Competition & Change

Competition & Change
2024, Vol. 0(0) 1–23

DOI: 10.1177/10245294241261878
journals.sagepub.com/home/cch
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Getting robots in 'our own hands': Structural drivers, spatial dynamics and multi-scalar industrial policy in China

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Abstract

Robots are a key digital production technology of the Fourth Industrial Revolution. In 2020, China accounted for one third of all industrial robots in operation globally. The emerging literature has mainly focused on the effects of robotization, while evidence on its drivers and spatial diffusion remain limited. We address this gap by producing new evidence on the complex mix of structural and policy factors driving fast robotization across China and its regions. We identify three 'structural drivers' of robotization – demand pull, supply push and capability preconditions – and study the resulting spatial dynamics of technology adoption. We find significant heterogeneity in robots' adoption across regions and sectors, in robots manufacturing and technological capabilities. Furthermore, we highlight the key role of a fourth 'policy driver' – industrial policy – and conduct an in-depth analysis of robotization policies at the national and province levels since 2016. We identify four main robotizing regional hubs in China – Guangdong, Yangtze-River-Delta, Beijing-Tianjin and Jilin-Liaoning. We finally analyse three emerging policy interfaces linking Made in China 2025 (within which China's robotization policy is framed) and the Belt and Road Initiative – that is, opening markets, shaping industry and standards, and directing finance. With this new multi-scalar industrial policy configuration, China is further reshaping the domestic and international political economy of robotization, ultimately moving the country ahead in the digital technology race.

Keywords

Robots, diffusion, structural drivers, industrial policy, China, regional hubs, made in China 2025, belt and road initiative

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JEL Codes
O14, O25, O30, R11

Introduction

The emergence and diffusion of new technologies of the so-called Fourth Industrial Revolution (4IR) is increasingly transforming the nature of industrial sectors and opening the way to new organizational and business models. Advances in technology, such as sensorization, additive manufacturing and intelligent automation, robots and collaborative robots, as well as related data analytics – Internet of Things (IoT), digital platforms and supply chains – have opened new windows of opportunity for industrial innovation (Sturgeon, 2021). These technologies and their 'fusion' into new digital technology systems have the potential to increase firms' productivity, reshape employment dynamics and redesign the geography of production (Andreoni et al., 2021).

The first computer-controlled automated production lines were installed in the USA in the 1970s. Further technological and commercial developments were reported in Germany and Japan throughout the 1980s and 1990s (Gasparetto and Scalera, 2019), especially thanks to the rise of ICTs and the fusion of electronic, electrical and mechanical engineering into mechatronics (Kodama, 1986). Since the early 1990s, Japan has gradually established world leadership in robot technologies and innovation, with country's industrial policy playing an important role (Johnson, 1982; Okimoto, 1989). Japan launched the Japan Robot Leasing Company and promoted concessional finance and fast depreciation of capital investments in robots. Since 2000, the geography of robotization has further shifted towards Asia, driven by the fast catching up of first South Korea and then China.[1]

Globally, the period between 2012 and 2017 has been the one with the strongest expansion in robot adoption, with average robot sales increasing by 19% (Compound Average Growth Rate, CAGR) over the period. This expansion was mainly driven by Asia (China, Japan and South Korea), where the CAGR for the same period reached 25%. The following 2 years recorded a global slowdown in growth (from 30% in 2017 to 6% in 2018) and, for the first time, a decline in 2019 (a 10% drop in new robot adoption) mainly due to sector-specific dynamics affecting robots users in automotive and electronic industries, as well as rising trade conflicts (IFR, 2021). Despite the pandemic, in 2020, robot adoption grew again by 0.5% driven by the electrical and electronics (E&E) industry which surpassed the automotive industry as the largest user of robots for the first time.

China became the biggest robot market in 2013, and since then has consolidated its position as world leader in robot adoption. Nonetheless, the literature has mainly generated cross-country evidence and country-level studies focussing on the impact of robotization on productivity and employment dynamics in advanced economies (e.g. Acemoglu and Restrepo, 2020; Graetz and Michaels, 2018). Evidence for developing countries remains limited, with few notable exceptions. Fu et al. (2021) found a disproportional impact of robotization among 74 developed and developing economies between 2004 and 2016, with insignificant gains in labour productivity and total employment in developing countries, but higher income inequality. Focussing on Brazil, Ferraz et al. (2020) found that adoption of more advanced digital production technologies (ADPTs) is associated with higher levels of firm capabilities and readiness, regardless of sectors and size. Delera et al. (2022) found that the diffusion of ADPTs remains limited in Ghana, Viet Nam and Thailand, however, their adoption is positively associated with firms' participation in Global Value Chains (GVCs) and results in a labour productivity premium. With a focus on the automotive value chain across 34 countries, Anzolin et al. (2022) found that Foreign Direct Investments (FDIs) per se do not drive robots adoption in the host country, but FDIs become a significant driver of robotization when interacted with proxies of host countries' innovation capabilities.

Recent contributions focussing on China look at the effects of robotization. Duan et al. (2023) find that robotization is associated with productivity increases among Chinese listed companies by improving human capital and innovation capabilities; however, the relationship is U-shaped (Du and Lin, 2022). Several studies also find positive effects of robot adoption on high-skilled employment (e.g. Hu et al., 2023; Tang et al., 2021; Wang et al., 2024), and a related rise in income inequality (Lai et al., 2023). Overall, robotization tend to have a positive effect on employment in the long term (Du and Wei, 2022), although broader firms' performances tend to improve more in capital-intensive sectors (Huang et al., 2023). There is also evidence of a link between robotization and industrial innovation (e.g. Han and Mao, 2023; Wang et al., 2023) and export quality and scope (Hong et al., 2023; Qi and Zhang, 2023), despite heterogeneity (Lu et al., 2023) and time-lags (Hong et al., 2022). A systematic literature review is presented in Appendix A.

Evidence on the drivers and spatial dynamics of robotization within China remain scarce, however. Cheng et al. (2019) combined aggregate industry-level and firm-level data to investigate both supply- and demand-side factors responsible for fast robotization in manufacturing in China (manufacturing sectors account for 80% of all robots). They find a positive relationship linking robotization to wage dynamics and manual tasks across firms; government subsidies are also found shaping robot adoption among firms. Fan et al. (2021) also find that robotization is driven by increasing labour cost (minimum wage), although robotization does not always meet cost-reduction expectations (Lei, 2022). Zhao and Gereffi (2022) highlight the different roles of industrial policies, public-private collaborations in R&D, technological spillovers from inward FDIs and international acquisitions in upgrading the domestic industrial robot industry. Synergistic configurations along GVCs can support upgrading (Fu and Cheng, 2022). Finally, Kimura (2022) finds that Chinese firms are catching up with technology leaders in the domains of robots' basic functions and robot sophistication.

Despite fast robotization and increasing investments of multinational robot manufacturers in China, the country is still catching up in the development of indigenous technological capabilities in robots. The Chinese government has targeted robotization in its latest and most important national industrial policy – that is, *Made in China 2025 (MIC25)* – to shift from robot adoption to robot production and technological leadership. Other national and province-level initiatives can be traced back to 2013 at least. These initiatives have evolved in a complex package of national and province-based industrial policies, as revealed by alarmed reports from the U.S. and Germany (Zenglein and Holzmann, 2019; NSCAI, 2021). To paraphrase Xi Jinping's vivid language in the context of food security when he states that 'The Chinese people's rice bowl must be firmly in their own hands at all times', China is equally trying to reach 'technology security' by getting robots in its 'own hands'.

By focussing on the drivers and spatial dynamics of robotization in China, we aim at filling an important knowledge gap. Against the evolving global landscape, we analyse the complex mix of structural and policy factors driving fast robotization across Chinese provinces. We proceed in three steps. First, we produce evidence on the international geography and structural drivers of robotization by distinguishing robot adoption from robot production and technological capability preconditions. Against this backdrop, we then identify and analyse three main structural factors – demand pull, supply push and capability preconditions – driving robotization and spatial dynamics in China. We produce evidence on production and technological capabilities for robots across Chinese provinces, including new estimates of the geographical distribution of robots within China. Finally, we focus our attention on a fourth driving factor, that is, the extent to which national and province-based industrial policy (and their interaction with 'structural drivers') are shaping robotization across regions in China. We also assess the extent to which China's robotization policy nested in MIC25 is increasingly boosted by the deepening of the Belt and Road Initiative (BRI), giving rise to a new multi-scalar industrial policy.

We find that China is the robotized factory of the world, however, a factory that still relies on foreign robot technologies heavily. This is why catching up in robotization is a major government priority. Central government-led industrial policies have been increasingly aligned and complemented with province-led initiatives since 2016 to localize technological innovation and exploit potential regional agglomeration economies. We identify the emergence of four main robotizing regions – that is, Guangdong, Yangtze-River-Delta (YRD), Beijing-Tianjin and Jilin-Liaoning. Each one of them is trying to exploit its strengths and work on its weaknesses, while responding to mounting competition across provinces. We finally found the emergence of three synergies linking MIC25 and BRI and underpinning China's leadership in robot technologies: opening markets for robots, shaping global industry and technology standards, finally directing finance towards robots technology diffusion.

The paper is outlined as follows. We first present materials and methods. We then identify and provide cross-country evidence of structural factors driving robotization. We address these structural drivers to explain emerging evidence on the disproportional distribution of robots across regions in China, and emerging regional agglomerations. Against this bakdrop, we analyse the evolution of national and province-based industrial policy for robotization in China. We conclude by reflecting on China's robotization trajectory and industrial policy lessons.

Theoretical approach, data and methods

In the analysis of technological trajectories – that is, technology innovation, diffusion and adoption – both evolutionary and structural economics focus on *demand-pull* – both quantity and quality – and *supply-push* dynamics – both technical change and changes in industrial structures (Dosi, 1982). Both push and pull dynamics, and their interaction, are necessary to drive learning within and across firms; they are cumulative and develop along patterns of complementarity in investments and technological capabilities development (Andreoni, 2014; Mowery and Rosenberg, 1989). Push and pull dynamics are also heterogenous across sectors (Pavitt, 1984) and geographies (Storper, 1997), resulting in sector-specific dynamics of change as well related spatial dynamics. We build on this body of literature to guide our empirical investigation of robotization in China.

The literature on robotization has largely relied on the International Federation of Robotics (IFR) datasets. The IFR provides annual data on the cumulated operational stock of industrial robots by sectors, and the annual flow of new robots for a large group of countries since 2005. As detailed in Appendix B, in line with the literature, we follow the approach proposed by Acemoglu and Restrepo (2020) to scale down robots adoption from the country to the province level. First, based on IFR (2021), we estimate robots adoption across a selection of manufacturing sectors at a national level. Second, building on from the National Bureau of Statistics of China (NBSC web data warehouse available at https://www.stats.gov.cn/english/), we estimate the distribution of the output from these sectors across regions and the distribution of the employment across regions. Based on these three estimates, we calculate the expected stock of industrial robots deployed across provinces and province-level cities as a percentage of the country's total and its density per inhabitant. Estimates are also reported in Appendix B.

The identification of manufacturing plants across China relied on a careful triangulation of specialized press, technical/consultancy reports and the companies' official websites and their financial reports. Triangulation was needed as each one of these sources presents some flaws. Starting from Technavio (2019) as a baseline, we further refined our identification of robot manufacturing plants in China by relying on firm-specific patents data. Patents are widely used as a reliable measure of technology output (Keller, 2004), and patent applicants a reliable proxy of the firms producing that output (OECD, 2009). We also rely on official reports from robots manufacturers and patent data to capture location of manufacturing plants in China, acquisitions of firms, and technological-innovation capabilities.

While several factors such as finance and broader skills can act as preconditions of technology adoption, we estimate the capability preconditions of robotization across Chinese regions only based on patent data. This solution stresses the capability to process and develop technologies (see Kimura, 2022 for an application to Chinese companies within the industrial robot GVC) and, thus, helps single out the preconditions factor from the broader supply push driver. Specifically, we referred to patents applications under the Patent Cooperation Treaty (PCT) administered by the World Intellectual Property Organization (WIPO) from the OECD, REGPAT database (July 2021). We selected the list of patent classes related to the domain of robotics and automation, identifying the class B25 J (manipulators; chambers provided with manipulation devices) as the technological key to extract a list of PCT applications from the database. We finally collected longitudinal data on applications according to the priority date, and allocated patents to Chinese regions to generate a detailed and comprehensive regional map of the technology preconditions of robotization in China.

Finally, the industrial policy analysis builds on an in-depth review of policy strategies and documents. Data from these documents have been triangulated and reviewed longitudinally to assess reliability and accuracy.

Structural drivers and spatial dynamics of robotization: Locating the China case

Demand-pull: Geography and sector-specificity of robot adoption

Industrial robot adoption across countries is highly concentrated. In 2017, when the stock of robots in operation reached its peak, 37 countries accounted for 95.9% of all robots in the world. The top 10 'robotised' countries accounted for 85.8% of the total, the top five alone for 74.8% of all robots. The top five include three leading industrialized nations – Japan, the USA and Germany – and two of the fastest industrialisers of the last century – South Korea and China. In 2020, the top five still accounted for 73.1% (Table 1). This geographical concentration reflects a key structural factor driving robotization, that is, the deployment of industrial robots is not homogenous across sectors. Thus, countries (and regions) specialized in those sectors that deploy robots the most are also those where robot users will exercise the strongest demand pull.

By 2017, 88% of industrial robots were deployed in the manufacturing sector, with automotive accounting for the largest sectoral share of industrial robots (36.81%; 32.2% in 2020). Automotive has always been the bedrock of manufacturing automation due to its high-volume production, modularization and stability in product design in OEMs (Anzolin and Andreoni, 2023). Electrical and electronics (E&E) is the other leading sector for robot adoption (24.25%; 25.3% in 2020). The production of micro-small parts at high speed, which characterizes this sector, makes automation and robots highly productive and profitable. Robots are capable of handling screens and coating circuit boards and assembling connectors faultlessly. In 2020, the other two major sectors with more robots in operation are metals (10.3%), and plastic and chemical products (6.3%). Together, these four sectors account for 74% of the world operational stock of industrial robots in 2020. The fact that

Table 1. Country-sectoral matrix and comparison between countries' total operational stocks of industrial robots (2020) and PCT applications (2007–2018)* as percentage of world totals. Source: authors' elaboration based on data from IFR (2021) and OECD, REGPAT database, July 2021.

	Operational stock of industrial robots (2020)					Share of world total	
Sector	Automotive (%)	Electric and electronic products (%)	Metals and machinery (%)	Plastic and chemical products (%)	Other sectors (%)	Operational stock of industrial robots (2020) (%)	Industrial robot PCT applications (2007–18) (%)
Country							
China	27.2	29.5	11.6	4.9	26.8	31.3	11.1
Japan	32.2	33.5	13.0	5.0	16.2	12.4	30.7
Rep. of Korea	28.3	53.6	2.9	2.6	12.7	11.4	5.9
United States	43.2	16.1	8.3	7.6	24.8	10.4	16.6
Germany	49.4	4.9	13.0	9.0	23.6	7.6	12.6
World	32.2	25.3	10.3	6.3	26.0	100.0	100.0

*IFR (2021) considers an industrial robot life cycle of 12 years. We count here integer patent applications over 12 years to produce comparable figures.

most industrial robots have been deployed in a few sectors and GVCs-stages so far, means that only countries specialized in these sectors have robotized due to sector-specific demand-pulls (De Backer et al., 2018).

Table 1 also shows a disaggregated country-sector matrix to capture sector-specific demand-pull dynamics for 2020. For the top five robotized countries, we calculated the distribution of robots across manufacturing sectors, and we benchmark each country-sector cell in the matrix against the average share across all countries. China and Korea score above average in the two leading sectors of E&E which underpin digital technologies. Network analyses have found that the South-East Asian region is where digital technologies GVCs are denser; hence, there is more inter-countries demand pull for final and intermediate components (Andreoni et al., 2023). In South Korea, which has the world's second highest density of industrial robots after Singapore (more than twice the density in Japan and Germany, almost four times the density in the USA), robot adoption is driven by country's catch up and regional agglomeration in electronics (Lee, 2013). On the contrary, the demand pull is stronger in automotive for Germany, USA and Japan (in the case of Germany, it includes its European supply network; Caéfalvay, 2020).

Supply-push: Geography and manufacturers of robots

While sector-specific robots users drive robot adoption across countries (and their regions) through a demand-pull, the geographical distribution of robot producers is determined by a combination of different supply push factors. These include: (i) path-dependency in robot production and technological capability leadership of certain countries (and their regions and firms); (ii) localization investment decisions (R&D and production plants) of world-leading robot manufacturers in domestic and foreign expanding markets; and (iii) new robot manufacturers attempting to compete with most established players in their domestic (or foreign) markets. Some of these supply push factors interact with sector-specific demand-pull dynamics discussed above.

The top 10 industrial robot manufacturers in the world, with revenues above US$1 billion are all headquartered in advanced economies (Table 2). Among them, Mitsubishi Electric is a highly diversified business group, while ABB specializes in robotics and flexible automation alongside power and heavy electrical equipment. The other listed companies specialize in industrial robots and intelligent automation systems. Four of them – Fanuc, ABB, KUKA and Yaskawa – had an estimated combined market share of 57% in 2019. Japan is the country with the biggest concentration of robot manufacturers and innovating robot technologies around three clusters in Kyoto City, Osaka City and Kobe City. With the

Table 2. Major industrial robot manufacturers in the world: segment revenue (2020), production facilities in China (2020) and industrial robot PCT applications (2007–2018). Source: authors' elaboration based on information from OECD, REGPAT database, July 2021, and companies' websites/financial reports.

Company	HQ country	Industrial robot specialization	Segment revenue (billion USD, 2020)	Industrial robot PCT applications (2007–18)	Production facilities in China (2020)
Mitsubishi electric	Japan	Factory automation and robots	10.8	118	6
Omron adept	Japan	Mobile robots, industrial robots and other automation equipment	3.0	71	1
ABB	Switzerland	Robotics and automation	2.9	323	1
Kawasaki	Japan	Industrial robots for several applications, including dual-arm SCARA robots working alongside humans	2.1	338	4
Fanuc	Japan	Arc welding robots, paint robots, palletizing robots, collaborative robots, and mini robots, AI	1.8	78	4
Dürr	Germany	Assembling and painting automation	1.8	33	1
Yaskawa	Japan	Industrial robots for welding, packaging, assembly, dispensing, material handling, spot welding, coating, and general automation	1.2	140	5
Fuji	Japan	Compact industrial robots (SCARA and multi-axes) and mobility support (health)	1.1	112	2
KUKA (Midea group)	Germany/China	Six-axis robots in different sizes, lightweight robots, heat and dirt-resistant robots, palletizing robots, and shelf-mounted robots	1.0	268	2

acquisition of KUKA (95%) by the Chinese company Midea Group in 2016, China has become the only emerging economy with a domestic world-leading system integrator in robotics.

The robot GVC involves several importers and exporters of robots. GVC integration offers some opportunities to emerging countries trying to catch up in 4IR technologies (De Backer et al., 2018; Sturgeon, 2021; Anzolin et al., 2022; Kimura, 2022). This is particularly the case for China, where the demand-pull of robot users has attracted the localization of robot production facilities since the mid-2000s, and some R&D centres since 2017 (ABB, 2020). In 2017, when China started accelerating its robotization efforts, Japan was the leading net exporter of industrial robots in the world, with a net export value of more than US$2 billion and China imported more than $1 billion worth of robots (based on UN Comtrade data, product class 847,950 – i.e. 'machinery & mechanical appliances; industrial robots'). By 2020, almost all leading robotics companies have built one or more production facilities in China, alongside their sale and post-sale service networks.

Capability preconditions: Spatial distribution of technological capabilities

The localization decisions of both robots producing and using companies are affected by a third factor: the presence of several foundational capability – especially technological – that act as 'preconditions' of robotization (Andreoni et al., 2021; Anzolin et al., 2022). The adoption and production of industrial robots presuppose productive organizations endowed with basic and intermediate production and technological capabilities (e.g. digital skills). These firm-level capabilities also need enabling infrastructures, such as reliable electricity, and connectivity. Moreover, to deliver productivity gains, robots require significant capital investment. While the cost of robots declined by 20% in real terms between 1990 and 2006, robots remain expensive. Robot integration and retrofitting of existing production lines and cells are costly processes, especially for SMEs, and hence requires access to finance. These preconditions are disproportionally distributed across countries, as revealed by several indicators of human and productive capabilities, industrial competitiveness and institutional development (Fagerberg et al., 2007; Crescenzi et al., 2012).

In 2017, only 25% of new robots installed in China were produced domestically by either international or domestic robot manufacturers. Moreover, Chinese companies managed to supply only components for the robot corpus (accounting for only 22% of the cost structure of a typical robot). More complex components of robot technologies such as – controllers, servo motors and reduction gears – accounting for over 70% of the cost of a typical robot, were produced by foreign suppliers (Made in China, 2025). Despite challenges in building the necessary technological capabilities to robotize, patent data analysis reveals a fast-changing scenario (Figure 1). Since 2016, China has recorded a dramatic acceleration in PCT applications. While Japan remains the global leader in PCT applications for robot technologies, China is overtaking the USA in patents to become the second technological leader in robot technologies. As discussed in Kimura (2022), an acceleration in PCT applications is evidence of fast development of technological capabilities in robotization.

Structural drivers and spatial dynamics of robotization in China: Results

Figure 2 summarizes the evidence on structural drivers of robotization in China, specifically, sector-specific demand pull (Panel 2.A), supply push and manufacturing capacity (Panel 2.B) and evolution in technology preconditions (Panel 2.C). These are presented longitudinally and in relation to the evolution in robots policy in China (Panel 2.D). This information is complemented by Figure 3 where information on the same structural drivers is mapped out by regions (Panel 3.A). Four robotics hubs are also highlighted (Panel 3.B) and discussed below.

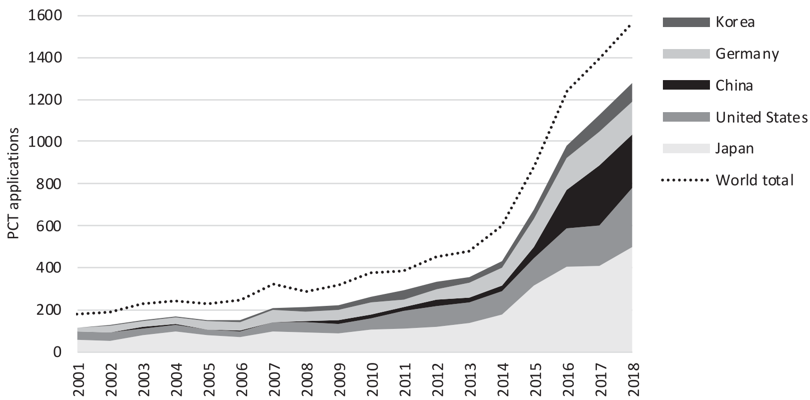

Figure 1. PCT applications by country and year, 2001–2018 (applicants, integer counts). Source: authors' elaboration on data from OECD, REGPAT database, July 2021.

Demand pull by sector and regional distribution

The adoption of industrial robots in China has been pulled by the automotive sector since 2012 (20%, 16% in 2020), although E&E industry recently overtook automotive (7% in 2012, 17% in 2020). This reflects the massive expansion of the E&E in China (Figure 2(A)). Miscellaneous activities persist in absorbing a substantial number of robots (15% in 2020). At regional level, we found that robotization across regions is highly heterogenous. Three factors explain this high heterogeneity. First, as expected, the width of robotization at the regional level is driven by the distribution of manufacturing and the presence of industries where robots are widely adopted. Second, this relation is clearer for the regions of extensive robotization; that is, those agglomerating many industrial robots as they feature the largest numbers of employees in manufacturing, such as Guangdong, Jiangsu and Zhejiang. Third, the distribution is fuzzier for regions where a higher share of industrial robots than employees are agglomerated (small numbers but high densities of industrial robots), such as Tianjin, Chongqing, Jilin and Shanghai.

Overall, robots adoption across regions in China (Figure 3(A)) appears to confirm the relevance of the sector-specific demand pull as the stocks of industrial robots are relatively larger where the E&E industry is more concentrated (output shares generally beyond 10%), while densities are higher where the automotive industry agglomerates more (output share of 7–10%). Guangdong is one exception, featuring both a large stock and high density of robots, due to high concentration of the E&E industry (42.2% of mobile phones and 57.2% of television sets) and automotive (12.4%).

Supply push by domestic and international robot manufacturers, and regional distribution

While domestic demand for robots remains higher than domestic supply, robot manufacturing capabilities have developed over the last three decades (Table 3). The national leading company, Estun, was established in the early 1990s and over the years specialized in 'CNC robotics' combining Computer Numerical Control machines with advanced robotics; this was made possible with the acquisition of technology assets abroad (Figure 2(B)). The second-largest company, Siasun, was established in 2000 as a spin-off of the Shenyang Institute of Automation of the Chinese

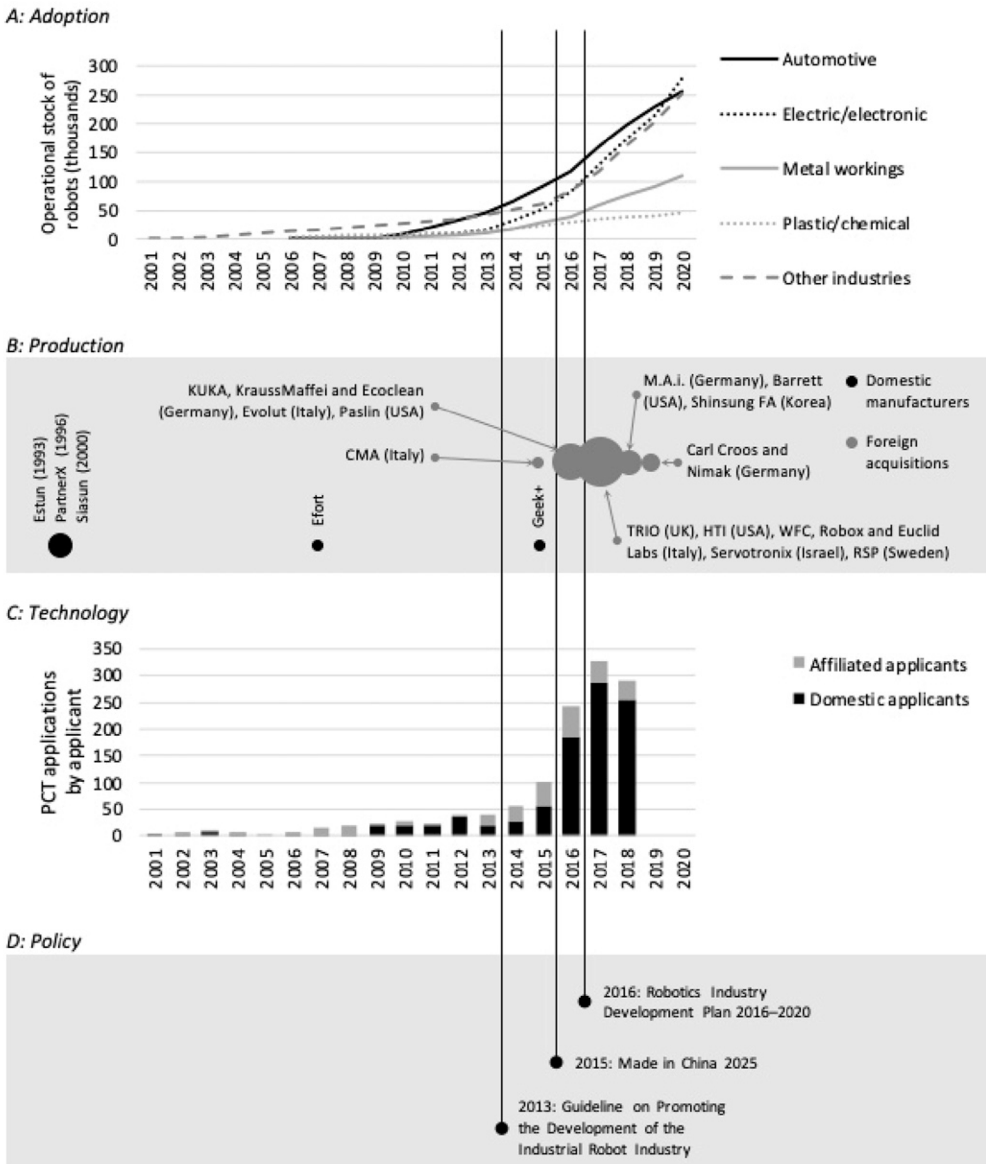

Figure 2. Structural and policy layers of robotization in China. *Panel A: Adoption.* Operational stock of industrial robots by main sector of deployment, 2001–2020. Source: authors' elaboration based on IFR (2021). *Panel B: Production.* Establishment of major Chinese industrial robot manufacturers and major acquisitions of foreign companies in the robotics industry by Chinese players, 2001–2020. Source: authors' elaboration based on multiple sources. *Panel C: Technology.* Industrial robot PCT applications in China by applicant origin: domestic and affiliated applicants, 2001–2018 (integer counts). Source: authors' elaboration on data from OECD, REGPAT database, July 2021. *Panel D: Policy.* Industrial policy framework for robotization in China, 2001–2020.

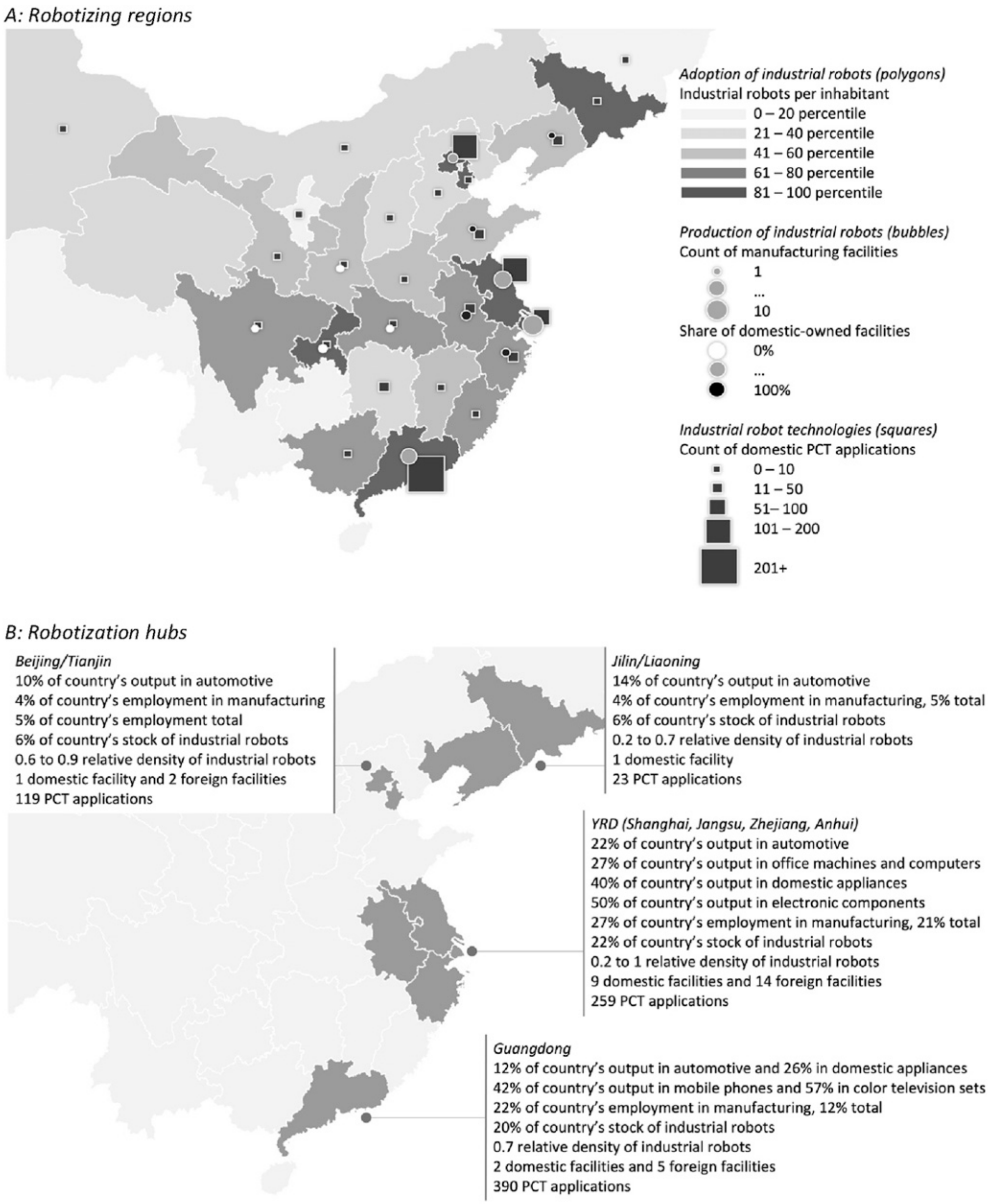

Figure 3. Robotization in China. *Panel A: Robotizing regions.* Adoption patterns (polygons), manufacturers (bubbles) and technologies (squares). *Panel B: Robotization hubs.* Summary information and local policy initiatives. Source: authors' elaboration on information from various sources. (A) Robotizing regions. (B) Robotization hubs.

Academy of Sciences. Despite their growth, all domestic players operate at a substantially smaller scale of revenues than the world-leading robot manufacturers (see Table 2 for a comparison).

Since 2015, acquisition of foreign companies has played an increasing role (Figure 2(B)), starting with CMA Robotics, a small Italian company becoming part of Efort. Italian and German companies

Table 3. Major Chinese industrial robot manufacturers in China: number of production facilities (2020) and PCT applications (2007–2018). Source: authors' elaboration based on information from OECD, REGPAT database, July 2021, financial and companies' websites.

Company	Year established	Industrial robot specialization	Total revenue (billion USD, 2020)	Industrial robot PCT applications (2007–18)	Production facilities in China (2020)
Estun	1993	Automation, motion control, industrial robots for a variety of applications	0.47	16	3
Siasun (China Academy of Sciences)	2000	Industrial, mobile, collaborative and service robots, smart logistics	0.42	4	4
Geek+	2015	Autonomous mobile robots	0.30	5	1
PartnerX	1996	Motion arms (brand EVOX)	0.25	8	1
Efort	2007	Mini, painting, and collaborative robots, various payloads robots	0.17	1	5

were the main targets of these acquisitions throughout 2016 and 2017. The acquisition of the German KUKA by Midea Group in 2016 represents the most relevant case. Alongside national players, global leading companies such as ABB, Fanuc and Yaskawa, operate in China through local subsidiaries (see Table 2 above on number of these production facilities in China).

From our mapping of both major domestic and foreign manufactures of robots across Chinese regions, we found some signs of robot manufacturers agglomeration (Figure 3(A)). First, the overall number of manufacturers (bubble size) tend to localize according to the density of robots demanded. Second, the localization of foreign manufacturers appears as feebly but positively associated with an increasing density of industrial robots. The domestic manufacturers as well as foreign-owned facilities localize in eight regions. However, co-localization is quite weak, occurring in only four regions: Guangdong, Beijing, Shanghai and Jiangsu (bubble colour). The largest concentration of manufacturing facilities is in Shanghai (ten), followed by Jiangsu (eight), and Guangdong (seven). And this concentration is mainly fostered by the localization of foreign-owned facilities: eight out of ten in Shanghai, six out of eight in Jiangsu and five out of seven in Guangdong (see Appendix B for more details).

Technological capabilities preconditions development across regions

Frontier-technology capabilities – measured as number of PCT applications in robotics – started emerging in China in 2001 (Figure 2(C), domestic applicants), 20 years after the first patents worldwide (Japan in 1979, followed by Germany and USA). Nonetheless, China reported an increasing number of applications since 2009 and a real upsurge since 2015. In addition, these technological capabilities have been progressively supplemented by those acquired abroad (affiliated applicants). By 2017, China generated 21% of the world frontier technologies in robotics. An astonishing result if compared to the fact that between 2001 and 2008 it was only 1% (Figure 1).

Despite this rapid growth, technological capabilities measured by patents remain concentrated in a few regions (Figure 3(A)). These are: Guangdong (390), Jiangsu, (146) and Beijing (114), followed by Shanghai (62) and Zhejiang (35). These are also the regions where we mapped 30 out of 40 robot production facilities (11 out of 14 domestic-owned and 19 out of 26 foreign-owned). The capability to supply more advanced technologies in China is critically driven, indeed, by agglomerations around foreign and indigenous 'seeds' of supply push, which are often associated with foreign companies and, more recently, indigenous ones (Prodi et al., 2018, 2020).

Regional robot hubs

By triangulating evidence on the structural drivers of robotization across Chinese regions (Figure 3(B)), we have identified four main regional robot hubs.

The first hub is Guangdong: an extensive manufacturing hub in China, where 22% of China' employment in manufacturing is concentrated. In 2020, the industrial base pulled 20% of the national stock of industrial robots; attracted investments in one out of five robots production facilities (28% of which domestic-owned). The density of robots remains lower than in other regions; this is mainly due to the regional concentration of E&E industries (especially, mobile phones and television sets accounting around 50% of China). A comparable concentration emerges for the technological capabilities in robotics (45% over the country's total of PCT applications), suggesting that Guangdong is the forerunner of a demand-pull extensive pattern of robotization.

A second hub is the Yangtze-River-Delta (YRD) region, which includes Shanghai, Jiangsu, Zhejiang and Anhui. Overall, this hub agglomerates 22% of the stock of industrial robots and 27% of the national employment in manufacturing, with a dis-homogeneous density ranging between 0.2 in Anhui and 1 in Shanghai. The wide area hosts 23 out of 40 robot manufacturing facilities (40% of which are domestic owned, only 20% in Shanghai). Furthermore, it is the second provider of domestic robot technologies (30%). Thus, the robotization pattern in the YRD appears to be one of supply pushed robotization. The centre of the hub, Shanghai, features more intensive robotization, which is attractive for foreign firms, and pulls the development trajectory of the three surrounding provinces.

The third hub, located in Beijing and the linked region of Tianjin, exhibits an intensive pattern of robotization: 6% of the national stock of industrial robots turns into one of the highest densities of industrial robots (0.6 in Tianjin and 0.9 in Beijing) among the Chinese regions (manufacturing accounts for less than 5% of the country's total). Despite its small size, the region agglomerates 8% of the manufacturing facilities and 14% of PCT applications, suggesting that supply, and especially technology-relevant activities, are the main drivers of robotization.

The fourth and last hub is located across the provinces of Jilin and Liaoning. It can be considered one of the original sites of robotization in China, since Jilin hosts one of the largest agglomerations in automotive (14%), while Liaoning hosts the headquarters of one national leading robot manufacturer (Siasun in Shenyang). Siasun operates the only production facility in the region. The overall concentration of manufacturing activities is relatively low (4% of country's employment) absorbing 6% of the national stock of robots, mainly triggered by the intensive pattern of robotization in automotive (the density of robots peaks at 0.7 in Jilin). Also, the generation of frontier technologies is limited (3% of PCT applications), suggesting that robotization is demand-pulled mostly.

Industrial policy driving robotization in China: Evolution

The Chinese government has forcefully targeted industrial robotization using its full package of industrial and innovation policy instruments since the *National High-Tech R&D programme (863 Programme)* issued in 1986 (Liu et al., 2011; Andreoni and Tregenna, 2020; Wen and Zhao, 2020). However, China's catching-up effort – moving from robot adoption to robot production and technological global leadership – has been mainly associated with the *Twelfth Five-Year Plan (2011–2015)*. The *Thirteenth Five-Year Plan (2016–2020)* has further advanced China's approach by emphasizing the importance of promoting a 'number of world-class development clusters for strategic emerging industries'. While this development has opened the way to several province-led industrial policy experiments and initiatives promoting robotization, the central government has retained a pivotal role in framing and governing a complex mix of national level and place-based central government-led industrial policy (Chen and Naughton, 2016; Naughton, 2018). Table 4 summarizes the development of this multi-scalar industrial policy framework for robotization in China focussing on the main steps, target and goals.

In 2015, with the launch of *Made in China 2025 (MIC25)* – a major plan to improve the competitiveness, innovation, technology, quality, reliability, and 'green-ness' of China's manufacturing sector – intelligent manufacturing and robots have received even more attention (Li, 2018). Robots have been recognized as the technology that will allow China to address the so-called 'double-press', according to Miao Wei, MIIT Minister. The double-press means competing with developed countries in advanced technologies and with developing countries for cheap labour. MIC25 is by far the most ambitious programme in Chinese history when it comes to robots. It aims to upgrade China's manufacturing industry by making China 'the world's largest producer of industrial robots and to master technologies for key components, a longstanding challenge for China's robotic industry' (authors' translation).

The *Robotics Industry Development Plan (2016–2020)* reports that China is still a relative latecomer. China still depends on imports for core components of industrial robots – that is, controllers, decelerators and servomotors. Chinese-made core components tend to be larger in size and lower in output power, especially compared with Japanese-made robots. Three- and four-axis machines still tend to be the most diffused, while six-axis robots capable of performing complex tasks like assembly, disassembly and welding are relatively less common.

Within the *MIC25* and the *Robotics Industry Development Plan (2016–2020)*, the industrial policy package includes instruments operating at the national and provincial levels. At the national level, the government relies on five main policy instruments: subsidies (Cheng et al., 2019; Lin, 2018); fiscal incentives, such as the State Council's announcement of cutting more than 60 billion yuan (US$8.78 billion) worth of taxes for small and micro-enterprises and high-tech firms in order to reduce its operating costs and spur innovation; promoting (and approving) company acquisition; promoting joint ventures (De Graaff, 2020); creating robotics centres and parks (Zenglein and Holzmann, 2019).

Since 2015, Chinese provinces have started announcing and implementing a variety of province-led industrial policy packages for robotization. Some of these policy instruments target increasing robot adoption, while others have increasingly targeted acquisition, development and agglomeration of productive and technological capabilities in robots. The overarching national industrial policy framework for robotization is meant to provide industrial policy alignment and governance co-ordination, as there is a recognition of their strategic importance in achieving targeted goals (Chang and Andreoni, 2020), and offers the main architecture for advancing China's national interests in the age of strategic competition (Singh, 2023). Table 5 provide most striking examples of central-led initiatives and province-led initiatives for the four robotization hubs.

Table 4. Industrial policy framework for robotization in China. Source: authors based on policy documents.

Plan/action	Target and goals
Twelfth five-year plan (MST, 2011–2015)	Reducing the overdependence on imported high-end equipment and its key components for domestic production; development of specific technologies, including robotics, sensors, industrial communication networks and controllers
Guideline on promoting the development of the industrial robot industry (MIIT, 2013–2020)	Tackling four weaknesses: a small industry base and reliance on imports for key components; China's common service platform standards and personnel; market competitiveness of country's own brands; market competition Goals: developing three to five globally competitive robot manufacturers; creating eight to 10 industrial clusters for the industry; reaching a 45% domestic market share for Chinese high-end robots; and increasing robot penetration to 100 per 10,000 workers
Thirteenth five-year national economic and social development plan (2016–2020)	Aligning the guideline to sectoral industrial policies
Made in China 2025 (2015–2025)	Owning the intellectual property rights (IPRs) of key components of industrial robots; becoming a leader in the development of next-generation robots; having one or two Chinese-owned companies ranked among the world top five companies Goals: replacing the import of industrial robots with domestically produced ones by 50% of total robots installed by 2020, and 70% of those installed by 2025; in the area of robot core components, moving from 50% of replacement by 2020 to 70% in 2025 and a projected 80% by 2030
Robotics industry development plan (MIIT, NDRC, MF, 2016–2020)	Promoting automation massively, including in the service sector; building in 10 types of industrial robots, performing an array of services, and even programming themselves Goals: annual industrial robot production of Chinese brands of up to 100,000 units, with 50,000 of these being six-axis industrial robots; achieving a volume of sales of service robots of over 30 billion yuan (US$4.7 billion)
New generation AI development plan (2016–2020)	Focussing on core components, hardware and software interfaces and standards for smart service robots and smart industrial robots

Provinces have implemented different schemes and incentive packages to become the biggest robot hub of China. In some cases, regional policies mirror the national-led policy initiatives; indeed, all provinces attempt to reach the High- and New-Technology Enterprise (HNTE) status that guarantees a significant reduction of the Corporate Income Tax (CIT) rate to encourage investments in high-tech and R&D. In other cases, province-led initiatives reflect the structural specificities of the region in terms of demand pull, supply push and capability preconditions and governments target their specific opportunities and constraints. For example, some regional governments have set up investment capital funds

Table 5. Central-led and province-led policies in the four robotization hubs. Source: authors based on policy documents.

Hub	Central-led policies	Province-led policies
Jilin–Liaoning	In 2018, the MIIT announced the establishment of a national Robotics centre in the Shenyang. The new centre focuses on tackling common bottlenecks across domestic robot producers, such as human-machine interaction technologies and compliant control. This centre is one of the 15 national centres focussing on emerging technologies, planned in MIC25 before 2020. The new centre joined several institutions, some of which are part of the so-called *China Robot Industry Alliance*, a non-profit national industry association	Policies in the northern provinces focus on the presence of the national robot innovation center, Harbin institute of technology, and other companies and institutions. It is worth noting that Siasun is owned by the China academy of sciences, which is one of the funders of the national robot innovation centre. This governance structure guarantees financial commitment and alignment with government industrial strategy direction
Guangdong	As part of the Midea's acquisition of KUKA, a robot park is due to be built in Shunde, where Midea is located. This park will have a manufacturing capacity of 100,000 robots and will focus on six-axes robots and new robot design for Chinese industries	The *Industrial Restructuring and Upgrading of Guangdong Province Three-year Action Plan (2015 to 2017)* focuses on developing cutting-edge industrial technologies and improving product quality, as well as manufacturing process efficiency. Policy measures to overcome gaps in capability preconditions for robotization include promotion of incubators and accelerators; innovative entrepreneurship schemes, including financial support for development of R&D centres within large-scale enterprises, and assuring the growing rate of investments in R&D departments. Finally, it aims to create a complete robot manufacturing industrial ecosystem via promoting demonstration extension services for industrial robot adoption The *Development Plan of Intellectual Manufacturing of Guangdong Province (2015 to 2025)* develops the idea of demonstration bases further and gives them a specific directionality. Guangdong province issues subsidies to companies of 15% to 30% of the robotic approach cost to help local manufacturers automate. Beyond robot adoption, the Foshan district is emerging as the most important robot production hub where Midea and KUKA have located three new ventures, and ABB located new investments

(continued)

Table 5. (continued)

Hub	Central-led policies	Province-led policies
Beijing–Tianjin		The government is leveraging the presence of AI companies that are developing in the area to attract 10 R&D headquarters and 10 leading robot companies (Xinhua, 2017). Several other targeted programmes have been also introduced. For example, with the programme on intelligent manufacturing and Robotics research, in accordance with the '*Comprehensive Plan for the Enhancing the Establishment of Beijing as a National Science, Technology and Innovation Centre (Guo Fa [2016] No. 52)*, and the relevant municipal-level 5-year plan *(Jing Zheng Fa [2016] No. 44)*, in 2018 the Beijing Municipal science and technology commission started funding a series of research projects to enhance the city's innovation capabilities in the field of intelligent manufacturing and robotics' (China Innovation Funding, 2020)
YRD		The 'Made in Shanghai' initiative is a comprehensive set of policies (subsidies, R&D centres, improved business environment, specialized districts, etc.) targeting both foreign high-tech and domestic companies. The policy aims to develop an innovation- and technology-driven 4IR cluster (Shanghai Municipal Commission, 2019). Thanks to the opportunities given by the Made in Shanghai Initiative, in 2021, ABB decided to invest US$150 million into one of the most advanced Robotics factory in China (ABB, 2020). Shanghai has also grown its aspiration to become an international hub for robotization, reflecting a new international industrial policy scale

and allocated resources to support robotization via targeted supply side initiatives (Guangdong and Beijing in particular), while others have done so via demand-side measures (YRD).

Shifting-up a gear: New multi-scalar industrial policy and BRI

China felt short on several goals of the Robotics Industry Development Plan (2016–2020). Domestic production of robots was planned to reach 50% in 2020, China stopped at 29.2%. This gap can be mainly attributed to the very ambitious target set in 2016, both in terms of import substitution and wide range of applications targeted, and ultimately to the fact that learning cycles in advanced robots technologies are relatively long. In December 2021, the MIIT launched the *Fourteenth Five-Year Plan for the Development of Robot Industry* whose long-term goal is to develop a domestic industry able to compete on international markets by 2035. In January 2023, the Ministry of Industry and Information Technology translated this renewed aspiration in the 'Robot + Application Action Plan'. This new plan focuses on ten key application areas and aims at achieving breakthroughs in more than 100 innovative applications, and over 200 model use cases. Moreover, 'It also emphasized efforts to build a collaborative innovation system for robot production and application and speed up the development and promotion of robot application standards'[2].

With the 14th plan and other policy documents which have advocated for a 'Digital Silk Road' (China's National Informatization Strategy), the multi-scalar industrial policy approach is increasingly including an international level to the national and province ones discussed above. The BRI provides a strategic platform to project domestic industries and their scale-intensive capabilities, leveraging international rising demand for technologies and shaping regional and global markets in specific sectors and technology domains (Calabrese et al., 2024). While it is difficult to identify 'the key scalar moments at which big policy ideas are transformed into new development geographies' (Klinger and Muldavin, 2019; see also Jones and Zeng, 2019), there are signs of emerging synergies between MIC25 and BRI. Specifically, BRI offers China's robotization efforts an important channel through which the ambitious goals of the MIC25 and the latest Plan for robotization can be reached. From our policy analysis and emerging contributions, we can identify three main mechanisms through which MIC25 will be boosted by a stronger alignment with BRI.

First, BRI opens new markets and export routes for robots and related digital production technologies. Zheng et al. (2021) show how the overall value chain connection between China and the Silk Road countries has been rising since 2001, with Southeast Asia being the most connected region, followed by Central and Eastern European countries. Li et al. (2022) provide evidence of the emerging core-periphery structure in the BRI industrial robots trade network. They also find that 'the Belt & Road industrial robot trade relationship shows a feature of steady growth, and the accessibility and trade efficiency of the intraregional trade are constantly improved'. A central factor shaping industrial robots trade networks within BRI, according to this study, is the technical distance of industrial robots. The technology gap also influences the potential productivity spillover effect of robots adoption in BRI host countries (Razzaq et al., 2021). Given the scale-intensive nature of robots manufacturing and its industries of adoption, BRI is expected to provide increasing market access for Chinese manufacturers of final robots and intermediate components.

Trade data seems to corroborate such emerging pattern and potential BRI dividend (Table 6). Between 2022 and 2023, Chinese exports of robots to BRI countries (BRIs) increased by 123%, against 48% for non-BRIs. By 2023, BRIs are the first market for China robots. Export of robots to BRIs has increased also in relative terms when we compare export of all commodities and a broader group of machineries which included industrial robots until 2021. Export of robots is a good proxy of the other two channels through which BRI contributes to robotization. This is because robot exports are a vector for exporting technology standards and services. Furthermore, being a capex-intensive technology, export of robots is often bundled with export financing and licensing contracts operated through various specialized financial institutions.

BRI offers China a platform to shape global industry and technology standards around the MIC25 digital framework, including digital production technologies like robots as well as related infrastructure connectivity technologies like 5G. Increasing market access allows Chinese companies to shape digital production technology adoption across firms and sectors of emerging economies. To remain competitive in digital global value chains, firms in these countries are looking for digital retrofitting of their production facilities and the fastest and most cost-competitive way. China can increasingly provide such technology systems, and in doing so set the technical standards and inter-operability technology standards. As stressed by Choudary (2020): 'Much like Google

Table 6. Exports of robots from China to World and BRIs, HS classification. Source: authors based on UNCOMTRADE and Green Belt and road initiative center, https://green-bri.org/.

		2017	2022	2023
All commodities	World (billions USD)	2263.37	3593.60	3379.75
	BRIs (billions USD)	781.96	1415.84	1372.62
	BRIs (share)	34.55%	39.40%	40.61%
847950 machinery and mechanical appliances; industrial robots (H5)	World (billions USD)	0.21	0.41	0.45
	BRIs (billions USD)	0.10	0.19	0.21
	BRIs (share)	47.34%	47.63%	45.48%
842870 industrial robots (H6)	World (billions USD)	NA	0.12	0.21
	BRIs (billions USD)	NA	0.05	0.11
	BRIs (share)		41.13%	51.29%

established itself as a dominant player in the smartphone ecosystem, China is attempting to do the same in an increasingly digital geopolitical landscape. […] China's National Informatization Strategy calls upon China's internet companies to go out into the world and support the creation of a "Digital Silk Road"—which refers to the export of Chinese technology alongside the Belt and Road Initiative (BRI), China's massive global infrastructure investment project. The "Digital Silk Road" is China's bet on a country-as-a-platform strategy'.

Finally, BRI is a platform to direct export finance towards robots adoption and diffusion. Since BRI, nearly 70% of Chinese overseas lending has been directed to state-owned companies, state-owned banks, special purpose vehicles, joint ventures and private sector institutions (AidData, 2021). One factor driving Chinese technology competitiveness abroad is its capacity to package technology and financial solutions. As discussed in Camba (2020), China channels two types of finance to the global south. State-backed capital which imposes a development model by modifying 'local orders', and flexible capital interested in extricating itself from the conditions imposed on it in China, and looking for new venues of accumulation and novel ways of organizing production. Different streams of finance coupling export technology trade offer different direct (and indirect) channels through which China as a state and Chinese companies can gain competitive advantage in the BRI.

Conclusions

Robotization in China and across its regions has been driven by a set of interacting structural factors – demand pull, supply push and capability preconditions – as well a key policy factor – industrial policy. The paper presented the first regional evidence on drivers of robotization in China and highlighted how demand pull, supply push and preconditions have resulted in regional heterogeneity and the emergence of robotization hubs. We have stressed how industrial policy has also played a key role in aligning underlying structural dynamics of demand, supply and localization.

The study identified the emergence of four main robotizing regions. Each one of them is trying to exploit its strengths and work on its weaknesses, while responding to mounting competition across provinces. Guangdong province needs robotization, given its well-developed industrial agglomerations in electronic and automotive. Leveraging this demand-pull strength, place-based policies are focussing on pushing both robots' adoption and domestic production. On the contrary, YRD is relying on relatively less targeted policies and leveraging its international attractiveness. Differently from both Guangdong and YRD, Beijing sees in the interaction between AI and Robotics an opportunity to overcome its manufacturing weaknesses by emerging as a technological-innovation hub.

National and place-based central government-led policies have been increasingly aligned and complemented with province-led initiatives since 2016. Our analysis revealed some differences in industrial policy approaches across regions. While Guangdong and Beijing and the Northern provinces have mainly relied on supply side incentives and their leverage of national funds, policies in YRD seem to be more focused on the demand side. Being the most advanced area in China, YRD provinces have all of the capability preconditions to attract and host robotics companies: high-level human capital, a developed high-tech machinery industry and a network of local and foreign suppliers. Automotive and electronic industries also guarantee high demand because the cost of labour in the area is the highest in China. Therefore, provinces in YRD do not have and need a detailed set of policies, as we have seen for the Guangdong province on top of programmes promoted at National level for robotics.

We finally emphasized the emerging synergies between China's national industrial policy for robotization and its BRI, and the emergence of a new multi-scalar industrial policy. Even though the links between these policies remain often implicit, there are clear emerging synergies that China will leverage to achieve its ambitious robotization goals. We emphasized three mechanisms through which BRI will be increasingly play a role in boosting Chinese domestic robotization effort – opening markets for robots; shaping global industry and technology standards; directing finance towards robots technology diffusion. By developing a multi-scalar policy alignment between national and province-led industrial policy under the MIC25 on the one hand and the BRI on the other, China is set to write a new chapter in the international political economy of robotization and further establish its position as the rising global leader in robotization.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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Supplemental Material

Supplemental material for this article is available online.

Notes

1. The empirical and policy analysis in our paper does not include Taiwan, Province of China.
2. Source: https://english.www.gov.cn/statecouncil/ministries/202,301/20/content_WS63c9d296c6d0a757729e5e28.html

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