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AGING, INDUSTRIAL ROBOT INPUT AND EXPORT PERFORMANCE: EVIDENCE FROM CHINESE INDUSTRIAL FIRMS

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Abstract. With the acceleration of aging and the development of robot, it affects the economic and trade development of countries around the world. However, few papers have provided insight into whether and how industrial robot input affects export in an aging real economy. This study examines the relationship between aging, industrial robot input and export performance from both theoretical and empirical perspectives. Theoretically, it integrates aging and industrial robot into a model of heterogeneous firms for analysis. Empirically, the study utilizes industrial firm data, customs data and census data in China from 2002 to 2016, established a fixed-effect regression model, complemented by a series of robustness tests and analyses of heterogeneity. The findings indicate that, although aging results in increased labour costs for firms and constrains research and development expenditure by both local governments and businesses, the negative impact of aging can be somewhat mitigated by the substitution, creation, and productivity effects of industrial robot inputs. While we may be unable to control the inevitability of aging and the rapid advancement of artificial intelligence, we can attain a deeper understanding of their theoretical mechanisms and transmission pathways. By adapting to these trends, we can offer valuable policy recommendations and theoretical foundations to support the economic development of countries.

Keywords: population aging, industrial robot input, export, labor market, artificial intelligence.

JEL Classification: O33, F14.

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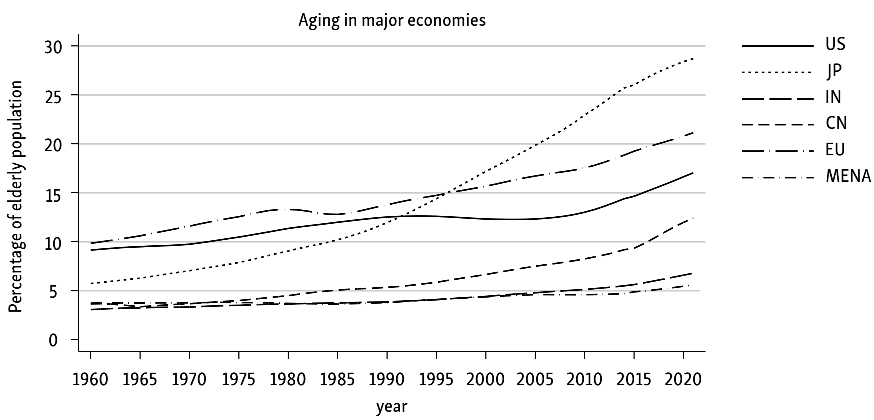
1. Introduction

1.1. Background

The global population is aging at an accelerating pace, which has significant and lasting effects on countries' economic development worldwide (Lutz et al., 2008; Bloom et al., 2015). According to the United Nations' (2024) World Population Prospects released in July 2024, the world is facing two major issues. First, fertility rates are declining globally, with projections indicating that the population could peak and start to decline by the end of the century. In 2023, the global fertility rate dropped to 2.25 children per woman, down from 3.31 in 1990. Notably, 55% of countries and regions now have fertility rates below the replacement level of 2.21, the rate needed to maintain a stable population size over the long term without immigration. Alarmingly, nearly one-fifth of countries report extremely low fertility rates, averaging less than 1.4. Second, as illustrated in Figure 1, World Bank data demonstrate that major economies globally are experiencing a significant demographic shift toward an aging population structure, with the elderly dependency ratio exhibiting a marked upward trend. As of 2022, the dependency ratio for people aged 65 and older was about 16% and is climbing rapidly. Japan stands out with the highest elderly dependency ratio, at around 50%, along with an aging level of approximately 29% (Goh et al., 2020; United Nations, 2024). By the late 2070s, the global population aged 65 and older is expected to surpass the number of individuals under 18. Demographic change poses major challenges for the supply of labor and economic growth, consequently impacting both firms' internal production structures and external export trade. Under such circumstances, seeking ways to mitigate the negative impact of aging on export trade has become an urgent issue for the governments. Most of the existing studies on aging and trade focus on the macro level: aging and gains from trade (Naito & Zhao, 2009), export share (Wu et al., 2021), high-technology exports (Tan et al., 2024), export potential (Torres, 2019). While aging certainly has a profound impact on national exports, many studies have explored aging with a focus on the country and industry level, lacking theoretical analysis of how ageing and industrial robotics impact firms' internal production structures and external export trade. however, firms are a micro component of Economic Entity, and firms' export behaviors affect the macroeconomy.

In Europe and other OECD countries, national and sectoral case studies further illuminate the interplay between ageing and automation. In continental European economies such as Germany, robotics constitutes a central pillar of the "Industry 4.0" transformation: Acemoglu and Restrepo (2022) note that firms adopting robotics across multiple European nations exhibit higher labour productivity, superior product quality, and stronger export orientation, indicating automation is being deployed to sustain competitiveness amid demographic pressures. Notably, French firms experienced significant productivity gains following robotics adoption; Kapetaniou and Pissarides (2025) further observe that in nations with robust innovation systems, such as Germany and other core EU economies, robotics frequently complements domestic skills and underpins industrial employment. Gong et al. (2023), examining the Japanese case, demonstrate that within Japan's ageing economy, industrial robots contribute to economic growth and sustainable development by enhancing productivity and facilitating the continued participation of high-value manufacturing. Yuan et al. (2025), utilising Chinese



Notes: Data on aging in each country are from the World Bank.

Figure 1. The aging of the world's major economies, 1960–2021

firm data, find that industrial robot imports stimulate firm innovation, indicating that automation not only boosts efficiency but also promotes product upgrades and exports of new products (Destefano & Timmis, 2024).

Collectively, these international studies reveal a coherent mechanism: the interplay between automation and ageing – two pervasive structural forces – is profoundly reshaping the internal production structures of firms worldwide, thereby influencing the macro-patterns of global export trade. This raises a fundamental theoretical question: how do these seemingly independent structural forces interact to influence both internal production and external trade? Delving into and addressing this question not only aids in resolving the challenges of global industrial chain disruptions and decoupling, but also points the way for developing nations' manufacturing sectors to navigate risks, safeguard economic security, and play a more significant role in international division of labour. Grounded in this core concern, this study focuses on the micro-level of firms, aiming to uncover how automation technologies influence both internal production costs and external export decisions, thereby providing empirical evidence and policy insights to address the aforementioned proposition.

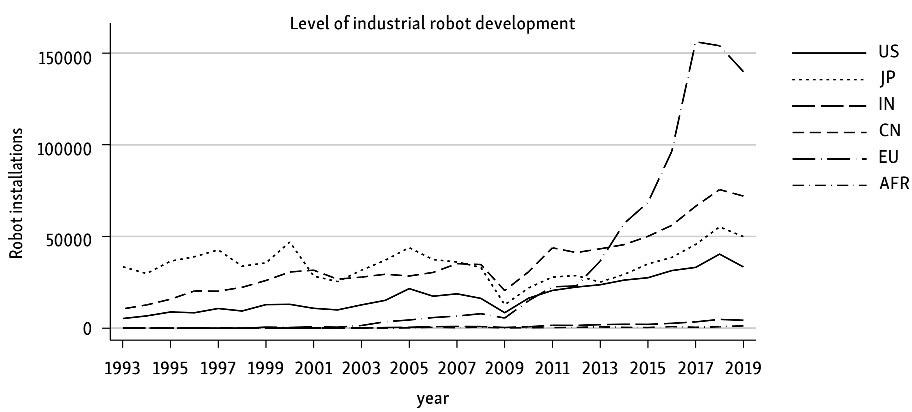
1.2. Population and trade

A substantive literature links demographic structure to comparative advantage in trade through shifts in factor endowments. As populations age, the relative scarcity of labour erodes the cost advantage of labour-intensive production, weakening export performance in economies specialised in such goods (Naito & Zhao, 2009; Yakita, 2014). At the micro level, urban demographic change also operates through identified channels: Silvanto et al. (2015) document a labour-cost mechanism (changes in wage pressures) and a human-capital mechanism (skill composition of immigrant workers), both of which transmit demographic shocks to firms' export behaviour. Two theoretical perspectives frame the sign and magnitude of ageing's trade effects. The first, rooted in endogenous-growth models, emphasises the innovation channel: labour supply conditions influence RandD effort and technological progress, with consequences for productivity and exports. From a Chinese perspective, Cai (2010) argues that a large working-age cohort delivered a "demographic dividend" that sustained high investment, accelerated capital deepening, and underpinned China's export surge since the 1990s. A second perspective extends precautionary-savings theory: growth in the non-working-age population raises uncertainty about future income and consumption, increasing current savings and, via external balances, supporting current-account surpluses and export growth (Yang & Ma, 2011). These frameworks yield competing predictions – ageing may depress labour-intensive exports via rising real wages (Bester & Petrakis, 2003), yet simultaneously bolster aggregate external surpluses via higher savings – implying that net effects are ultimately an empirical matter and likely heterogeneous across sectors and regions.

Against this background, our study examines ageing's impact on export performance for China through complementary theoretical and empirical lenses. We articulate testable implications from the factor-endowment and savings channels and then evaluate them using Chinese industrial firm, customs, and census data. This approach enables us to quantify the direct effects of demographic change on firms' exports and to assess how macro-level savings dynamics map into micro-level trade outcomes, providing evidence that can reconcile the divergent predictions in the existing literature.

1.3. Industrial robot and trade

Industrial robots serve as a cornerstone technology within the broader artificial intelligence ecosystem. The temporal evolution of industrial robot adoption, as documented by the International Federation of Robotics (IFR) and visualized in Figure 2, reveals a sustained and accelerating expansion in installations across diverse economic regions from 1993 through 2020. How does industrial robot affect firm exports? From labour perspective, industrial robot improves labour productivity, providing efficient labour for firm production and high-quality employees for firm exports (Du & Lin, 2022). First, industrial robot has a substitution effect on labour, replacing inefficient labour and integrating labour and capital factors to improve firm export efficiency and stability (Zhou et al., 2024). Second, the application of industrial robot not only forces workers to change from low-skilled to high-skilled, but also empowers the innovative development of labour education, improving the learning effect and productivity of workers (Bas & Strauss, 2015). From the perspective of firm costs, industrial robot can reduce production and trade costs, improve firm production efficiency, and thus promote firm export trade (Díaz Pavez & Martínez-Zarzoso, 2024). First, the use of logistics robots can reduce transportation and handling costs and improve logistics and transportation efficiency. Second, can the search and information costs of transactions can be effectively reduced, with the help of industrial robot industrial robot and digital technologies such as the Internet and big data. industrial robot greatly reduces the time spent searching for information and communicating, and improves the efficiency of export cooperation (Díaz Pavez, & Martínez-Zarzoso, 2024). Third, the using of industrial robots can reduce the operating costs of manual decision-making through mechanised and standardised processes. From the perspective of technological innovation, industrial robot can use digital technological innovation to improve the quality of export products (Long et al., 2020), thereby improving the export competitiveness and added value of exports. First, industrial robot has a technology spillover effect, which can identify and design complex models to achieve innovation in production and management. Second, industrial robot can unleash human innovation and enhance the level of scientific and technological research and development and the competitiveness of firms through the collation and output of existing knowledge and combinatorial innovation.



Notes: Data on robot installations by country are from the International Federation of Robotics (IFR).

Figure 2. Industrial robot development in the world's major economies, 1993–2020

1.4. Main findings and contributions

It is true that artificial intelligence equipment and industrial robots are leading the way to future development and opportunities. Seizing the development opportunities of new technologies can not only compensate for the negative impact of the disappearance of the demographic dividend, but is also the only way for a country to establish a first-mover advantage and guide the transformation of the demographic dividend into a talent dividend. In this regard, most scholars agree that the application of industrial robot has a positive impact on export trade, which leads to a question of great theoretical significance and practical value: in the reality of China's accelerating aging, how will the decline of the working-age population combined with the development and application of industrial robot affect China's export trade? What lessons can other countries learn from this?

This paper examines the moderating effects of industrial robot inputs and aging mechanisms on firm exports, aiming to make contributions in three key areas. First, from a research perspective, this paper focuses on Chinese micro-firms, contrasting with most studies that adopt a macro-level approach. It examines both the effects and theoretical mechanisms of population aging on export performance. Additionally, it investigates whether industrial robot inputs can mitigate the adverse effects of aging – such as labor shortages and productivity declines – thereby enhancing the export performance of firms and contributing to stable economic and trade development in aging countries. The paper also explores the underlying logic behind these conclusions. Second, in terms of research content, this study merges the concepts of aging and industrial robot input to analyze their combined effects on firms' export decisions and earnings through a heterogeneous export model. This paper emphasizes the endogenous technological characteristics of industrial robots, moving beyond existing measurements that mainly focus on national and industry levels, thereby examining the moderating effects of industrial robots in a more nuanced way. It extends the exploration of the interaction between population aging and firms' export activities. Third, regarding research design, this paper comprehensively investigates the mechanisms through which aging impacts export trade. It specifically assesses how aging affects the export performance of firms in developing countries, using China as a case study. This analysis considers different demographic phases, particularly during the demographic dividend and post-demographic dividend periods, as well as variations across geographic locations and types of firms.

2. Theoretical mechanisms

2.1. Theoretical model

This paper builds on the heterogeneous firm export model constructed by Melitz (2003) and Zhao et al. (2016), and infirms industrial robot and aging into the theoretical framework to theoretically explain the impact of population aging on firm exports and its mechanism of action.

2.1.1. Consumer preference and demand function

The following are the utility functions (U) and budget constraints (E_x) of representative foreign consumers (x):

$$U = \left[\int_{n \in \Omega} q_x(n)^{\frac{\sigma-1}{\sigma}} dn \right]^{\frac{\sigma}{\sigma-1}}; \tag{1}$$

$$E_x = \int_{n \in \Omega} p_x(n) q_x(n) dn, \tag{2}$$

where, the subscript (σ), (Ω) denote Substitutable elasticity goods and Collection of final consumer products. The demand function for the product (q_x) and the corresponding price index (P_x) for foreign consumers (x) can be obtained through the principle of utility maximisation under budget constraints.

$$q_x(n) = E_x P_x^{\sigma-1} p_x(n)^{-\sigma}; \tag{3}$$

$$P_x = \left[\int_{n \in \Omega} p_x(n)^{1-\sigma} dn \right]^{\frac{1}{1-\sigma}}. \tag{4}$$

2.1.2. Firm production and aging population

Introduce industrial robot input (γ), aging (θ) and development expenditure (*a*) into the model by assuming that the production function of the firm (*q*) is:

$$q = A(\gamma K)^{\phi} l^{1-\phi}, \tag{5}$$

where the subscript *A*, *K*, l and ϕ denote the level of technology, capital, labor and proportion of capital factors $(\phi \in (0,1))$. Since government research and development expenditure can to some extent make up for the lack of research and development in firms, reduce the research risks of firms and promote technological progress in firms, it is assumed that the level of technology is determined by government research and development expenditure and time (Czarnitzki & Licht, 2010), that is, it is assumed that technology $A = aT$. Based on existing research, population aging has a significant effect of increasing wage costs (Graetz & Michaels, 2018; Wang et al., 2015). Moreover, the price of labor is usually directly proportional to the worker's ability to work. Therefore, it is assumed that the price of labor $\omega = \theta b$. *b* refers to the worker's ability. A variable cost for a firm is $\omega l + P_k K$. In addition, the marginal cost function of the firm (*MC*) and the price of the firm's product (*p*) can be obtained through the conditions of minimizing firm costs and the cost-plus pricing principle.

$$MC = \frac{1}{A} \left(\frac{P_k}{\phi} \right)^{\phi} \left(\frac{\omega}{1-\phi} \right)^{1-\phi}; \tag{6}$$

$$p = \frac{1}{\rho} MC = \frac{1}{\rho A} \cdot \left(\frac{P_k}{\gamma \phi} \right)^{\phi} \left(\frac{\omega}{1-\phi} \right)^{1-\phi}. \tag{7}$$

Combining with Eq. (3), the revenue function of the exporting firm is:

$$R = E_x \left[\frac{\tau P}{p_x} \right]^{1-\sigma} = E_x \tau^{1-\sigma} P_x^{\sigma-1} \left[\frac{1}{\rho A \gamma^{\phi}} \left(\frac{P_k}{\phi} \right)^{\phi} \left(\frac{\omega}{1-\phi} \right)^{1-\phi} \right]^{1-\sigma}; \tag{8}$$

$$\frac{\partial R}{\partial \theta} = R \frac{(1-\phi)(1-\sigma)}{\omega} \frac{\partial \omega}{\partial \theta} < 0. \tag{9}$$

In Eq. (8), the export earnings of an firm are jointly determined by the technological level (A), industrial robot input (γ) and the price of the labour factor (ω). Among them, the first derivatives of the technological level (A) and the price of the labour factor (ω) of the firm are further obtained by solving Eq. (8) respectively, and we find that $\frac{\partial R}{\partial A} > 0$ and $\frac{\partial R}{\partial \omega} < 0$. It means that the export earnings of firms increase with the improvement of their technological level, while decreasing with the increase of the price of the labour factor. In Eq. (9), because of $\sigma > 1$ and $\partial \omega / \partial \theta > 0$, therefore $\frac{\partial R}{\partial \theta} < 0$. This shows that rising population aging may reduce a firm's export earnings.

2.2. Theoretical mechanisms

This study will next analyse how an aging population affects an firm's export trade through the price of labour and the level of technology. The mechanism of action mainly comes from two aspects. First, an aging population has a cost effect, which will cause the wages of workers to rise. As the rise in wages increases the variable and fixed costs of the firm, the firm will respond by reducing the number of employees and lowering production (Feng et al., 2024), resulting in a decrease in exports (Zhao et al., 2016). Second, population aging will, on the one hand, hinder the growth of innovation efficiency in high-tech industries by crowding out government investment in research and development (Liu & Lin, 2020; Ruggeri & Zou, 2007), and on the other hand, the financial burden brought about by population aging will be partially transferred to firms, increasing their tax burden, crowding out their research and development expenditure, and hindering technological.

2.2.1. Labour price mechanism

A deepening of the aging of the population will first and foremost impact the labour market. An aging population will lead to a decrease in the total labour force and an increase in the old-age dependency ratio. A decrease in the labour supply will lead to an increase in the price of the labour factor, causing an imbalance between supply and demand in the labour market. With the disappearance of the "demographic dividend", the comparative advantage of labour-intensive products will be weakened, thereby affecting export trade (Krueger, 2006). Most academics believe that an increase in labour costs will have a negative impact on exports. Early literature discussed the impact of minimum wages on trade between countries at the national level and concluded that rising minimum wages would have a negative impact on trade between countries (Bekkers, 2011). Cai (2010) believes that with the disappearance of China's demographic dividend and the deepening of its aging population, wages will rise, weakening the export advantages of labour-intensive firms and suppressing China's export trade. In addition, some scholars agree with the classic "efficiency wage" theory and oppose the negative impact of rising labor factor prices on export trade. They believe that wage increases will improve worker motivation and thus increase labor productivity (Spark, 1991), which will promote firm production and exports. Du and Qu (2009) believe that the growth of labor compensation is often accompanied by a faster increase in labor productivity, which has a positive impact on exports. This is based on the calculation of data from manufacturing firms above a designated size in China from 2000 to 2007.

2.2.2. Mechanism of progress impediment

An analytical synthesis of pertinent literature reveals that demographic aging undermines technological advancement through three interconnected mechanisms involving the contraction of scientific research expenditures, a conceptual framework that is visually represented in Figure 3. First, population aging will increase local governments' health expenditure and social security expenditure for the elderly population, which will increase the pressure on local finances and squeeze local governments' scientific and technological expenditure. Second, on the one hand, local governments, under pressure from aging-related expenditure, will often increase tax revenue to alleviate the financial burden. Increased taxation will also squeeze firms' research and development expenditure, which will have a negative impact on technological progress. On the other hand, the rising labour costs caused by aging will also affect technological progress by squeezing research and development expenditure of firms (Prskawetz et al., 2006). Technological progress is an important engine of export trade. The open-end endogenous growth theory believes that technological progress and technological innovation generated by international capital flows will have a positive impact on the country's economic growth and export trade (Cheng, 2002). Third, the innovation activities of firms are an important factor in technological progress. Aging will affect the physical strength and innovation capabilities of workers, which is not conducive to firm research and development and innovation. As older employees are relatively less creative and less energetic, they will have a negative impact on firm technological innovation (Kanfer & Ackerman, 2000). Dou (2019) used data from 43 countries from 1994 to 2016 years of data, found that aging has a significant negative effect on innovation and hinders technological progress through

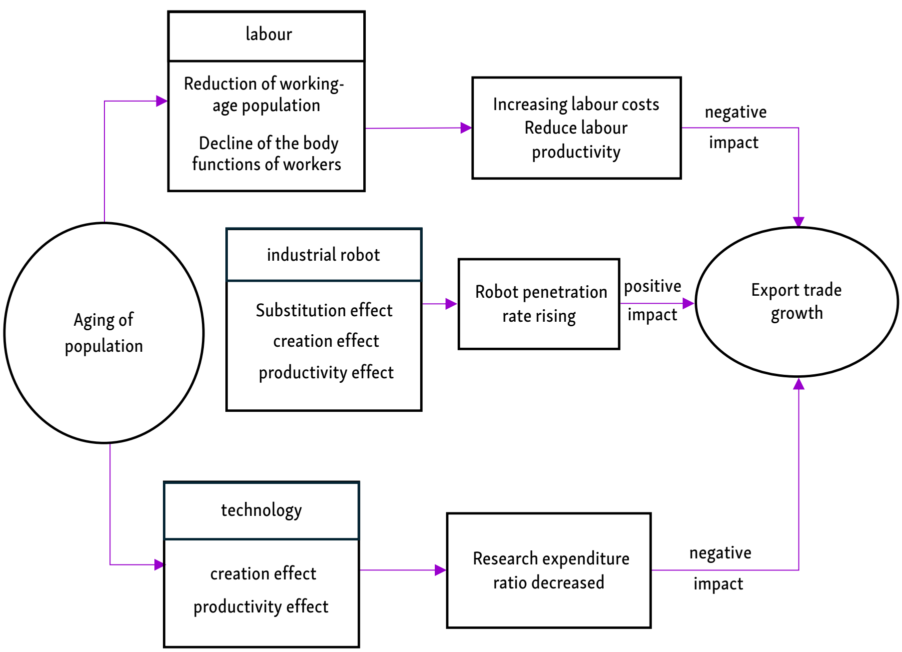


Figure 3. Mechanism roadmap

three mechanisms: reducing individual research and development efficiency, weakening basic research, and suppressing consumer and market vitality. Meyer's research shows that the more senior employees there are in an firm, the more difficult it is for the firm to adopt new technologies and methods, resulting in a low level of innovation and creativity (Bertschek & Meyer, 2009).

Taking the partial derivative of the firm's export earnings with respect to the degree of aging, and then taking the partial derivative of research and development expenditure on the basis of Eq. (9), the effect of population aging on research and development expenditure can be expressed as:

$$\frac{\partial^2 R}{\partial\theta\partial a} = -R\frac{\left(1-\sigma\right)^2\left(1-\phi\right)}{\omega A}\frac{\partial A}{\partial a} < 0. \tag{10}$$

Among them $\frac{\partial^2 R}{0\theta\partial a} < 0$. This shows that the lower the proportion of research and development expenditure, the greater the negative impact of an aging population on exports.

2.2.3. Industrial robot modulation effect

The more aging countries are, the more they tend to apply industrial robots (Acemoglu & Restrepo, 2017, 2018). The application of artificial intelligence and robotics can effectively promote the organic integration of labour and capital, integrate traditional production factors and improve the quality of capital factors (Wang et al., 2024). Internationally, the penetration rate of robots is commonly used to measure the development level of industrial robot input (Acemoglu & Restrepo, 2022; He et al., 2024). First, industrial robot has a substitution effect, which helps to improve the level of automation in firms, replace some of the labour force, and effectively reduce labour costs, thereby alleviating the negative impact of aging. Second, industrial robot has a productivity effect. Firms can effectively improve their production efficiency and enhance their export competitiveness through the application of automation technology. Automation technology can effectively reduce production defects caused by labour shortages, thereby improving the quality of products produced by firms.

This paper takes the partial derivative of industrial robot input (γ) with respect to Eq. (9) to obtain the following equation:

$$\frac{\partial^2 R}{\partial\theta\partial\gamma} = -\frac{\phi\left(1-\phi\right)\left(1-\sigma\right)^2}{\omega\gamma}\frac{\partial\omega}{\partial\theta}R < 0\,. \tag{11}$$

Eq. (11) shows that the exports of firms with a high level of industrial robot input are less negatively affected by an aging population. In the era of AI, industrial robot is not only a key factor in international trade, but also an important source of total factor productivity. Countries that have not yet achieved industrial intelligence will lose their competitive advantage. According to the new trade theory, the export decision of an firm depends on its productivity level. Firms with a higher productivity level tend to export more (Naudé et al., 2015). The application of artificial intelligence and industrial robot can significantly improve the production efficiency of firms and promote their exports (Zhao et al., 2016).

3. Research design

3.1. Regression model setting

This research draws on Cai et al. (2022) research methods and sets up the following econometric model to examine the impact of an aging population on firm export trade:

$$lnEX_{ft} = a_0 + a_1 aging_{ct} + \gamma C + \beta_f + \beta_t + \beta_i + \beta_r + \varepsilon_{ft}. \tag{12}$$

In Eq. (12), the subscript $lnEX_{ft}$, $aging_{ct}$ and C denote the logarithm of the export value of the f firm, the aging level of the city c where the firm is located in the year t and control variable set. β_f denotes the fixed effect of the firm, β_t year fixed effect, β_i industry fixed effect, β_r city fixed effect, ε_{ft} random disturbance term. The estimated coefficient of aging a_1 is of the greatest concern in this paper, as it characterises the impact effect of firm exports on population aging.

3.2. Variable description

3.2.1. Explained variable

The explained variable in this paper is firm exports $\left(lnEX_{ft}\right)$. The China Customs Database records detailed information on each of the firm's import and export transactions in a given year, including transaction amount, transaction quantity, mode of transport, etc. The firm's export value can be obtained by summing the annual export transaction amounts, and taking the logarithm. In addition, in order to increase the reliability of the results, this paper further uses the export delivery value recorded in the China Industrial Firm Database as a replacement indicator for firm exports for robustness testing.

3.2.2. Explanatory variable

The explanatory variable in this paper is population aging $\left(aging\right)$, which is measured by the proportion of the population over the age of 65, according to the internationally accepted standard for measuring aging. Combining data availability and referring to existing literature (Cai & Han, 2022; Feng & Li, 2023), this paper uses data from the 2005, 2010 and 2020 Chinese national population censuses to construct an indicator of population aging. The census data records detailed information on the year of birth of individuals. According to the theory of large samples, when the sample of individuals is large enough, the characteristics of the sample can to some extent reflect the information of the whole population. This paper calculates the age of the population based on the information on the year of birth of individuals recorded in the microdata of the census, and statistically aggregates the number of people of all ages at the city level. Since data on aging at the firm level are not available, the degree of aging in each city is calculated from census and sample survey data. It is assumed that the demographic and labour force aging faced by firms within each city are consistent with the changes in the environment, and that there are only differences between cities. In addition, this paper also uses the elderly dependency ratio as a proxy variable for robustness testing.

3.2.3. Moderating variables

The moderating variable in this paper is industrial robot input (*Inrobot*). Following Acemoglu (2022) and He et al. (2024), the penetration rate of industrial robots is used to measure industrial robot input. First, robot products are identified using HS codes from the China Customs Database. HS 6-digit codes 847950 (multifunctional robots and robotic end-effectors), 851531 (arc welding robots), 851521 (resistance welding robots), 851580 (laser welding robots), 842489 (painting robots), 842890 (handling robots) and 848640 (IC factory robots) are marked for identification. In the second step, the total amount of each robot import transaction of the firm in the customs data is summed to form a panel data set of robot transaction amounts by firm and year. In the third step, considering the characteristics of robots as an embedded technological capital that will have a sustained and positive impact on firms, the robot transaction amounts are aggregated on the basis of the panel data to construct industrial robot proxy variable. The reason for using China Customs' import robot data as a measure in this paper is as follows: Firstly, while the IFR's robot data is confined to national and industry levels, our customs data allows us to access import information at the firm level. By excluding trading companies that specialize in robot imports, we gain

Table 1. Variable details

Variables initials		Variables details	Variables sources
InEX	Explained variable	Firm export volume	China Customs data, natural logarithm of the total export value of firms + 1
aging	Explanatory variable	Aging population	Data from the Chinese census, proportion of population over 65 years of age
Inrobot	Moderator	Import value of robots	China Customs Database, natural logarithm of the amount of robots imported by firms + 1
Inage	Control variable	Age of the firm	China Industrial Firm Database, Natural logarithm of the year minus the year of establishment plus 1
Infinance		Financing constraint	China Industrial Firm Database, Natural logarithm of the ratio of accounts receivable to total assets + 1
Insize		Scale of business	China Industrial Firm Database, Natural logarithm of the number of employees + 1
Inasset		Capital intensity	China Industrial Firm Database, Take the natural logarithm of the ratio of fixed assets to the number of employees + 1
InPe		Urban population size	Chinese Urban Statistical Yearbook, Year-end registered population + 1 natural logarithm
lncitysize		Size of urban population	Chinese Urban Statistical Yearbook, Take the natural logarithm of the land area of the administrative area + 1
Infdi		Foreign investment	Chinese Urban Statistical Yearbook, Natural logarithm of the amount of foreign investment actually utilized + 1
rkzz		Natural growth rate of population	Chinese Urban Statistical Yearbook, Natural increase per 1,000 urban population
open		Openness to trade	Chinese Urban Statistical Yearbook, Ratio of total city imports and exports to city GDP

a clearer picture of the robots actually used by firms. This granularity is particularly beneficial for micro-level analysis and research. Secondly, the IFR data indicates that over 70% of China's industrial robots are imported from overseas. Our customs data effectively captures the import and utilization trends of robots within China, as noted in Cai and Qi (2021). Thirdly, although the IFR has been tracking the installation and stock of robots in China since 1993, the data for robot installations prior to 2007 is heavily skewed with numerous zero-values. This makes it challenging for analytical purposes. Therefore, utilizing the customs database is a more appropriate choice for our research.

3.2.4. Control variables

Control variables used in this paper mainly come from two levels: the firm level, including firm age, firm scale, firm financing constraints and capital intensity. Considering that firms with older ages tend to accumulate, the city level, including urban population size, area, natural population growth rate and degree of opening to the outside world. The following table shows the meaning of each variable in detail.

3.3. Data source

The data used in this paper mainly come from four sources. First, firm-level data mainly come from the China Industrial Firm Database from 2002 to 2016. Second, firm-level import and export data come from the China Customs Database from 2002 to 2016. Third, data on population aging mainly come from the population censuses in 2005, 2010 and 2015. Fourth, control variables at the city level mainly come from the China City Statistical Yearbook.

Table 2. Descriptive statistics

Variables	Observations	Mean	S.D	Min.	Max.
lnEX	585050	14.002	2.1116	7.6079	18.134
aging	585050	0.0966	0.0325	0.0162	0.1652
lnrobot	585050	0.7205	2.7545	0.0000	19.168
lnsize	585050	5.4027	1.0949	0.6931	11.963
lnfinance	585050	0.1624	0.1353	–6.8274	2.1642
lnage	585050	2.1117	0.6723	0.0000	7.6069
lnasset	585050	4.1739	1.3663	0.0000	15.641
lnPe	585050	6.2069	0.6255	3.7067	8.1195
lncitysize	585050	8.9114	0.7292	5.4681	12.442
rkzz	585050	4.2414	4.2718	–8.900	49.255
lnfdi	585050	11.726	1.4959	2.4849	14.336
open	585050	0.9213	0.8831	–0.5198	4.6222

Moreover, the Chinese Industrial Firm Database, established by the National Bureau of Statistics, boasts advantages such as a large sample size, comprehensive indicators, and extensive time series. However, it also suffers from issues including sample mismatch, variable missingness, and variable anomalies. Therefore, this paper adopts and refines the methodology proposed by Nie et al. (2012) to match the industrial firm data. Prior to matching, the National Economic Industry Classification codes and regional administrative codes were standardised. Concurrently, drawing upon the approach of Tian and Yu (2014), the manufacturing samples were adjusted to exclude those with missing, negative, or zero values for total output, sales revenue, industrial value-added, intermediate inputs, total fixed assets, and the annual average balance of net fixed assets. Manufacturing samples with missing, negative, or zero values for total output, sales revenue, industrial value added, intermediate inputs, total fixed assets, and average annual net fixed assets were excluded. Samples with missing or less than 8 employees were also discarded. To measure firm exports more scientifically and accurately, following the approach of Zhao et al. (2016), we excluded samples lacking firm names, export destination countries, or product names; transactions below USD 50 or with quantities less than 1; agricultural and resource product samples; products with fewer than 100 total samples; and intermediary trade agent samples (1). Finally, drawing on Wang et al. (2015), we matched the two datasets. Initial matching was performed using firm names and years. Unmatched companies were then re-matched using years, the last seven digits of telephone numbers, and postcodes to minimise sample loss and reduce selection bias. The final dataset comprises 585,055 observations and 188,739 firms, covering the period from 2002 to 2016. The table below presents descriptive statistics for each variable.

4. Analysis of empirical test results

4.1. Results of baseline regression

Based on Eq. (12), this paper employs the least squares method for estimation, progressively incorporating firm-level variables. Table 3 presents the benchmark regression results concerning the impact of population ageing on firm exports. Column (1) of Table 3 regresses the population ageing variable in isolation, controlling for city-level, year-level, industry-level, and individual-level fixed effects within the benchmark model, whilst utilising cluster standard errors at the individual level.

The results show that population aging has a significant negative impact on firm exports. Aging reduces the scale of firm exports and is not conducive to export growth. In columns (2)–(5), the baseline regression model in column (1) is regressed on the firm age and capital intensity, firm size and financing constraints, urban population size and urban area, as well as the natural growth rate of the population, the level of foreign investment and the degree of trade openness. The results show that although the coefficients of the explanatory variables fluctuate slightly, the overall fluctuation is not significant and remains statistically significant at the 1% level.

Table 3. Basic regression results

Variables	(1)	(2)	(3)	(4)	(5)
	lnEX	*lnEX*	*lnEX*	*lnEX*	*lnEX*
aging	−1.428*** (−5.00)	−1.151*** (−3.60)	−1.458*** (−4.69)	−1.343*** (−4.13)	−1.746*** (−5.36)
lnage		0.287*** (31.10)	0.161*** (17.89)	0.158*** (17.17)	0.159*** (17.36)
lnasset		−0.021*** (−6.85)	0.140*** (38.77)	0.139*** (38.22)	0.136*** (37.39)
lnsize			0.446*** (78.33)	0.442*** (76.79)	0.440*** (76.28)
lnfinance			0.590*** (25.63)	0.586*** (25.48)	0.590*** (25.67)
lnPe				−0.083*** (−5.76)	−0.041*** (−2.75)
lncitysize				0.030 (1.64)	0.023 (1.24)
rkzz				−0.002** (−2.64)	−0.002** (−2.16)
lnfdi					0.035*** (5.43)
open					0.084*** (9.51)
Constant	14.248*** (518.51)	13.710*** (357.46)	10.813*** (207.63)	11.100*** (56.81)	10.476*** (49.93)
Observations	638,382	566,081	564,343	540,070	539,688
R^2	0.795	0.798	0.805	0.808	0.808

Notes: *, ** and *** indicate that the estimated value is significant at the 10%, 5% and 1% levels, respectively. The t-value is in brackets. All regressions control for city, year, industry and individual effects and are clustered to the individual level.

4.2. Robustness test

Although the benchmark regression results have alleviated the problem of omitted variables to some extent by adding firm- and city-level control variables as well as region, year, industry, and individual fixed effects, there are still some unavoidable measurement errors, outliers, endogeneity issues, sample selection issues, common trends, and interference from some unobservable factors.

4.2.1. Measurement error

This paper demonstrates that substituting export delivery value from Chinese industrial firm data as an explanatory variable can mitigate measurement error to some extent. The estimation results in column (1) of Table 4 indicate that the ageing coefficient remains negative and retains statistical significance at the 1% level. Furthermore, the study employs the old-age dependency ratio (the ratio of elderly to working-age population) as an alternative explanatory variable to gauge societal burden on the ageing population.

Table 4. Results of the robustness check 1

Variables	(1)	(2)	(3)	(4)	(5)
	lnE	lnEX	lnEX	lnEX	lnEX
aging	–4.558*** (–5.25)		–1.746*** (–5.36)	–2.135*** (–6.15)	–1.928*** (–4.96)
Depr		–1.005*** (–4.59)			
Control	Yes	Yes	Yes	Yes	Yes
Constant	–0.219 (–0.43)	10.461*** (0.210)	10.476*** (49.93)	8.803*** (13.53)	10.196*** (43.61)
Observations	487,117	539,688	539,688	418,126	425,672
R^2	0.692	0.808	0.808	0.807	0.819

4.2.2. Outlier treatment

This paper mainly deals with possible outliers by bilateral truncation, excluding 20 large and medium-sized cities, and excluding the impact of the 2008 financial crisis. First, the explanatory variables and the dependent variable were subject to bilateral truncation at the 1% level, as shown in Table 4 (3). The results show that the test results are basically consistent with those of the basic regression. Second, 20 large and medium-sized cities were removed from the original data for regression. Due to the possible siphon effect and special economic and political status brought about by the size of the city, firms and population will be attracted to large cities, thus affecting the empirical results. Table 4, column (4) shows that the empirical conclusions after excluding the 20 large and medium-sized cities are basically the same as the original model, which indicates that the conclusion that an aging population has a negative impact on firm exports is universal at the city level. Finally, the data samples for 2008 and 2009 were excluded to rule out the impact of the financial crisis on the regression model. The results in column (5) show that after controlling for the impact of the 2008 financial crisis, the conclusion that an aging population has a significant negative impact on firm exports has not changed.

4.2.3. Endogeneity treatment

The endogeneity problem that may face the research conclusions of this paper is reverse causality. On the one hand, aging will raise the price of labor factors, which will inhibit export trade. On the other hand, considering the flow of population between cities, cities with more exporting firms tend to drive employment, attract young people, and lead to a lower aging level in the city, which causes the reverse causality problem. In order to alleviate the impact of reverse causality on the research conclusions, this paper will use the instrumental variable method to test for endogeneity.

First, Engbom (2019) endogenous treatment approach is employed, using lagged total births as an instrumental variable to mitigate endogeneity. This study utilises lagged births as an instrumental variable (IV1) to weaken the impact of reverse causality. Theoretically, birth cohorts are correlated with both contemporary and prior economic factors. The growth effects driven by urban firm exports manifest with a lag rather than immediately. Consequently, the lagged birth cohort exogenously influences current urban economic variables, satisfying the exogeneity assumption for the error term in the instrumental variable model. First-order estimation results are presented in Table 5(5). Following instrumental variable testing, the KP-LM statistic is significant at the 1% level, indicating that the explanatory variable and instrumental variable satisfy the minimal correlation requirement. Furthermore, the KP-Rkwald F-statistic of 752.1 exceeds the critical value of 16.38 for the Stock-Yogo weak instrumental variable identification F-test at the 10% significance level, rejecting the null hypothesis of weak instrumentality. The results demonstrate the soundness and validity of the instrumental variable selection in this study. The significant negative coefficient for ageing indicates the reliability of the research conclusions.

Secondly, following the methodology of Acemoglu et al. (2022), lagged birth rates were employed as instrumental variables to address endogeneity issues. Table 5(6) presents the test results. The KP-LM statistic is significant at the 1% level, confirming that the explanatory variable and instrumental variable satisfy the minimum correlation requirement. Moreover, the KP-Wald F statistic of 443.6 exceeds the critical value of 19.93 for the Stock-Yogo weak instrumental variable identification test at the 10% significance level, thereby rejecting the null hypothesis of weak instrumental variables. Furthermore, the Hansen J statistic p = 0.753, passing the over-identification test. These results confirm that the instrumental variable satisfies both the weak instrumental variable test and the adequacy of instrumental variable identification test. The continued significant negative coefficient for ageing further corroborates the core conclusions of this paper.

4.2.4. Sample selection issues

This paper uses a fixed-effect model to analyze the impact of population aging on firm exports, automatically excluding the sample of non-exporting firms. However, whether a firm exports or not will be affected by many factors. For example, a firm's financing constraints, size, and time of establishment will also affect its willingness to export and the scale of exports. In order to correct for possible sample selection bias, this paper uses the Heckman two-step method to estimate the impact of population aging on firm exports. Table 5 (1)–(2) shows that in the first stage selection equation, the coefficient of aging's impact on the willingness to export (y) is significantly negative; in the second stage quantitative equation, the Wald test passes the 1% significance level test, indicating that the model has sample selection bias. In addition, athrho is significantly different from 0, indicating that the disturbance terms in the corresponding regression equations of the two stages are related, which is consistent with the basic assumptions of the Heckman model. The Heckman two-stage correction adopted in this paper is reasonable and effective. The results after correction show that the impact coefficient of aging on firm exports is significantly negative, which is consistent with the results of the basic regression, indicating that the conclusions of this paper are robust.

4.2.5. Common trend problem

This paper reduces the estimation bias caused by common trends by adding joint fixed effects to the regression equation. Although this paper adds city, year, industry and individual fixed effects to the baseline regression analysis, there may still be a common trend problem, which may lead to biased regression results. First, a year-industry fixed effect is added to eliminate

Table 5. Results of the robustness check 2

Variables	Heckman		Joint fixed effects		Tool variable	
	(1)	(2)	(3)	(4)	(5)	(6)
	y	*lnEX*	Tear–Ind	City–Ind	IV1	IV2
aging	–0.0584** (–4.235)	–0.4796** (–2.199)	–0.950*** (–5.327)	–1.799*** (–4.328)	–4.42*** (–3.716)	–3.92** (–4.297)
l.lnEX		0.8473*** (2.585)				
Control	Yes	Yes	Yes	Yes	Yea	Yes
Athrho		–0.2107*** (2.882)				
Wald p	0.0000					
KP–LM					1698.1***	888.82***
Wald rk F					752.10 [0.000]	443.60 [0.000]
Hansen J						12.98 [0.753]
Observations	570,042	429,681	539,660	539,188	369,405	42,026

industry characteristics that change over time. Second, city-industry fixed effects are added to eliminate industry characteristics that vary with regions. The results show that the regression equation has not been fundamentally changed by the addition of joint fixed effects. The coefficient of the impact of an aging population on exports is close to that of the baseline regression and is significant at the 1% level.

4.3. Heterogeneity analysis

4.3.1. Regional heterogeneity

The negative impact of population ageing on export performance is not uniformly distributed across China's territory, but instead reflects deep-seated structural and institutional disparities. Our four-region analysis (Eastern, Central, Western, and Northeastern) shows that the Northeastern region exhibits a significantly stronger negative ageing-export effect, whereas the Eastern (coastal) region experiences only a modest impact. For the Central and Western inland provinces, we do not detect any statistically significant association between ageing and exports. This pattern underscores the role of regional economic structure, policy environment, and technological adaptability in shaping how ageing translates into trade outcomes.

The most pronounced ageing-induced export decline is observed in China's Northeastern "rust belt". This region has long been dominated by heavy industry (steel, machinery, petrochemicals) and state-owned firms, and has lagged behind other parts of the country in industrial restructuring and diversification. At the same time, the Northeast faces acute demographic pressures: rapid population ageing coincides with a substantial outflow of young and skilled workers to more dynamic coastal regions. The combination of few emerging industries and a shrinking skilled workforce means that demographic ageing is transmitted more directly into reduced production capacity and weakened export competitiveness.

Table 6. Heterogeneity analysis 1

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	East	Northeast	Middle	West	Capital-intensive	Labor-intensive
aging	−1.434***	−5.523**	−0.900	0.227	−0.569	−2.283***
	(6.341)	(2.689)	(2.068)	(2.909)	(3.622)	(4.474)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Constant	10.370*** (9.214)	−5.117 (12.119)	8.135*** (10.566)	11.298*** (12.160)	8.818*** (10.351)	10.633*** (7.346)
Observations	469,060	24,210	28,462	16,813	197,130	201,061
R^2	0.809	0.811	0.780	0.781	0.820	0.829
Fisher test	−5.743***		−1.232		−1.234**	

Note: To test the significance of the difference in the CFLOW coefficient between groups, this paper uses Fisher's grouped regression test (500 auto-samples) to obtain an empirical p-value.

The central government's "Revitalisation of Northeast China" initiative was designed precisely to address these intertwined structural and demographic challenges – by modernising industry, attracting investment, and revitalising the traditional industrial base. In principle, such policies should ease the twin pressures of ageing and export decline by accelerating technological upgrading and drawing in human capital; in practice, their impact has so far been limited, leaving the region disproportionately exposed to demographic headwinds. By contrast, the eastern coastal provinces – such as Guangdong, Jiangsu, and Zhejiang – are far less vulnerable to the export consequences of ageing, reflecting greater resilience rooted in both technological and demographic flexibility. These provinces serve as China's economic engines, with diversified, innovation-intensive industrial structures. Higher capital intensity and faster diffusion of automation and digital technologies allow firms to offset rising labour costs and incipient labour shortages associated with an older workforce, while sustained in-migration from other regions replenishes the local labour pool. In the Central and Western regions, the estimated relationship between ageing and export volumes is insignificant, which is consistent with their economic geography and development trajectory. China's export boom has historically been concentrated in the eastern coastal belt, with a small number of coastal provinces accounting for roughly half of total exports, whereas Central and Western provinces have developed a much smaller export base owing to their inland location and higher transport costs to world markets. Their weaker integration into global value chains means that exports are, at least for now, less directly exposed to labour-supply shocks driven by demographic change. Taken together, these regional patterns reinforce our central argument that the link between ageing and trade is highly context-dependent: it is most acute in regions with large, labour-intensive export manufacturing sectors, and much weaker in areas where export activity is limited or where technological and demographic adjustment mechanisms are more developed.

4.3.2. Heterogeneity of capital intensity

Considering that the capital intensity of different firms may differ when facing the impact of aging, this paper draws on the research of Yuan and Luo (2023) and divides the sample into

10 groups according to the per capita fixed assets of firms from small to large, with the first 4 groups being “capital-intensive” and the last 4 groups being “labor-intensive” for firm-level heterogeneity analysis. Table 6 (5)–(6) shows the regression results of capital-intensive and labor-intensive firms. The results show that the group coefficient between capital-intensive and labor-intensive firms passed the significance test. Labor-intensive firms are significantly negatively affected by aging, while the effect of aging on capital-intensive firms did not pass the significance test. The possible reason is that population aging first affects the labor market, leading to an increase in the price of the labor factor, which reduces the cost advantage of China’s manufacturing industry (Tu et al., 2022). Labor-intensive firms are more dependent on labor, and they are also more affected by aging, which is consistent with Li’s conclusion (Li et al., 2021). Capital-intensive firms are less dependent on labor, and when aging rises, capital-intensive firms can further use the capital factor to replace some of the labor force, thereby counteracting the negative impact of aging. Therefore, the negative impact of aging on capital-intensive firms is not significant.

4.3.3. Time heterogeneity

Referring to the World Bank’s World Development Indicators, the four groups of the ”demographic dividend” are classified: the pre-demographic dividend group, the early demographic dividend group, the late demographic dividend group, and the post-demographic dividend group, and the comparability of the data is comprehensively considered. This paper divides the research sample into two stages: the demographic dividend period and the post-demographic dividend period for comparative analysis. Since China’s working-age population peaked in 2011 and has been decreasing year by year (Zhou & Lei, 2017), this paper divides the period into two stages: 2002–2011 as the demographic dividend period and 2012–2016 as the post-demographic dividend period.

Table 7 shows that the estimated coefficient of the impact of aging on exports during the demographic dividend period is significantly negative. As the aging population gradually increases, the cost advantage of China’s export firms gradually decreases. As the working-age population peaks and declines, China has entered the post-demographic dividend period. The estimated coefficient of the impact of aging on exports is significantly positive. A possible reason is that with the development and popularization of robots and other intelligent devices, the cost of using industrial robot has been greatly reduced, and the substitution and creation effects of industrial robot have emerged (He et al., 2024), which has brought capital and labor to a new balance and promoted the production efficiency of firms and the improvement of exports (Artuc et al., 2023; Ndubuisi & Avenyo, 2018). The empirical p-value shows that the coefficient between different groups of population aging has passed the significance test, and the corresponding coefficient is –6.932, which indicates that the above analysis in this paper is reasonable.

4.3.4. Ownership heterogeneity

There are significant differences between firms with different ownerships in terms of their response to the external trade environment, resource acquisition capabilities, and business purposes, which may lead to differences in their response to the impact of population aging. On the one hand, foreign-invested firms have a professional global perspective and mature business models due to cross-border investment, and are more adaptable to the impact of aging, which may reduce the negative impact of population aging (Czaja & Lee, 2007). On the other hand, state-owned firms may be able to obtain sufficient funding and policy support to withstand the risks of aging compared to private firms. Therefore, with reference to the research of Tian and Wang (2021), this paper divides the full sample into state-owned firms and foreign-funded and private firms based on the type of firm registration.

Table 7. Heterogeneous analysis 2

Variable	(1)	(2)	(3)	(4)
	Period of demographic dividend	Post-period of demographic dividend	Foreign and state-owned firms	Private firms
aging	–0.727* (4.433)	2.325** (5.053)	–1.902*** (4.414)	–3.048*** (2.525)
Control	Yes	Yes	Yes	Yes
Constant	9.809*** (10.42)	12.346*** (4.467)	10.334*** (6.273)	11.050*** (5.432)
Observations	359,405	165,449	315,574	172,670
R^2	0.818	0.918	0.823	0.783
Fisher test	–6.932***		1.146***	

The results of the heterogeneity test of firm nature are shown in Table 7 (3)–(4). State-owned and foreign-funded firms are less affected by aging, while private firms are more negatively affected by aging. The possible reason is that, against the background of the policy of "the state advancing and the private sector retreating", various hidden restrictive policies restrict the development of private firms, which are in a relatively weak position. Therefore, private firms have weaker risk resistance capabilities (Xu et al., 2017) and are more negatively affected by aging. In addition, the regression coefficient difference test between private firms and foreign-funded state-owned firms passed the grouping, which indicates that the above comparative analysis is reasonable.

5. Transduction mechanism test

5.1. Model setting

In order to examine the mechanism of the role of an aging population in firm exports, this paper constructs the following mediating effect model to test the mechanism:

$$InEX_{ft} = a_3 + a_4 aging_{ct} + \gamma C_{ft} + \beta_f + \beta_t + \beta_i + \beta_r + \varepsilon_f; \tag{13}$$

$$W_{sT} = d_0 + d_1 aging_{ct} + \gamma C_{ft} + \beta_f + \beta_t + \beta_i + \beta_r + \varepsilon_{ft}; \tag{14}$$

$$InEX_{ft} = d_2 + d_3 aging_{ct} + d_4 W_{sT} + \gamma C_{ft} + \beta_f + \beta_t + \beta_i + \beta_r + \varepsilon_{ft}, \tag{15}$$

where, subscript W_{sT} denote mediating variable (price of labor and technology).

5.2. Price mechanism of labor factor

According to the previous discussion and analysis, changes in the price of labor factors are an important channel through which population aging affects firm exports. From a production perspective, as labor costs rise, the optimal ratio of production inputs for companies is disrupted. Other things being equal, companies cannot achieve the previous optimal ratio of inputs, resulting in reduced production and increased efficiency. From a demand perspective, rising labor prices lead to a reduction in the cost advantage of companies, a decline in the competitiveness of their exports, and a suppression of firm exports.

Table 8. Mechanism test

Variable	(1) *lnEX*	(2) *lnsalary*	(3) *lnEX*	(4) *lntech*	(5) *lnEX*
aging	–1.763*** (–5.326)	2.845*** (–7.163)	–1.484*** (–5.325)	–0.182*** (–6.003)	–2.137*** (–8.331)
lnsalary			–0.170*** (10.03)		
lntech					1.208*** (20.29)
Control	Yes	Yes	Yes	Yes	Yes
Constant	10.465*** (0.210)	10.861*** (0.092)	10.147*** (0.015)	0.034*** (0.002)	10.749*** (0.214)
Observations	539,693	429,235	538,271	476,345	471,060
R^2	0.808	0.784	0.808	0.893	0.817

This paper draws on Wang et al. (2015) to use the average wage level of employees in each city relative to the national average wage level to measure the factor price of labor. Table 8 (2) shows that the positive relationship between population aging and labor factor prices is significant (γ= 2.845, p < 0.01), which is consistent with the test results of Wang et al. (2015) and Yang et al. (2014). When aging and labor factor prices are simultaneously included in the regression model, the negative effect of labor factor prices on firm exports is significant (γ= –0.17, p < 0.01). At the same time, the negative effect of an aging population on firm exports is significant (γ= –1.484, p<0.01), and the labour factor price mechanism plays a partial mediating role between an aging population and firm exports. Among them, the direct effect is –1.484 and the mediating effect is –0.279, which verifies that the labour factor price mechanism is valid.

5.3. Technological progress hindrance mechanism

Technological progress affects every aspect of firm production and exports, and is an important mechanism through which population aging affects exports. First, technological progress and independent innovation will enhance the added value of firm exports through the "markup rate effect" and "relative price effect", promote the upgrading of import policies from export-oriented to innovation-oriented, and improve the export competitiveness of firms. Second, technological progress will reduce firm production costs, which will have a positive impact on export trade and promote an increase in total exports. Third, technological progress will improve the production efficiency of firms, thereby improving the quality of their export products and enhancing their export competitiveness (Bas & Straus, 2015). This paper uses the ratio of science and technology expenditure to urban fiscal budget expenditure at the city level as a proxy variable for technological progress to study the hindering effect of aging on technological progress. Table 8 (4)–(5) shows that population aging significantly reduces the proportion of local government research expenditures ($\gamma = -0.182$, $p < 0.01$), which has a negative impact on technological progress. Technological progress itself is an important booster of firm production and exports. This paper verifies the mechanism by which population aging has a negative impact on firm exports by hindering technological progress.

5.4. The moderating effect of industrial robot input

5.4.1. Moderating effect model setting

In order to test whether industrial robot has a positive moderating effect on the impact of an aging population on firm exports, this paper establishes the following moderating effect model for analysis:

$$lnrobot = c_0 + c_1 aging_{ft} + c_2 aging * lnrobot + \gamma_1 C_{ft} + \beta_f + \beta_t + \beta_i + \beta_r + \varepsilon_{ft}; \quad (16)$$

$$lnEX_{ft} = b_0 + b_1 aging_{ft} + b_2 lnrobot + b_3 aging * lnrobot + \gamma_1 C_{ft} + \beta_f + \beta_t + \beta_i + \beta_r + \varepsilon_{ft}, \quad (17)$$

where, $lnrobot$ represents industrial robot inout; $lnrobot \times aging$ represents the interaction term of an aging population and industrial robot. If the b_2 symbol is significantly positive, it indicates that industrial robot input plays a positive moderating effect on the impact of an aging population on firm exports; otherwise, it exacerbates the negative effect of an aging population on exports.

5.4.2. Regression results of the moderating effect

Table 9 shows the regression results. Column (1) shows the results of the baseline regression with the addition of the industrial robot $(lnrobot)$ variable. The results show that industrial robot has a significant positive effect on firm exports, which is consistent with the results of He et al. (2024) and Yuan et al. (2024). Column (2) adds the interaction term of population aging and industrial robot $(aging * lnrobot)$, the results show that industrial robot plays a positive moderating role in it; columns (3)–(4) conduct a robustness test of the moderating effect by replacing the core explained variable (export delivery value) and the core explanatory variable (old-age dependency ratio) respectively. The results are consistent with the previous moderating effect results and are significant at the 1% level, which shows that the moderating effect is robust and reliable. The previous section explained from the empirical results that industrial robot input mitigates the negative impact of aging on firm exports. The main mechanism is as follows: first, in the medium to long term, the price of the capital factor of industrial robot is generally lower than the price of the labour factor, enabling companies to replace some inefficient labour, counteracting the negative impact of rising labour prices caused by aging. This results in higher productivity, while also effectively reducing production and operating costs, promoting investment in research and development, and further boosting productivity (Engbom, 2019). Second, industrial robot can integrate the two factors of production, capital and labor, to optimize the optimal input ratio of capital and labor and improve the efficiency of resource allocation. Third, the application of industrial robot can standardize the production process, greatly reducing the number of errors in manual labor and defective products, thereby improving product quality. Companies with high-quality products will have higher export competitiveness and firm markup rates, which will have a positive impact on the firm's export trade.

Table 9. Moderating effect

Variable	(1)	(2)	(3)	(4)
	lnEX	*lnEX*	*lnE*	*lnEX*
aging	–1.674*** (0.325)	–1.648*** (0.326)	–4.455*** (0.869)	
depr				–0.941*** (0.219)
lnrobot	0.018*** (0.002)	0.018*** (0.002)	0.019*** (0.005)	0.019*** (0.002)
*aging * lnrobot*		0.119*** (0.040)	0.484*** (0.090)	
*depr * lnrobot*				0.097*** (0.030)
Control	Yes	Yes	Yes	Yes
Constant	10.486*** (0.210)	10.478*** (0.210)	–0.234 (0.512)	10.464*** (0.210)
Observations	539,688	539,688	487,117	539,688
R^2	0.808	0.808	0.692	0.808

6. Conclusions and policy implications

6.1. Conclusions

Keynes and the new trade protectionists argue that exports function similarly to domestic investment, both exhibiting a multiplier effect. A certain level of trade surplus can foster economic growth, making the export performance of firms vital to a country's economic development. However, with the rise of global aging and declining birth rates, a pressing challenge for countries worldwide is how to offset the negative impacts of aging through advancements in science and technology in order to achieve stable economic and trade growth. Industrial robots have emerged as a crucial driver for long-term economic growth, yet there is limited research on how industrial robots influence exports in aging economies.

This research investigates the profound effects of population aging and industrial robot adoption on firm exports in China, employing customs and industrial firm data, along with national census and sample survey data from 2002 to 2016. The findings are as follows: First, the paper constructs a heterogeneous export model incorporating aging and industrial robot inputs. It posits that aging not only significantly curtails firms' export propensity but also diminishes the scale of their exports and their export revenue and performance. Regionally, the Northeastern region is most acutely affected by aging, whereas the impact is relatively mild along the East Coast, indicating that more vulnerable areas may be disproportionately affected by aging.

Second, the impact of aging varies across firm types. Private firms are more susceptible to the adverse effects of aging, whereas foreign-invested and state-owned firms are less so. This suggests a relative lack of resilience in private firms to withstand such risks. Third, during China's demographic dividend period, population aging exerts a negative influence on export performance. However, in the post-demographic dividend era, aging compels firms to adopt industrial robots to replace less efficient labor, thereby enhancing production efficiency and export competitiveness. This shift is expected to stimulate export growth. From a mechanistic perspective, aging leads to a shrinking working-age population, which in turn raises labor costs and increases operational expenses. Moreover, it burdens local governments with higher healthcare costs, strained finances, and reduced funding for scientific research, potentially hindering technological advancement and negatively impacting export production. Furthermore, the study finds that industrial robots can act as a positive moderator in the relationship between aging and export trade. As the robot penetration rate increases, it is expected to mitigate the adverse effects of aging and bolster export performance.

6.2. Policy recommendations

The empirical results of this paper have policy implications that extend beyond the Chinese context and are relevant for many aging, export-oriented economies. A central message is that population ageing does not affect all regions and firms uniformly: older, structurally rigid industrial regions and privately owned, labour-intensive exporters are particularly vulnerable, whereas more diversified, technologically advanced regions are better able to absorb demographic shocks. Policy design should therefore move away from "one-size-fits-all" prescriptions and instead adopt a layered approach that differentiates across space and firm type.

First, at the macro level, governments need coherent "demographic-productivity-trade" strategies rather than isolated demographic or trade measures. On the demographic side, policies that ease the costs of childbearing (family allowances, childcare provision, flexible work arrangements) can, over time, slow the pace of ageing, but their effects are inevitably gradual. In the short to medium term, the primary lever is to raise effective labour supply per capita: extending working lives in a flexible way, investing heavily in adult retraining, facilitating internal and cross-border labour mobility, and reducing barriers for older workers and women to participate fully in the labour market. These measures increase the stock of skills available to export-oriented sectors and help convert a shrinking working-age population into a more productive one. For aging economies with persistent skill shortages, carefully designed labour-migration schemes focused on tradable sectors can complement domestic policies.

Second, our regional heterogeneity results suggest that older industrial regions ("rust belts") require targeted, place-based industrial policies. In such regions, ageing coincides with legacy heavy-industry structures, slower restructuring, and net out-migration of young workers. Rather than relying solely on generic revitalisation programmes, governments should explicitly link regional support to smart industrial upgrading. One practical instrument is a time-bound "smart transformation fund" that co-finances investment in industrial robots, digital infrastructure, and process innovation for firms in structurally weak, ageing regions, conditional on measurable upgrading outcomes (e.g. adoption of advanced production technologies, diversification into higher value-added export products). At the same time, policy should encourage the emergence of new tradable activities – such as green equipment, medical devices, or business services – that are less sensitive to routine labour shortages. Improving connectivity (transport, logistics, digital infrastructure) between ageing industrial heartlands and global markets can further reduce the disadvantage created by their initial geography. Although the empirical application of this paper focuses on Northeast China, the logic applies equally to older manufacturing regions in other countries that face similar combinations of ageing, industrial legacies and export exposure.

Third, the firm-level results indicate that private, especially smaller and labour-intensive, firms are more exposed to the negative export effects of ageing than large state-owned or capital-intensive firms. This calls for a differentiated firm-level policy mix that lowers the barriers for vulnerable firms to adopt productivity-enhancing technologies. A promising approach is to design tax and subsidy instruments explicitly tied to automation and complementary skill investment. For example, governments can offer enhanced tax credits or accelerated depreciation allowances for verified expenditure on industrial robots, AI-based production systems, and related digital infrastructure, provided firms simultaneously commit to worker retraining or internal mobility programmes. Matching grants or leasing schemes for automation equipment, targeted at small and medium-sized exporters with limited collateral, can further reduce fixed adoption costs and prevent a widening technology gap between large and small firms. Such "automation-for-adaptation" schemes are particularly relevant in countries where private firms account for a large share of employment and exports but face tighter financial constraints and weaker bargaining power in input markets.

Fourth, because automation and ageing interact in ways that can both raise productivity and displace certain types of jobs, innovation policy and social policy need to be coordinated. Public support for RandD in automation, robotics and digital technologies should be complemented by active labour-market policies that help displaced workers move into expanding tasks and sectors. Innovation grants and public procurement can prioritise technologies that are explicitly labour-complementary – for example, assistive robotics, digital tools that augment worker capabilities, or platforms that allow older workers to remain productive with adjusted workloads. At the same time, strengthening income support, portable social insurance, and continuous training rights can make workers more willing to accept firm-level automation decisions, thereby accelerating the diffusion of productivity-enhancing technologies that ultimately sustain export competitiveness in aging societies.

Finally, the paper's heterogeneity findings imply that policy evaluation should be disaggregated. Governments should systematically monitor how ageing and automation policies affect different regions (e.g. older industrial vs. dynamic metropolitan areas) and different firm types (private vs. state-owned, SMEs vs. large firms, labour- vs. capital-intensive sectors). This would allow calibration of support schemes over time – for instance, phasing out generous automation subsidies in already technology-frontier regions while maintaining or strengthening them in lagging, ageing regions; or gradually shifting from broad-based tax incentives to more targeted instruments linked to export performance and innovation outcomes. In this sense, the Chinese case examined in this paper offers a template: although the institutional details differ across countries, many aging, open economies face similar combinations of demographic headwinds, regional disparities and ownership structures. Designing stratified, empirically informed policies that connect demographic trends, firm behaviour, and trade outcomes is therefore central to sustaining export performance in the post-demographic-dividend era.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The data are available from the corresponding author on reasonable request.

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