p\right)^{1-\gamma}}{(1-\alpha)\beta}\right)\right]. \tag{29}$$

Next, we divide by $p$ to get to the growth rate of the robot stock per capita:

$$\frac{\dot{p}}{p}=\frac{1}{p}\frac{1}{c(p)}\left[s\left[(1-\beta)l_s^\gamma+\beta\left(p+l_u\right)^\gamma\right]^{\frac{1-\alpha}{\gamma}}k^\alpha-(n+\delta)\left(p+\frac{\alpha\beta\left(l_u+p\right)+\alpha(1-\beta)l_s^\gamma\left(l_u+p\right)^{1-\gamma}}{(1-\alpha)\beta}\right)\right]. \tag{30}$$

To arrive at the solution in which long-run economic growth is positive, we need to have that $\dot{p}/p>0$ for $p\to\infty$. As $1/[c(p)p]>0$, we only need to look at the asymptotics of $sy-(n+\delta)(p+k)$. For $p\to\infty$, we observe the following:

$$\begin{aligned}
&k=\frac{\alpha\beta\left(l_u+p\right)+\alpha(1-\beta)l_s^\gamma\left(l_u+p\right)^{1-\gamma}}{(1-\alpha)\beta}\approx\frac{\alpha p}{1-\alpha}, \\
&k^\alpha\approx\left(\frac{\alpha}{1-\alpha}\right)^\alpha p^\alpha, \\
&(1-\beta)l_s^\gamma+\beta\left(p+l_u\right)^\gamma\approx\beta p^\gamma, \\
&\left[(1-\beta)l_s^\gamma+\beta\left(p+l_u\right)^\gamma\right]^{\frac{1-\alpha}{\gamma}}\approx\beta^{\frac{1-\alpha}{\gamma}}p^{1-\alpha}.
\end{aligned}$$

Thus, the term in squared brackets in Equation (30) is positive for $p \to \infty$ if

$$\begin{aligned} & s\beta^{\frac{1-\alpha}{\gamma}} p^{1-\alpha} \left(\frac{\alpha}{1-\alpha}\right)^{\alpha} p^{\alpha} - (n+\delta)\left(\frac{\alpha}{1-\alpha}+1\right) p > 0 \\ \Leftrightarrow\ & s\beta^{\frac{1-\alpha}{\gamma}} \left(\frac{\alpha}{1-\alpha}\right)^{\alpha} > (n+\delta)\left(\frac{1}{1-\alpha}\right) \\ \Leftrightarrow\ & s\beta^{\frac{1-\alpha}{\gamma}} \alpha^{\alpha}(1-\alpha)^{1-\alpha} > n+\delta. \end{aligned} \tag{31}$$

# References


Abeliansky, A., Martinez-Zarzoso, I., and Prettner, K. (2015). The Impact of 3D Printing on Trade and FDI. cege Discussion Paper 262.

Acemoglu, D. (1998). Why do New Technologies Complement Skills? Directed Technical Change and Wage Inequality. *Quarterly Journal of Economics*, Vol. 113:1055–1090.

Acemoglu, D. (2002). Directed technical change. *The Review of Economic Studies*, Vol. 69(No. 4):781–809.

Acemoglu, D. (2009). *Introduction to Modern Economic Growth*. Princeton University Press.

Acemoglu, D. and Autor, D. (2012). What Does Human Capital Do? A Review of Goldin and Katz's The Race between Education and Technology. *Journal of Economic Literature*, Vol. 50(No. 2):426–463.

Acemoglu, D. and Restrepo, P. (2016). The Race Between Man and Machine: Implications of Technology for Growth, Factor Shares and Employment. NBER Working Paper No. 22252.

Acemoglu, D. and Restrepo, P. (2017). Robots and Jobs: Evidence from US Labor Markets. NBER Working Paper No. 23285.

Atkinson, A., Piketty, T., and Saez, E. (2011). Top Incomes in the Long Run of History. *Journal of Economic Literature*, Vol. 49(No. 1):3–71.

Autor, D. (2002). Skill Biased Technical Change and Rising Inequality: What is the Evidence? What are the Alternatives? url: `https://economics.mit.edu/files/558`. [accessed on 03/01/2018].

Autor, D. H. (2014). Skills, education, and the rise of earnings inequality among the "other 99 percent". *Science*, Vol. 344(No. 6186):843–851.

Autor, D. H. and Dorn, D. (2013). The Growth of Low-Skill Service Jobs and the Polarization of the US Labor Market. *American Economic Review*, Vol. 103(No. 5):1553–1597.

Autor, D. H., Dorn, D., and Hanson, G. H. (2016). The China Shock: Learning from Labor-Market Adjustment to Large Changes in Trade. *Annual Review of Economics*, Vol. 8:205–240.

Barkai, S. (2018). Declining labor and capital shares. available at http://home.uchicago.edu/~barkai/doc/BarkaiDecliningLaborCapital.pdf [accessed on 10/03/2018].

Barrie, J. (2014). Computers Are Writing Novels: Read A Few Samples Here. Available at http://www.businessinsider.com/novels-written-by-computers-2014-11?IR=T [Accessed on January 22, 2017].

Benzell, S. G., Kotlikoff, L. J., LaGardia, G., and Sachs, J. D. (2015). Robots are us: Some economics of human replacement. NBER Working Paper 20941.

Cass, D. (1965). Optimum growth in an aggregative model of capital accumulation. *The Review of Economic Studies*, Vol. 32(No. 3):233–240.

Dauth, W., Findeisen, S., Suedekum, J., and Woessner, N. (2017). German Robots – The Impact of Industrial Robots on Workers. CEPR Discussion Paper 12306.

De Santis (2002). Wage inequality between and within groups: trade-induced or skill-bias technical change? Alternative age models for the UK. *Economic Modelling*, Vol. 19:725–746.

Diamond, P. A. (1965). National debt in a neoclassical growth model. *American Economic Review*, Vol. 55(No. 5):1126–1150.

Elsby, M. W. L., Hobijn, B., and Şahin, A. (2013). The Decline of the U.S. Labor Share. *Brookings Papers on Economic Activity*, Fall 2013:1–63.

Ford, M. (2015). *Rise of the Robots: Technology and the Threat of a Jobless Future.* Basic Books, NY, USA.

Gasteiger, E. and Prettner, K. (2017). A Note on Automation, Stagnation, and the Implications of a Robot Tax. Free University of Berlin, School of Business & Economics Discussion Paper 17/2017.

Goldin, C. and Katz, L. (2008). The Race Between Education and Technology: The Evolution of U.S. Wage Differentials, 1890-2005. National Bureau of Economic Research Working Paper 12984.

Graetz, G. and Michaels, G. (2015). Robots at Work. CEPR Discussion Paper 10477.

Grossmann, V., Steger, T. M., and Trimborn, T. (2013). Dynamically optimal R&D subsidization. *Journal of Economic Dynamics and Control*, Vol. 37:516–534.

Hémous, D. and Olsen, M. (2016). The Rise of the Machines: Automation, Horizontal Innovation and Income Inequality. Mimeo.

Jung, S., Lee, J.-D., Hwang, W.-S., and Yeo, Y. (2017). Growth versus equity: A CGE analysis for effects of factor-biased technical progress on economic growth and employment. *Economic Modelling*, Vol. 60:424–438.

Karabarbounis, L. and Neiman, B. (2014). The Global Decline of the Labor Share. *The Quarterly Journal of Economics*, Vol. 129(No. 1):61–103.

Koopmans, T. C. (1965). On the concept of optimal economic growth. In *The Econometric Approach to Development Planning*. Amsterdam: North Holland.

Krusell, P., Ohanian, L., Ríos-Rull, J.-V., and Violante, G. (2000). Capital-Skill Complementarity and Inequality: A Macroeconomic Analysis. *Econometrica*, Vol. 68(No. 5):1029–1053.

Mallick, S. and Ho, S. (2008). On Network Competition and the Solow Paradow: Evidence from US Banks. *The Manchester School*, Vol. 76(No. S1):37–57.

Mallick, S. and Sousa, R. (2017). The skill premium effect of technological change: New evidence from United States manufacturing. *International Labour Review*, Vol. 156(No. 1):113–131.

Matemilola, B., Bany-Ariffin, A., and Azman-Saini, W. (2013). Impact of leverage and managerial skills on shareholders' return. *Procedia Economics and Finance*, Vol. 7:103–115.

Milanovic, B. (2016). *Global Inequality. A New Approach for the Age of Globalization.* Harvard University Press, Cambridge, MA, USA.

Nemlioglu, I. and Mallick, S. (2017). Do Managerial Practices Matter in Innovation and Firm Performance Relations? New Evidence from the UK. *European Financial Management*, Vol. 23(No. 5):1016–1061.

Neves, P., Afonso, O., and Sequeira, T. (2018). Population growth and the wage skill premium. *Economic Modelling*, 68:435–449.

Piketty, T. (2014). *Capital in the Twenty-First Century.* The Belknap Press of Harvard University Press.

Piketty, T. and Saez, E. (2003). Income Inequality in the United States 1913-1998. *The Quarterly Journal of Economics*, Vol. 118(No. 1):1–39.

Piketty, T., Saez, E., and Stantcheva, S. (2014). Optimal Taxation of Top Labor Incomes: A Tale of Three Elasticities. *American Economic Journal: Economic Policy*, Vol. 6(No. 1):230–271.

Prettner, K. (2018). A note on the implications of automation for economic growth and the labor share. *Macroeconomic Dynamics.* (forthcoming).

Prettner, K. and Strulik, H. (2017). The Lost Race Against the Machine: Automation, Education, and Inequality in an R&D-Based Growth Model. Hohenheim Discussion Papers in Business, Economics, and Social Sciences 08-2017.

Prettner, K. and Strulik, H. (2018). Trade and productivity: The family connection redux. *Journal of Macroeconomics*, Vol. 56:276–291.

Ramsey, F. P. (1928). A mathematical theory of saving. *The Economic Journal*, Vol. 38(No. 152):543–559.

Restrepo, P. (2018). Skill Mismatch and Structural Unemployment. Available at `http://pascual.scripts.mit.edu/research/01/PR_jmp.pdf]` [Accessed on 10/02/2018].

Rosen, S. (1981). The Economics of Superstars. *American Economic Review*, Vol. 71(No. 5):845–858.

Sachs, J. D., Benzell, S. G., and LaGardia, G. (2015). Robots: Curse or blessing? A basic framework. NBER Working Paper 21091.

Sachs, J. D. and Kotlikoff, L. J. (2012). Smart machines and long-term misery. NBER Working Paper 18629.

Sochirca, E., Afonso, O., and Mazeda Gil, P. (2013). Technological-knowledge bias and the industrial structure under costly investment and complementarities. *Economic Modelling*, Vo. 32:440–451.

Solow, R. M. (1956). A contribution to the theory of economic growth. *The Quarterly Journal of Economics*, Vol. 70(No. 1):65–94.

Steigum, E. (2011). *Frontiers of Economics and Globalization: Economic Growth and Development*, chapter 21: Robotics and Growth, pages 543–557. Emerald Group.

The Economist (2017). Adidas's high-tech factory brings production back to Germany. Making trainers with robots and 3D printers. The Economist, January 14th 2017.

United States Census Bureau (2017). Historical Income Tables. Url: https://www.census.gov/data/tables/time-series/demo/income-poverty/historical-income-people.html [accessed on 08/14/2017].

World Bank (2016). World Development Indicators & Global Development Finance Database. Available at: http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators#.

- The real wages of low-skilled workers have been shrinking in the US since decades
- Per capita output and the wages of high-skilled workers have been increasing
- We propose an economic growth model with automation to explain these trends
- Automation has the potential to raise economic prosperity but also wage inequality
- Investments in higher education can reduce the effect of automation on inequality

**RICHARD B. FREEMAN**
Harvard University, USA, and IZA, Germany

I Z A
World of Labor
Evidence-based policy making

# Who owns the robots rules the world

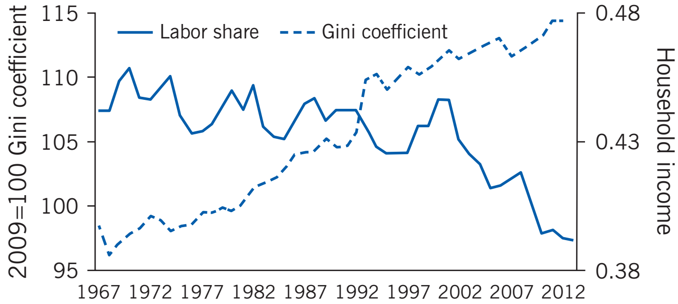
## Workers can benefit from technology that substitutes robots or other machines for their work by owning part of the capital that replaces them

Keywords: robots, job displacement, lower pay, income inequality, employee ownership

## ELEVATOR PITCH

Robots, that is any sort of machinery from computers to artificial intelligence programs that provides a good substitute for work currently performed by humans, can increasingly replace workers, even highly skilled professionals, and thus reduce opportunities for good jobs and pay. But, with appropriate policies, the higher productivity due to robots can improve worker well-being by raising incomes and creating greater leisure for workers. Consider the way Google reduces the need for reference librarians and research assistants, or the way massive open online courses reduce the need for professors and lecturers. How these new technologies affect worker well-being and inequality depends on who owns them.

US labor's declining share in income, and increasing income inequality




*Source*: Data from St Louis Federal Reserve. Online at: http://research.stlouisfed.org/fred2/.

## KEY FINDINGS

### Pros

- Policy can eliminate technology-induced joblessness.
- Labor can gain from labor-saving and capital-saving technologies if its supply is less elastic than capital's.
- Skill-biased technical change could raise the relative demand for skilled workers faster than the supply of skilled workers increases.
- Workers can earn more of their income from capital than from working—by owning part of the robots that replace them.

### Cons

- Robots, software, and apps are replacing labor. Robots could take the good jobs at high pay and leave the low-pay jobs to humans.
- The distribution of income in advanced countries has shifted toward capital.
- The ownership of robots is the prime determinant of how they affect most workers.

## AUTHOR'S MAIN MESSAGE

As companies substitute machines and computers for human activity, workers need to own part of the capital stock that substitutes for them to benefit from these new "robot" technologies. Workers could own shares of the firm, hold stock options, or be paid in part from the profits. Without ownership stakes, workers will become serfs working on behalf of the robots' overlords. Governments could tax the wealthy capital owners and redistribute income to workers, but that is not the direction societies are moving in. Workers need to own capital rather than rely on government income redistribution policies.


doi: 10.15185/izawol.5 | Richard B. Freeman © | May 2015 | wol.iza.org

## MOTIVATION

What explains the high rate of joblessness, slow growth of real wages, and continued inequality in many advanced countries years after the Great Recession? Some analysts and headline writers believe that the development of robots and other machines with artificial intelligence explains much of the jobs problem (see **Robot substitutes for human labor**). Behind the headlines are advances in artificial intelligence that create machines that are far better substitutes for human intelligence than seemed possible just a few years ago: the Google driverless car; the chess-playing computer Deep Blue, beating Kasparov as world champion; Watson, the artificially intelligent computer system, becoming the greatest Jeopardy player; the Google search engine knowing more than any of us on every subject.

**Robot substitutes for human labor**

The term "robots" refers broadly to any sort of machinery, from computers to artificial intelligence programs, that provides a good substitute for work currently performed by humans. This ranges from computers with artificial intelligence programs that bear no resemblance to humans, to robot vaccuum cleaners and Google cars, to social robots designed to look and act as if they are human. It does not matter whether a robot/machine has a humanoid appearance, as long as it can perform human functions. Advances in computer power and the development of artificial intelligence programs and wiring of microchips that can assess information and make decisions are rapidly improving the ability of machines to perform complicated tasks that seemed impossible just a decade or so ago. Taking the continuing progress in developing smarter technologies as a given, the focus here is on the social and economic issue of the ownership of these technologies.

## DISCUSSION OF PROS AND CONS

The 2012 publication *Race against the Machine* makes the case that the digitalization of work activities is proceeding so rapidly as to cause dislocations in the job market beyond anything previously experienced [1]. Unlike past mechanization/automation, which affected lower-skill blue-collar and white-collar work, today's information technology affects workers high in the education and skill distribution. Machines can substitute for brains as well as brawn. On one estimate, about 47% of total US employment is at risk of computerization [2].

If you doubt whether a robot or some other machine equipped with digital intelligence connected to the internet could outdo you or me in our work in the foreseeable future, consider news reports about an IBM program to "create" new food dishes (chefs beware), the battle between anesthesiologists and computer programs/robots that do their job much cheaper, and the coming version of Watson ("twice as powerful as the original") based on computers connected over the internet via IBM's Cloud [3]. On the darker side, you do not have to be paranoid to be paranoid about the potential technologies that the super-secret computers of the US National Security Agency (NSA) have on their digital drawing-boards.

Dr Who, on behalf of humanity, please give up acting on the 50th anniversary BBC show! Come back to the real world and stop the NSA's Daleks and Cybermen before it is too late!

While concern about the economics of computerization is widespread, many observers view the notion that robots destroy jobs as misguided technocratic thinking, science-fiction fantasy, or neo-Luddite nonsense. Fears of machines creating mass unemployment arose during some past periods of extended joblessness and were proved false as the economy recovered full employment. In the Great Depression, US President Franklin D. Roosevelt blamed unemployment on his country's failure to employ the surplus labor created by the efficiency of its industrial processes [3], while the technocracy movement sought to resolve the problem by replacing markets with planning by engineers. In the early 1960s, widespread fears that automation was eliminating thousands of jobs per week led the Kennedy and Johnson administrations to examine the link between productivity growth and employment. In the 1990s, Jeremy Rifkin predicted that technology would produce the "End of Work"—just before the dot.com boom raised the ratio of employees to the adult population in the US to an all-time peak [4].

## What happens to employment and leisure?

Mainstream economists' traditional response to the fear of automation and robots is the professional version of Alfred E. Neuman's "What, me worry?" response to life: "The market will take care of everything." If the new technologies create some joblessness, a bit of expansionary macro fiscal and monetary policy will guarantee sufficient demand to restore full employment. If, in the distant future, people are satiated with consumption goods and services, the economist's answer is also reassuring: People will simply reduce their hours at work and allocate more time to leisure, as Keynes predicted in his 1930 article on "Economic Possibilities for Our Grandchildren" [5].

How will we spend our leisure in this ideal state? Perhaps as we increasingly do now—playing computer games and watching videos. If the computer stomping us in digital war or sports contests discourages us from becoming gamers, or if TV soap operas get boring, we can try the kinds of activity that Keynes presumably envisaged: lawn tennis or cricket, tea in the garden, admiring great art or symphonic music.

Economics holds that comparative advantage rather than absolute advantage determines trade. By extension, even if robots and other machines dominate humans at all jobs, comparative advantage guarantees that we will find work at the activities where the relative advantage of machines is least. If you understand comparative advantage but still fear robots turning you jobless, technophiles of innovation will denounce you as a neo-Luddite alarmist, a socialist, or a sociologist—or something worse.

## What happens to wages and incomes?

Employment, however, is just one side of the labor market calculus. What happens to wages is also important to well-being. If robots take the good jobs at high pay and humans get the low-pay leftovers, the living standards of persons dependent on labor income will fall. In such a scenario, Luddite fears would appear more realistic than assurances that comparative advantage guarantees work for all in a well-functioning economy.

But economics has a response to this danger. Herbert Simon's 1965 analysis of technological change showed that, in a well-functioning market economy, labor gains from labor-saving and capital-saving technologies—as long as the labor supply curve is less elastic than the capital supply curve [6]. In a full-employment economy, any technological advance raises the pay for the input with inelastic supply relative to the input with elastic supply. By treating capital as elastic and labor as inelastic, Simon essentially put Malthus upside down.

The historical facts fit Simon's model. On the price side, the real return to capital has been roughly constant in the long run, which implies an infinitely elastic supply curve, while real wages have trended upward. On the quantity side, the stock of physical capital and the stock of knowledge capital have increased massively relative to labor. The world population has grown but birth rates have plummeted as societies have become richer, suggesting that population growth will continue to fall far short of the growth of knowledge and capital. But Simon treated labor as homogeneous, and ignored the distribution of ownership of robots and related machines that is central to analyzing the impact of robots/mechanization on society.

## Treating labor as heterogeneous under skill-biased technical change

Labor economists treat labor as heterogeneous by making wage differences between skilled or educated workers and less skilled/less educated workers a prime area of research. Some analysts examine the job tasks and specific skills used in different occupations. As skill differentials increased over the past 40 years, despite a huge shift in the workforce toward skilled labor, many analysts have sought to explain the pattern of change in terms of skill-biased technical change that raised relative demand for skilled workers faster than the increasing supply of skilled workers. As we lack independent measures of the bias of technological change, it is hard to "prove" that technology does what the models claim it does. In almost all studies, technological change is an unmeasured factor operating behind the scenes.

The skill-biased story can explain some of the main facts, which is why economists devised it, although it does not fit all of the data [7]. And there is evidence that factors beyond technology—such as trade and immigration from low-wage, highly populous countries to advanced countries, and the weakening of trade unions throughout the advanced world—have also contributed to increased skill differentials and inequality. Since all advanced countries have access to the same technologies and have increased their supply of highly educated and skilled workers, moreover, the skill-bias hypothesis offers little insight into the different levels of inequality among countries. Inequality is higher in countries like the US, where labor market institutions such as trade unions and welfare state protections for workers are weak, than in countries where those institutions are stronger, as they are in many European countries.

The skill biased technology hypothesis captures part of reality but falls far short of a complete explanation of rising skill differentials and inequality, much less of changes in employment and unemployment over time and among countries. Moreover, to the extent that robotization has begun to extend up the skill ladder, with robots able to substitute for professionals as well as other workers, the bias of labor-saving technology will change. It is perhaps telling that the box of headlines on job-replacing robots shows no particular bias by level of skill. Whenever any task becomes cheaper to do with a machine than a person, eventually that task will shift to the machine unless humans take pay cuts. The "iron law" of the effect of robots on pay is that increased substitutability with human skills puts downward pressure on the wages of persons doing competing tasks–a pressure likely to grow in the future as technology improves the competence of robots and lowers their cost.

## Inequality in income and in capital

If "robots" are capital equipment that embodies modern technology, the distribution of income in virtually all advanced countries has shifted toward robots/capital and against labor for the past two decades. From 1990 to 2009 the share of national income in wages, salaries, and benefits declined in 26 of 30 OECD countries, including all of the large economies—those of the US, Germany, Japan, the UK, and France [8]. Labor's share of national income declines when productivity increases faster than real wages.

**Robots vs workers: Recent headlines from news articles on robots and work**

- Dorrier, J. "Burger robot poised to disrupt fast food industry." *SingularityHUB*, August 8, 2014.
- Kotler, S. "The uncanniest valley: What happens when robots know us better than we know ourselves." *Forbes*, July 20, 2014.
- Meltzer, T. "Robot doctors, online lawyers and automated architects: The future of the professions?" *The Guardian*, June 15, 2014.
- North, A. "Our robot nightmares." *New York Times Op-Talk*, June 29, 2014.
- Lewis, C. "GoCart robot delivers food in elderly and health care facilities." *RobotEnomics*, September 1, 2014.
- O'Toole, J. "Robots will replace fast-food workers." *CNN Money*, September 4, 2014.
- Jordan, B. "Chinese test self-printing robots." *Fox News*, March 4, 2014.
- "DR Congo recruits robots as traffic police." *Al Jazeera*, March 20, 2014.
- Gaudin, S. "Robots are taking mid-level jobs, changing the economy." *ComputerWorld*, October 31, 2011.
- Peplow, M. "Organic synthesis: The robo-chemist." *Nature* 512 (2014): 20–22.
- Klein, E. "How robots will replace doctors." *The Washington Post*, October 1, 2011.
- Aquino, J. "Nine jobs that humans may lose to robots." *NBC News.com*, 2012.
- "One in three jobs will be taken by software or robots by 2025." *Slashdot*, October 6, 2014.
- Worstall, T. "Phew, the robots are only going to take 45 percent of all the jobs." *Forbes*, September 18, 2013.
- Miller, C. "As robots grow smarter, American workers struggle to keep up." *New York Times: The Upshot*, December 15, 2014.
- Szondy, D. "Lowe's trials robot sales assistants." *Gizmag*, November 4, 2014.
- Niiler, E. "HERB: A robot that can unload a dishwasher and (sometimes) take apart an Oreo." *The Washington Post*, September 15, 2014.
- Eyre, M. "'Boris' the robot can load up dishwasher." *BBC News*, September 14, 2014.
- Flowers, A. "If a computer can diagnose cancer, will doctors become obsolete?" *FiveThirtyEight*, August 22, 2014.
- Dorrier, J. "Robots able to pick peppers, test soil, and prune plants aim to replace farm workers." *SingularityHUB*, November 8, 2014.

The magnitude of the declines varies: with the way national surveys measure wages, prices, gross domestic product (GDP), and employment; with the proportion of the workforce that is self-employed; with the difficulty of measuring labor and capital inputs; and with the proportion in the public sector, where productivity is hard to measure. In the US, labor's share, as estimated by the Bureau of Labor Statistics, fell more than labor's share as estimated by the Department of Commerce, and both differ from the OECD's estimates of the decline in labor's share. In developing countries, where many workers are in the informal sector, measurement difficulties are greater than in the advanced countries, but the share of national income going to labor seems also to have fallen, with a huge drop in China during its period of rapid growth. Given that capital income is distributed more unequally than labor income, the increased share of national product going to capital acts to raise income inequality in all countries.

Labor market analysis of inequality focuses, as noted, on incomes from labor. But here, too, capital is a substantial contributor to inequality. It is a substantial contributor to inequality in labor incomes because highly paid chief executive officers (CEOs) and top executives are paid stock options, restricted stock grants, and bonuses tied to capital income. While mode of pay does not tell the whole story (CEO-dominated boards could raise salaries if they were unable to pay executives through shares), it is telling that the persons with the greatest power in corporations prefer to be paid as owners rather than as wage and salary workers.

How should the increase in income inequality be assessed? Ages ago, when taxes on individuals and corporations were high and the distribution of wages relatively compressed in most advanced countries, the notion that greater inequality might spark innovation and economic growth had some plausibility. Some inequality is a necessary incentive to induce people to work harder. Narrowing the distribution of income and taxing businesses that make large profits through innovation reduces the incentive for entrepreneurship that is one of the virtues of capitalism. But today, after three decades or so of income redistribution from the middle class to the super-wealthy, that sort of argument has little traction. Organizations that favored labor market reforms that increased inequality, such as the OECD, now worry that "greater inequality in the distribution of market income…might endanger social cohesion" [8]. Others worry about the well-being of low-income citizens and their children as real wages and incomes fall. If the trend toward greater inequality continues, our societies will turn into a modern form of feudalism, with a few billionaires and their ilk dominating economic markets and governments as well, just as the lords and ladies of medieval Europe dominated their societies. The founders of the US believed that democracy could not survive with such high levels of inequality.

## Ownership is the key determinant of the impact of robots on workers

The "who-owns-the-robots-rules-the-world" thesis is simple: Regardless of whether technological advance is labor-saving or capital-saving, skill-biased or not, and regardless of the speed with which robots or other machines approach or exceed human skill sets, the key to the effect of the new technologies on the well-being of people around the world is who owns the technologies.

A thought experiment readily captures the importance of ownership on effect. Consider a world in which we create robots/machines that are sufficiently good at mimicking our work activities that they could readily replace us and earn what we currently earn. Would this technology make us better off, or worse off?

If we owned our replacements, we would have our current earnings and our time freed from labor to spend as we wished—playing computer games, drinking tea in the garden, engaging in wild orgies, or seeking other productive activity, possibly at lower wages. We would be better off.

If other persons owned our replacement robots, we would be jobless and searching for new work at lower pay while the owners of the robots would reap the pay/marginal product from the machines that took our jobs. The distribution of income would shift from us toward the owners of capital. They would be better off. We would be worse off.

## Replacement robots far-fetched?

In the academic world the replacement robots are in clear sight. They go under the name of Massive Open Online Courses (MOOCs), which allow students anywhere in the world to download lectures produced by video experts, with access to chat rooms for discussions. Many colleges and universities credit students for taking MOOCs just as they do for taking live lectures. MOOC videos can feature famous professors at leading universities, regular faculty at any college or university, or whoever or whatever can produce a course that teaches students the relevant knowledge and skills. Because videos have effectively zero marginal cost to replicate, they are far less expensive than hiring full-time faculty to lecture students on the same material semester after semester.

Now imagine that you are one of the faculty who currently gives lectures as part of your job. Each semester you explain multivariate calculus and complex numbers using a blackboard and chalk. Suddenly your university announces that they have found the "killer MOOC video" for calculus and complex numbers, and give you your walking papers. Students around the world would much prefer to have the Rapping Mathster on the MOOC video teach them calculus and complex numbers than some babbling professor.

Perhaps you will find work as a temporary offline adjunct faculty, running sections and grading exams at reduced pay. Perhaps you will curse the MOOC video and leave academia (and maybe end up on Wall Street, where you can help other displaced quants destroy the world's financial system for the second time). Only if you had property rights over using the new technology in your course or shares in the firm that made the video would you directly benefit from MOOC technology. Who owns the property rights to the videos/robots rules the higher education world.

## Solution?

What, then, is the solution to the declining economic position of labor in relation to capital, and the increased ability of robots and related technology to substitute for workers on many tasks?

One possibility is that trade unions could raise wages through collective bargaining and gain for workers a share of the higher productivity. That is the way workers have historically sought to increase their wages when firms have done better. But throughout the advanced world the influence of trade unions has weakened, becoming near to irrelevant in the private sector in some countries, such as the US.

Another possibility is that governments could use tax-and-spend policies to redistribute income toward lower-income citizens. That is the way welfare states have historically shifted income distributions from high-income to low-income citizens. But throughout the advanced world budgetary constraints and aging populations limit what most can do on the welfare side. In countries facing financial problems, the Troika—the International Monetary Fund (IMF), the European Commission, and the European Union (EU) Central Bank—have endorsed austerity programs that require countries to adopt policies that weaken trade unions, and reduce the pay and social benefits of ordinary workers. To be sure, social and political forces can change sharply in short periods of time. Big changes almost always come in short, sharp spurts. But it is difficult to see a burst of union activism and government programs changing the distribution of income toward labor in a future when robots are increasingly able to substitute for humans at workplaces.

Robots of the world unite? Maybe, but that may not benefit those of us who are flesh and blood instead of metal and circuits.

There is only one solution to the long-term challenge posed by machines substituting for human skills and reducing demand for skilled labor. That is for you, me, all of us to have a substantial ownership stake in the robot machines that will compete with us for our jobs and be the vehicle for capital's share of production. We must earn a substantial part of our incomes from capital ownership rather than from working. Unless workers earn income from capital as well as from labor, the trend toward a more unequal income distribution is likely to continue, and the world will increasingly turn into a new form of economic feudalism. We have to widen the ownership of business capital if we hope to prevent such a polarization of our economies.

There are diverse pathways to spread the ownership of capital. Ownership can take the form of worker assets in private pension funds or other collective savings vehicles that invest in shares on the stock market or that invest directly in equity in other firms. It can also take the form of workers buying shares or putting money in mutual funds themselves. But the form of ownership that potentially has the greatest economic benefit in dealing with robotization and the falling share of labor income is employee ownership.

Employee ownership refers to the many mechanisms for workers to gain an ownership stake in their firm: through owning shares held by an employee ownership trust; through receiving stock options as part of their pay; through having part of their pay come in the form of profit-sharing or other forms of group incentive pay; through being able to buy shares at low prices via employee stock purchase plans.

Firms with compensation policies that give workers some capital stake in their firm have better average performance than others. They do this by inducing workers to work harder and smarter [9]. Exemplar firms throughout the world operate in these ways: John Lewis in the UK, Mondragon in Spain, and Google and most of the high-tech firms in the US.

## LIMITATIONS AND GAPS

Because there are no independent measures of technological change, proving that technology does what models claim that it does is difficult. A skill-biased model can explain some of the facts but does not fit all the data. And factors beyond skills also contribute increased skill differentials and technology.

Labor market analysis of inequality focuses on incomes from labor, but capital is a substantial contributor to inequality.

## SUMMARY AND POLICY ADVICE

Stipulate that the main claims of this paper are correct: that the upward trend in capital's share and rising inequality combined with advances in artificial intelligence and robotization are moving our societies toward a 21st-century economic feudalism in which the owners of capital dominate the economy, and society more broadly. The problem in such a world is not workers losing jobs to machines. As long as the relative advantage of machines varies, there will be work for humans. The problem is that the owners of the machines will receive the vast bulk of the benefits of the technological progress. Whether such inequality will threaten social disorder, as the OECD and many other groups fear that current inequalities may do, or whether people will accept the new feudal order, is still unknown. But a world of massive inequality is surely not the most desirable outcome from technological change that can make everyone better off.

The best solution to this problem is for workers to own large shares of capital. How can citizens press policymakers to help spread employee ownership more widely? The US introduced tax benefits for Employee Stock Ownership Plans (ESOPs) in 1974, which helped spur a large ESOP sector that employs about 11 million workers today. The EU has endorsed such schemes in its various Pepper Reports and encouraged these forms of organization, though with, at best, modest success [10]. France mandated profit-sharing in the 1960s under de Gaulle. Tory and Labour governments in the UK have encouraged employment share purchase schemes. Many countries give tax breaks to employee stock purchase plans. But even without such breaks, enough firms in the US have extended some form of ownership stake to their workers that on the order of half of American employees get some part of their pay through profit-sharing, options, or stock ownership. In the US, at least, people with widely different ideological and economic views find attractive the notion of spreading ownership. One can imagine governments giving preferential treatment in procurement to firms that meet some basic "employee ownership" financial standard.

Given the different histories and economic structures of the advanced capitalist countries, each country will have to choose the way that best fits it to spread worker ownership of capital so as to give a stream of earnings from the technologies changing the world of work. If we don't succeed in spreading the ownership of capital more widely, many of us will become serfs working on behalf of the owners. Who owns the robots rules the world! Let us own the robots.

### Acknowledgments

The author thanks an anonymous referee and the IZA World of Labor editors for many helpful suggestions on earlier drafts.

### Competing interests

The IZA World of Labor project is committed to the *IZA Guiding Principles of Research Integrity*. The author declares to have observed these principles.

# REFERENCES

## Further reading

Atkinson, R. "Robots taking all our jobs? Ridiculous." InformationWeek, September 26, 2013. Online at: http://www.informationweek.com/global-cio/interviews/robots-taking-all-our-jobs-ridiculous/240161845

Snyder, M. "Robots and computers could take half our jobs within the next 20 years." The Economic Collapse, September 30, 2013. Online at: http://theeconomiccollapseblog.com/archives/oxford-professors-nearly-half-our-jobs-could-be-automated-within-the-next-20-years

## Key references

[1] Brynjolfsson, E., and D. McAfee. *Race against the Machine: How the Digital Revolution is Accelerating Innovation, Driving Productivity, and Irreversibly Transforming Employment and the Economy*. Lexington, MA: Digital Frontier Press, 2012.

[2] Frey, C. B., and M. A. Osborne. *The Future of Employment: How Susceptible are Jobs to Computerisation?* Oxford Martin School Working Paper, September 17, 2013. Online at: http://www.oxfordmartin.ox.ac.uk/downloads/academic/The_Future_of_Employment.pdf

[3] Hardy, Q. "IBM to announce more powerful Watson via the internet." *New York Times*, November 13, 2013. Online at: http://www.nytimes.com/2013/11/14/technology/ibm-to-announce-more-powerful-watson-via-the-internet.html?_r=0&pagewanted=print

[4] Rifkin, J. *The End of Work: The Decline of the Global Labor Force and the Dawn of the Post-Market Era*. Kirkwood, NY: Putnam Publishing Group, 1995.

[5] Pecchi, L., and G. Piga (eds). *Revisiting Keynes: Economic Possibilities for our Grandchildren*. Cambridge, MA: MIT Press, 2008.

[6] Simon, H. A. *The Shape of Automation (for Men and Management)*. New York: Harper and Row, 1965.

[7] Mishel, L., J. Schmitt, and H. Shierholz. *Robots: Assessing the Job Polarization Explanation of Growing Wage Inequality*. Economic Policy Institute Working Paper No. 295, January 11, 2013. Online at: http://www.epi.org/publication/wp295-assessing-job-polarization-explanation-wage-inequality

[8] OECD. *OECD Employment Outlook 2012*. Paris: OECD, 2012.

[9] Blasi, J. R., R. B. Freeman, and D. L. Kruse. *The Citizen's Share: Putting Ownership Back in Democracy*. New Haven, CT: Yale University Press, 2013.

[10] Lowitzsch, J., I. Hashi, and R. Woodward. *The PEPPER IV Report: Benchmarking of Employee Participation in Profits and Enterprise Results in the Member and Candidate Countries of the European Union*. Berlin: Inter-University Centre at the Institute for Eastern European Studies, Free University of Berlin, 2009. Online at: http://www.efesonline.org/LIBRARY/2009/PEPPER%20IV%20Web%20Oct-09.pdf

**The full reference list for this article is available from the IZA World of Labor website (http://wol.iza.org/articles/who-owns-the-robots-rules-the-world).**

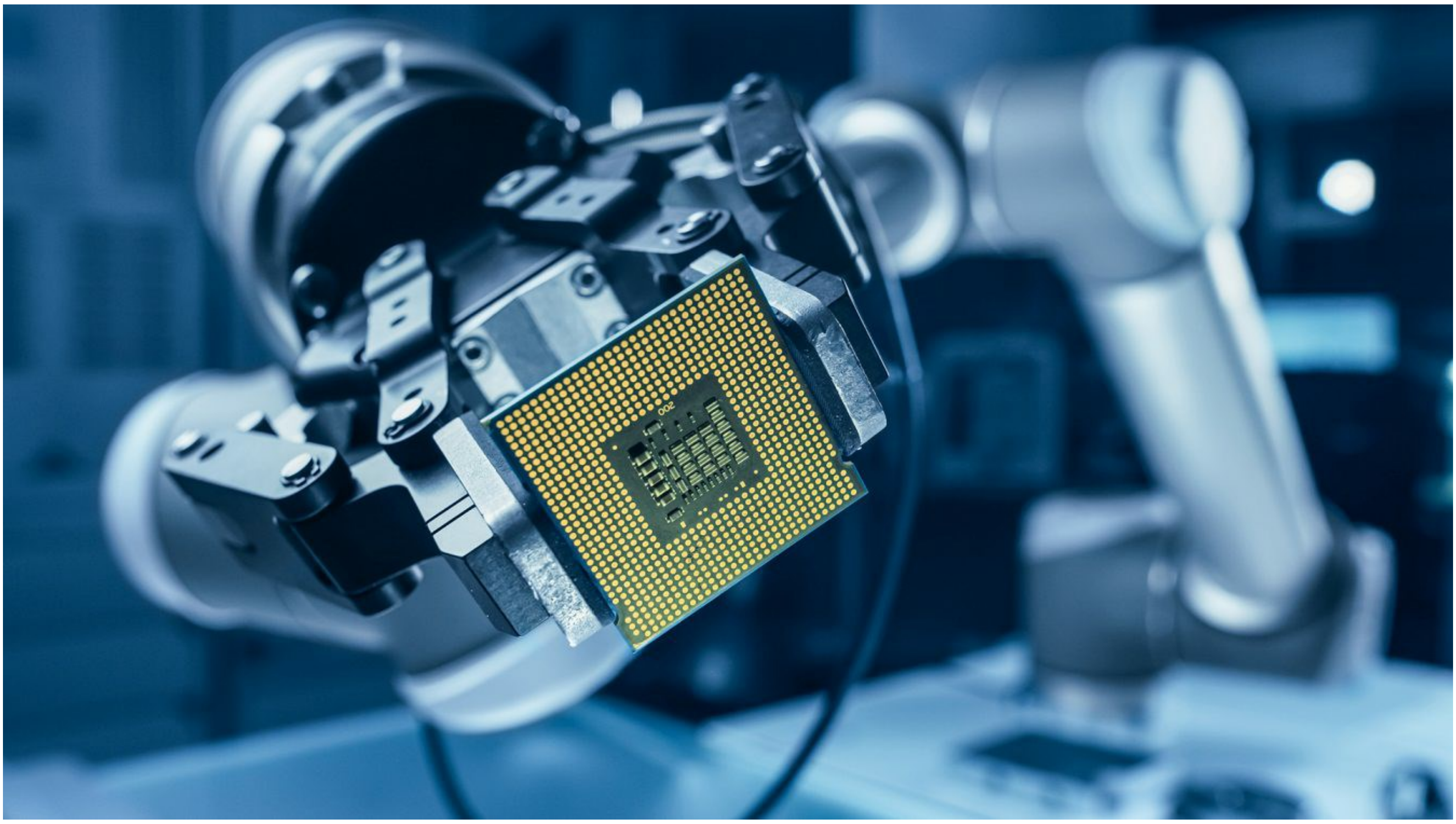
Perspectives

# Why China is focused on a robotic future

11 May 2022

The Chinese government has identified industrial robots as crucial to the country's economic strategy, using its 14th Five-Year Plan to announce that China will be a key source of global robotics innovation by 2025.[1]

Research analyst Daisy Zhang, part of Macquarie's Asia Equity Research team, says that while some of the impetus for this announcement comes from a desire to break the current reliance on expensive imported robots by building domestic capability, there are deeper economic factors at play.



Robots are vital to China's high- tech manufacturing sector, which will grow in importance over the coming years. But they could also be an effective tool for addressing many of the structural issues the economy is likely to face, specifically when it comes to an ageing population."

Daisy Zhang
Asia Equity Research team, Macquarie Capital

## China’s robotics sector today

For almost a decade now, China has been the world’s largest market for robotics. In 2020 alone, it installed 140,500 robots, accounting for as much as 44 per cent of all installations globally.[2] More importantly, the sector is expected to grow at a capitalised annual growth rate (CAGR) of 20 per cent in the five years to 2025. As a result, in 2020, robotics manufacturing density reached 246 units per 10,000 people, or almost twice the global average[3].

### Market size of industrial robots in China - 2017-2025E

Source: MIR, Macquarie Research, April 2022

Proportionally, these robots are being used to perform handling operations (42 per cent), electronics (37 per cent), welding (21 per cent) and automotive tasks (16 per cent). And, to date, the majority of the robots carrying out these operations have been imported ones. In 2019, China sourced around 71 per cent of new robots from foreign suppliers - most notably Japan, the Republic of Korea, Europe and the United States.[4]

## China's source of robots

Source: MIR, Macquarie Research, April 2022

China’s Ministry of Industry and Information Technology says that it will become the most robot-intensive country in the world by 2025. To achieve this, it will establish three to five robotics industry zones and double the intensity of robot manufacturing. In doing so, it will develop robots to work on tasks across 52 nominated industries, ranging from traditional fields such as automotive construction through to new areas such as health and medicine.[5]

## Why a domestic robotics industry matters so much

Zhang says that as well as fill a hole in the labour force, robots will also play a central role in powering China’s expansion of emerging industries and, potentially, new industries of their own.

China’s focus on developing a homegrown robotics sector is part of an overall push to become the world’s tech leader, with digital innovation receiving priority under the most recent Five-Year Plan. It is also consistent with the government’s stated policy of ‘dual circulation’, which will see China attempt to reduce reliance on overseas markets while fostering domestic consumption.[6]

But there is even more to its robotics focus than that, according to Zhang.

"China’s population is growing older, which means there will be fewer workers available to perform those tasks that need to be done to keep the economy going. Robots will be needed as labour supplementation, stepping in to fill that gap while improving efficiencies in the labour market."

In many ways, the scale of this challenge will be unprecedented, given how rapidly China is ageing. The effects of longer life expectancy, increased wealth and the one- child policy mean that between 1970 and 2020 the country's median age doubled from 19.2 to 38.4. While this is still well below some developed countries such as Japan (48.6), Germany (46.5) and Italy (46.5), it is already higher than both the United States (38.1) and Australia (37.0)[7].

The rate of China's ageing is so rapid that projections indicate that by 2050, China's median age will be 48, placing close to 40 per cent of the country's population - or some 330 million people - over the retirement age of 65.[8,9] To put that into perspective, even Japan, currently home to the world's oldest population, has well under 30 per cent of its people over this age.

## Performing the four Ds and more

Zhang says that as well as fill a hole in the labour force, robots will also play a central role in powering China's expansion of emerging industries and, potentially, new industries of their own.

"China is placing a lot of emphasis on smart manufacturing, and this is another key focus of the current Five-Year Plan. Many emerging technologies, such as new energy and lithium batteries, will require robotics." she says.

In 2021, the demand for industrial robots from lithium battery, warehouse logistics, and photovoltaic industries recorded 131 per cent, 103 per cent, and 51 per cent year-on-year growth respectively. The demand from these emerging industries is expected to remain stronger than in traditional industries, such as automotive and 3C (computer, communication, and consumer electronics).

"There are also a whole range of jobs which we call the four D's - dirty, dangerous, dull and dedicated tasks - which still need to be done and are much better performed by robots than humans. We expect to see growing demand from these sectors too," Zhang says.

Zhang argues that Chinese-manufactured robots could also start to supplant imported robots in areas in which they're already used, especially as they are likely to come at a significantly cheaper price than overseas-built ones.

"We put the price advantage of China's robots at 20 to 30 per cent," she explains. "When combined with fast product delivery and quick after-sales response, we expect the market share of domestic robot producers to rise significantly"

## Obstacles in the path

Despite the positive outlook for China's robotics industry, there are some challenges. The government itself notes in the 14th Five Year Plan that it must 'overcome supply and demand imbalances and supply chain stability'. It also cites 'a lack of technology accumulation, a weak industrial foundation and insufficient high-end supplies,' as obstacles in its path.[10]

On top of this, the domestic robotics industry as it currently stands is fragmented. The largest domestic producer, Etsun, enjoys just a 4.2 per cent market share. In this environment, picking winners can be difficult, although Zhang says that there are some companies that already enjoy a competitive advantage.

"Etsun is an established player and currently the seventh-largest supplier of robots in China. It is also one of the few domestic industrial robot suppliers with an integrated supply chain. The company is targeting a production volume of 50,000 units by 2025, up from 11,000 units in 2021."

"Leader Harmonious Drive System is also another key player, which is China's largest domestic harmonic speed reducer manufacturer, a critical component in industrial robots, it has a 20 per cent market share in China.

"Due to high technical requirement and the R&D investment required, most robot manufacturers procure speed reducers from external vendors, instead of seeking production in-house.

"While the speed reducer sector has been dominated by Japanese suppliers in the global and domestic market, we now see an enormous potential with continuous investment and R&D in this space."

## An unstoppable force

Despite these obstacles, Zhang observes that the robotisation of China is an "inevitable trend driven by substitution and strong demand from emerging industries," and one that will come to define China's economy over the next decades.

"The continuous increase in the industrial robot industry chain has lowered the capital threshold for enterprises to carry out automation transportation. We will see more and more businesses installing robots. Increasingly, these will be Chinese made."

"With this momentum, we have really entered a new era of technology transformation as robots are used to meet customers' needs for a higher quality and comprehensive service."

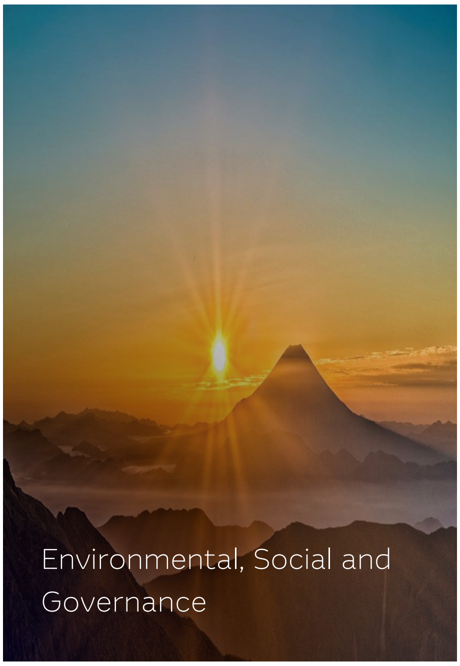

1. International Federal of Robotics, 'Understanding the New Five-Year Development Plan for the Robotics Industry In China'
2. International Federal of Robotics,' The new World Robotics 2020 Industrial Robots report shows a record of 2.7 million industrial robots operating in factories around the world'
3. China Daily, 'China aims to be hub of global robotics industry'
4. International Federal of Robotics, 'China Aims for Global Leadership in Robotics with new 5-year Plan'
5. Xinmei Shen, 'Rising automation power China aims to be a world robot champion by 2025', South China Morning Post, 29 Dec 2021'
6. China Power, 'Will the Dual Circulation Strategy enable China to compete in a Post-Pandemic World?'
7. Statista, 'Aging population in China'
8. John Kemp, 'China's productivity more important than its ageing population', Reuters, 12 May 2021'.
9. China Power, 'Does China have an ageing problem?'
10. He Huifeng, 'China's industrial automation efforts give hope to struggling industries but underlying problems persist'. South China Morning Post, 11 jan 2022

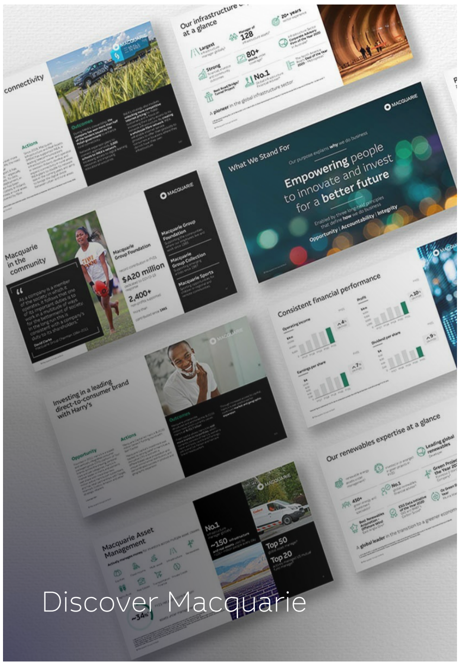


Learn more —

Macquarie Asia Equity Research →

Macquarie Capital →


## Disclaimer

This information is a general description of the Macquarie Group only. Before acting on any information, you should consider the appropriateness of it having regard to your particular objectives, financial situation and needs and seek advice. No information set out above constitutes advice, an advertisement, an invitation, a confirmation, an offer or a solicitation, to buy or sell any security or other financial, credit or lending product or to engage in any investment activity, or an offer of any banking or financial service. Some products and/or services mentioned on this website may not be suitable for you and may not be available in all jurisdictions. All securities and financial products or instrument transactions involve risks. Past performance of any product described on this site is not a reliable indication of future performance.

Xinmei Shen · 6 Jan 2020 · 3 min read

# China says AI robots won’t lead to significant job loss

There has long been a debate on whether robots will end up putting a large part of the population out of work. Now China says that AI and automation will indeed replace some jobs, but it won’t be as damaging as feared.

Photo credit: viteethumb/123RF

That’s according to a report published this week by the Chinese Academy of Social Sciences, a national think tank. It says that during China’s 14th Five-Year Plan, which starts in 2021, the rise of robots will not lead to “significant” job destruction.

Citing the report, state-run *People’s Daily* says low-skilled workers won’t be directly rendered obsolete – but will instead be transferred to other jobs.

Driven to become one of the world’s strongest manufacturing powers by 2020 while facing the pressure of an aging population, China has been developing and adopting robots in different industries.



Ecommerce companies including Alibaba and JD.com have automated some of their warehouses and deployed delivery robots.

(*Abacus* is a unit of the *South China Morning Post*, which is owned by Alibaba.)

Restaurants and hotels in China have also installed service robots, delivering food to people's tables and rooms. Some cities also started using police robots, which patrol the streets, snap photos of dangerous drivers, and alert people who are jaywalking.

Industrial robots that help boost manufacturing power are also widely used. China installed 154,032 industrial robots in 2018 according to the International Federation of Robotics (IFR), more than the number of industrial robots installed in Europe and the Americas combined.

But because of an outsized workforce, China still lags behind in terms of robot density – the number of industrial robots deployed for every 10,000 manufacturing workers. In 2019, China had 97, far behind the US with 200 and South Korea's 710, according to the IFR. China aims to boost that number to 150 by 2020.



People in China believe that there is a benefit to a more automated workforce: One survey conducted last year by UK digital marketing firm Dentsu Aegis Network found that 65% of Chinese respondents think that AI and robotics will help create more jobs instead of taking them.

But that's not always true. Foxconn, a key manufacturing partner for Apple, among others, cut 60,000 jobs in a factory in the eastern city of Kunshan in 2016 while installing robots. The southern city of Dongguan, one of China's manufacturing hubs, has cut its manufacturing workforce by 280,000 and installed 91,000 robots in the past five years.

The new report by the Chinese Academy of Social Sciences also said that during China's 13th Five-Year Plan (which ends this year), robots and other AI applications will have taken roughly 8 million to 10 million manufacturing jobs from migrant workers, averaging 1.6 million to 2 million per year.

Still, many are positive about the long-term outlook. Estimations by economists for the percentage of jobs replaced by robots varies depending on their methods, but by 2037 AI and related technologies could create 12% more jobs, according to a PwC report from September 2018. That would mean an additional 93 million jobs.

PwC predicts that AI and related technologies could displace up to 26% of existing jobs in China over the next two decades, but the income effect could create additional jobs by 38%. Labor-saving technologies could lower product prices, and companies might need more workers to address extra demand. They could also improve the quality of existing products, which could enable new products that need additional workers, PwC says.

But even positive projections point to one possibly glaring problem: inequality. The Chinese Academy of Social Sciences suggests levying a tax on the use of robots to fund retraining workers threatened by automation. It's an idea promoted by Bill Gates and already in place in South Korea.

*Visit abacusnews.com or subscribe to the newsletter via abacusnews.com/newsletter for the latest China tech news, reviews, and product launches.*



RECOMMENDED READS

Editing by Charmaine de Lazo

(And yes, we're serious about ethics and transparency. More information here.)

**Share**

Community Writer
Xinmei Shen
Xinmei Shen is a producer at Abacus (abacusnews.com). She's interested in how people make and use tech in China.

VIEW ALL COMMENTS