sustainability

Article

Industrial Robots, Economic Growth, and Sustainable Development in an Aging Society

Chi Gong [1], Xianghui Yang [2,*], Hongru Tan [3,*] and Xiaoye Lu [1]

[1] Department of Global Business, Kyonggi University, Suwon 16227, Republic of Korea
[2] School of Economics, Sichuan University, No.24, South Section 1, Yihuan Road, Chengdu 610068, China
[3] Bay Area International Business School, Beijing Normal University, Zhuhai 519087, China
* Correspondence: yxh_person@163.com (X.Y.); hongrutan@bnu.edu.cn (H.T.)

Abstract: The impact of industrial robots and aging on economic growth is analyzed using both theoretical and empirical models in this paper. An aging mechanism is integrated into the task model and Solow model, which integrates the existing relationship between industrial robots and economic growth. Our data come from the International Robot Federation, Penn World Table, and the World Bank, and we obtain robot usage data and macroeconomic data for 77 countries and regions between 1993 and 2019. We found that industrial robots can stimulate economic growth, but aging does not affect it. It is worth noting that aging has more adverse effects on economies using industrial robots than economies without industrial robots. Further, according to mechanism analysis, the main channel of economic growth is industrial robots replacing labor, followed by improving total factor productivity (TFP), a measure of technological change in an economy. Given endogenous problems, the results are still stable.

Keywords: industrial robot; aging society; economic growth

Citation: Gong, C.; Yang, X.; Tan, H.; Lu, X. Industrial Robots, Economic Growth, and Sustainable Development in an Aging Society. *Sustainability* **2023**, *15*, 4590. https://doi.org/10.3390/su15054590

Academic Editors: V. Ravi., Suresh Subramoniam and Bijulal D.

Received: 27 November 2022
Revised: 28 February 2023
Accepted: 28 February 2023
Published: 4 March 2023

1. Introduction

The aging of the population has made it unsustainable to rely on labor-intensive industries to drive economic growth. In parallel, some countries' economies have shifted from rapid growth to high-quality development, but they find themselves in the position of "getting old before getting rich". In order to meet their national development needs, these countries began to use industrial robots in the production process. Automation has allowed these countries to maintain economic growth without relying on a large labor force. This has helped to reduce costs, increase productivity, and reduce the risk of human error. Additionally, robots can work 24 h a day and can be used in hazardous working conditions that may be too dangerous for humans.

Manufacturing has been impacted by the use of industrial robots. As a result of their low cost, unlimited working hours, and excellent performance in manufacturing, industrial robots offer many advantages. According to Acemoglu [1], the use of industrial robots in manufacturing has had a mixed effect on the US economy. Some areas are most affected by the mixed impact of robots. In China, industrial robots have become an integral part of the upgrading of manufacturing. However, the development of productivity and technological progress is not the panacea for solving all social problems. Highly specialized industrial robots significantly affect job replacement, which leads to technical unemployment. Especially in an aging society, the labor substitution effect and the "employment" effect of robots are more complicated and may also be a double-edged sword. With an aging population and high-quality economic development, it is necessary to examine the economic implications of robots in an aging society.

In the aftermath of COVID-19, the global economy is depressed, and many countries are experiencing dual pressures related to employment and the aging of their populations. The global unemployment rate for 2020 was 6.57%. The previous literature has primarily focused on the impact of population aging on economic aggregates, total factor productivity, etc., while there has been little research examining the impact of population aging on high-quality economic development. The research on how to mitigate the effects of population aging on economic development also concentrates on measures such as delaying the retirement age. In spite of the fact that Zeira, Acemoglu, Yang Guang, and other scholars have studied the economic impacts of robots, the mechanism by which industrial robots affect economic development is still unknown [1–3]. Moreover, understanding the implications of raising the retirement age and the influence of industrial robots can provide a comprehensive insight into how to address the challenge of population aging and economic development. A major objective of this paper is to explore whether the use of industrial robots can influence economic growth in the context of an aging population by using the intermediary effect model.

2. Literature Review

Existing research focuses on the impact of industrial robots on productivity and the substitution of human capital. There is a strong correlation between industrial robots and economic development [4,5]. Industrial robots play a role in accelerating economic growth, and can advance economic development by affecting productivity return on invested capital and improving total factor productivity [3,6–8]. Wang Wen [9] and Wei Dongming [10] found that industrial robots accelerate structural upgrades in China's service sector and promote upgrades and rationalization of industrial structures. Additionally, scholars view industrial robots as technological progress, arguing that industrial robots enhance productivity mainly by improving technological efficiency and promoting scale efficiency [7,11,12]. Industrial robots also play an important role in sustainable development, reducing energy consumption and promoting green technology innovation [13–15]. While many studies point to the role of robots in accelerating economic growth, its social effects may be negative. Yongwei Chen [16] and Jiahui Wei [17] noted that the usage of industrial robots brings more serious employment and distribution problems, which leads to unbalanced economic development. Zhaokui Feng [18] also found that for the Japanese economy, robots can improve labor productivity in manufacturing, service industry, and agriculture, accelerate national economic growth, and alleviate the economic and social problems caused by aging, but there are classic Marxism problems between people and robots, labor and capital. Moreover, industrial robots have an impact on economic growth through different mechanisms, and they have regional differences [19–21]. For example, industrial robots have a positive impact in the eastern and central regions and the opposite in the west. Meanwhile, industrial robot advances economic development by increasing return on capital and total factor productivity [22,23].

There are not only differences in the relationship between robots and economic growth, but also many differences between robots and the labor market. So, the conflicts between robot and human capital have become an important aspect of such research, and the substitution effect and employment effect have become an important direction of research. According to Xuguang Song [24], there are more complementary substitution effects between robots and labor force, and labor supply affects the accelerative effect of robots on economic growth, and regional differences are also evident. Qingjiang Han [25] found that industrial robots have a significant impact on the employment structure of the manufacturing industry, promoting employment in productive services and high-end services. Weixiao Lu [26] and others found that the application of industrial robots has enabled more labor to shift to the service sector, driven the development of productive service, improved the employment rate of services, and promoted the development of service trade. According to Qinghua Wu [27], industrial robots create jobs in general. However, most scholars tend to agree that robots lead to unemployment. Lan Ma [28] and Juan Ming [29] have observed that China's labor force is being replaced by robots on a large scale. As a result of robots' substitution effect on the Chinese labor market, unskilled labor is most affected [30–32]. Xueling Yan [33] found that the stocks of manufacturing robots increasing by 1% resulted in jobs decreasing by 4.6%, which had an insignificant impact on wage levels. The findings of Yongqin Wang [34] also tend to support employment substitution. Some scholars have also found that industrial transfer acts as an intermediary variable for employment reduction as a result of industrial robots [35,36].

Although both theoretical and empirical studies support the idea that industrial robots are conducive to economic development, whether there is a conflict between industrial robots and employment is not conclusive [37,38]. Studies have focused on the relationship between robots and economic growth, and between robots and employment issues, not considering the impact of reduced labor supply from aging [39,40]. For example, in existing studies, robots bring about employment effect and substitution effect, and industry and regional differences are significant influencing variables, but they are not considered by the academic community [41–45].

3. Theoretical Model

Studies about the sources of economic growth imply land, capital, labor, and total factor productivity are all the sources of economic growth [1,41]. Based on the analysis of the sources of economic growth, we assume that capital investment as K, labor force input as L, total factor productivity as A, which are the main reason for accelerating economic growth. If the economic growth meets the Cobb–Douglas function, there are:

$$Y = AK^{\alpha}L^{1-\alpha} \tag{1}$$

Further, we assume that the total economic population is N, the elderly population aged 65 and over of population is a, and the population aged under 15 is b. Total factor productivity is attributed to technological progress by Solow, but the harsh preconditions of his economic growth model fail to reflect the actual economy's performance. Because many scholars believe that institutional changes and the improvement in resource allocation efficiency will also promote the growth of total factor productivity, this paper believes that total factor productivity can be divided into two parts: technological progress and resource allocation efficiency improvement, namely:

$$TFP = techch \times effch \tag{2}$$

$techch$ represents technological innovation and $effch$ represents the improvement of resource allocation efficiency. The usage of industrial robots can influence techch, on the one hand, and replace L, on the other hand.

Guang Yang [3] extends the Acemoglu and Restrepo's model [1] of robot affecting economic growth, namely:

$$Y = AK^{\alpha}\left(\frac{M}{I-X+1}\right)^{(1-\alpha)(I-X+1)}\left(\frac{L}{X-I}\right)^{(1-\alpha)(X-I)} \tag{3}$$

M represents the amount of robot use, and L represents the labor input. In accordance with Acemoglu and Restrepo's assumption that aggregate output is achieved by combining a range of tasks $[X-1,X]$, tasks in $[I,X]$ are technologically non-automated and must be performed by labor, whereas tasks in $[X-1,I]$ are technologically automated and must be performed by robots.

Assuming that the working age population participates in production activities, the non-working age population does not participate in production activities (assume a is population aged under 15 and b is the population aged over 64), as described above:

$$L = N * (1-a-b) \tag{4}$$

So, we can get the production function of the economy:

$$\begin{cases} Y = TFP * K^{\alpha} * \left(\frac{M}{I-X+1}\right)^{(1-\alpha)(I-X+1)} * \left(\frac{N*(1-a-b)}{X-I}\right)^{(1-\alpha)(X-I)} \\ TFP = techch \times effch \end{cases} \quad (5)$$

Assuming $c = (1-\alpha)(I-X+1)$, $d = (1-\alpha)(X-I)$ and $e = (1-\alpha)(I-X+1)ln(I-X+1) + (1-\alpha)(X-I)ln(X-I)$, and taking logarithms on both sides of Equation (5), we can obtain Equation (6).

$$\begin{cases} ln(Y) = ln(TFP) + \alpha ln(K) + cln(M) + dln(\mathrm{N}) + dln(1-a-b) + e \\ ln(TFP) = ln(techch) + ln(effch) \end{cases} \quad (6)$$

where $[X-1, X]$ represents the interval of a single economic task, $[X-1, I]$ indicates that the task located in the interval requires the robot input, and $[I, X]$ means that the task of the interval requires only labor force and no robot.

Capital, robots, and population are all positively related to economic growth, while aging has a negative impact on economic growth. While robots are put into production as a production factor, there is not only a substitution effect, but also the effect of technological progress. The interaction between robots and aging may lead to another effect of aging on economic growth.

4. Empirical Analysis

4.1. Modeling

A simplified version of the regression that analyzes the effects of industrial robot on economics growth is as follows:

$$\mathrm{lnY = lnM} \quad (7)$$

Then, following the theoretical model, we set the following econometric model without considering industrial robots' effects:

$$lnY_{it} = \beta_0 + \beta_2 lnK_{it} + \beta_3 lnN_{it} + \beta_4 a_{it} + \sum \beta_i X_{it} + \gamma_i + \lambda_t + \epsilon_{it} \quad (8)$$

To consider such effects based on economic relations with industrial robots, one variable is added to Equation (1) as follows:

$$lnY_{it} = \beta_0 + \beta_1 lnM_{it} + \beta_2 lnK_{it} + \beta_3 lnN_{it} + \beta_4 a_{it} + \sum \beta_i X_{it} + \gamma_i + \lambda_t + \epsilon_{it} \quad (9)$$

Following Equation (6), the following system is used to consider the mediation effect of industrial robots:

$$\begin{cases} ln(Y) = \beta_0 + \beta_1 ln(TFP) + \beta_2 ln(K) + \beta_3 ln(M) + \beta_4 ln(\mathrm{N}) + \beta_5 a_{it} + \epsilon_{it} \\ ln(TFP) = \beta_0 + \beta_1 ln(M) + \beta_1 ln(\mathrm{RD}) \end{cases} \quad (10)$$

For Equations (7)–(10), i means the country or region, t means the year. Y_{it} indicates the GDP of the i country or region in the t year, M_{it} indicates the stocks of industrial robot of the i country or region in the t year, K_{it} and N_{it} indicates the annual capital stock and total population of the i country or region in the t year, respectively. a_{it} indicates the proportion of the aging population in the total population. X_{it} represents other control variables, including various price indexes, R&D proportion of GDP, and the share of exports to high-income economies, which respectively control the price factors, research and development factors and export factors, and these variables and the capital stock and labor supply control the influence of other factors on economic growth. γ_i and λ_t represent country or region and year fixed effects, respectively, which control other variables and temporal trends that may affect GDP. ϵ_{it} represent the estimated model residues and we cluster residues to the national or regional level. In addition, the adverse effects of heteroscedasticity on the estimation results are eliminated by taking a logarithmic approach. This paper focuses on the estimation coefficient β_1 of lnM_{it} and β_4 of a_{it}. The greater the value of lnM_{it} indicates the greater usage of industrial robots. The greater a_{it}, the greater the aging of the country or region. According to the theory, we predict that the symbol of β_1 is significantly positive and the symbol of β_4 is uncertain, which shows that the industrial robot is conducive to economic growth, while aging has uncertain economic impact due to robot replacement and technological progress.

4.2. Data Source and Descriptive Statistics

In the above model, output is a function of total factor productivity, labor force, capital stock, robot inputs, and other factors of production. The total population and the aging rate together determine the input level of the workforce. As a major country involved in economic globalization, the exchange rate, the price level and the return on domestic capital will all affect the level of the capital stock, so it is necessary to control the impact of the exchange rate, the price level, and the return on capital rate. The export structure and research and development level will affect China's total factor productivity, and they also need to be considered.

The data used in this paper has three main sources: the industrial robot data comes from the world industrial robot data released by the International Federation of Robots (*IFR*). The database only contains the installation number and stocks of industrial robots in 100 countries or regions in 1993–2019 and is classified by industry. GDP, TFP, capital stock, price level and other data are derived from Penn World Table (PWT10.0) released by the University of Pennsylvania, which contains nationally comparable macroeconomic indicators. Aging and population data comes from the World Bank database, and data about the aging and population from 1993 to 2019 are obtained. We match country names and years and obtain non-balance panel data of 77 countries in 1993–2019. The reason of excluding data from 2020–2021 is that the COVID-19 epidemic will significantly impact the research results once data from 20–22 years are added. The sources of the variables used are shown in the following Table 1:

Table 1. Variables description.

Variables	Meaning	Source
Y	GDP (USD)	PWT10.0
K	Capital stock (USD)	PWT10.0
ctfp	TFP level	PWT10.0
pl_c	Consumer price level	PWT10.0
pl_i	Capital forms a price level	PWT10.0
pl_g	Government consumer price level	PWT10.0
pl_x	Export price level	PWT10.0
M	Robot stock (station)	IFR
N	Total population (person)	The World Bank
rd	R&D expenditure for GDP (%)	The World Bank
a	The aging population (%)	The World Bank
eth	Commodity exports to high-income economies (%)	The World Bank
xr	Exchange rate (USD)	P WT10.0
irr	Return on capital (%)	PWT10.0

This paper makes simple statistics of the various macroscopic variables, and the results are shown in the following Table 2:

Table 2. Descriptive statistics of each variable.

Variable	Unit	Observation	Mean	Std.dev	Minimum	Maximum
M	10,000	1944	5.499	21.84	0	283.4
Y	USD 10,000	1944	107.8	247.8	0.544	2079
K	USD 10,000	1944	444.2	970.2	1.785	10,154
ctfp	/	1744	0.747	0.247	0.0544	2.396

Table 2. *Cont.*

Variable	Unit	Observation	Mean	Std.dev	Minimum	Maximum
irr	%	1863	0.0977	0.0613	0.01000	0.458
xr	dollar	1944	40,112	1,732,112	0.000	76,369,942
pl_c	/	1944	0.625	0.819	0.112	23.12
pl_i	/	1944	0.622	1.337	0.120	34.44
pl_g	/	1944	0.631	0.714	0.0311	18.42
pl_x	/	1944	0.568	0.0937	0.347	0.758
rd	%	1046	1.253	0.968	0.0161	4.407
eth	%	1927	71.21	18.34	2.719	98.26
a	%	1944	11.27	5.598	0.686	28.00
N	1,000,000	1942	72.52	204.8	0.264	1398

The data in Table 2 shows that the selected samples are significantly different in distribution and can represent various periods of economic development.

4.3. Empirical Results and Analysis

The usage of industrial robots represents technological progress, with a causal relationship with total factor productivity. The usage of industrial robots can improve production efficiency and essentially improve total factor productivity, so to fully measure the economic effect of industrial robots we must consider its intermediary effect.

So, the empirical analysis is primarily divided into three sections: the first focuses on the empirical investigation of the relationship between industrial robots, capital, aging, population, and economic growth, the second on the relationship between industrial robots and economic growth, and the third on the endogenous issue.

The benchmark regression results of Table 3 are obtained from the above model. The column (1)–(3) implies results without individual effects, and the column (4)–(6) presents the results with individual effects. It is clear that without regard to industrial robots (column 2 and 5), capital investment, population growth, and trade development would accelerate economic growth, and the inflation of household consumption price levels is detrimental to the long-term growth of the economy. Furthermore, when taking into account the industrial robots (column 3 and 6), the results demonstrate that capital investment and population growth are even more beneficial to economic growth, while the inflation of household consumption price levels has a greater negative impact on the economy. Whether individual effect exists or not, the positive impact of R&D on economic growth is not significant. Industrial robots, as a factor of production, accelerate economic growth once they are applied. Whether or not industrial robots were used, aging has a consistent impact on the economy over time. The differences lie in that aging is not conducive to economic growth if we do not control individual effect while the correlation between aging and economic growth becomes not significant if we control it. In general, the sample data is difficult to support the conclusion that aging is conducive to economic growth. It is worth noting that aging has more adverse effects on economies using industrial robots than economies without industrial robots ($-0.0115 < -0.0108$), probably because industrial robot speeds up aging and excessive aging creates a shortage of quality labor force.

Table 3. Baseline regression.

Variables	(1) lnY	(2) lnY	(3) lnY	(4) lnY	(5) lnY	(6) lnY
lnM	0.110 ***		0.00945 ***	0.109 ***		0.00927 ***
	(0.00286)		(0.00233)	(0.00286)		(0.00228)
lnK		0.667 ***	0.637 ***		0.607 ***	0.578 ***
		(0.0198)	(0.0209)		(0.0220)	(0.0230)
a		−0.0108 ***	−0.0115 ***		0.00668	0.00546
		(0.00400)	(0.00399)		(0.00486)	(0.00483)

Table 3. *Cont.*

Variables	(1) lnY	(2) lnY	(3) lnY	(4) lnY	(5) lnY	(6) lnY
lnN		0.263 ***	0.275 ***		0.448 ***	0.423 ***
		(0.0234)	(0.0235)		(0.0749)	(0.0746)
pl_c		−1.000 ***	−0.967 ***		−1.007 ***	−0.983 ***
		(0.0760)	(0.0759)		(0.0769)	(0.0765)
pl_i		1.470 ***	1.418 ***		1.433 ***	1.384 ***
		(0.0637)	(0.0645)		(0.0643)	(0.0649)
pl_g		0.0304	0.0398		−0.00399	0.0120
		(0.0508)	(0.0505)		(0.0519)	(0.0517)
pl_x		0.165 *	0.108		0.295 ***	0.244 **
		(0.0960)	(0.0965)		(0.104)	(0.104)
rd		0.0210	0.0185		0.00207	0.00253
		(0.0162)	(0.0161)		(0.0171)	(0.0170)
eth		0.00247 ***	0.00230 ***		0.00312 ***	0.00284 ***
		(0.000598)	(0.000595)		(0.000656)	(0.000654)
Constant	12.09 ***	−1.438 ***	−1.211 ***	12.10 ***	−3.939 ***	−3.117 ***
	(0.137)	(0.302)	(0.307)	(0.0180)	(1.191)	(1.199)
Observations	1944	1036	1036	1944	1036	1036
Company FE	NO	NO	NO	YES	YES	YES
R2	0.437	0.852	0.855	0.437	0.855	0.858

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

In regard to the relationship between industrial robots and economic growth, many research findings support the argument that industrial robots will accelerate economic growth. The paper's theoretical analysis also identifies industrial robots as a new technology that replaces labor force, on the other hand, as a new development that signifies technological progress. Thus, TFP is an impact mechanism of industrial robots on economic growth. In other words, industrial robots increase efficiency through technological advancements and replace human labor, thereby improving full factor productivity and accelerating economic growth. TFP growth is affected by other factors such as R&D intensity. Therefore, this paper analyzes the mediation effects of TFP and obtains the results of Table 4 through structural equations (SEM). Table 4 shows the impact of industrial robots on TFP and the impact of various variables on economic growth; we decompose the effect of industrial robot on economic growth in Table 5. In Table 4, the results indicate that the application of industrial robots is conducive to growth of TFP, and that the growth of TFP can accelerate economic growth, thus proving that the transmission mechanism of industrial robots involves improving TFP in order to accelerate economic growth.

In this paper, the above mediation effects are decomposed using the bootstrap method, as shown in Table 5. The direct effect of industrial robots on TFP and GDP is 0.006 and 0.013, respectively. The indirect effect of industrial robots on GDP is 0.007, and the total effect on GDP is 0.020. It is not difficult to calculate that the indirect effect of industrial robot on GDP accounts for 35% (over 1/3) of the total effect. The relationship between industrial robots and labor force substitution has also been proven in some studies.

The results above demonstrate the role of industrial robots in accelerating economic growth, which has strong policy significance. However, the above results may have endogenous problems. For example, the number of industrial robots might be correlated with other economic factors that are also positively related to economic growth. Developed countries actively adopt industrial robots not just because they can stimulate economic growth. Referring to Yang Guang's method, we use the other countries' industrial robot stocks as an instrument variable [3]. Because the robot stocks in other countries cannot directly affect the domestic economic growth due to the flow of factors, and the stocks of domestic robots and other countries are related, it is a feasible instrument variable.

Table 4. Mediation effect analysis.

Variables	(1) ctfp	(2) lnY
ctfp		1.151 ***
		(0.0786)
lnM	0.00569 ***	0.0132 ***
	(0.00137)	(0.00189)
rd	−0.0478 ***	−0.0290 ***
	(0.00947)	(0.0107)
lnK		0.495 ***
		(0.0157)
a		0.0441 ***
		(0.00363)
lnN		0.571 ***
		(0.0588)
Constant	0.0155 ***	0.0121 ***
	(0.00273)	(0.00260)
Observations	999	999

Standard errors in parentheses. *** $p < 0.01$.

Table 5. The decomposition of intermediary effects.

	Direct Effects		Indirect Effects	Total Effects	
	ctfp	lnY	lnY	ctfp	lnY
ctfp		1.151 ***			1.151 ***
		0.079			0.079
lnM	0.006 ***	0.013 ***	0.007 ***	0.006 ***	0.020 ***
	0.001	0.002	0.001	0.001	0.003

Standard errors in parentheses. *** $p < 0.01$.

The results in Table 6 show that the industrial robot have an extremely significant positive impact on economic growth and can also significantly improve TFP, which is consistent with the conclusions in Tables 3 and 4. The adoption of industrial robots can significantly increase total factor productivity, and thus significantly accelerate economic growth. Overall, the conclusions of this paper are significant and robust.

Table 6. Robustness test—endogeneity discussion.

Variables	(1) lnY	(2) ctfp	(3) lnY	(4) ctfp
lnM	0.0144 ***	0.00418 ***	0.133 ***	0.00561 **
	(0.00169)	(0.00141)	(0.0249)	(0.00231)
lnK	0.495 ***		0.0790	
	(0.0128)		(0.0915)	
ctfp	1.215 ***		1.075 ***	
	(0.0300)		(0.0805)	
rd	−0.0206 *	−0.0432 ***	0.0237	−0.0476 ***
	(0.0124)	(0.0117)	(0.0325)	(0.0130)
a	0.0416 ***		0.00332	
	(0.00329)		(0.0114)	
lnN	0.520 ***		0.0651	
	(0.0507)		(0.158)	
Constant	−4.379 ***	0.800 ***		
	(0.797)	(0.0147)		
Observations	999	999	998	998
R-squared	0.921	0.017	0.503	0.016
IV	NO	NO	YES	YES

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5. Conclusions and Enlightenment

With the development of artificial intelligence technology, many simple repetitive and creative jobs will be replaced with robots, which will undoubtedly have a significant impact on all aspects of the economy. Currently, however, most research focuses on the effects of industrial robots on employment, and relatively little is known about their effects on economic growth in the aging society. The study of the impact of industrial robots on economic growth is currently faced with two significant challenges: first, industrial robots are not included in traditional economic statistics in some countries, which makes it difficult to collect relevant data. In addition, economists are still trying to incorporate industrial robots into existing production functions, but it is unclear how this will affect the total factors' productivity in an aging society. Moreover, some scholars have examined the impact of industrial robots on economic growth and total factor productivity, but the two have not been combined in research.

This paper explores the relationship between industrial robots, aging, and economic growth. Aging is introduced into the task model and the Solow model and meanwhile we include the existing mechanism between industrial robots and economic growth. Compared with the existing research, we construct a more detailed model about industrial robots, aging, and growth, and fit with the data. Our work shows that industrial robots affect aging and economic growth. Both theoretical and empirical analysis show that the adoption of industrial robots can significantly accelerate economic growth, and there is no evidence to support the argument that aging is favorable for economic growth. The result holds while considering a robust test. It is further found that the main way for industrial robots to accelerate economic growth is factor substitution, followed by the total factor productivity improvement by industrial robots. The result has very strong policy implications. On the one hand, industrial robots can accelerate economic growth and alleviate the adverse impact of aging; on the other hand, industrial robots will appear to substitute the labor force [1], and cause the problem of unemployment again. This paper explains the economic impact and social impact of industrial robots from the perspective of the intermediary effect, but there are still some deficiencies, such as the endogenous problems are not well solved, and the two-way causal relationship between industrial robots and technological progress is not considered.

Based on the research conclusion of this paper, we believe that: (1) Based on Table 6, we can see that industrial robots have an extremely significant positive impact on economic growth. Thus, from the perspective of economic growth, the government should develop the industrial robot industry and issue supportive industrial policies. We should devote resources to develop industrial robots and intelligent robots, promote the extensive adoption of industrial robots, and accelerate economic growth. However, this will be very difficult if you do not have the right talent on board. So, it requires the government to reform the talent education system and provide the talents necessary for the development of industrial robots. In other words, in order to cultivate high-quality talents who will be able to master emerging technologies such as robots within a relatively short period of time, it is essential to establish and improve personnel training systems in this area as soon as possible. Nevertheless, a talent incentive mechanism and an employment incentive mechanism must be developed as soon as possible in order to promote talent reform and optimize the training environment. Further, the government must formulate relevant policies to encourage faster development of robotics research, and it is necessary to vigorously develop robotics. (2) As we know, our sample data is difficult to use to support the conclusion that aging is conducive to economic growth. An excessively aging society leads to a heavy social burden and the decline of the labor force, which is not conducive to the improvement of people's living standards. Industrial robots can effectively alleviate the adverse effects of aging. To encourage the development and improvement of the industrial robot industry, local governments must adopt fiscal, taxation, and financial policies. As a result, these policies should provide manufacturing companies with favorable incentives for R&D in robotics and robot applications. (3) Pay great importance to unemployment.

Table 5 shows that the direct impact of industrial robots on the economy takes up the majority of the total effect and means that industrial robots accelerate economic growth by factor substitution. Therefore, industrial robots will replace human labor and result in the loss of jobs. The extensive adoption of industrial robot could lead to a substitute labor force, causing further unemployment. Structural changes maybe occur in the labor market, so the government should plan its policies in advance to deal with possible unemployment. Consequently, in order to accelerate industrial robot development, we must not only consider the transformation of the labor force and rehiring, but also use technology to create more employment opportunities. Additionally, the government should provide basic social relief to those who have lost their jobs due to the use of industrial robots, as well as minimize the negative effects of these technologies. (4) It is essential to pay attention to the construction of supporting infrastructure. The application of industrial robots has a wide range of applications, involving all aspects of daily life. However, the use of these technologies requires cooperation between a number of different facilities. For example, most robots we use today are controlled remotely via a network and programs, which results in a higher network requirement. It is expected that humans will be able to control robots more efficiently if 5G and 6G technologies are applied on a large scale. It is therefore imperative that we focus on building infrastructures that are compatible with new technologies in order to ensure that these new technologies can contribute fully to economic growth in an aging society.

Author Contributions: Conceptualization, C.G. and H.T.; data curation, X.Y. and X.L.; formal analysis, H.T., X.Y. and X.L.; investigation, C.G. and H.T.; methodology, C.G. and H.T.; supervision, C.G.; writing—original draft, X.Y. and X.L.; writing—review and editing, C.G., H.T. and H.T.; funding acquisition, C.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Social Science Fund of China (Grant No. 21BJY128).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Acemoglu, D.; Restrepo, P. Robots and jobs: Evidence from US labor markets. *J. Political Econ.* **2020**, *128*, 2188–2244. [CrossRef]
2. Zeira, J. Workers, Machines, and Economic Growth. *Q. J. Econ.* **1998**, *113*, 1091–1117. [CrossRef]
3. Guang, Y.; Yu, H. The Usage of Industry Robots, Technology Upgrade and Economic Growth. *China Ind. Econ.* **2020**, *37*, 138–156.
4. Le Roux, J. Industrial Robot Population Density and the Neoclassical Growth Model. Ph.D. Thesis, University of Pretoria, Pretoria, South Africa, 2017.
5. Soliman, K. Are Industrial Robots a new GPT? A Panel Study of Nine European Countries with Capital and Quality-adjusted Industrial Robots as Drivers of Labor Productivity Growth. *EIIW Discuss. Pap.* **2021**. Available online: https://ideas.repec.org/p/bwu/eiiwdp/disbei307.html (accessed on 26 November 2022).
6. Leesakul, N.; Oostveen, A.-M.; Eimontaite, I.; Wilson, M.L.; Hyde, R. Workplace 4.0: Exploring the Implications of Technology Adoption in Digital Manufacturing on a Sustainable Workforce. *Sustainability* **2022**, *14*, 3311. [CrossRef]
7. Chen, Y.; Lin, C.; Chen, X. Artificial intelligence, aging and economic growth. *Econ. Res.* **2019**, *54*, 17.
8. Barnabas, B.N.; Abimiku, J. The use of Robots for Sustainable Labour Force and National Development. *Int. J. Comput. Inf. Technol.* **2015**, *4*. Available online: https://www.ijcit.com/archives/volume4/issue2/Paper040210.pdf (accessed on 26 November 2022).
9. Wang, W.; Niu, Z.; Sun, Y. Service Industry under the Impact of Industrial Robots:Structural Upgrading or Low-end Locking. *Stat. Res.* **2020**, *37*, 54–65.
10. Wei, D.; Gu, N.; Han, Y. Is AI Driving the Transformation and Upgrading of Industrial Structure – An Empirical Test Based on China's Industrial Robot Data. *Financ. Sci.* **2021**, *14*, 70–83.
11. Chen, Z. Economic Consequences of "the Second Machine Revolution": Growth, Employment and Distribution. *Study Explor.* **2019**, *2*, 101–113.
12. Cho, J.; Kim, J. Identifying Factors Reinforcing Robotization: Interactive Forces of Employment, Working Hour and Wage. *Sustainability* **2018**, *10*, 490. [CrossRef]
13. Zhang, X.; Liu, P.; Zhu, H. The Impact of Industrial Intelligence on Energy Intensity: Evidence from China. *Sustainability* **2022**, *14*, 7219. [CrossRef]

14. Lee, C.-C.; Qin, S.; Li, Y. Does industrial robot application promote green technology innovation in the manufacturing industry? *Technol. Forecast. Soc. Chang.* **2022**, *183*, 121893. [CrossRef]
15. Kolmykova, T.; Merzlyakova, E.; Kilimova, L. Development of robotic circular reproduction in ensuring sustainable economic growth. *Econ. Ann.-XXI* **2020**, *186*, 12–20. [CrossRef]
16. Chen, Y.; Zeng, O. Robots and Productivity: A Research based on Provincial Panel Data. *J. Shandong Univ. (Philos. Soc. Sci.)* **2020**, 82–97. [CrossRef]
17. Wei, J.; Gu, N.; Wei, D. Regional development gap between industrial robots and China's manufacturing industry: Late mover advantage or first mover advantage? *Econ. Manag. Res.* **2022**, *43*, 13.
18. Feng, Z. Dialectical Analysis of the Impact of Robot on Japanese Economy. *Jpn. Stud.* **2016**, *153*, 73–96.
19. Carbonero, F.; Ernst, E.; Weber, E. *Robots Worldwide: The Impact of Automation on Employment and Trade*; Report number: 36; International Labour Organization: Geneva, Switzerland, 2020.
20. Brouwer, E.; Kleinknecht, A.; Reijnen, J.O. Employment growth and innovation at the firm level. *J. Evol. Econ.* **1993**, *3*, 153–159. [CrossRef]
21. Yunus, N.M.; Said, R.; Azman-Saini, W.N.W. Spillover effects of FDI and trade on demand for skilled labour in MALAYSIAN manufacturing industries. *Asian Acad. Manag. J.* **2015**, *20*, 1.
22. Han, M.; Qiao, G. Research on the Heterogeneous Impact of Industrial Robots on China's Regional Economy:Based on the Perspective of New Structural Economics. *J. Technol. Econ.* **2020**, *39*, 85–94.
23. Szajna, A.; Kostrzewski, M. AR-AI Tools as a Response to High Employee Turnover and Shortages in Manufacturing during Regular, Pandemic, and War Times. *Sustainability* **2022**, *14*, 6729. [CrossRef]
24. Song, X.; Zuo, M.H. Industrial Robot Input, Labor Supply and Labor Productivity. *Reform* **2019**, *9*, 45–54.
25. Han, Q. Application of industrial robots and changes in employment structure—Effects and mechanisms. *Ind. Technol. Econ.* **2022**, *41*, 50–58.
26. Lu, W.; Meng, X. Industrial robot application, employment market structure adjustment and service trade development. *Int. Econ. Trade Explor.* **2021**, *37*, 4–20.
27. Wu, Q.; Zhou, X. Heterogeneous Effect of Industrial Robot on Employment—Based on Development Periods and Industries. *Forum Sci. Technol. China* **2020**, *288*, 74–82+110.
28. Ma, L. Whether Will There Be a Scale Replacement of Robot to Labor in China?: Study Based on the Experience of Japan and South Korea. *World Econ. Stud.* **2015**, *269*, 71–79+128–129.
29. Ming, J.; Hu, J. Industrial robot application, labor protection and employment of heterogeneous skilled labor. *Popul. Econ.* **2022**, *253*, 106–121.
30. Graetz, G.; Michaels, G. Industrial robots have boosted productivity and growth, but their effect on jobs remains an open question. *EUROPP | European Politics and Policy—LSE Blogs*. 2015. Available online: https://blogs.lse.ac.uk/europpblog/2015/08/05/industrial-robots-have-boosted-productivity-and-growth-but-their-effect-on-jobs-remains-an-open-question/ (accessed on 26 November 2022).
31. Bard, J.F. An assessment of industrial robots: Capabilities, economics, and impacts. *J. Oper. Manag.* **2015**, *6*, 99–124. [CrossRef]
32. Wang, L.; Zhao, J.; Sun, J.; Dong, Z. The impact of biased technology on employment distribution and labor status in income distribution: Evidence from China. *Chin. Manag. Stud.* **2020**, *14*, 135–158. [CrossRef]
33. Yan, X.; Zhu, B.; Ma, C. Employment under Robot Impact:Evidence from China Manufacturing. *Stat. Res.* **2020**, *37*, 74–87.
34. Wang, Y.; Dong, W. How the Rise of Robots Has Affected China's Labor Market: Evidence from China's Listed Manufacturing Firms. *Econ. Res. J.* **2020**, *55*, 159–175.
35. Kang, Q.; Lin, G. Industrial Robots and Migrant Workers' Employment: Substitution or Promote. *J. Shanxi Univ. Financ. Econ.* **2021**, *43*, 43–56.
36. Han, M.; Han, Q.; Xia, L. The impact of industrial robot application on manufacturing employment: An empirical study based on the data of prefecture level cities in China. *Reform* **2020**, *4*, 22–39.
37. Han, M.; Zhao, Y. Employment effect of industrial robots on China's manufacturing industry. *Ind. Technol. Econ.* **2019**, *38*, 10.
38. Khatib, O.; Yokoi, K.; Brock, O.; Chang, K.; Casal, A. Robots in human environments: Basic autonomous capabilities. *Int. J. Robot. Res.* **1999**, *18*, 684–696. [CrossRef]
39. Manyika, J.; Chui, M.; Miremadi, M.; Bughin, J.; George, K.; Willmott, P.; Dewhurst, M. A future that works: AI, automation, employment, and productivity. *McKinsey Glob. Inst. Res. Tech. Rep. D* **2017**, *60*, 1–135.
40. Cabrales, A.; Hernandez, P.; Sanchez, A. Robots, labor markets, and universal basic income. *Humanit. Soc. Sci. Commun.* **2020**, *7*, 185. [CrossRef]
41. Cortes, G.M. Where have the middle-wage workers gone? A study of polarization using panel data. *J. Labor Econ.* **2016**, *34*, 63–105. [CrossRef]
42. Lordan, G.; Neumark, D. People versus machines: The impact of minimum wages on automatable jobs. *Labour Econ.* **2018**, *52*, 40–53. [CrossRef]
43. Benzell, S.G.; Kotlikoff, L.J.; LaGarda, G.; Sachs, J.D. Robots Are Us: Some Economics of Human Replacement (No. W20941). *Natl. Bur. Econ. Res.* **2015**, *53*, 335–339. [CrossRef]

44. DeCanio, S.J. Robots and humans—Complements or substitutes? *J. Macroecon.* **2016**, *49*, 280–291. [CrossRef]
45. Ni, B.; Obashi, A. Robotics technology and firm-level employment adjustment in Japan. *Jpn. World Econ.* **2021**, *57*, 101054. [CrossRef]