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Fewer babies and more robots: economic growth in a new era of demographic and technological changes

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Abstract
This paper surveys recent research on the macroeconomic implications of demographic and technological changes. Lower fertility and increasing longevity have implications on the age population structure and, therefore, on the balance between savings and investment. Jointly with meagre productivity growth, this implies a low natural rate of interest that conditions the effectiveness of monetary and fiscal policies, especially in a world of high debt. New technological changes (robots, artificial intelligence, automation) may increase productivity growth but at the risk of having disruptive effects on employment and wages. The survey highlights the main mechanism by which demographic and technological changes, considered both individually and in conjunction, affect per capita growth and other macroeconomic variables.

Keywords Population ageing · Technological progress · Innovation · Automation · Economic growth

JEL Classification J11 · O33 · O41

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1 Introduction

In most developed countries, the weight of the working-age population in total population is bound to decrease significantly in the forthcoming decades because of the retirement of the baby boomers, decreasing fertility during the recent past decades, and further increases in longevity. At the same time, there is a new wave of technological changes, built upon the development of robotics and artificial intelligence (AI) that is generating some anxiety about the displacement of human labour with disruptive effects on employment and wages.

Awareness of these trends has led to a revival of the secular stagnation hypothesis (Hansen 1939). Its main insight is characterising a macroeconomic regime under which low labour supply growth, population ageing, poor productivity growth, and high public debt leads to a savings glut, depressed investment, and, hence, a very low natural interest rate and a permanent deficit of aggregate demand that may not be corrected by macropolicies. As for technological changes, the conventional wisdom, focused on factor-augmenting technological progress, concludes that productivity growth is associated with changes in the composition of employment by worker skills but does not affect the long-run level of aggregate employment. This view is being challenged on the presumption that robotisation and AI, rather than being complement to human labour and, hence, increase labour productivity, may lead to a global displacement of workers, regardless of their skills.

When considered together, demographic and technological changes give rise to some conceptual questions regarding the determinants of economic growth, namely, (i) Does population ageing impulse automation and, hence, productivity growth (and, if so, how)?, (ii) Do robotisation and AI have different economic implications from factor-augmenting technological progress?, (iii) To what extent a very low natural rate of interest associated to population ageing and either low productivity growth or disruptive technological changes constrain macrostabilisation policies?, and if so, (iv) What are the policy alternatives to combat a persistent deficit of aggregate demand?

This paper surveys recent literature on macroeconomics and labour economics and provides empirical evidence that have some bearing on these questions. It highlights the main transmission mechanisms involved in the analysis of the macroeconomic implications of demographic and technological changes. Awareness of these transmission mechanisms is important for designing economic policies (both in the macrostabilisation front and with long-run objectives) that could address the big challenges of the new macroeconomic scenario

The structure of the paper is as follows. Section 2 lays out the characteristics of the demographic trends, reviews models that formalise the secular stagnation hypothesis and the determinants of the natural rate of interest, and revisits the empirical evidence on the impact of demographics on GDP, employment, and productivity. Section 3 is devoted to models of technological progress that beyond factor-augmenting technological progress consider the possibility of global displacement of workers (and not only skills) by robots and AI. Section 4 highlights the main general equilibrium effects and the aggregate constraints relevant to understand the consequences of demographic and technological changes jointly considered. Finally, Sect. 5 concludes with general remarks, some of them related to policy implications.

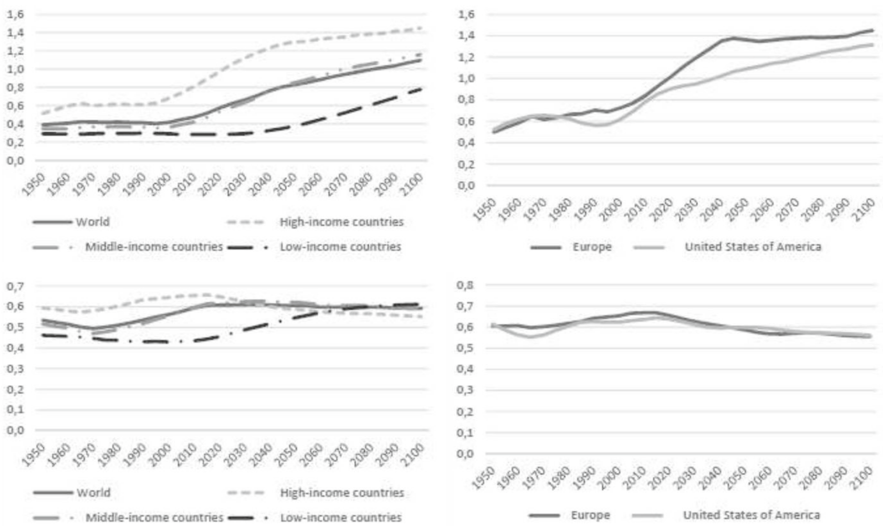

Fig. 1 Population ageing. First row: population 50 and above/population 20–49 years of age. Second row: share of population 20–69 in total population. *Source*: United Nations, Population Division

2 The revival of the secular stagnation hypothesis

In this, Sect. 1 highlights some basic facts about demographic changes and provides some background on the macroeconomic implications of these changes by, first, laying out a simple model of the natural rate of interest, and, secondly, by looking at the cross-country/time series correlations between some demographic indicators and macroeconomic variables (GDP per capita, employment rate, and productivity growth).

2.1 The new demographic scenario

The current demographic scenario is the result of three main developments: (i) baby boomers approaching the retirement age, (ii) a permanent fall in fertility rates, and (iii) a continuous rise of longevity.

Figures 1 and 2 provide some statistics on these factors that shape population forecasts for the rest of this century.[1] As a result of the baby boomers approaching retirement ages, the share of older population started to increase in the last decade of the XXth century (Fig. 1). Due to the fall in fertility and the increase in longevity (see Fig. 2), population ageing will continue increasing during the rest of the XXIst century (at a higher rate in the first five decades). Thus, between 2015 and 2050, the ratio of the population aged 50 and above over the population aged 20–49 years of age will increase by 42 pp in Europe (from 0.93 to 1.35) and by 25 pp in the USA (from 0.86 to 1.11), while the share of population 20–69 (a good approximation to working-age

[1] Data from the Population Division of the United Nations cover the period 1950–2100, with forecasts based on some assumptions for the years after 2015.

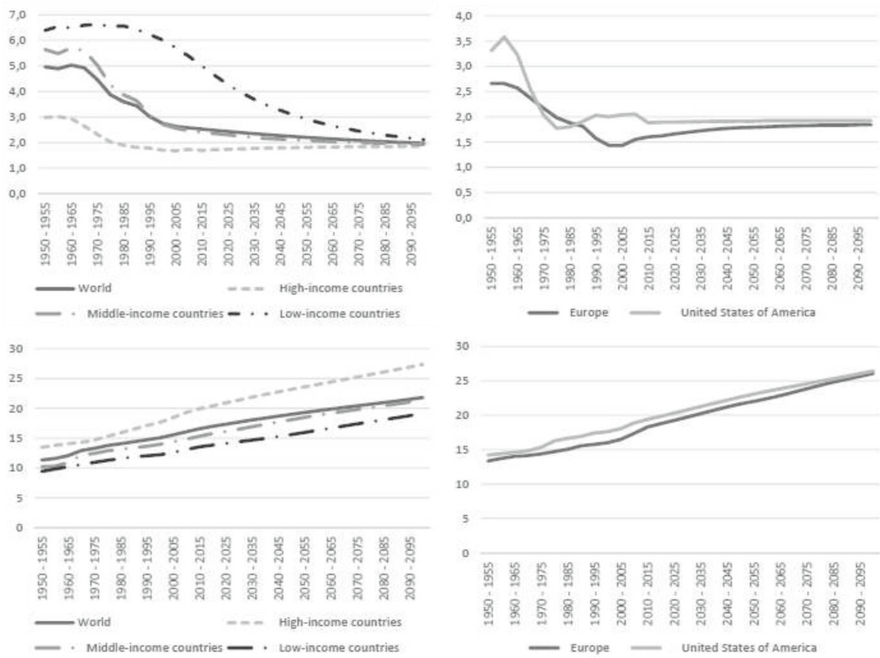

Fig. 2 Fertility and longevity. First row: fertility rate (number of children per woman). Second row: life expectancy at 65 years of age. *Source*: United Nations, Population Division

population) in total population will decrease by 8 pp in Europe (from 67% to 59%) and by 4 pp in the USA (from 64% to 60%).

2.2 Demography and macroeconomics: a first pass

In principle, there are several channels by which demographic changes may have macroeconomic implications. Apart from mechanic scale effects of the size of the population, the age structure is mostly relevant for wealth accumulation. Insofar as, the propensity to consume out of wealth depends on age, changes in fertility, mortality, and the relative size of the retired population which have implications for savings. Moreover, investment also depends on working-age population and productivity growth. Hence, these demographic changes affect the balance between savings and investment that determines the so-called natural rate of interest (i.e. the rate of interest at which savings are equal to investment *at full employment*). When monetary policy cannot accommodate the natural rate of interest because of the zero lower bound (ZLB) constraint on policy rates, the economy is bound to get trapped into an equilibrium with low growth and high unemployment.

The mechanisms by which demographic change affects savings are well understood (see, for instance, Carvalho et al. 2016). First, there is a *deleveraging effect* (emphasised by Eggertsson and Mehrotra 2014) associated with the lower size of the young population cohorts and, hence, less demand for credit. Secondly, there is also an increase in aggregate desired savings as adult workers (now the baby boomers) reach the age period at which labour productivity peaks in the working life cycle. Thirdly, as longevity increases, savings also increase, and more so when, because of high public debt, future pension transfers are expected to fall. Moreover, if future productivity growth is expected to be lower than the current one, the increase in desired savings associated with the above-mentioned demographic changes is even higher (Jimeno 2015).

As for investment, lower labour supply growth increases the capital–labour ratio and, hence, to a period of capital depletion and investment slowdown (Hall 2017). As in the case of savings, the effects of demographic changes on investment are amplified by high debt and low expected productivity growth, insofar as these two factors also reduce firm demand for capital, and may potentially originate “stagnation traps” (Benigno and Fornaro 2017): weak aggregate demand depresses growth (through lower consumption and investment), and low expected future growth depresses demand. Aksoy et al. (2019) also identify an additional channel by which population ageing leads to lower investment and growth running through lower innovation.[2]

2.3 The natural rate of interest

Standard estimates of the natural rate of interest (i.e. Laubach and Williams 2003; Holston et al. 2017) show that both in the USA and in Europe, they are on a decreasing trend since the 1980s; currently, close to zero or even in negative values. Unfortunately, as Fiorentini, Galesi, Perez-Quirós, and Sentana (2018, FGPS henceforth) show, there is a large degree of uncertainty in those estimates when the output gap is insensitive to the interest rate, and when inflation is insensitive to the output gap, phenomena are associated with a situation in which the ZLB binds. To solve this problem, FGPS (2018) propose an alternative estimation strategy that delivers a general decline in natural interest rates that started from the beginning of the XXth century until roughly the 1960s; thereafter, natural interest rates follow a generalised rise that peaks around the end of the 1980s; and eventually, rates converge to very low or even negative levels over the 2000s, so that currently the natural rates of interest, both in the US and in Europe, are close to -2%.

Moreover, FGPS (2018) attribute the initial rise and subsequent decline of the natural rate of interest that started in the 1960s to three factors: productivity growth, demographic changes, and risk. A productivity slowdown may explain the fall in the natural rate of interest by a decrease in investment, while population ageing and increasing risk may do the same, through a rise in the propensity to save. In their results, changes in the demographic composition account for most of the rise and fall of the natural interest rate in the USA, the euro area, and Canada, while productivity growth is not very significant, and risk explains part of the rise of the real interest rate, and a substantial component of the fall since roughly the 1990s.

[2] On this link, see also Derrien et al. (2017).

2.3.1 Some theoretical background

To identify the main determinants of the natural interest rate and provide some insights on the likelihood of a secular stagnation scenario, I consider a version of Eggertsson and Mehrotra's (2014) three-period OLG model, extended to include exogenous technical progress, and a public sector accumulating debt in order to implement some income transfers across generations. The focus is mainly on how savings decisions and demand for credit determine the natural interest rate, and to that end, both productivity growth and inter-generational transfers by fiscal policy are important factors to consider.[3]

Households At each moment, three generations (young, y, middle, m, and old, o) coexist. The size of the young generation at t is denoted by N_t^y, and it exogenously grows at rate n_t. Hence, $N_t^y = (1+n_t)N_{t-1}^y = (1+n_t)N_t^m = (1+n_t)(1+n_{t-1})N_t^o$.

The young generation is credit constrained, does not produce, and receives no income. Therefore, to consume, they borrow from the middle generation, up to a limit D_t (inclusive of interest payments).

The middle generation provides labour (inelastically), receives all income (labour earnings and capital income, Y), and saves: (i) to pay for debt accumulated while young, (ii) to buy capital (at price p^k), (iii) to lend to the young generation (B_t^m), and iv) to hold public bonds (B_t^g). Capital depreciates at rate δ.

There is a public sector that taxes income at rate τ_t and spends $N_t^m G_t$, to be financed by tax revenues, $\tau_t Y_t$, and (one-period) bonds held by the middle generation, $N_t^m B_t^g$. Public expenditures are assumed to be spent in providing income to the old generation (as in a Pay-As-You-Go pension system).

The old generation consumes all of its savings (plus interest receipts) and government transfers.[4]

Thus, the household's problem is:

$$\max_{\{c_t^y, c_{t+1}^m, c_{t+2}^o\}} E_t[\log c_t^y + \beta \log c_{t+1}^m + \beta^2 \log c_{t+2}^o]$$

$$\text{s.t. } c_t^y \leq B_t^y; \qquad (1+r_t)B_t^y \leq D_t$$

$$c_{t+1}^m + p_{t+1}^k \frac{K_{t+1}}{N_{t+1}^m} + (1+r_t)B_t^y = (1-\tau_{t+1})\frac{Y_{t+1}}{N_{t+1}^m} - (B_{t+1}^g + B_{t+1}^m)$$

$$c_{t+2}^o = p_{t+2}^k(1-\delta)\frac{K_{t+1}}{N_{t+1}^m} + (1+r_{t+1})(B_{t+1}^g + B_{t+1}^m) + \frac{N_{t+2}^m}{N_{t+2}^o} G_{t+2}$$

where β is the time discount factor, and r is the real interest rate at which households borrow and lend.

The Euler equation for consumption is:

$$\frac{1}{c_t^m} = \beta \frac{1+r_t}{c_{t+1}^o}$$

[3] This section draws from Jimeno (2015).

[4] For simplicity and without loss of generality, I leave aside mortality risk and changes in retirement age that affect the relative size of the old cohort.

while consumption of the old generation is determined by the corresponding budget constraint, and, something similar happens for the young generation assuming that the debt constraint binds:

$$c_t^y = \frac{D_t}{1+r_t}$$
$$c_t^o = p_t^k k_{t-1}(1-\delta) + (1+r_{t-1})(B_{t-1}^g + B_{t-1}^m) + \frac{N_t^m}{N_t^o} G_t$$

where $k_{t-1} = \frac{K_{t-1}}{N_{t-1}^m}$. Thus, savings (per member of the middle generation, excluding capital investment) at time t are given by:

$$-(B_t^m + B_t^g) = \frac{\beta}{1+\beta}\left[(1-\tau_t)y_t - D_{t-1} - p_t^k k_t\right] - \frac{1}{1+\beta}\frac{1+n_t}{1+r_t} G_{t+1} - \frac{1}{1+\beta}\frac{(1-\delta)p_{t+1}^k k_t}{1+r_t}$$

while the demand for loans is the sum of the (private) debt of the young generation and the supply of (public) bonds:

$$\frac{N_t^y D_t}{1+r_t} + N_t^m B_t^g$$

Public debt dynamics The accumulation of public debt is straightforward: the supply of public bonds is the sum of the bonds issued in the previous period, interest payments, and the primary deficit to be financed each period:

$$N_t^m B_t^g = N_{t-1}^m B_{t-1}^g (1+r_{t-1}) + N_t^m G_t - \tau_t Y_t$$
$$B_t^g = \frac{1+r_{t-1}}{1+n_{t-1}} B_{t-1}^g + G_t - \tau_t \frac{Y_t}{N_t^m}$$

Hence, the debt-to-GDP ratio ($b = N^m B^g / Y$) is given by

$$b_t^g = \frac{1+r_{t-1}}{1+n_{t-1}} \frac{y_{t-1}}{y_t} b_{t-1}^g + g_t - \tau_t$$

where $y = Y/N^m$ and $g = G/y$.

Supply side The production function is Cobb–Douglas and there is exogenous technological progress (indexed by A_t, growing at the exogenous rate a_t). Labour supply is inelastic, so that employment is given by proportion of the middle generation who is working, and capital is rented out in the same period as when investment takes place:

$$Y_t = A_t K_t^{1-\alpha} L_t^{\alpha}; \qquad L_t = (1-u_t) N_t^m$$

where u_t is the unemployment rate. Normalised by the size of the middle generation, N_t^m, the production function can be written as follows

$$y_t = A_t k_t^{1-\alpha}(1-u_t)^{\alpha}$$

Hence, the FOC for cost minimisation are:

$$w_t = \frac{\alpha y_t}{1-u_t} \tag{1}$$

$$r_t^k = \frac{(1-\alpha)(1-\tau_t)y_t}{k_t} \tag{2}$$

the corresponding Euler equation for capital is:

$$\frac{p_t^k - r_t^k}{c_t^m} = \frac{\beta[p_{t+1}^k(1-\delta_t)]}{c_{t+1}^o}$$

and the arbitrage condition linking the rental rate of capital and the real interest rate is:

$$r_t^k = p_t^k - \frac{(1-\delta)p_{t+1}^k}{1+r_t} \geq 0 \tag{3}$$

For the given current and future price of capital and the depreciation rate, this equation gives the impact of the real interest rate on capital accumulation, assuming away financial distortions that could introduce an additional wedge between the real interest rate and the rental rate of capital. Combining Eqs. (1) to (3) with the production function yields the following relationship:

$$\frac{1}{1+r_t} = \frac{p_t^k - \widetilde{A}_t(1-\tau_t)w_t^{\frac{\alpha}{\alpha-1}}}{(1-\delta)p_{t+1}^k} \tag{4}$$

where $\widetilde{A} = (1-\alpha)\alpha^{\frac{\alpha}{1-\alpha}} A^{\frac{1}{1-\alpha}}$.

Wage and price determination Eggertsson and Mehrotra (2014) consider downward nominal wage rigidity, so that wages are given by:

$$W_t = \max\left\{\overline{W_t}, P_t F_L(K_t, N_t^m)\right\}$$
$$\overline{W_t} = \gamma W_{t-1} + (1-\gamma)P_t F_L(K_t, N_t^m)$$

where P is the aggregate price level, and $F_L(.)$ is the marginal productivity of labour.

Alternatively, I also consider the possibility of wages being constrained by real rigidities.[5] In this case, I assume that the real wage cannot decrease below a certain

[5] See Shimer (2012) on the relevance of real wage rigidities in generating jobless recoveries.

level, $\overline{w_t}$, because of the existence of wage norms or imperfections in the labour market, and, hence, the prevailing wage is given by

$$w_t = \max\left\{\overline{w_t}, F_L(K_t, N_t^m)\right\}$$

Monetary policy Monetary policy is determined by a Taylor rule with a zero lower bound on the policy nominal interest rate, while the Fisher equation relates nominal and real interest rates, so that, respectively:

$$1 + i_t = \max\left\{1, (1 + i_t^*)\left(\frac{\Pi_t}{\Pi^*}\right)^{\phi_\pi}\right\}$$
$$1 + r_t = \frac{1 + i_t}{\Pi_{t+1}}; \quad \Pi_{t+1} = \frac{P_{t+1}}{P_t}$$

where i_t^*, Π^*, and ϕ^π are policy parameters.

Full employment equilibrium Consider first, the case in which neither wage rigidities nor the ZLB are binding. In this case, the economy is at full employment, and the real interest rate, $r_{t,}^f$, is determined by the condition equating supply and demand for loans, i.e.:

$$\begin{aligned} 1 + r_t^f &= \frac{1 + i^*}{\Pi^*} \\ &= \frac{(1+\beta)\left[(1+n_t)d_t + (1-\delta)p_{t+1}^k \frac{kt}{yt}\right] + (\tau_{t+1} + b_{t+1}^g)(1+n_t)\frac{y_{t+1}}{y_t}}{\beta\left[\alpha(1-\tau_t) - d_{t-1}\frac{y_{t-1}}{y_t} - b_t^g\right]} \end{aligned} \quad (5)$$

where $d = D/y$. This equation identifies the determinants of the natural interest rate (r_t^f), given paths for the expected price of capital (p_{t+1}^k) and output per capita growth ($\frac{y_{t+1}}{y_t}$), which are endogenous variables of the model. However, with a long-run perspective under which exogenous technological change determines both the relative price of capital and productivity growth, it provides some interesting insights:

- The population growth rate: as population growth falls (n_t), the natural interest rate falls, since there are fewer young people demanding credit. Notice however that there is another effect of population growth on the natural interest rate. First, as population growth falls, expected transfers to the old generation also fall, since the relative size of the middle generation to finance those transfers will be smaller. This implies lower future income for the old generation and, thus, an increase in savings that pushes down the natural interest rate even further.
- (Current and next-period) Productivity growth rates: a higher current productivity growth rate, a_t, increases savings since it allows the middle generation to pay for its debt accumulated while young using a lower fraction of its income. Hence, disposable income available for savings is higher, and the natural rate is lower.

Higher next-period productivity growth, a_{t+1}, decreases savings since expected transfers to the older generation are higher, for given tax rates and debt ratios, and, thus, the natural interest rate is higher.

- The future value of capital: a decrease in the price of capital or a higher depreciation rate decrease the equilibrium real interest rate, since future expected income of the middle generation is lower, and, hence, its savings are higher.
- Private debt: the lower the demand for credit by the young generation, d_t, the lower the equilibrium real interest rate. Also, the lower the private debt accumulated by the middle generation while young, the higher savings are, and, thus, the lower is the natural rate.
- (Current and next-period) Tax rates and public debt ratios: a higher current tax rate crowds out savings by lowering disposable income, and, hence, increases the natural rate. A higher next-period tax increases expected future income of the old generation and, thus, it also crowds out savings and increases the natural rate of interest. As for the debt ratios, the current one increases the demand for loans, while the future one, increases expected transfers to the old generation, so that high debt ratios push the natural rate up.[6]

The secular stagnation regime There is, however, an alternative equilibrium under which either because of a deleveraging shock, or declining population and productivity growth, the natural rate of interest is negative, and the ZLB prevents the policy interest rate to fall to accommodate it. When this happens, the real interest rate is higher than the natural rate, and output and employment are below their full employment levels. In this regime, wage rigidities are important for the adjustment of policies that try to close the gap between the actual and the natural rates of interest by increasing inflation expectations. With downward nominal wage rigidity, these policies reduce real wages and, hence, savings, while increasing capital profitability and investment demand. Alternatively, if real wages are rigid downwards, increasing inflation expectations has a lower effect on the real rate and, hence, on output and employment.[7]

2.4 Demographic change and economic growth

Apart form its impact on the natural interest rate, there are other transmission mechanisms by which demographic change may have an impact on per capita GDP growth. One is the mechanic composition effect from the diminishing weight of the working-age population (as the employment rate falls, GDP per capita also falls). Another is through labour productivity growth, either by changing the capital–labour ratio or by affecting total factor productivity (TFP) growth.

The empirical evidence on the effects of demographic change on productivity growth is steadily increasing. While Acemoglu and Restrepo (2017a) argue that population ageing, by giving an impulse to automation, may result in higher GDP per capita

[6] Under a specification of the utility function allowing for precautionary savings, there will be an additional negative effect on savings from increasing uncertainty over future productivity growth, price of capital, taxes, and public debt ratios.

[7] See Jimeno (2015) for a more formal discussion of the equilibria under alternative assumptions regarding wage determination.

Table 1 Population ageing and growth of GDP per capita

	GDP per capita (annual rate of growth)		
	1950–2015	1990–2015	OECD 1990–2015
Change in	**0.386*****	**0.538*****	**− 0.018**
Old ratio	**(0.134)**	**(0.165)**	**(0.096)**
#Observations	8657	4162	846
#Countries	168	168	34

Old ratio is the proportion of population aged 50 and more over the population aged 20–49. Country fixed effects included. $^{***}p$-value < 0.01, $^{**}p$-value < 0.05, $^{*}p$-value < 0.1

Table 2 Population ageing and employment rate

	Change in employment rate		
	1950–2015	1990–2015	OECD 1990–2015
Change in	**0.020**	**0.046****	**0.023**
Old ratio	**(0.020)**	**(0.023)**	**(0.029)**
#Observations	7761	4087	846
#Countries	166	166	34

Old ratio is the proportion of population aged 50 and more over the population aged 20–49. Country fixed effects included. $^{***}p$-value < 0.01, $^{**}p$-value < 0.05, $^{*}p$-value < 0.1

(insofar as the higher productivity of new machines compensates for the negative effect of a lower employment rate), Aksoy et al. (2019), by stressing the importance of the age structure of the population for innovation, conclude that in forthcoming decades, GDP per capita growth will be lower. In this regard, Eggertsson et al. (2018) also argue that the positive effect found by Acemoglu and Restrepo (2017a) vanished during the 2008–2015 period, when the ZLB was binding and the economy was, arguably, in a secular stagnation regime.

Just to illustrate the main facts, and following Acemoglu and Restrepo (2017a), Tables 1, 2, 3, and 4 present measures of the statistical association between population ageing (measured as the proportion of population aged 50 and more over the population aged 20–49), on the one hand, and per capita GDP growth, employment, and TFP and labour productivity growth, on the other. They are obtained by linear regressions with annual data since 1950 for 168 countries.[8] When considering all the countries, either for the whole sample period (1950–2015) or for the most recent one (1990–2015), population ageing is associated with increase in GDP per capita that are brought up by both higher employment rates and, especially, higher productivity growth.[9] However, when considering only OECD countries during the most recent period (1990–2015),

[8] Acemoglu and Restrepo (2017a) use the same data but look at the changes over the whole sample period. Obviously, the time horizon at which demographic changes have macroeconomic implications is likely to be larger than one year. However, even without paying too much attention to the dynamics of these effects, the statistical association between demographic changes and macro variables is easily observed even at a high frequency.

[9] Results that are qualitatively similar to those obtained by Acemoglu and Restrepo (2017a).

Table 3 Population ageing and labour productivity growth

	labour productivity (annual rate of growth)		
	1950–2015	1990–2015	OECD 1990–2015
Change in	**0.409*****	**0.487*****	**– 0.055**
Old ratio	**(0.126)**	**(0.150)**	**(0.064)**
#Observations	7761	4087	846
#Countries	166	166	34

Old ratio is the proportion of population aged 50 and more over the population aged 20–49. Country fixed effects included. ***p-value < 0.01, **p-value < 0.05, *p-value < 0.1

Table 4 Population ageing and Total Factor Productivity (TFP)

	TFP (annual rate of growth)		
	1950–2015	1990–2015	OECD 1990–2015
Change in	**0.346*****	**0.379*****	**0.012**
Old ratio	**(0.105)**	**(0.134)**	**(0.060)**
#Observations	5662	2784	846
#Countries	112	112	34

Old ratio is the proportion of population aged 50 and more over the population aged 20–49. Country fixed effects included. ***p-value < 0.01, **p-value < 0.05, *p-value < 0.1

arguably the countries and the period where automation has proceeded more rapidly, there is no statistically significant association between population ageing, on the one hand, and GDP per capita growth, employment, and productivity growth. These results cast doubts on the extent to which automation is driving the observed co-movements between population ageing and macroeconomic variables.

3 The new technological era: searching for robots and their macroeconomic implications

Low population growth and population ageing do not necessarily lead the economy to a secular stagnation regime. If trend productivity growth remains high, the balance of savings and investment at full employment may still deliver a conventional macroeconomic equilibrium with the standard properties (see Eq. 5). Macroeconomic models typically consider factor-augmenting technological progress that leads to higher economic growth without disruptive effects on employment and wages. The question is then if, in the demographic transition that is about to happen, the economy will enjoy sufficient productivity growth and of the same nature as in previous episodes of rapid technological changes.

By now, it is pretty clear that the new wave of technological changes is coming mostly from developments in robotics and AI For definition purposes, a robot is (International Federation of Robotics 2017):

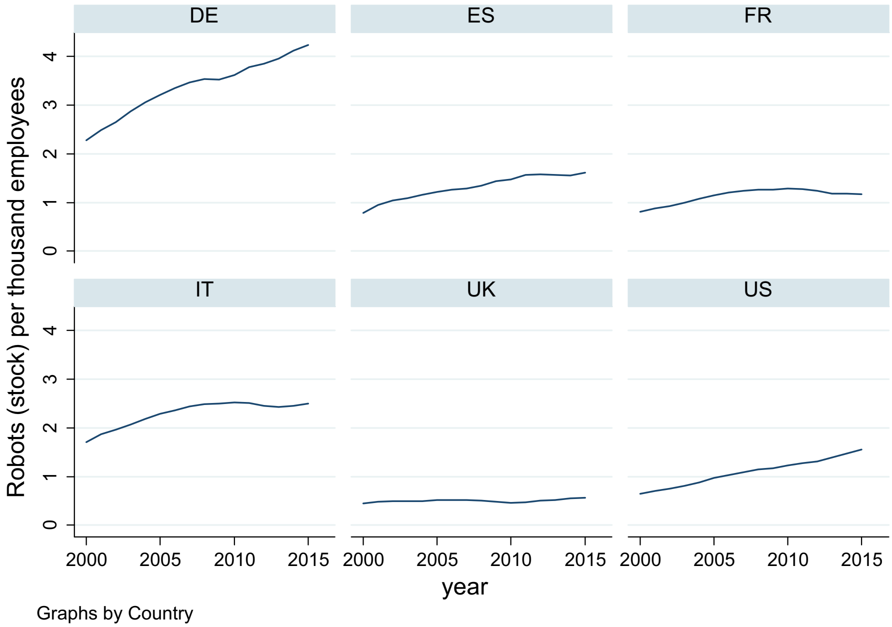

Fig. 3 Penetration of industrial robots (selected countries). *Source*: WRIB and EU KLEMS

> "An automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications"

There are industrial robots (used in manufacturing) and service/professional robots (used for non-commercial tasks, usually by lay persons). Implicit in the definition, there is the assumption that robotisation and automation are closely equivalent concepts, as both refer to the development by which an industrial robot ("a machine") is able to fulfil productive tasks previously performed by human labour.

Data on the stock of industrial robots, so-defined, are provided by the data set *World Robotics Industrial Robots (WRIB)* constructed by aggregating data from national robot associations and robot suppliers. This data set covers nearly all industrial robot suppliers worldwide (around 90% of market share). According to these data, in 2016, there were around 300,000 industrial robots in the world, and the stock of industrial robots was expected to increase at an average annual rate of 15% during 2016–2020.

By combining the WRIB data set with EU KLEMS, I compute the ratio of industrial robots to employment. Figure 3 plots this ratio for selected countries during the recent period (2000–2015).[10] The cross-country variation is very much related to the sectoral composition of output, since robots are more prevalent in manufacturing. As for the time evolution, it seems that automation is progressing more rapidly in Europe (mostly,

[10] EU KLEMS (http://www.euklems.net/) is a dataset providing cross-country measures of output, inputs, and productivity.

in Germany) than in the USA.[11] In any case, it is noteworthy that the penetration of robots so far is fairly low and, therefore, the main consequences of automation are still to be revealed.

As for AI, defined as "the capability of a machine to imitate intelligent human behaviour" or "an agent's ability to achieve goals in a wide range of environments", the possibilities are even wider than for automation. AI makes it more plausible to automate an ever-increasing number of tasks previously performed by human labour and also changes the process by which new ideas and technologies are created, helping to solve complex problems. Thus, by scaling up creative efforts, AI could lead to singularities under which there is unbounded machine learning, and, therefore, unbounded growth (Aghion et al. 2017). While developments in AI leading to more automation are reflected in the statistics on the penetration of robots in production (presented above), the new development affecting the creation of new tasks and technologies are, by their own nature, more difficult to measure given the state-of-the-art statistical methods.

3.1 Models of automation: a review

The conventional wisdom about the economic consequences of technological changes boils down to two main conclusions: (i) over the long-run GDP per capita, labour productivity, and TFP all grow at the same rate, and (ii) over the same period, there are no significant effects of technological progress on employment, although its sectoral and occupational compositions do change. This is basically the result of considering technological changes as factor-augmenting, assuming elasticities of substitution between labour and capital that are not too low, and looking at the evolution of employment and wages at the balanced-growth path. Autor and Salomons (2018) review the evidence thoroughly and show that indeed, technological changes affect the sectoral and occupational composition of employment (with job polarisation and increase in wage inequality being distinguishing features of the most recent experience in this regard) but without altering employment and unemployment equilibrium rates.

When analysing automation, the dominant approach is the *task-based framework* (Acemoglu and Restrepo 2018a) that leads to different transmission mechanisms from the conventional factor-augmenting approach that focuses instead on the skill contents of technological change.[12] Under the task-based framework, output is produced by a combination of tasks that can be performed by capital (equipment/machines/robots) and labour, either in combination or in isolation.

The new approach also encompasses three different effects of technological change. One is the *displacement effect* that decreases labour demand as human labour is replaced by machines, and capital intensity increases. This effect is in part compensated by the *productivity effect* generated by the cost-reducing consequences of new technologies (as under factor-augmenting technological change). Finally, there is the

[11] The quantitative results of the calibrated model by Basso and Jimeno (2018) suggest that this is related to the fact that population ageing started earlier and is proceeding at a higher pace in Europe than in the USA.

[12] An earlier of model of automation is Zeira (1998) upon which the task-based framework is developed. See also Zeira (2006). As for studies on the skill contents of technological change, see Autor et al. (2003).

reinstatement effect, namely, the creation of new tasks and new goods and services that require human labour. However, the transmission mechanisms by which those effects take place are somehow different to those associated with the conventional factor-augmenting technological progress.

Hence, to implement this framework one has to take a stance on which tasks are performed by which inputs (the different forms of capital and labour), the degree of complementarity between capital and labour, how new tasks are invented, and, finally, how new machines/robots are produced and used in the production of other goods and services. As a result, there are alternative views on how robots and AI should be modelled for economic analysis.

First, new machines could be considered the combination of capital, code, and skilled labour, so that robots will be as if human skills/intelligence were embedded in capital equipment. Alternatively, one can think of robots/AI as code embodied in capital that reproduces itself and is able to solve problems without any need to be "intelligent" in a human sense.[13]

There is a second issue regarding which tasks could be performed by the new machines, beyond whether they become "capital with human skills" or tools that are able to perform tasks without the need of replicating human skills. One view is that flexibility, judgement, and common sense are difficult to automate (*Polanyi's paradox*), and, hence, workers will remain more productive than machines in tasks requiring versatility, adaptability, and human contact and interactions. Another view is that while high-level reasoning requires few computational resources to replicate, low-level sensorimotor skills require much more (*Moravec's paradox*). Hence, it will be low-skilled/manual tasks what will be mostly performed by workers.

In any case, be the displacement effect of technological changes concentrated on high skilled or on manual tasks, another issue is to what extent there will be either full substitution of workers by machines or there will be complementarities between machines and human labour to be exploited. Again, two alternative views emerge. One is that machines will never be able to perform all the tasks needed for production of goods and services and, hence, there will always be jobs to be filled by workers. Another contemplates full automation (a *singularity*) made it possible by regularizing the environment, so that tasks can be fulfilled only by machines without the needs of flexibility, judgement, and common sense embedded in (some) workers. A similar outcome might arise by developing machines that attempt to infer tacit rules from context, abundant data, and applied statistics, so that by learning they become able to fulfil any task.

Given all the uncertainties, it is not surprising that studies trying to quantify the number of jobs "at risk of being automated" offer a wide range of estimates (see, for instance, Arntz et al. 2017; Frey and Osborne 2017). As for observed effects on employment and wages, there is also no consensus: Graetz and Michaels (2018) find that increased robot use contributed 0.37 pp to annual labour productivity growth, with nil employment effects, but reducing low-skilled workers' employment share. Acemoglu and Restrepo (2017b) find that one more robot per thousand workers reduces the

13 This is A.I. as making a machine behave in ways that would be called intelligent if a human was so behaving, not necessarily as humans do behave in the same task.

employment to population ratio by 0.18–0.34 pp and wages by 0.25–0.5%. Lordan and Neumark (2018) conclude that increasing the minimum wage decreases significantly the share of automated employment held by low-skilled workers, and increases the likelihood that low-skilled workers in automated jobs become unemployed. Finally, Dauth et al. (2017) find that every robot destroys two manufacturing jobs (23% of overall decline in manufacturing employment), mostly for entrants, but has no displacement effect on incumbents, so that at the aggregate, there are no aggregate losses in employment. They also find that robots raise productivity but not wages.

3.2 Analysing the macroeconomic effects of automation

An early attempt at introducing automation in macroeconomic and growth models is by Benzell et al. (2015). They envisage robots as the combination of code and capital goods, so that high-tech workers produce code, while low-tech workers are employed in tasks in the production of services.[14] Thus, production of goods and services is given by:

$$
\begin{aligned}
y(i) &= z_t \left[\theta_k \widetilde{k}_t(i)^{\alpha} + (1-\theta_k) l_t(i)^{\alpha}\right]^{\frac{1}{\alpha}} \\
l_t(i) &= \left[\theta_a \widetilde{a}_t(i)^{\phi} + (1-\theta_a) n_t(i)^{\phi}\right]^{\frac{1}{\phi}} \\
A_t &= \delta A_{t-1} + z H_{A_t}
\end{aligned}
$$

where Y_t: Goods, S_t: Services, G_t: low-tech workers, H_t: high-tech workers (H_S employed in S, and H_S in the production of code, A).

Under this specification of technology, the displacement effect is most evident. The introduction of new code reduces the compensation of low-skilled workers and savings, and, hence, both investment and the stock of capital. This mechanism has two relevant implications, one is that it generates *boom/bust technological cycles*. Another is that machines might lead to a "immiseration scenario" under which capital is crowded out and the labour income share falls substantially. Thus, despite the large productivity gains associated with robotics and AI, the possibility of a stagnation equilibrium similar to the secular stagnation equilibrium cannot be disregarded.

A more sanguine view of the displacement effect is in Lin and Weise (2018) who envisage robots as plain substitutes of labour in a DSGE framework. They assume that the inputs are capital and an aggregation of robots and human labour. Thus, if $\widetilde{k}_t$ is utilisation-adjusted traditional capital, $\widetilde{a}_t$ is utilisation-adjusted robots, and n_t human labour input, production of intermediate input i, $y(i)$, is given by:

$$
\begin{aligned}
y(i) &= z_t \left[\theta_k \widetilde{k}_t(i)^{\alpha} + (1-\theta_k) l_t(i)^{\alpha}\right]^{\frac{1}{\alpha}} \\
l_t(i) &= \left[\theta_a \widetilde{a}_t(i)^{\phi} + (1-\theta_a) n_t(i)^{\phi}\right]^{\frac{1}{\phi}}
\end{aligned}
$$

[14] Resembling what happens in Google: "Humans work themselves out of jobs by teaching the machines how to act".

where z is a productivity shift parameter.

From here, they focus on the implications for business cycles and monetary policy. Their main results are that (i) a fall in the relative price of robots causes labour's share to fall, (ii) responses to z_t and monetary policy shocks depend on the elasticity of substitution in the aggregation of robots and human labour, ϕ, and (iii) the presence of robots weakens the correlation between output and employment and, hence, increase the volatility of output, inflation, and employment.

A more comprehensive framework of the consequences of robots substituting human labour in production requires modelling of the generation of new tasks. This is what Acemoglu and Restrepo (2018a, 2019) have accomplished in a series of recent working papers. They assume that tasks are produced by combining either labour or capital with a task-specific intermediary $q(i)$. Some tasks $i > I$, $I \in [N-1, N]$ can only be produced by labour, while others, $i \leq I$, $I \in [N-1, N]$ could be automated and produced either by capital or labour. Thus,

$$y(i) = B\left[\eta q(i)^{\frac{\varsigma-1}{\varsigma}} + (1-\eta)\left(\gamma(i)l(i)\right)^{\frac{\varsigma-1}{\varsigma}}\right]^{\frac{\varsigma}{\varsigma-1}}, \quad i > I$$

$$y(i) = B\left[\eta q(i)^{\frac{\varsigma-1}{\varsigma}} + (1-\eta)(k(i)+\gamma(i)l(i))^{\frac{\varsigma-1}{\varsigma}}\right]^{\frac{\varsigma}{\varsigma-1}}, \quad i \leq I$$

In their framework, besides the conventional *productivity effect*, there are two main driving forces. First, there is automation that implies that robots *displace* workers, and, secondly, there is the creation of new complex tasks where humans have some comparative advantage (the so-called *reinstatement effect*). Under this framework, there are two crucial elements. One is how new tasks are created and whether they are performed by human labour or by machines. Another is the mechanism by which the economy converges to a balanced-growth path, if it does. Acemoglu and Restrepo (2018a) assume that the creation of new tasks is endogenous, depends on resources devoted to innovation, and new tasks are initially performed by human labour, and consider a balanced-growth path under which the set of automated tasks grows at the same rate as the set of tasks performed by human labour. They find that depending on innovation, there could be periods in which automation runs ahead of the creation of new complex tasks, but they eventually self-correct with the economy returning to a situation where employment and the labour share remain invariant to the pace of automation.

Aghion et al. (2017) argue that the existence and characteristics of the balanced-growth path in this type of models are the consequences of the so-called "Baumol's cost disease", namely, relative price adjustments resulting in growth being determined by the production factor whose productivity increases by less (or, as they put it, by growth "constrained not by what we are good at but rather by what is essential and yet hard to improve"). They show that this mechanism generates sufficient conditions for a balanced-growth path to exist, even with nearly complete automation.

This literature review suggests that there are good reasons to believe that new technological changes, based on the development of robotics and AI, may have macroeconomic implications beyond those considered by conventional analysis. Rather than focusing on skills and the complement/substitution relationship between labour and new capital goods, it may be more relevant to consider a task-based framework under which worker displacement may occur for *all* skills, and worker reinstatement depends on innovation rather than on training and human capital accumulation. Moreover, given the disruptive effects on employment and wages that this technological change may have, the higher productivity growth brought by automation might not translate into higher long-run growth. The next section presents some new results that illustrate these two claims.

4 Robotics, artificial intelligence, and population ageing

Under the task-based framework for the analysis of technological changes, there are several transmission mechanisms by which population ageing might condition innovation, automation, and growth. One arises from assuming that workers of different ages have different skills with regard to the risk of being automated. This generates an interesting transmission channel by which demographic changes translate into the creation of new tasks and automation, and, hence, affect growth and the labour share. For instance, Acemoglu and Restrepo (2018b) argue that population ageing fosters automation because middle-aged workers have skills used in tasks that are more easily automated. Another interesting hypothesis is that population ageing alters the consumption baskets, affecting the relative price of goods and, hence, giving different incentives for innovation, and automation of tasks performed in production.

Nevertheless, for addressing the macroeconomic implications of the combination of population ageing and automation, it is necessary to build a fully fledged general equilibrium model where innovation, automation, capital, and labour demand are all endogenously determined, and the resource constraints of the economy are precisely spelled out. Basso and Jimeno (2018) carry out this type of exercise in an economy where there are four main structures: (i) A goods production sector where producers aggregate intermediate goods/tasks and a continuum of intermediate goods firms that employ a composite of goods from all firms (inputs), capital and either robots or labour, (ii) A robot production sector that transforms final goods into robots and sells them to intermediate producers, (iii) An innovation sector that generates new tasks (product creation) and develops procedures so that robots can be used in an existing tasks, iv) Households with a life cycle structure (worker, retired), supplying labour (workers), accumulating assets, and consuming a composite of all varieties produced.

This model contains most of the transmission mechanisms by which demographic and technological changes affect the economy. First, due to the life cycle structure, population ageing has an impact on savings (and, hence, on the equilibrium interest rate) as stressed by the literature on the revival of secular stagnation. Secondly, since it adopts the task-based framework for production, it also embeds the productivity, displacement, and reinstatement effects highlighted by the recent literature on technological changes. Thirdly, by modelling endogenous growth by innovation and automation, and by making them explicit the relative profitability of both activities and the resources employed by them, it gives raise to a trade-off (static and dynamic) between innovation and automation that is often neglected. This trade-off arises from

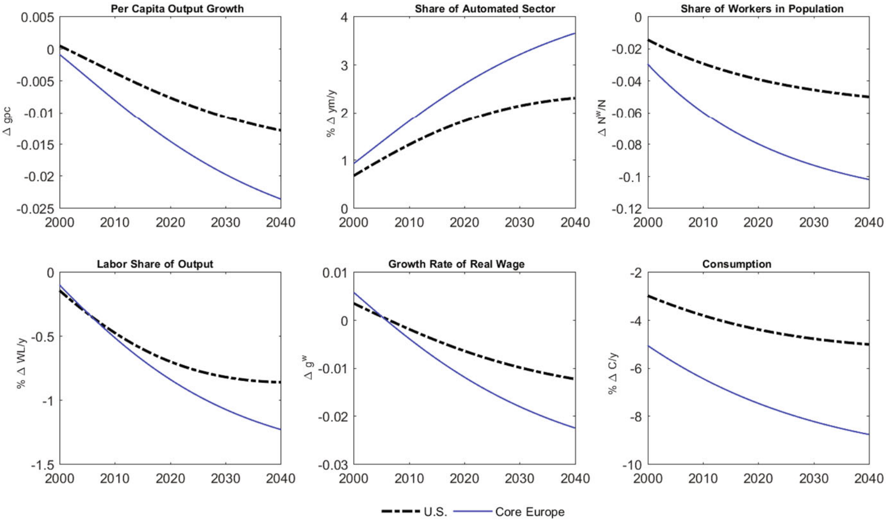

Fig. 4 Effects of demographic transition in Europe and in the USA. Note: The figure plots the effects of the projected demographic changes in each region. Unless stated, the percentage change relative to the initial balanced-growth path is reported. Per Capita Output growth $= \frac{y_t}{y_{t-1}}$—Change relative to the initial balanced-growth path, Share of Automated Sector—$\frac{\int_{i \in A_t} y_{i,t} di}{y_t}$, Share of Workers in Population—$\frac{N_t^w}{N_t}$- Change relative to the initial balanced-growth path, Labour Share of Output $\frac{W_t L_t}{y_t}$, Growth Rate of real wage—$\frac{W_t}{W_{t-1}}$- Change relative to the initial balanced-growth path, Consumption—$\frac{C_t}{y_t}$. Core Europe: The aggregate of Germany, France, Italy, and Spain. *Source*: Basso and Jimeno (2018)

two constraints. One is the more resources that are devoted to automation, there are less resources available for innovation. Another is that if innovation slows down, eventually automation also slows down, as tasks ought to be invented before they can be automated. Finally, it gives some scope to the possibility that population ageing may make innovation more difficult by the special relevance of young workers labour supply for this sector.

Needless to say, the results of simulations carried out with a calibrated version of the Basso and Jimeno (2018) model are contingent on several assumptions regarding the specifications of production, innovation and automation sectors. However, under standard assumptions required to make the economy converge to a balanced-growth path, two main conclusions can be drawn from their analysis. One is that a reduction in labour supply, in the long-run, decreases per capita growth. The intuition (and analytical result) is that as the economy converges to a new balanced-growth path, the shares of the labour intensive and the automated sectors in final production ought to remain constant, which means that the stock of robots and labour supply must grow at the same rate, which is lower due to the fall in fertility. The second set of (numerical) results is obtained by simulating the demographic transition in the USA and in the main European countries, as forecasted by the Population Division of the United Nations. Initially, as interest rates fall due to the increase in savings brought up by the fall in fertility and the rise of longevity, there are more resources to invest in capital accumulation, automation, and innovation, and, hence, the growth rate increases. However, as labour supply declines as the demographic transition progresses, there is less innovation (because of the labour supply effect on R&D) and, hence, less new tasks created, and, eventually, less automation. (Since the introduction of robots need new tasks to be created.) Therefore, eventually the growth rates of consumption, investment, and GDP decrease (see Fig. 4).

5 Concluding remarks

The macroeconomic implications of demographic changes are relatively well known. After all, there is a long tradition of overlapping generation models where the standard transmission mechanisms (mostly through changes in savings and investment) have been extensively analysed. Extending these models to consider other likely effects of population ageing is now enjoying a revival in economic research. For instance, implications for the effectiveness of traditional macrostabilisation policies are the focus of many applications of the state-of-the-art models (see, for instance, Carvalho et al. 2016, for monetary policy, and Basso and Rachedi 2017, for fiscal policy). Consequences for the needs of inter-generational redistribution associated with population ageing are also a top item in the research agenda regarding pensions and the design of social policies. What is less certain is the macroeconomic implications of the new wave of technological changes, associated with robotics and artificial intelligence.

Shifting analysis from factor-augmenting technological change (which constitutes the conventional wisdom) to a task-based framework in which replacement, productivity, and reinstatement effects can all take place simultaneously provides new insights on how robotics and artificial intelligence may impinge upon the economy. This paper has surveyed recent developments in the macroeconomic analysis of demographic and technological changes to provide some insights on the nature of the uncertainties that arise by the interaction between demography and technology.

We draw two main messages. First, by revisiting recent results from the application of the task-based framework for the analysis of technological change, we identify three main sources of uncertainty about their macroeconomic implications: (i) the degree to which new machines and human labour will be complements or substitutes in the production of existing tasks embedded in the production of goods and services, (ii) the speed to which tasks performed by human labour could be automated, and (iii) the rate at which new tasks are created. Secondly, by looking at the effects of technological change under the task-based framework taking place at the same time that population ageing, we conclude that it is likely that even though population ageing creates incentives for automation, per capita growth will slow down during the demographic transition that most countries are going through.

Apart from the policy implications for macrostabilisation policies already mentioned, there are many other areas of economic policies that will be affected by these demographic and technological changes. Together with negative effects on per capita growth, the new wave of technological changes may bring a decline in labour shares, at a time in which conventional social policies, which mostly channelled taxes from the young to the old, will require more resources. This probably will require a full reconsideration of the fiscal and transfer systems. Nevertheless, it could be a good idea to delay it until we really know what is going on with robotics and AI.

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