The Robotics Revolution

The Next Great Leap in Manufacturing

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THE NEXT GREAT LEAP IN MANUFACTURING

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INTRODUCTION

It has been roughly four decades since industrial robots—with mechanical arms that can be programmed to weld, paint, and pick up and place objects with monotonous regularity—first began to transform assembly lines in Europe, Japan, and the U.S. Yet walk the floor of any manufacturer, from metal shops to electronics factories, and you might be surprised by how many tasks are still performed by human hands—even some that could be done by machines. The reasons are simple: economics and capabilities. It is still less expensive to use manual labor than it is to own, operate, and maintain a robotics system, given the tasks that robots can perform. But this is about to change.

The real robotics revolution is ready to begin. Many industries are reaching an inflection point at which, for the first time, an attractive return on investment is possible for replacing manual labor with machines on a wide scale. We project that growth in the global installed base of advanced robotics will accelerate from around 2 to 3 percent annually today to around 10 percent annually during the next decade as companies begin to see the economic benefits of robotics. In some industries, more than 40 percent of manufacturing tasks will be done by robots. This development will power dramatic gains in labor productivity in many industries around the world and lead to shifts in competitiveness among manufacturing economies as fast adopters reap significant gains.

A confluence of forces will power the robotics takeoff. The prices of hardware and enabling software are projected to drop by more than 20 percent over the next decade. At the same time, the performance of robotics systems will improve by around 5 percent each year. As robots become more affordable and easier to program, a greater number of small manufacturers will be able to deploy them and integrate them more deeply into industrial supply chains. Advances in vision sensors, gripping systems, and information technology, meanwhile, are making robots smarter, more highly networked, and immensely more useful for a wider range of applications. All of these trends are occurring at a time when manufacturers in developed and developing nations alike are under mounting pressure to improve productivity in the face of rising labor costs and aging workforces.

To assess the potential impact of the coming robotics revolution on industries and national competitiveness, The Boston Consulting Group conducted an extensive analysis of 21 industries in the world's 25 leading manufacturing export economies, which account for more than 90 percent of global trade in goods. We analyzed five common robot setups to understand the investment, cost, and performance of each. We examined every task in each of those industries to determine whether it could be replaced or augmented by advanced robotics or whether it would likely remain unchanged. After accounting for differences in labor costs, productivity, and mix by industry in each country, we developed a robust view of more than 2,600 robot-industry-country combinations and the likely rate of adoption in each.

The following are some of the key findings of this research:

- *Robotics use is reaching the takeoff point in many sectors.* The share of tasks that are performed by robots will rise from a global average of around 10 percent across all manufacturing industries today to around 25 percent by 2025. Big improvements in the cost and performance of robotics systems will be the catalysts. In several industries, the cost and capabilities of advanced robots have already launched rapid adoption.

- *Adoption will vary on the basis of industry and country characteristics.* Among high-cost nations, Canada, Japan, South Korea, the UK, and the U.S. currently are in the vanguard of those deploying robots; Austria, Belgium, France, Italy, and Spain are among the laggards. Some economies, such as Thailand and China, are adopting robots more aggressively than one might expect given their labor costs. Four industrial groupings—computers and electronic products; electrical equipment, appliances, and components; transportation equipment; and machinery—will account for around 75 percent of robotics installations during the next decade.

- *Manufacturing productivity will surge.* Wider adoption of robots, in part driven by a newfound accessibility by smaller manufacturers, will boost output per worker up to 30 percent over the medium term. These gains will be in addition to improvement from other productivity-enhancing measures, such as the implementation of lean practices.

- *Savings in labor costs will be substantial.* As a result of higher robotics use, the average manufacturing labor costs in 2025—when adjusted for inflation and other costs and productivity-enhancing measures—are expected to be 33 percent lower in South Korea and 18 to 25 percent lower in, for example, China, Germany, the U.S., and Japan than they otherwise would have been.

- *Robots will influence national cost competitiveness.* Countries that lead in the adoption of robotics will see their manufacturing cost competitiveness improve when compared with the rest of the world. South Korea, for example, is projected to improve its manufacturing cost competitiveness by 6 percentage points relative to the U.S. by 2025, assuming that all other cost factors remain unchanged. High-cost nations—such as Austria, Brazil, Russia, and Spain—that lag behind will see their relative cost competitiveness erode.

- *Advanced manufacturing skills will be in very high demand.* As robots become more widespread, the manufacturing tasks performed by humans will become more complex. The capacity of local workers to master new skills and the availability of programming and automation talent will replace low-cost labor as key drivers of manufacturing competitiveness in more industries. There will be a fundamental shift in the skills that workers will need in order to succeed in advanced-manufacturing plants.

The right time for making the transition to advanced robotics will vary by industry and location. But even if that time is several years away, companies need to prepare now. They must gain a clear understanding of the cost dynamics in their global production networks and develop insight into the robotics trends both in their industries and in each country in which they manufacture. They must remain constantly up to date with regard to changes in the price and performance of robotics relative to the cost of human labor, what the competition is doing, and how the technology is likely to evolve. Perhaps most important, manufacturers must start developing the workforces, technical skills, and processes needed to compete in the robotics age—and ensure that their investments translate into productivity gains and stronger cost competitiveness.

THE FORCES BEHIND THE ROBOTICS TAKEOFF

INDUSTRIAL ROBOTS—MACHINES THAT can be automatically controlled and reprogrammed and that can manipulate objects and move along three or more axes—were first introduced in Europe, Japan, and the U.S. in the 1960s. About 1.4 million industrial robots are in use around the world today.

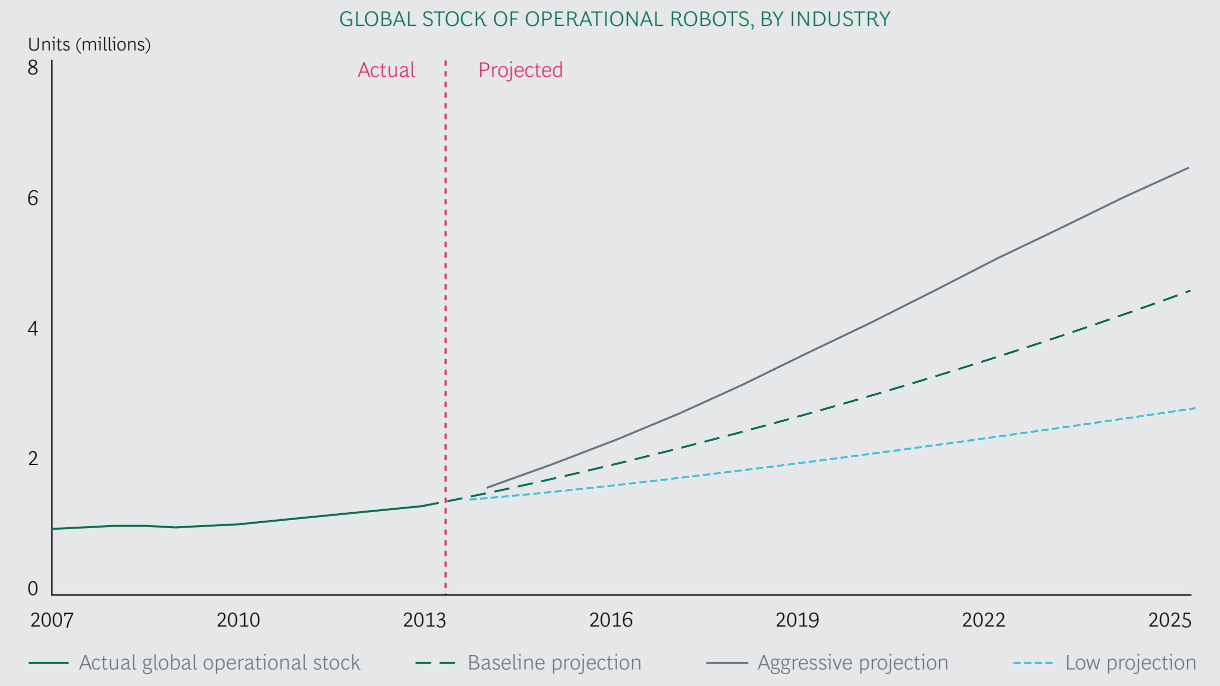
Yet even in many high-cost economies, the use of robots has remained limited in most industries. In Italy, for example, only one-half of 1 percent of tasks have been automated in the chemical and primary-metals industries, though around 14 to 16 percent could be automated today. Adoption rates have also remained surprisingly low in industries that long have been at the forefront of automation. Fewer than 8 percent of tasks in the U.S. transportation-equipment industry are automated, for example, compared with a potential of 53 percent. The global installed base for robots has been growing by around 2 to 3 percent annually for around a decade—roughly in line with growth in manufacturing output.

The use of industrial robots is also highly concentrated. Nearly three-quarters of all robots operate in just four industrial groupings: computers and electronic products; electrical equipment, appliances, and components; transportation equipment; and machinery. What's more, 80 percent of the robots sold each year are deployed in just five countries: China, Germany, Japan, South Korea, and the U.S. And because robotics systems have historically been so expensive to own and operate, they are found mainly in large factories owned by corporations with big capital budgets.

A dramatic takeoff in advanced robotics is imminent.

A number of economic and technical barriers to wider adoption are beginning to fall, however. As a result, a dramatic takeoff in advanced robotics is imminent. We expect that growth in the installed base of robotics will accelerate to around 10 percent annually during the next decade, by which time installations will surpass 4 million. (See Exhibit 1.) Annual shipments of robots will leap from around 200,000 units in 2014 to more than 500,000 by 2025 according to our baseline projection, and to more than 700,000 in a more aggressive scenario. Even so, we project that, by 2025, those installations will represent only about one-quarter of all manufacturing tasks and far less than that amount in other industries and major manufacturing economies. The growth potential over the long term, therefore, should remain immense.

Exhibit 1 | Global Robotics Installations Will Increase by About 10 Percent Annually Over the Coming Decade



Sources: International Federation of Robotics; BCG analysis.
Note: Market size is estimated from an evaluation of jobs within U.S. industries that may be automated, and the estimate is then extended to global manufacturing output by industry.

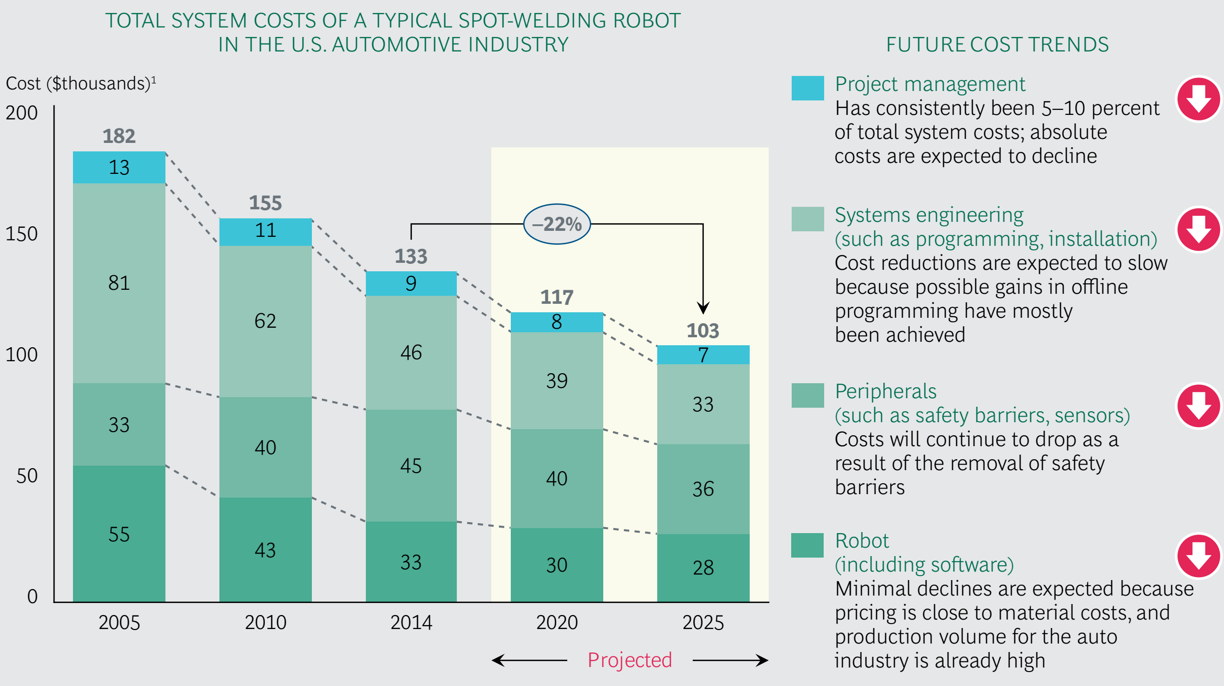
Three major trends are speeding global industries toward an inflection point at which advanced industrial robots will become much more commonplace. That point will be characterized by greater cost-effectiveness for robots when compared with human labor, technological advances that are wiping out barriers to adoption in key sectors, and the arrival of systems that smaller manufacturers can afford and easily use.

Cost and Performance

For many organizations, the biggest reason for not replacing manual labor with robots is purely economic. We believe that most organizations begin to ramp up their investment in automation when the cost of employing human labor rises high enough above the cost of owning and operating robotics systems to make human labor less cost-effective. We have assumed conservatively that this point is reached when the cost of human labor becomes 15 percent higher than the cost of robotics labor. Yet even with the relentless rise in wages around the world, the gap remains wide enough to prevent mass deployment.

The economics of advanced robotics are improving rapidly, however. For example, the total cost of purchasing and deploying a robotics system for spot welding in the U.S. automotive industry plunged from an average of $182,000 in 2005 to $133,000 in 2014 (not adjusted for inflation). By 2025, the total cost is projected to drop by approximately another 22 percent, to around $103,000. The prices of robotics hardware and software, which account for only one-quarter of that total cost, are around 40 percent lower than they were a decade ago. The cost of systems engineering—which includes installing, programming, and integrating a robotics system into a factory—has declined even more. Ten years ago, the average systems-engineering costs of a spot-welding robot amounted to $81,000. Those costs are now down to around $46,000, on average, and are likely to keep dropping for the rest of the decade. The costs of peripheral equipment—such as sensors, displays, and expensive safety structures that protect workers and that together typically cost more than the robots themselves—are plunging as well. (See Exhibit 2.) In fact, safety barriers may not be required at all for many next-generation robots.

Exhibit 2 | While the Costs of Advanced Industrial Robots Fall, Their Performance Is Steadily Improving



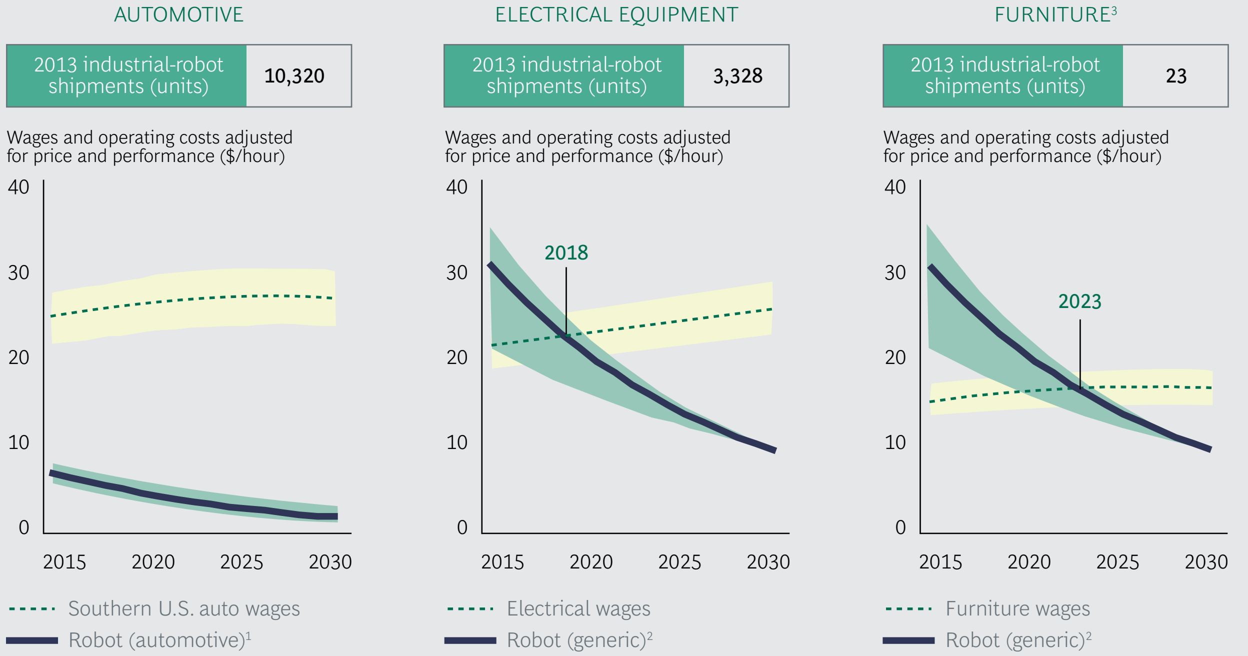
Sources: ABB, *Economic Justification for Industrial Robotic Systems,* 2007; International Federation of Robotics, *World Robotics: Industrial Robots*; expert interviews; BCG analysis.
Note: Because of rounding, not all numbers add up to the totals shown.
[1]Values are in nominal U.S. dollars.

At the same time that costs have been declining, the performance of robotics systems has been improving by around 5 percent per year. Taken together, the changes in price and performance for spot welding, for example, have been translating into an annual 8 percent improvement in the cost of robotics. To put this into perspective: an investment of $100,000 today buys a robotics system that is capable of performing more than twice as much work as a robotics system costing the same amount a decade ago. This pace of improvement in price and performance is expected to be sustained for the foreseeable future.

Robotics systems are thus becoming an economically viable alternative to human labor in more and more industries. A human welder today earns around $25 per hour (including benefits), while the equivalent operating cost per hour for a robot is around $8 when installation, maintenance, and the operating costs of all hardware, software, and peripherals are amortized over a five-year depreciation period. In 15 years, that gap will widen even more dramatically. The operating cost per hour for a robot doing similar welding tasks could plunge to as little as $2 when improvements in its performance are factored in. (See Exhibit 3.)

Other industries are quickly approaching inflection points. The U.S. electronics and electrical-equipment manufacturing industries currently deploy about 3,300 industrial robots, many of them relatively basic and designed to perform simple tasks. But manufacturers are in the process of adding more versatile—and more expensive—robots to take on increasingly complex tasks. Today, the cost of a "generic" robotics system—which has a high degree of flexibility and thus can take on many different types of work—is around $28 per hour. By 2020, this cost is projected to fall to less than $20 per hour, which would be below the average human worker's wage. This will enable a significant increase in the number of tasks that can be automated. We estimate that, as a result, the percentage of tasks

Exhibit 3 | Robotics Are Already an Economically Viable Alternative to Human Labor in Many U.S. Industries



Sources: U.S. Bureau of Labor Statistics; Industrial Federation of Robotics, *World Robotics: Industrial Robots*; expert interviews; BCG analysis.
Note: Assumes an 8 percent rate of improvement in price and performance. Hourly rates for labor include benefits and overhead, an increase of about 50 percent over base hourly pay. All values shown in nominal 2014 U.S. dollars.
[1]The cost is for a typical spot-welding robot system in the U.S. automotive industry.
[2]An example of a generic robotics system is ABB's IRB 2400.
[3]Includes other wood products.

handled by advanced robots will rise from 8 percent today to 26 percent by the end of the decade.

Some industries will be slower to adopt. In furniture manufacturing, where tasks remain more difficult to automate, the economic payoff of using robots is still a number of years away. Based on our estimates, the adoption of robots in that industry won't begin in earnest until 2020; and it will be near the end of the next decade before even 10 percent of tasks are automated.

Technological Advances

The technical capabilities of most industrial robots today are still quite limited. Traditional robots are rigid: they are fixed in the same location and can handle only objects that are of a uniform size, oriented in a predictable way, and moving at a determined speed. Most can process images and detect features on objects, but they lack the logic capabilities to make decisions about those objects.

What's more, heavy and expensive safety devices have been required to protect workers from robots in operation. Robots are typically found isolated in the corner of a work environment, performing tasks that are highly repetitive and require consistency and accuracy or tasks that are hazardous to humans. If the robots are mobile, collision avoidance systems are often necessary as well. Such impediments have greatly narrowed robots' usefulness for many industrial applications.

Thanks to leaps in technology, however, advanced robotics systems can now perform tasks and work in environments that are far less structured. As costs drop, companies can afford to buy robots with arms that rotate freely, giving them more flexibility to handle objects and enabling them to deal with objects whose dimensions, features, and properties vary. Robots also have more sophisticated sensors to see and feel objects and can be more quickly and easily reprogrammed to perform different tasks. Advanced robots are more "intelligent" as well. They can apply logic to make decisions about objects, judge quality, and receive and provide feedback to other parts of a production system through information technology. Special safety barricades are not required for many advanced robots, which means that they can work side-by-side with humans. Even some very low-cost robots can work together with humans to complete their collective tasks.

Improvements are driving wider adoption by small and midsize manufacturers.

These capabilities have greatly expanded the utility of robots in a range of industries. Meat processing is one good example. Cutting and trimming meat is very challenging for traditional robots because the pieces of meat come in different shapes, and their properties can vary significantly. One German company has solved this problem with a 3D visual-inspection system that enables advanced robots to trim and cut.

One traditional obstacle to wider robotics use in the fabricated-metals industry has been the difficulty of translating computer-aided-design drawings for complex jobs, such as grinding a gear to remove burrs and other defects, into instructions for a robot. Computer-aided-manufacturing software tools such as Robotmaster, by Jabez Technologies—which integrates robot programming, simulation, and code generation—make doing so much easier.

Electronics manufacturing has presented special challenges for automation. Robots are often used to place components onto flat surfaces, such as circuit boards, for example. But it has been difficult to design a robot that can install very small parts, such as connectors, at odd angles with high degrees of precision and at very high speeds—the abilities necessary to build an automotive battery, for instance. As a result, the industry remains quite labor intensive. But there is progress: Japanese robotics giant Fanuc has demonstrated a high-speed robot that rotates along six axes and has the dexterity to perform such tasks.

Most advanced robots can be quickly reprogrammed for new jobs, giving manufacturers the flexibility to produce small batches of customized products without additional capital investment. Wiring accessory manufacturer ABB Elektro-Praga, for example, needed to increase throughput at its factory in the Czech Republic. The company wanted machines that could pick parts from a bin and orient them properly for assembly, a task that conventional robots could not perform at high speed and with precision. It also wanted robots that could work on different product configurations with minimal adjustment. ABB Elektro-Praga installed several of ABB's IRB 140 robots on a new assembly line linked to a vision system equipped with digital cameras. The vision system enables the robots to orient parts and place them at a cycle time of 2.3 seconds per electrical socket, for example. It takes only 10 minutes to adjust the system to pick and place parts for different products, which are often changed up to 30 times each week. As a result of the new system, ABB Elektro-Praga says that it has boosted throughput of each shift by a factor of about nine. Only one worker is required to oversee the entire robotics assembly line.

Accessibility for Small Manufacturers

The steady improvements in cost, performance, and functionality of robotics systems are driving another force in the next manufacturing revolution: the wider adoption of robots by small and midsize manufacturers. Until recently, such systems have been prohibitively expensive and overly complex for enterprises with limited capital budgets and engineering resources.

The new generation of innovative systems is putting robots within the financial reach of small enterprises. Universal Robots, for example, markets the UR5, an industrial robot that is designed for material handling and assembly and has a base price of $34,000. Its two arms rotate along six axes, resulting in remarkable flexibility for a machine of that price. By our analysis, the total cost of installing such low-cost generic robots can range from $50,000 to $100,000 when accounting for associated costs and the project management required to make it all come together. Universal says that the average cost of installing the UR5 is around $50,000. Two of Rethink Robotics' robots—Baxter and the company's high-performance robot, Sawyer—are designed for precision applications, such as machine tending and circuit board testing. Each costs around $40,000, including accessories, warranties, and installation. Because they can be redeployed quickly and easily across multiple product lines, the Rethink robots can be used in high-mix environments that are impractical for conventional industrial robots.

In addition to their low cost, the UR5 and Rethink robots can easily be moved by hand and repurposed by workers with no programming experience. They can safely work next to humans on the same production line without expensive barricades or other protective equipment, eliminating a major cost associated with conventional industrial robots.

RSS Manufacturing & Phylrich—a Costa Mesa, California, manufacturer of high-end plumbing fixtures and faucets with 72 employees—illustrates how such machines can pay off for even small and midsize manufacturers. The company wanted an inexpensive automation solution that could easily be moved to perform different production tasks in the factory, so it purchased a UR5. One of the robot's first jobs was to help fill an order to make 700 valves a month. With its existing computer-numerical-control milling machine, the company could produce only 400 valves a month with two work shifts. By using the UR5 robotic arm to feed parts into and remove them from the milling machine around the clock, RSS was able to fill the order in 11 days while increasing production capacity by 30 percent. By using the UR5 for another job—to feed tubes into a bending machine—the company was able to produce 1,500 pieces in four hours, a task that otherwise would have taken two to three days. The company estimates that it achieved a return on its investment in a few months.

As economic and technical barriers continue to fall, robots are becoming accessible for more companies. The production efficiencies will spread beyond individual factories through entire supply chains, industries, and national economies.

INDUSTRIES AND ECONOMIES LEADING THE ROBOTICS REVOLUTION

For the past few decades, the scramble for competitive advantage in manufacturing has largely revolved around finding new and abundant sources of low-cost labor. Rapidly rising wages in most big emerging markets are bringing the era of easy gains from labor cost arbitrage to a close. A little more than a decade ago, for example, Chinese labor costs were around one-twentieth of those in the U.S. Today—after accounting for productivity, logistics, and other costs—the manufacturing cost gap between China and the U.S. has nearly disappeared for many products that are sold in the U.S. (See *U.S. Manufacturing Nears the Tipping Point: Which Industries, Why, and How Much?*, BCG Focus, March 2012.)

As a result, manufacturers the world over are under intensifying pressure to gain advantage the old-fashioned way: by improving their productivity. This imperative came through loud and clear in our 2014 BCG Global Manufacturing Cost-Competitiveness Index, which revealed changes in direct manufacturing costs of the world's 25 leading manufacturing export economies from 2004 to 2014. In the economies where cost competitiveness improved or held steady during that period—such as Mexico, the Netherlands, the UK, and the U.S.—productivity growth largely offset increases in such direct costs as wages and energy. Economies whose productivity did not keep pace with rising costs—including Australia, Brazil, China, and most countries of Western Europe—either lost ground in manufacturing cost competitiveness or faced increasing pressure. (See *The Shifting Economics of Global Manufacturing: How Cost Competitiveness Is Changing Worldwide*, BCG report, August 2014.)

Even though the shift toward automation has been a driver of productivity improvement for decades, advanced robots will help to accelerate this trend and will boost productivity even further in a number of ways. Robots can complete many manufacturing tasks more efficiently, effectively, and consistently than human workers, leading to higher output with the same number of workers, better quality, and less waste. Robots will free up skilled workers to focus more of their time on higher-value tasks. Because advanced robots often can perform many tasks autonomously, moreover, they can keep working through the night as human workers sleep, in effect serving as a third production shift.

To estimate the potential productivity gains from wider adoption of robots, we calculated the savings in total manufacturing labor costs over the next decade under the conservative assumption that machines will perform at least one-quarter of the manufacturing tasks that can be automated, compared with a global average of around 11 percent today. We adjusted our model for differences in robotics adoption rates by economies and industries, as well as projected increases in factory wages.

We estimate that, as a direct result of installing advanced robots, and depending on the location, output per worker in manufacturing industries will be 10 to 30 percent higher in 2025 than it is today. This increase will be over and above the productivity gains that can be expected to come from other measures, such as lean production practices and better supply-chain management. The impact on cost is likely to be just as dramatic. We estimate that, because of wider robotics use, the total cost of manufacturing labor in 2025 could be 16 percent lower, on average, in the world's 25 largest goods-exporting economies than they would be otherwise.

All manufacturers and economies will not share these benefits equally, however, because adoption rates of advanced robotics will vary sharply. The basic economic trade-off between the cost of labor and the cost of automation will continue to be a primary consideration. So will the technical capabilities of machines to replace manual labor. Labor laws, cultural barriers to substituting machines for humans, the availability of capital, the foreign-investment-policy environment, and the age and skill levels of workers are also important considerations.

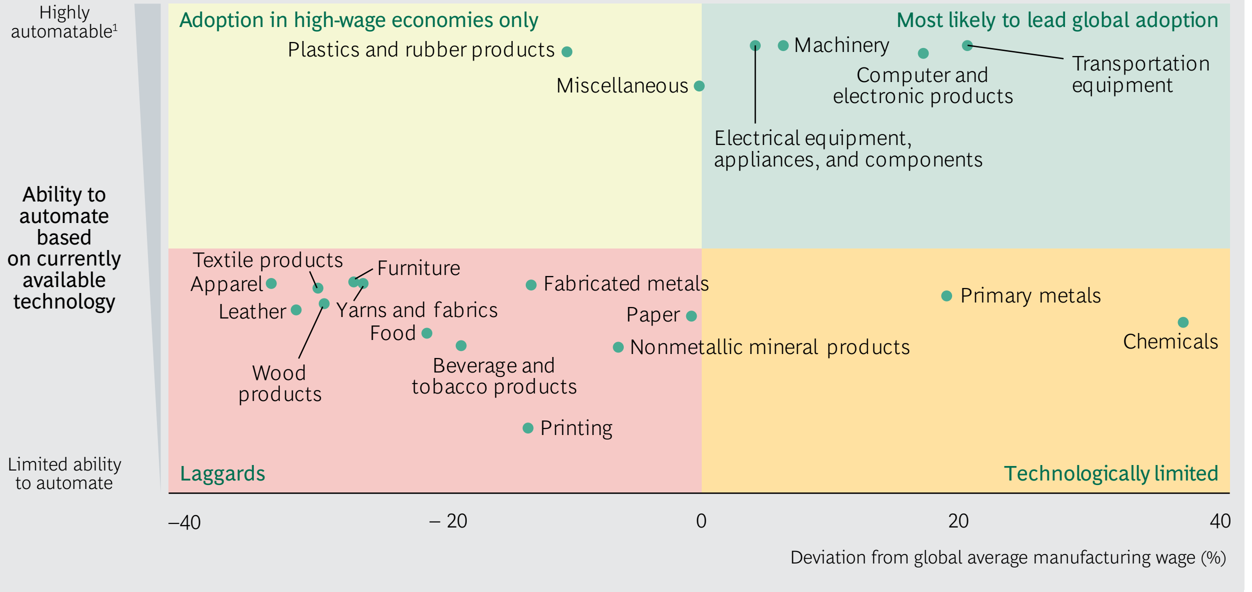
To get a fuller picture of advanced robotics' potential to boost productivity, therefore, it is important to assess the opportunities and challenges industry by industry and economy by economy.

The Impact on Industries

Two key considerations will heavily influence how widely robots are deployed in industries. How cost-effective is it to substitute machines for human labor? And how easy is it to automate production tasks? (See Exhibit 4.)

Manufacturing industries in which labor accounts for the highest portion of costs are generally the most likely candidates for automation, although it will be more challenging for some industries than others. Labor costs range from around 15 percent of production costs in typical chemical, food-product, and steel plants to approximately 30 percent in ap-

EXHIBIT 4 | Some Industries Are More Likely to Benefit from Robotics Because of High Wages and Automatable Tasks



Sources: U.S. Bureau of Labor Statistics, "International Labor Comparison of Hourly Compensation Costs in Manufacturing Industries, 2012"; BCG analysis.
Note: Petroleum and coal manufacturing are not depicted because of a high and variable wage premium, consistent with immovable, resource-intensive industries.
¹These are defined as occupational tasks that have the potential to be replaced with advanced robotics.

parel, furniture, fabricated-metals, electronics, and printing facilities. Location is also important, of course. Industries concentrated in a low-cost economy—such as India, where manufacturing wages adjusted for productivity averaged $5.25 per hour, with benefits, in 2014—will be less likely to adopt automation than those based in a high-cost economy, such as Australia, where hourly productivity-adjusted labor costs average $55.70. But there are also major cost differences among industries. Whether manufacturing for the petroleum and coal production industries takes place in a high-cost economy or a low-cost one, for example, the median wage is about double that for all manufacturing industries. In the apparel industry, wages are 32 percent lower, on average.

> Some industries have tasks that simply are not robot friendly.

The technical limits of wider robotics use will also vary by industry. Each industry has its own set of job roles—such as material handlers, welders, assemblers, and quality inspectors—and each role has its own set of tasks. Some of these tasks are potentially automatable, while others are not. Furthermore, different production tasks call for different robotics functions—some of which will require more expensive robotics systems than others. A machine that simply lifts materials of the same shape and size from one place and moves them to another may be far less costly than one able to visualize and feel nonuniform materials. What's more, some industries have tasks, such as picking up pieces of cloth to be sewn into apparel, that simply are not robot friendly and therefore will likely be done, for the most part, by workers in low-cost locations for at least the near to medium term. The growth potential of robots in these industries is more limited. If a way could be found to automate such processes, however, robotics could transform the clothing industry from one in which manufacturing is done globally to one that is more local.

We calculated the costs of robotics for 21 industries by aggregating all of the production tasks and types of robots required by those industries. We then adjusted those costs for expected improvements in performance and projected them over ten years. Finally, we amortized the investment in robotics systems over five years to arrive at a cost per hour in U.S. dollars and compared that amount with the projected labor costs in each economy. On the basis of these cost-performance projections and automatable tasks, we developed estimates for robot adoption for the next decade in each of the 21 industries.

The four industry groups that currently account for the vast majority of global robot use will remain in the vanguard: computers and electronic products; electrical equipment, appliances, and components; transportation equipment; and machinery. (See Exhibit 5.) According to our projections, these four industry groups will account for around 75 percent of robot installations globally through 2025. (See Exhibit 6.) Currently, at least 85 percent of the production tasks in these industries are automatable. Most tasks involving assembly and the tending of machines, for example, are highly repetitive and involve rigid materials, so they can be performed by relatively basic robots. Wages in these industries are also relatively high because many tasks require highly skilled workers. Global wages in the transportation and computer industries, for example, are roughly 20 percent higher than average global manufacturing wages.

As a result, in many economies, investments in robotics systems in these industries are likely to generate a return on investment in the near term. Robotics systems currently cost around $10 to $20 per hour, on average, to own and operate in the U.S. in these sectors—already below the cost of human labor—and will decline further over the next decade. We project, therefore, that robots will perform 40 to 45 percent of production tasks in each of these industries by that time, compared with fewer than 10 percent today.

In another cluster of industry groups, robots will most likely be adopted in high-wage economies in the near term, and wider adoption

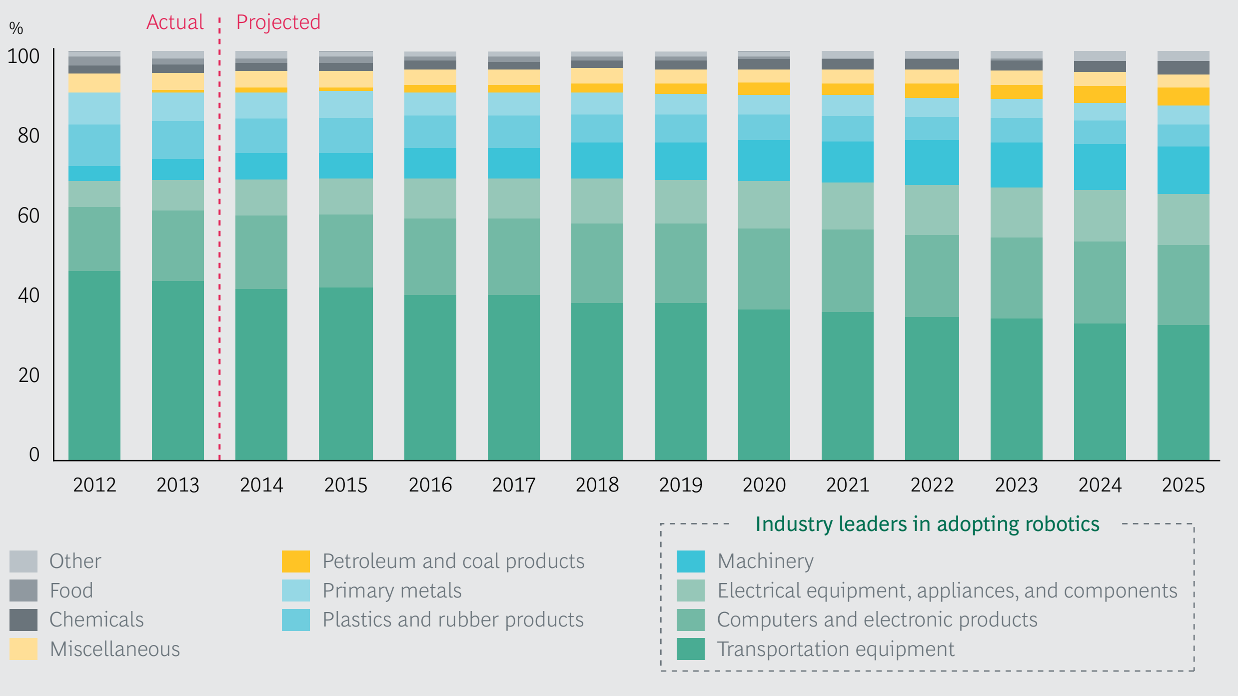
Exhibit 5 | Four Industries Will Lead the Adoption of Advanced Industrial Robots

INDUSTRY	RATIONALE AND IMPLICATIONS
Computers and electronic products Electrical equipment, appliances, and components Transportation equipment Machinery	• More than 85 percent of production tasks within the industry are identified as potentially automatable • High manufacturing wages in the industry will lead to economical adoption in most economies • Will reach near saturation in the late 2020s
Plastics and rubber products Miscellaneous Petroleum and coal products Primary metals	• Limited penetration today; high percentage of automatable tasks • Moderate factory wages • Likely to be adopted only in high-wage economies in the near term; future decreases in the cost of robotics will drive further adoption
Chemicals Nonmetallic mineral products Wood products Paper Fabricated metals Food Textile mill products	• Materials are typically ill suited for manipulation by robots; current technology limits robots to a few tasks • Low manufacturing wages • Significant future adoption will require low-cost solutions or technological breakthroughs

Sources: OECD STAN Bilateral Trade Database; BCG analysis.

Exhibit 6 | Four Industries Will Account for About 75 Percent of Robotics Installations by 2025

GLOBAL STOCK OF OPERATIONAL ROBOTS, BY INDUSTRY[1]



Sources: International Federation of Robotics; BCG analysis.
[1]Includes the current stock of robots and changes by shipment volume that add to the operational stock of robots. Historical trends indicate that around 60 percent of all shipments add to operational stock while the remainder are replacement purchases. The analysis assumes that the fraction adding to the operational stock will remain constant through the next decade.

will occur as the costs and performance of systems improve. These groups include plastics and rubber products; petroleum and coal products; and primary metals. We project that robots will perform 10 to 20 percent of tasks in these industries globally by 2025. Economics will be the main limitation. Although around 86 percent of tasks in plastics and rubber-products plants can be automated—such as material handling, assembly, welding, and machine operation—manufacturing wages are expected to remain relatively lower. This will limit the financial benefits of automation, especially in low-wage emerging markets.

A number of industries will remain a poor fit for robots in the near term. Chemicals, wood products, paper, fabricated metals, food processing, and textile products are prominent examples. We project that robots will perform only about 1 to 5 percent of tasks in these industries a decade from now. Global manufacturing wages in these industries are low because they tend to have a smaller portion of automatable jobs and because the economic trade-offs don't justify broad robotics adoption, at least for now.

Over the next decade, five countries will account for 80 percent of robot shipments.

Technical impediments to widespread robot use also exist in certain industries. As mentioned previously, the biggest hurdles for machines in apparel manufacturing are the abilities to pick up single pieces of cloth and then align them so that they can be cut and fed through a sewing machine—tasks that are still better done by humans. As a result, the hourly cost of owning and operating a robot in a U.S. apparel, textile, chemical, or paper plant ranges from around $40 to $47. By 2025, that cost is projected to drop to around $20 to $25 per hour, which would still not be competitive with labor in apparel factories in many countries. In other industries, many of the tasks that can be automated—such as handling heavy or hazardous materials—are already performed by machines.

The Impact on Economies

Robotics will penetrate the manufacturing sector to different degrees in different economies as well. The mix of industries in each economy will be one of the variables in assessing robot penetration. Another will be regulations that make it difficult and very expensive for companies to replace workers; economies with such regulations will probably adopt robotics at lower rates. Other variables include the cost, supply, and flexibility of labor and the availability of investment capital.

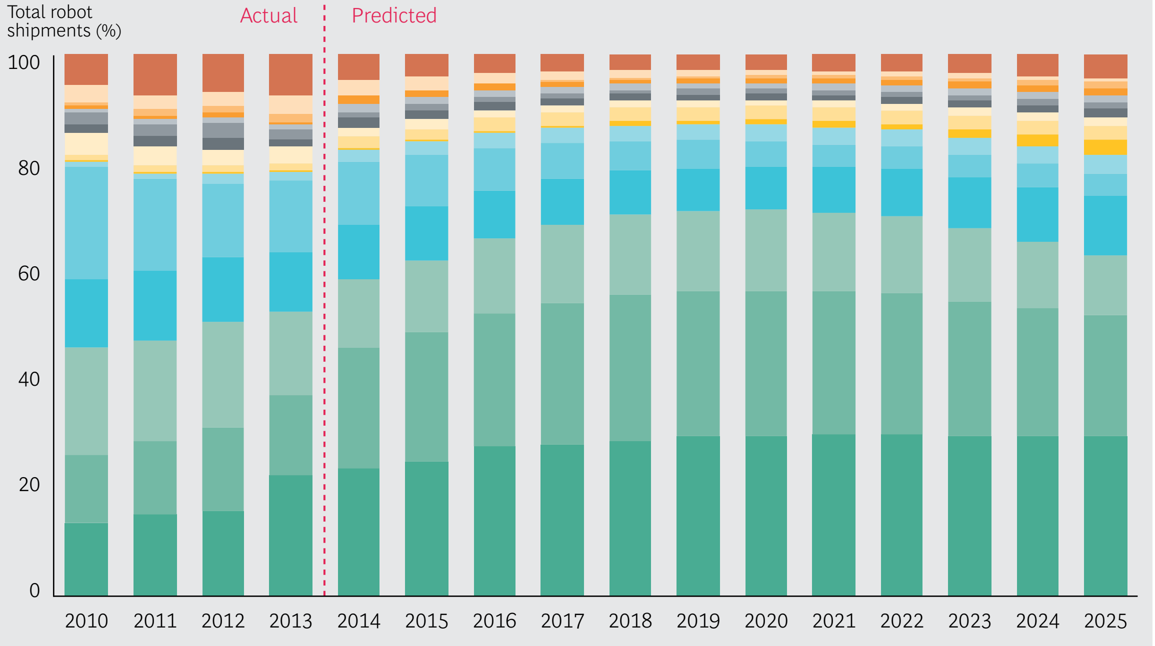
On the basis of these factors and current trends, our projections show that five countries—China, the U.S., Japan, Germany, and South Korea—will account for around 80 percent of robot shipments over the next decade; China and the U.S. alone will account for around half of those shipments. (See Exhibit 7.)

We found that industries in certain economies are embracing robots much more energetically than we would expect, given the underlying economic factors. In other economies, robotics adoption is lagging even though the economic rationale for automation seems compelling.

To get a sense of who is in the vanguard, we analyzed the world's 25 biggest manufacturing export economies. These economies, which account for around 90 percent of goods exports, are included in the 2014 BCG Global Manufacturing Cost-Competitiveness Index. We grouped these economies into four categories of robotics adopters: aggressive, fast, moderate, and slow. (See Exhibit 8.)

Aggressive Adopters. Indonesia, South Korea, Taiwan, and Thailand have been installing more robots than would be expected given these economies' productivity-adjusted labor costs. South Korea, for example, is installing robots at a pace that is about four times the global average. As a result, robots in South Korea are projected to perform around 20 percent of tasks—considered the takeoff point for adoption—by 2020 and 40 percent of tasks by 2025. Thailand's manufacturing sector is installing robots at around the same pace, while companies in Taiwan and Indonesia are installing them at about twice the rate

EXHIBIT 7 | Five Economies Will Account for Nearly 80 Percent of Robot Shipments Through 2025



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
UNITS (THOUSANDS)	112	151	146	163	200	250	300	350	400	450	500	550	550	500	500	450
TOP FIVE (%)	79	77	76	78	80	81	83	83	84	84	84	83	83	81	80	77

Other, Taiwan, Mexico, Australia, Brazil, Thailand, France, Italy, Canada, Russia, UK, South Korea, Germany, Japan, U.S., China

Sources: International Federation of Robotics; BCG analysis.

EXHIBIT 8 | Major Goods-Exporting Economies Follow Four General Patterns of Robotics Adoption

ADOPTION CATEGORIES	ECONOMIES
AGGRESSIVE	Indonesia, South Korea, Taiwan, Thailand
FAST	Canada, China, Japan, Russia, UK, U.S.
MODERATE	Australia, Czech Republic, Germany, Mexico, Poland
SLOW	Austria, Belgium, Brazil, France, India, Italy, Netherlands, Sweden, Spain, Switzerland

Sources: The Economist Intelligence Unit; Organisation for Economic Co-operation and Development; The Fraser Institute; ETUI's website www.worker-participation.eu; Ius Laboris; L&E Global; Thomson Reuters Practical Law; BCG analysis.

of average economies. In developing economies, such as Indonesia, one motive for installing robots faster than might seem warranted is to help factories achieve the same quality standards as those in developed economies. If these trends continue, robots in some developing economies will perform around 50 percent of tasks by 2025, and adoption will reach the traditional market-saturation point for technology—approximately 60 percent—in 15 to 20 years.

Robots in some developing economies will perform 50 percent of tasks by 2025.

The high adoption rate is partly explained by the fact that all four economies are experiencing higher-than-average wage growth, have some of the lowest unemployment rates in the world, and have workforces that are aging fast. South Korea has even launched a new five-year plan to expand its intelligent-robot industry and promote widespread adoption. The plan calls for $2.6 billion in public and private investment; a tripling of annual revenues, to $7 billion; and $2.5 billion in annual exports by 2018. Forward-looking businesses, therefore, are investing in robots when they build new capacity. What's more, workers can be dismissed with relatively little severance pay under current labor regulations, making it easy to replace humans with robots in these aggressive-adopter economies.

Fast Adopters. Canada, China, Japan, Russia, the UK, and the U.S. are all witnessing rapid adoption that is in line with their economic outlook. As mentioned earlier, industries generally ramp up automation when using robots becomes 15 percent cheaper per hour than employing humans. We project that robots in some of these economies will perform 30 to 45 percent of tasks by 2025 and that adoption will reach the saturation point in 20 to 25 years.

Manufacturers in the fast-adopter economies often incur limited costs when dismissing employees. Government approval typically is not required for layoffs, although some economies, such as China, are starting to toughen their policies. Severance benefits, if required at all, usually range from two days to one month per year of service. Most fast-adopter economies also have relatively high labor costs, when adjusted for productivity, and several economies have rapidly aging workforces.

Nevertheless, companies in China are installing robots in new factories even though wages in most of China remain relatively low. This may be because companies anticipate that the rapid rise in Chinese wages over the past decade will continue for the foreseeable future. They could also be anticipating that skill shortages in several provinces will worsen. In fact, robot purchases in China rose particularly sharply in 2013, when it more closely fit the pattern of an aggressive adopter. In that year, robot shipments increased by 59 percent—to 37,000 units—far outpacing China's 11 percent expansion in manufacturing output and 6 percent growth in hourly productivity-adjusted wages. If China continues on this more aggressive adoption path, average total labor costs in manufacturing could be 30 percent lower in 2025. If it remains a fast adopter, however, costs are expected to be 24 percent lower.

Moderate Adopters. Australia, the Czech Republic, Germany, Mexico, and Poland are installing robots at a measured pace that is in line with those countries' economic growth. Industries are ramping up automation investment more moderately than fast adopters when they reach the inflection point of 15 percent cost savings over workers. Robots are expected to perform 30 to 35 percent of tasks by 2025, and adoption is not likely to reach market saturation before 2035, at the earliest.

Labor regulations that require employers to justify work dismissals and disburse severance pay slow down robot adoption. Restrictions on foreign ownership and government control over market interest rates in several economies also deter investment in automation.

Slow Adopters. Austria, Belgium, Brazil, France, India, Italy, the Netherlands, Sweden, Spain, and Switzerland are installing robots at the slowest rate among the top 25 manufacturing export economies. This is despite the fact that, with the exception of India, these nations have some of the highest labor costs, when adjusted for productivity. They also have aging workforces and are expected to face serious skill shortages. If this trend continues, robots will perform at most 15 percent of tasks by 2025, and it will take several decades to reach market saturation. This will make it harder for the slow adopters to compete with the faster ones.

Regulations in some economies that prohibit replacing workers with robots are among the biggest barriers to automation. Companies must often negotiate with governments to dismiss workers and then must pay high severance packages to those former employees—in some cases equal to more than two years of wages. In India, for example, companies with more than 100 employees require permission from the ministry of labor and employment to fire someone. This lack of flexibility not only hinders the automation of existing factories, it also discourages new long-term capital investment in production facilities. In other economies, heavy government control of interest rates and restrictions on foreign ownership and investment are additional deterrents to slow adopters.

These differences in robotics adoption may seem small and less noticeable now. But over time they are likely to lead to significant gaps in productivity gains and manufacturing costs among leading export economies—especially as more and more industries reach the inflection point and investment in robots accelerates. Indeed, we believe that as wage gaps between low-cost and high-cost economies continue to narrow, robot adoption could emerge as an important new factor that will contribute to redrawing the competitive balance among economies in global manufacturing.

HOW ROBOTS WILL REDEFINE COMPETITIVENESS

To understand the likely winners and losers in the robotics revolution, we estimated the impact that projected robotics-adoption rates would have on productivity and labor costs in each of the 25 leading manufacturing export economies, given their mix of industries. (See Exhibit 9.)

In many cases, the impact on cost competitiveness will be dramatic. According to our projections, the biggest beneficiaries will be manufacturers in South Korea, where the combined cost of human labor and robotics in 2025 will be an estimated 33 percent lower than it would be without greater robotics adoption. That is double the average cost reduction estimated across all 25 economies—and should give South Korea a real advantage.

We estimate that labor costs will be around 25 percent lower in Japan, 24 percent lower in Canada, 22 percent lower in the U.S., 21 percent lower in Germany and the UK, 20 percent lower in Australia, and 18 percent lower in China and the Czech Republic.

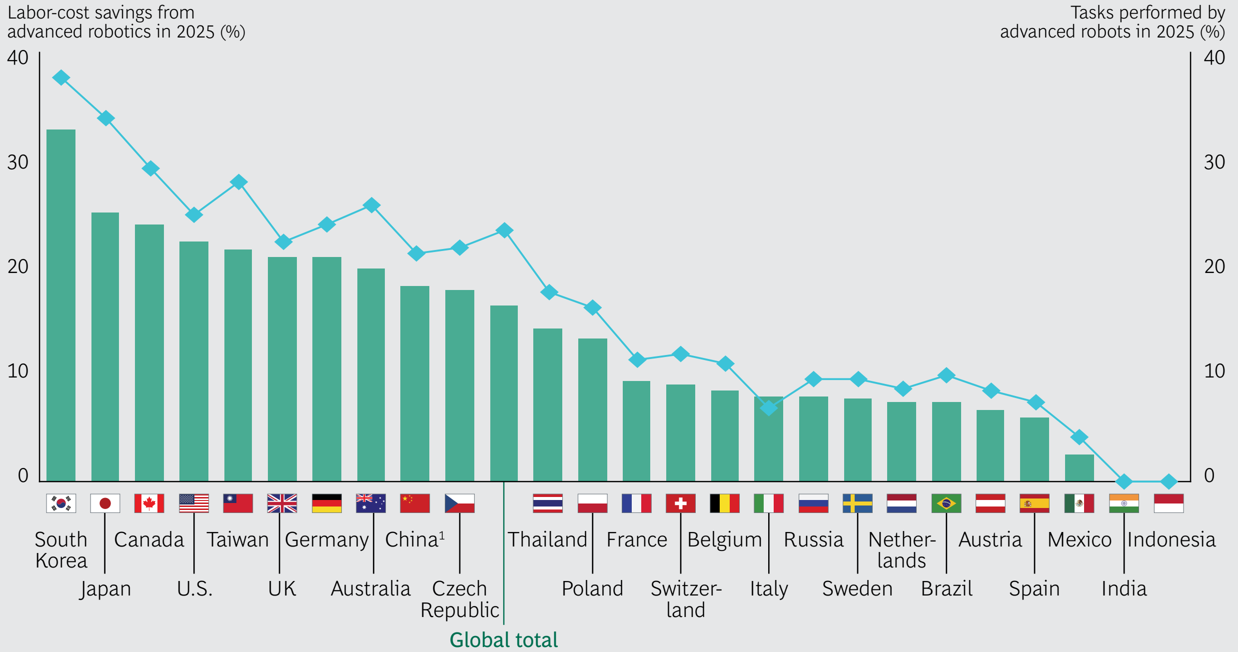
Economies that are expected to adopt robotics relatively slowly will see far less impressive cost reductions. We project that robots will lower costs by just 3 percent in Mexico and will have negligible influence on labor costs in India and Indonesia, where manufacturing wages are expected to remain very low through 2025.

The savings from advanced robots will also be modest in a number of developed economies that already suffer from a combination of relatively high wages, low productivity, tight labor markets, and labor restrictions. In France, Switzerland, Belgium, Italy, Russia, Sweden, Austria, the Netherlands, Brazil, and Spain, labor cost reductions will range from about 9 percent to 6 percent. This translates into losses in competitiveness of as much as 4 points for a host of economies, when indexed against the U.S. (See Exhibit 10.)

In economies such as India and Mexico, losing ground will have little tangible impact. Because labor rates are projected to remain low in those economies for the next ten years, they will still likely have very competitive cost structures a decade from now—and will, therefore, remain attractive locations for the many industries in which automation is difficult.

Several high-cost economies, however, stand to fall further behind. Cost increases that have exceeded productivity growth have eroded the competitiveness of, for example, Belgium, Brazil, France, and Italy over the past decade. We expect these economies to be slow to invest in automation, despite the strong economic case for doing so and the urgent need to accelerate productivity, because of a host of economic, cultural, and social barriers. Such tardiness will likely lead to further deterioration of these economies' competitiveness.

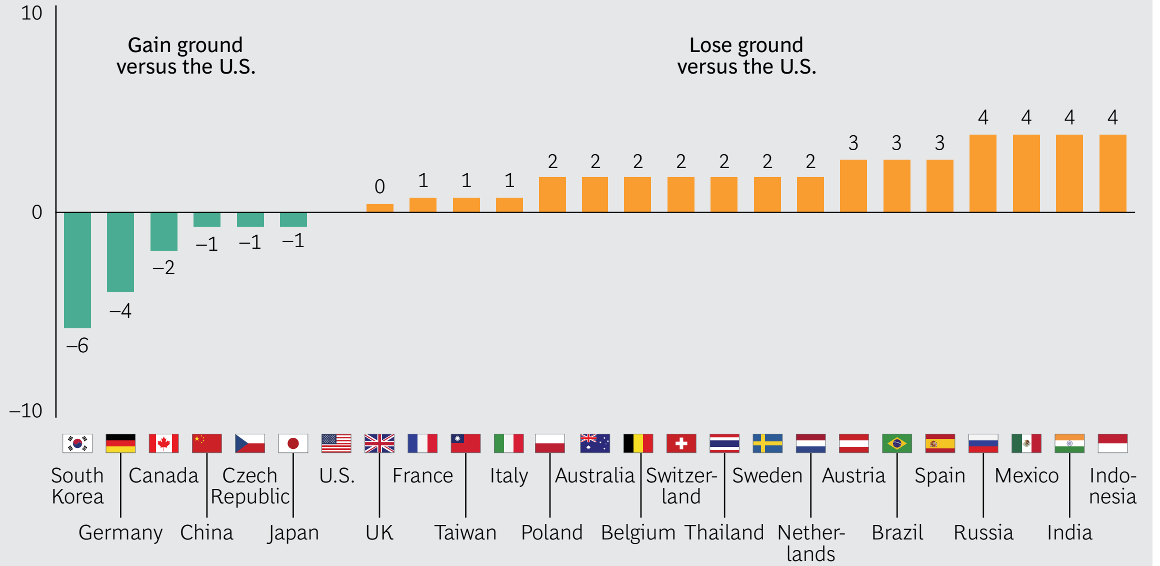
Exhibit 9 | Greater Adoption of Robots Could Lead to Global Labor-Cost Savings of About 16 Percent by 2025



Sources: OECD STAN Bilateral Trade Database; U.S. Bureau of Labor Statistics; BCG analysis.
[1]The China figures are based on labor data for the Yangtze River Delta region.

Exhibit 10 | Robots Could Shift the Economics of Global Manufacturing

THE POTENTIAL CHANGE IN BCG'S MANUFACTURING COST-COMPETITIVENESS INDEX AS A RESULT OF ROBOTICS, 2014–2025[1]



SCENARIOS	South Korea	Germany	Canada	China	Czech Republic	Japan	U.S.	UK	France	Taiwan	Italy	Poland	Australia	Belgium	Switzerland	Thailand	Sweden	Netherlands	Austria	Brazil	Spain	Russia	Mexico	India	Indonesia
Aggressive	–11	–12	–3	–5	–4	–2	0	0	–6	1	–5	1	1	–2	–2	2	–0	0	0	1	2	6	6	7	7
Conservative	–4	–0	–1	–0	0	–1	0	–0	–0	–0	–0	1	1	0	0	1	0	0	1	1	1	1	1	2	2

Sources: OECD STAN Bilateral Trade Database; U.S. Bureau of Labor Statistics; BCG analysis.
Note: Each economy is measured relative to the U.S., thus a one-point gain versus the U.S. means that the direct manufacturing costs of the economy in question will become one percentage point cheaper relative to the U.S. by 2025.
[1]BCG's Global Manufacturing Cost-Competitiveness Index tracks changes in direct manufacturing costs in the world's top 25 export economies. For further information, see *The Shifting Economics of Global Manufacturing: How Cost Competitiveness Is Changing Worldwide,* BCG report, August 2014.

PREPARING FOR THE ROBOTICS REVOLUTION

FEW MANUFACTURING COMPANIES WILL be left untouched by the new robotics revolution. But getting the timing, cost, and location right will be critical. Investing in expensive robotics systems too early, too late, or in the wrong location could put manufacturers at a serious cost disadvantage against global competitors. To gain competitive advantage, companies need to adopt a holistic approach to the robotics transition. We recommend that companies take the following actions:

- *Understand the global landscape.* First, companies need a clear picture of the trends in robot adoption around the world and in their industries. They need to know how the price and performance of robots are likely to change in comparison with the total cost of labor in each economy where they manufacture—and how this comparison is likely to change in the years ahead. They must also factor in other considerations, such as the flexibility of labor rules and the future availability of workers, that support or hinder wider robotics adoption in a given economy. It is important to keep in mind that these are moving targets.

- *Benchmark the competition.* Companies need to be well aware of what their competitors are currently doing and understand what they will do in the future. If robotics adoption is expected to rapidly increase in their industry, they should assume that the total cost of systems will fall. This knowledge will help companies more accurately estimate the cost and timing of investments as well as make decisions about where to locate new capacity.

- *Stay technologically current.* Rapid advances in technology mean that companies must stay abreast of the evolving capabilities of advanced robotics systems. They should have a clear view of whether and how quickly innovation is resolving technical barriers that so far have inhibited the use of robots, such as the ability to manipulate flexible or oddly shaped materials or to operate safely alongside workers. Just as important, when will these new applications be cost-effective? As they take stock of the new capabilities and the improvements in price and performance, many companies—even small and midsize manufacturers—may discover that installing robotics is more cost-effective than they once thought. In some cases, having a view on the evolution of robotics and automation can help a company determine whether it is better to wait for a better technology to emerge or to implement a new process that allows them to upgrade technology without having to duplicate what they have already done. In many ways, timing is crucial.

- *Prepare the workforce.* As more factories convert to robotics, the availability of skilled labor will become a more important factor in the decision about where to locate production. Tasks that still require manual labor will become more complex, and the ability of local workforces to master new skills will become more critical. The availability of programming and automation talent will also grow in importance. Companies and economies must prepare their workforces for the robotics revolution and should work with schools and governments to expand training in such high-compensation professions as mechanical engineering and computer programming.

- *Prepare the organization.* Even if the economics don't yet favor major capital investment, companies should start preparing their global manufacturing operations now for the age of robotics. They should make sure that their networks are flexible enough to realize the benefits of robotics as installations become economically justified in different economies and as suppliers automate. They should get themselves up to speed on new advanced-manufacturing technologies and think about how they will transform their current production processes so that these technologies can achieve their potential. For many manufacturers, adapting to the age of robotics will require a transformation of their operations.

Manufacturers do not have the luxury of waiting to act until the economic conditions for robotics adoption are ripe. Our projections show that when the cost inflection point arrives, robotics installation rates are likely to accelerate rapidly. This will provide the opportunity to create a substantial competitive advantage. Companies and economies that are ready to capitalize on the opportunity will be in a position to seize global advantage in manufacturing.

FOR FURTHER READING

The Boston Consulting Group publishes many reports and articles on global manufacturing that may be of interest to senior executives. Examples include the following.

The Rise of Robotics
An article by The Boston Consulting Group, August 2014

The Shifting Economics of Global Manufacturing: How Cost Competitiveness Is Changing Worldwide
A report by The Boston Consulting Group, August 2014

Prepare for Impact: 3D Printing Will Change the Game
An article by The Boston Consulting Group, September 2013

Behind the American Export Surge: The U.S. as One of the Developed World's Lowest-Cost Manufacturers
A Focus by The Boston Consulting Group, August 2013

The U.S. Manufacturing Renaissance: How Shifting Global Economics Are Creating an American Comeback
An e-book, knowledge@Wharton, November 2012

U.S. Manufacturing Nears the Tipping Point: Which Industries, Why, and How Much?
A Focus by The Boston Consulting Group, March 2012

NOTE TO THE READER

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