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The impact of aging and automation on the macroeconomy and inequality

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Non-technical summary

Research Question

Population aging and technological progress in automated production are two major trends that are going to affect all developed economies in the future. Population aging is said to reduce (per-capita) output growth and consumption, partially due to the decline in aggregate labor supply. Progress in automation technologies can augment economy-wide productivity, but it may pose a threat to the jobs of millions. Against this background, we address the following questions: Does population aging foster the increased use of robotics? How does higher productivity in robot technologies affect the macro economy? How do these trends interact when occurring simultaneously? Moreover, what does all this imply for inequality with regard to labor income, wealth and consumption?

Contribution

We address these questions by means of a life-cycle model in which a representative firm produces a final good using routine and non-routine labor as well as traditional and automation capital (e.g. robots). Robots can substitute for routine labor. Individuals are born as a routine worker. With a given probability, they either retire (as routine worker) or become a non-routine worker. A non-routine worker also retires someday, and all retirees pass away eventually. This model framework allows us to analyze if the emergence of these trends affects different groups differently (and if so, how and to what extent).

Results

We find that population aging fosters the increased use of robotics in production, ultimately resulting from lower capital costs. Higher productivity of automation technologies itself also fosters the increased use of robotics in production. Both trends reduce the labor share of income. Inequality with regard to labor income, wealth and consumption increases. Although expected advances in automation technologies are able to mitigate or even circumvent output losses in the aggregate and improve consumption possibilities for everyone, this comes at the cost of increased inequality because non-routine workers benefit disproportionately.

Nichttechnische Zusammenfassung

Fragestellung

Alle entwickelten Volkswirtschaften werden künftig mit Bevölkerungsalterung und Fortschritten bei Automatisierungstechnologien im Produktionsprozess konfrontiert. Bevölkerungsalterung hat in der Tendenz negative Effekte auf Output und Konsum (pro Kopf), ausgelöst auch durch den Rückgang der Bevölkerung im arbeitsfähigen Alter. Fortschritte bei Produktionsautomatisierung erhöhen die gesamtwirtschaftliche Produktivität, gefährden aber möglicherweise die Jobs von Millionen. Vor diesem Hintergrund stellen sich folgende Fragen: Trägt Bevölkerungsalterung zu einem gesteigerten Einsatz von Automatisierungstechnologien bei? Wie beeinflusst Fortschritt bei Automatisierungstechnologien die Makroökonomie? Was passiert, wenn diese Entwicklungen gleichzeitig auftreten? Und was bedeutet das alles für Ungleichheit bei Lohneinkommen, Vermögen und Konsum?

Beitrag

Zur Analyse dieser Fragen nutzen wir ein makroökonomisches Lebenszyklusmodell, in dem eine repräsentative Firma Konsum- und Investitionsgüter mit Hilfe von Routine- und anspruchsvollerer Arbeit sowie mit traditionellem und Automatisierungskapital (bspw. Roboter) herstellt. Roboter können menschliche Routinearbeiten substituieren. Annahmegemäß werden alle Individuen zunächst mit der Fähigkeit geboren, Routinearbeiten durchzuführen. Mit einer bestimmten Wahrscheinlichkeit können sie im Lebensverlauf anspruchsvollere Aufgaben übernehmen. Mit Hilfe dieses Modellaufbaus können wir untersuchen, ob die beiden oben angesprochenen Entwicklungen unterschiedliche Auswirkungen auf die verschiedenen Bevölkerungsgruppen haben (und, wenn ja, welche und in welchem Ausmaß).

Ergebnisse

Bevölkerungsalterung und technologischer Fortschritt begünstigen den verstärkten Einsatz von Automatisierungstechnologien, letztendlich ein Resultat der (relativ gesehen) niedrigeren Kapitalkosten. Beide Entwicklungen reduzieren den Anteil, den Arbeit im Produktionsprozess einnimmt. Obwohl technologischer Fortschritt tatsächlich aggregierte Output- und Konsumverluste abmildern oder sogar verhindern und die aggregierten Konsummöglichkeiten erhöhen kann, ist abzusehen, dass Ungleichheit bei Arbeitseinkommen, Vermögen und Konsum zunehmen wird.

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The Impact of Aging and Automation on the Macroeconomy and Inequality*

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Abstract

We build a life-cycle model in which a representative firm produces a final good using routine and non-routine labor as well as traditional and automation capital (e.g. robots). Robots can substitute for routine labor. We show that both, population aging and higher robot productivity, foster the increased use of robotics. Population aging decreases and progress in robot technology increases long-run output per capita. In both cases, inequalities in labor income, wealth and consumption rise. Although expected advances in automation technologies are able to mitigate or even circumvent output losses in the aggregate and improve consumption possibilities for everyone, this comes at the cost of increased inequality because non-routine workers benefit disproportionately.

Keywords: Life-Cycle model, Automation, Robots, Inequality

JEL classification: J11, J23, J24, O33, O49

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1 Introduction

Population aging and technological progress in automated production processes (using artificial intelligence, AI henceforth, or robots, for example) are two major trends that are going to affect all developed economies in the future. Technological advances are likely to make our lives easier and more convenient in many ways. Nevertheless, there are fears that working life could undergo radical change as a result. Some researchers believe that there is a significant chance of AI outperforming humans in many tasks within a time span that most of us will live to see (see Grace, Salvatier, Dafoe, Zhang, and Evans, 2018). For example, driverless cars could pose a threat to the jobs of millions of bus and taxi drivers, robots could replace cashiers as well as staff in the medical, the legal and the educational profession, or in translation services (The Economist, 2019; Chui, Manyika, and Miremadi, 2015; Dengler and Matthes, 2018; Ford, 2015; Brynjolfsson and McAfee, 2014). It is also discussed already whether or not AI can replace (computational) economists some time soon (Maliar, Maliar, and Winant, 2019). Pessimistic forecasts suggest that around half of existing jobs in the United States will be particularly affected by the expected technological progress, and some fear that 83% of the jobs in the low-wage sector could be scrapped (see Frey and Osborne, 2017; Acemoglu and Restrepo, 2018d, 2019c). Similar, slightly lower numbers are found for Europe, see Chiacchio, Petropoulos, and Pichler (2018).[1]

On the other side of the spectrum are "technology optimists", who stress that the rise in productivity implied by the technological progress will lead to higher aggregate income and new lines of work being opened up in the medium term (see Autor, 2014). This is especially relevant when taking into account the second major trend: population aging. Increased longevity and low fertility is said to reduce per-capita output, output growth, investment and real interest rates (Carvalho, Ferrero, and Nechio, 2016; Aksoy, Basso, and Smith, 2017; Aksoy, Basso, Smith, and Grasl, 2019; Papetti, 2019; Sudo and Takizuka, 2019). The negative effects can become stronger when aging contributes to a reduction in innovation and/or business churn (Hopenhayn, Neira, and Singhania, 2018; Liang, von Hui, and Lazear, 2018; Ouimet and Zarutskie, 2014; Pugsley and Sahin, 2018; Röhe and Stähler, 2020). Technological progress, it is therefore argued, can mitigate or even circumvent these negative aging-induced effects (Acemoglu and Restrepo, 2017; Graetz and Michaels, 2018). In this paper, we contribute to this discussion by analyzing

i) whether or not population aging fosters the increased use of robotics,

ii) how higher productivity in robot technologies affects the macro economy,

iii) how these trends interact when occurring simultaneously,

iv) and what all this implies for inequality with regard to labor income, wealth and consumption.

We address these questions by means of an extended life-cycle model along the lines of Gertler (1999) and Carvalho et al. (2016). We extend their model by assuming the

[1] In a recent paper, Klenert, Fernandez-Macias, and Anton (2020) put these pessimistic (empirical) findings into perspective. They find that, in Europe, the existence of industrial robots may have created jobs in the manufacturing sector. However, they also find that jobs/tasks in these sectors have changed.

existence of two types of labor, namely routine and non-routine workers, and two types of capital, traditional and automation capital. Individuals are born as a routine worker. With a given probability, they either retire (as routine worker) or become a non-routine worker. A non-routine worker also retires someday, and all retirees pass away eventually.[2] A representative firm produces a unique final good. Robots and routine workers are substitutes. Traditional capital and labor as well as the two labor types are complements. The remaining model elements are standard.

We find that population aging fosters the increased use of robotics in production. The reason is that, as life expectancy increases, individuals increase their savings when young(er) to consume when old(er). The savings glut reduces the real interest rate which, in the end, reduces capital interest/costs (see Carvalho et al., 2016, as well as Baldanzi, Prettner, and Tscheuschner, 2019, and Gehringer and Prettner, 2019). In addition, lower fertility rates eventually generate a scarcity of labor, which increases wages. Firms substitute (more) expensive workers by (now cheaper) robots, and the labor share of income falls (see also Acemoglu and Restrepo, 2018a, and Basso and Jimeno, 2019). We can show that the reduction in the labor share of income is entirely borne by routine workers, who are the ones that can be substituted for. Non-routine workers actually gain because, due to complementarity, the increased use of robotics fosters marginal productivity of non-routine workers.

Higher productivity of automation technologies itself also fosters the increased use of robotics in production. For given wages and capital interest rates, it becomes more attractive to now use (more productive) robots relative to routine labor services. This drives down wages for routine workers relative to wages for non-routine workers and reduces the labor share of income, which is in line with findings by Acemoglu and Restrepo (2018b,d, 2019a,c), Karabarbounis and Neiman (2014), and Prettner (2019), among others. Brynjolfsson and McAfee (2014) provide a very comprehensive overview. Due to the same mechanism described above already, this is shouldered by routine workers; see also Autor (2014), Berg, Buffie, and Zanna (2018), Eden and Gaggl (2018), Dauth, Findeisen, Südekum, and Woessner (2017), Hemous and Olsen (2014) and Kharlamova, Stavytskyy, and Zarotiadis (2018).

Population aging per se has negative effects on per-capita output (see Aksoy et al., 2019, and the other literature mentioned above). If population aging and progress in automation technologies occur at the same time, however, these effects are mitigated and can even be overturned when the technological progress is sufficiently strong (Acemoglu and Restrepo, 2017, and Graetz and Michaels, 2018). Yet, this comes at the cost of a further decline in the labor share of income, borne by routine workers, and further (relative) wage losses of routine workers. The different developments of (expected lifetime) labor income imply an increase in wealth inequality. Relatively lower labor income and capital income, in turn, imply that consumption inequality also increases as a result.

Our findings suggest that advances in automation technologies can help to reduce aggregate income losses resulting from population aging. However, to reap the full benefits from technological progress and to avoid "social unrest" (as it has, for example, taken

[2]The terms "routine" and "non-routine" are not necessarily synonym to being (formally) unskilled and skilled. As discussed in Autor and Dorn (2013), Deming (2017) and Atalay, Phongthiengtham, Sotelo, and Tannenbaum (2018, 2020), among others, non-routine social, analytic and interactive tasks in jobs have increased notably – skills that may but do not have to be associated with formal education.

place during the Industrial Revolution; see Allen, 2009, and Katz and Margo, 2014, for a discussion), promoting inclusion and participation of those who are likely to lose (at least in relative terms) is important. We think that our model can, also because of its tractability, serve as a suitable laboratory for analyzing costs and benefits of upcoming policy suggestions in this direction in future research (see, among others, Prettner and Strulik, 2019 and Gasteiger and Prettner, 2020, for a discussion).

The rest of the paper is structured as follows. The model and its calibration is described in Section 2. In Section 3, we describe the simulation experiments and show the results. Section 4 concludes.

2 The model

We use a closed-economy flexible-price model featuring a life-cycle structure in the line with Gertler (1999) and Carvalho et al. (2016). The economy is populated by households, a representative firm, and the government. In the household sector, workers consume final goods, work and save, while retirees exclusively consume out of their asset wealth. Agents save via traditional physical capital, government bonds and, in addition to the standard framework, automation or robot capital, respectively. Workers can be one of two types: a routine or a non-routine worker. The representative firm produces a unique final good using routine and non-routine labor services as well as traditional and robot capital. Following Eden and Gaggl (2018), we assume that traditional capital and labor as well as the two types of labor are gross complements (a discussion can be found in, for example, DeCanio, 2016). Automation capital and routine labor, in contrast, are gross substitutes. In line with Acemoglu and Autor (2011), Acemoglu and Restrepo (2018d, 2019a,b) and Eden and Gaggl (2018), among others, we formalize this by assuming a nested CES production function. The government sets its spending exogenously and finances its expenditures through lump-sum taxes.

2.1 Life-cycle structure

At any point in time, individuals belong to one of four groups. They can either be a worker (w) or a retiree (r), and both of that either of routine (ro) or non-routine (nr) type. New workers are born as a routine worker at rate $(1-\omega_t+n_t^w)$. Conditional on being a routine worker in the current period, an individual faces a probability ω_t of remaining a routine worker in the next period. Hence, the routine working-age population grows at rate n_t^w, and $(1-\omega_t+n_t^w)$ can be interpreted as the "fertility rate".

With probability $(1-\omega_t)\cdot\omega_t^{o,ro}$, the routine worker becomes a retiree of type ro, who faces a survival probability γ_t^{ro} next period. A routine-type retiree thus dies with probability $(1-\gamma_t^{ro})$. With probability $(1-\omega_t)\cdot(1-\omega_t^{o,ro})$, the routine worker becomes a non-routine worker, who will retire with probability $(1-\omega_t^{o,nr})$. The non-routine retiree survives with probability γ_t^{nr}. Hence, the laws of motion for workers and retirees of type

$i \in \{ro, nr\}$ are

$$\begin{aligned}
N_{t+1}^{w,ro} &= (1 - \omega_t + n_t^w) \cdot N_t^{w,ro} + \omega_t \cdot N_t^{w,ro} = (1 + n_t^{w,ro}) \cdot N_t^{w,ro}, \\
N_{t+1}^{w,nr} &= (1 - \omega_t) \cdot (1 - \omega_t^{o,ro}) \cdot N_t^{w,ro} + \omega_t^{o,nr} \cdot N_t^{w,nr}, \\
N_{t+1}^{r,ro} &= (1 - \omega_t) \cdot \omega_t^{o,ro} \cdot N_t^{w,ro} + \gamma_t^{ro} \cdot N_t^{r,ro}, \\
N_{t+1}^{r,nr} &= (1 - \omega_t^{o,nr}) \cdot N_t^{w,nr} + \gamma_t^{nr} \cdot N_t^{r,nr}.
\end{aligned}$$

The share of all retirees over all workers, i.e. the old age dependency ratio, is given by

$$\Psi_t = \frac{N_t^{r,ro} + N_t^{r,nr}}{N_t^{w,ro} + N_t^{w,nr}} = \frac{\Psi_t^{ro} + s_t^{nr} \cdot \Psi_t^{nr}}{(1 + s_t^{nr})}, \tag{1}$$

with

$$\begin{aligned}
s_{t+1}^{nr} &= \frac{N_{t+1}^{w,nr}}{N_{t+1}^{w,ro}} = \frac{(1 - \omega_t) \cdot (1 - \omega_t^{o,ro})}{(1 + n_t^w)} + \frac{\omega_t^{o,nr}}{(1 + n_t^w)} \cdot s_t^{nr}, \\
\Psi_{t+1}^{ro} &= \frac{N_{t+1}^{r,ro}}{N_{t+1}^{w,ro}} = \frac{(1 - \omega_t) \cdot \omega_t^{o,ro}}{1 + n_t^w} + \frac{\gamma_t^{ro}}{1 + n_t^w} \cdot \Psi_t^{ro}, \\
s_{t+1}^{nr} \cdot \Psi_{t+1}^{nr} &= \frac{N_{t+1}^{r,nr}}{N_{t+1}^{w,ro}} = \left(\frac{(1 - \omega_t^{o,nr})}{(1 + n_t^w)} + \frac{\gamma_t^{nr}}{1 + n_t^w} \cdot \Psi_t^{nr} \right) \cdot s_t^{nr},
\end{aligned}$$

where s_t^{nr} indicates the share of non-routine over routine workers and Ψ_t^i is the share of type-i workers over type-i retirees.

2.2 Decision problem of retirees and workers

Workers inelastically supply one unit of labor each period, while retirees do not work. Preferences for an individual of type $\{z, i\}$, with $z \in \{w, r\}$ and $i \in \{ro, nr\}$, are a restricted version of the recursive non-expected utility family that assumes risk neutrality (see Epstein and Zin, 1989):

$$V_t^{z,i} = \left\{ \left(C_t^{z,i}\right)^\rho + \beta_{t+1}^{z,i} \left[E_t \left(V_{t+1} | \{z, i\}\right)\right]^\rho \right\}^{\frac{1}{\rho}}, \tag{2}$$

where $C_t^{z,i}$ denotes consumption and $V_t^{z,i}$ the value of utility in period t. To account for the probability of death, workers and retirees have different discount factors. Specifically, it holds that $\beta_{t+1}^{r,i} = \beta \cdot \gamma_{t+1}^i$ and $\beta^{w,i} = \beta$. Moreover, the expected continuation value, $E_t \left(V_{t+1} | \{z, i\}\right)$, differs between worker types as well as workers and retirees, due to the transition probabilities between groups. In particular,

$$E_t \left(V_{t+1} | \{r, i\}\right) = V_{t+1}^{r,i},$$

while

$$E_t \left(V_{t+1} | \{w, nr\}\right) = \omega_{t+1}^{o,nr} \cdot V_{t+1}^{w,nr} + (1 - \omega_{t+1}^{o,nr}) \cdot V_{t+1}^{r,nr},$$

and

$$E_t\left(V_{t+1}|\{w,ro\}\right) = \omega_t \cdot V_{t+1}^{w,ro} + (1-\omega_t)\cdot\left\{\omega_t^{o,ro}\cdot V_{t+1}^{r,ro} + (1-\omega_t^{o,ro})\cdot V_{t+1}^{w,nr}\right\}.$$

This life-cycle model is analytically tractable because the transition probabilities are independent of age (see, for example, Blanchard, 1985; Weil, 1989; Gertler, 1999; Ferrero, 2010; Carvalho et al., 2016, for a discussion). However, standard risk-averse preferences would imply disproportionately strong precautionary savings motives for young agents to insure against the risk of aging (see, for example, Farmer, 1990 and Gertler, 1999). By separating the elasticity of intertemporal substitution, $\sigma \equiv (1-\rho)^{-1}$, from risk aversion, the preference specification we have chosen allows for a reasonable response of consumption and savings to changes in interest rates, which is discussed thoroughly in Ferrero (2010) and Carvalho et al. (2016), among others.

Retirees: An individual born in period j and retired as type i in period τ chooses consumption $C_t^{r,i}(j,\tau)$ and assets $K_t^{r,i}(j,\tau)$, $B_t^{r,i}(j,\tau)$ and $K_t^{rob,r,i}(j,\tau)$, denoting traditional physical capital, government bonds and robot capital, respectively, subject to

$$\begin{aligned} &C_t^{r,i}(j,\tau) + I_t^{r,i}(j,\tau) + I_t^{rob,r,i}(j,\tau) + B_t^{r,i}(j,\tau) \\ &\qquad = \frac{1}{\gamma_t^i}\left[r_t^k \cdot K_{t-1}^{r,i}(j,\tau) + r_t^{rob,k}\cdot K_{t-1}^{rob,r,i}(j,\tau) + R_{t-1}\cdot B_{t-1}^{r,i}(j,\tau)\right], \end{aligned}$$

and the laws of motion for the traditional and the robot capital stock, $K_t^{r,i}(j,\tau) = (1-\delta^k)\cdot K_{t-1}^{r,i}(j,\tau)/\gamma_t^i + I_t^{r,i}(j,\tau)$ and $K_t^{rob,r,i}(j,\tau) = (1-\delta^{rob,k})\cdot K_{t-1}^{rob,r,i}(j,\tau)/\gamma_t^i + I_t^{rob,r,i}(j,\tau)$, where $\delta^k \in (0,1)$ and $\delta^{rob,k} \in (0,1)$ denote the corresponding capital depreciation rates. The type-i retiree thus obtains interest payments on physical capital holdings for traditional and automation capital at rates r_t^k and $r_t^{rob,k}$, and on government bonds at a gross rate R_{t-1}. We assume that, for retirees, a perfectly competitive mutual fund industry invests the proceeds and pays back a premium over the market return to compensate for the probability of death (see Yaari, 1965; Blanchard, 1985). This explains the term $1/\gamma_t^i$ in the above equations. Retirees use their income to finance consumption, capital and government bond holdings.[3]

Additionally, the optimization problem is subject to the consistency requirement that the retiree's initial asset holdings upon retirement correspond to the assets held in the last period as a worker, i.e. $K_{\tau-1}^{r,i}(j,\tau) = K_{\tau-1}^{w,i}(j)$, $B_{\tau-1}^{r,i}(j,\tau) = B_{\tau-1}^{w,i}(j)$ and $K_{\tau-1}^{rob,r,i}(j,\tau) = K_{\tau-1}^{rob,w,i}(j)$. In the absence of aggregate uncertainty, the Euler equations of the maximization problem imply

$$R_t = r_{t+1}^k + (1-\delta^k) = r_{t+1}^{rob,k} + (1-\delta^{rob,k}). \tag{3}$$

Hence, the returns on holding physical capital and government bonds must equalize. Defining total assets of a retiree as $A_t^{r,i}(j,\tau) \equiv K_t^{r,i}(j,\tau) + K_t^{rob,r,i}(j,\tau) + B_t^{r,i}(j,\tau)$ allows

[3] In our model, the mutual funds are type-i specific and only redistribute within group i. This prevents equalization of returns in the insurance market, which would otherwise dampen the effects of life expectancy differences across worker types significantly (see also Ferrero, 2010, for a discussion).

us to re-state the type-i retiree's budget constraint compactly as

$$C_t^{r,i}(j,\tau) + A_t^r(j,\tau) = \frac{R_{t-1} \cdot A_{t-1}^{r,i}(j,\tau)}{\gamma_t^i} \tag{4}$$

due to the equality of returns. As usual in the literature, consumption of each retiree results to be a fraction of total wealth (see the technical appendix of Carvalho et al., 2016, for a details on the formal derivation):

$$C_t^{r,i}(j,\tau) = \xi_t^r \cdot \left(\frac{R_{t-1} \cdot A_{t-1}^{r,i}(j,\tau)}{\gamma_t^i} \right), \tag{5}$$

where the marginal propensity to consume satisfies the following first-order non-linear difference equation

$$\xi_t^{r,i} = 1 - \gamma_{t+1}^i \cdot \beta^\sigma \cdot R_t^{\sigma-1} \cdot \frac{\xi_t^{r,i}}{\xi_{t+1}^{r,i}}. \tag{6}$$

Workers: Making use of the above definition of total assets, $A_t^{w,i}(j) \equiv K_t^{w,i}(j,\tau) + K_t^{rob,w,i}(j) + B_t^{w,i}(j)$, and the no-arbitrage condition (3), a worker of type i born in j chooses consumption $C_t^{w,i}(j)$ and assets $A_t^{w,i}(j)$ for $t \geq j$ to maximize equation (2) for $z = w$ subject to

$$C_t^{w,i}(j) + A_t^{w,i}(j) = R_{t-1} \cdot A_{t-1}^{w,i}(j) + W_t^i - T_t^w \tag{7}$$

and $A_j^{w,ro}(j) = 0$ as routine workers start their lives with zero assets. It must also hold that assets of a non-routine worker who has just become a non-routine worker correspond to the assets held in the last period as a routine worker, i.e. $A_{j-1}^{w,nr}(j) = A_{j-1}^{w,ro}(j)$. The worker's budget constraint differs from the one of retirees in two aspects. First, in addition to the interest received from asset accumulation, the worker receives type-specific real wages, W_t^i, and has to pay lump-sum taxes T_t^w (independent of type i). Second, workers do not turn to the mutual funds industry and, hence, do not receive the additional return that compensates for the probability of death.[4] Furthermore, remember that the expected continuation value of workers of type i in equation (2) is differentiated as described above. Solving the worker's optimization problem shows that workers' consumption is a fraction of total wealth, too. Total wealth is defined as the sum of financial and non-financial (human) wealth (again, see the technical appendix of Carvalho et al., 2016, for a details on the formal derivation),

$$C_t^{w,i}(j) = \xi_t^{w,i} \cdot \left(R_{t-1} \cdot A_{t-1}^{w,i}(j) + H_t^{w,i}(j) \right), \tag{8}$$

[4] Allowing them to do so would provide complete insurance against the probability of retirement and, thus, shut down most of the life-cycle dimension of the model.

where

$$H_t^{w,ro}(j) = W_t^{ro} - T_t^w + \frac{\omega_{t+1} \cdot H_{t+1}^{w,ro}(j)}{\Omega_{t+1}^{ro} \cdot R_t} + \frac{\left(1-\omega_{t+1}^{o,ro}\right) \cdot (1-\omega_{t+1})}{\Omega_{t+1}^{ro} \cdot R_t} \cdot H_{t+1}^{w,nr}(j),$$
$$H_t^{w,nr}(j) = W_t^{nr} - T_t^w + \frac{\omega_{t+1}^{o,nr} \cdot H_{t+1}^{w,nr}(j)}{\Omega_{t+1}^{nr} \cdot R_t} \tag{9}$$

represents the discounted value of current and future wage income net of taxation (i.e. human wealth), expressed recursively, for a worker of type i. For workers of type ro, we have to take into account that they may become a type-nr worker with probability $\left(1-\omega_{t+1}^{o,ro}\right) \cdot (1-\omega_{t+1})$. Human wealth hence depends on the type of a worker due to the different continuation values, but it is independent from individual characteristics within group i. As for retirees, workers' marginal propensity to consume out of wealth evolves according to

$$\xi_t^{w,i} = 1 - \beta^\sigma \cdot \left(\Omega_{t+1}^i \cdot R_t\right)^{\sigma-1} \cdot \frac{\xi_t^{w,i}}{\xi_{t+1}^{w,i}}. \tag{10}$$

The adjustment terms

$$\Omega_t^{nr} \equiv \omega_t^{o,nr} + (1-\omega_t^{o,nr}) \cdot (\xi_t^{r,nr}/\xi_t^{w,nr})^{1/(1-\sigma)}$$
$$\Omega_t^{ro} \equiv \omega_t + (1-\omega_t) \cdot \left[\omega_t^{o,ro} \cdot (\xi_t^{r,nr}/\xi_t^{w,nr})^{1/(1-\sigma)} + (1-\omega_t^{o,ro}) \cdot (\xi_t^{w,nr}/\xi_t^{w,ro})^{1/(1-\sigma)}\right]$$

depend on the ratio of the marginal propensities to consume between retirees and workers and workers of type nr and ro, respectively. It can be shown that $\xi_t^{r,i}/\xi_t^{w,i} > 1 \forall t$. This indicates that retirees discount future income streams at an effectively higher rate than retirees, reflecting the expected finiteness of their life.

2.3 Aggregation of households' decisions

Any aggregate variable $S_t^{z,i}$ for group $\{z,i\}$ takes the form $S_t^{z,i} \equiv \int_0^{N_t^{z,i}} S_t^{z,i}(j)dj$. As we have seen in the previous subsection, the marginal propensities to consume out of wealth are independent from individual characteristics. Given the linearity of the consumption functions discussed above, the aggregate type-$\{z,i\}$ consumption levels are

$$C_t^{w,i} = \xi_t^{w,i} \cdot \left(R_{t-1} \cdot A_{t-1}^{w,i} + H_t^w\right), \tag{11}$$
$$C_t^{r,i} = \xi_t^{r,i} \cdot R_{t-1} \cdot A_{t-1}^{r,i}, \tag{12}$$

and economy-wide consumption is defined as

$$C_t = C_t^{w,ro} + C_t^{r,ro} + C_t^{w,nr} + C_t^{r,nr}. \tag{13}$$

$A_{t-1}^{z,i}$ is total financial wealth that members of group $\{z,i\}$ carry from period $t-1$ to t. It must hold that $A_t = A_t^{w,ro} + A_t^{r,ro} + A_t^{w,nr} + A_t^{r,nr} = K_t + K_t^{rob} + B_t$, where the aggregation for K_t, K_t^{rob} and B_t is analogous. The aggregate values for human wealth evolve according to

$$
\begin{aligned}
H_t^{w,ro} =& W_t^{ro} \cdot N_t^{w,ro} - T_t^{ro} + \frac{\omega_{t+1} \cdot H_{t+1}^{w,nr}}{(1+n_{t+1}^{w,ro}) \cdot \Omega_{t+1}^{ro} R_t} + \frac{\left(1-\omega_{t+1}^{o,ro}\right) \cdot (1-\omega_{t+1})}{(1+n_{t+1}^{w,ro}) \cdot s_{t+1}^{nr} \cdot \Omega_{t+1}^{ro} \cdot R_t} \cdot H_{t+1}^{w,nr}, \\
H_t^{w,nr} =& W_t^{nr} \cdot N_t^{w,nr} - T_t^{nr} + \frac{\omega_{t+1}^{o,nr} \cdot H_{t+1}^{w,nr}}{(1+n_{t+1}^{w,nr}) \cdot \Omega_{t+1}^{nr} R_t},
\end{aligned} \tag{14}
$$

where $T_t^i = N_t^{w,i} \cdot T_t^w$ and $(1+n_t^{z,i}) = N_{t+1}^{z,i}/N_t^{z,i}$. In contrast to the individual consumption decisions, the mutual fund no longer plays a role for consumption of retirees as a group. This is because the assets "left over" from those who pass away are transferred to the other retirees and remain in the same group. Analogously, we have to take into account type-specific working-age population growth for the aggregate values of human wealth.

If we let $\lambda_t^{z,i} \equiv A_t^{z,i}/A_t$ denote the share of total financial assets held by group $\{z, i\}$ and note that $\lambda_t^{w,ro} + \lambda_t^{w,nr} + \lambda_t^{r,ro} + \lambda_t^{r,nr} = 1$ must hold, we can use equations (11) and (12) to derive the laws of motion for the distribution of financial wealth across groups to be[5]

$$
\begin{aligned}
\lambda_t^{r,nr} \cdot A_t =& \omega_t^{o,nr} \cdot (1-\xi_t^{r,nr}) \cdot \frac{R_{t-1}^w \cdot \lambda_{t-1}^{r,nr} \cdot A_{t-1}}{1+n_t^{r,nr}} \\
&+ (1-\omega_t^{o,nr}) \cdot \left(1 - \lambda_t^{r,ro} - \frac{1-\omega_t^{o,ro} \cdot (1-\omega_t)}{\omega_t} \cdot \lambda_t^{w,ro}\right) \cdot A_t,
\end{aligned}
$$

$$
\begin{aligned}
\lambda_t^{w,nr} \cdot A_t =& (1-\xi_t^{w,nr}) \cdot \frac{R_{t-1}^w \cdot \lambda_{t-1}^{w,nr} \cdot A_{t-1}}{1+n_t^{w,nr}} \\
&+ s_t^{nr} \cdot (W_t^{nr} - T_t^{nr} - \xi_t^{w,nr} \cdot H_t^{w,nr}) + \frac{(1-\omega_t^{o,ro}) \cdot (1-\omega_t)}{\omega_t} \cdot \lambda_t^{w,ro} \cdot A_t, \\
\lambda_t^{r,ro} \cdot A_t =& (1-\xi_t^{r,ro}) \cdot \frac{R_{t-1}^w \cdot \lambda_{t-1}^{r,ro} \cdot A_{t-1}}{1+n_t^{r,ro}} + \frac{(1-\omega_t)}{\omega_t} \cdot \omega_t^{o,ro} \cdot \lambda_t^{w,ro} \cdot A_t, \\
\lambda_t^{w,ro} \cdot A_t =& (1 - \lambda_t^{w,nr} - \lambda_t^{r,ro} - \lambda_t^{r,nr}) \cdot A_t.
\end{aligned} \tag{15}
$$

The distribution of assets across groups is an additional state variable in our model. It keeps track of the heterogeneity in wealth accumulation due to the worker-type and life-cycle structure.

2.4 Production

We assume that the final good Y_t is produced by a perfectly competitive representative firm. Following Acemoglu and Restrepo (2018c), Berg et al. (2018) and Eden and Gaggl (2018), among others, the production function is of a nested CES type in which traditional capital and labor as well as the two types of labor are gross complements. Automation

[5] Aggregate assets for retirees of type i depend on the total savings of those who have already been retired in that group plus the savings of those who retire now. Aggregate savings of workers of type ro depend only on the savings of those who remain in that group, and savings of workers of type nr depend on those who remain in that group plus those savings of ro-type workers who have just become a type-nr worker.

capital and routine labor are gross substitutes. More precisely, it is given by

$$Y_t = \left[(1-\alpha)\cdot K_{t-1}^{sub_{k,l}} + \alpha \cdot \tilde{n}_t^{sub_{k,l}}\right]^{1/sub_{k,l}}, \tag{16}$$

with

$$\begin{aligned}
\tilde{n}_t &= \left[\left(1-\alpha^{sk}\right)\cdot \left(N_t^{w,nr}\right)^{sub_{sk}} + \alpha^{sk}\cdot rob_t^{sub_{sk}}\right]^{1/sub_{sk}}, \\
rob_t &= \left[\left(1-\alpha^{rob}\right)\cdot \left(\tilde{x}_t^{rob}\cdot K_{t-1}^{rob}\right)^{sub_{rob}} + \alpha^{rob}\cdot \left(N_t^{w,ro}\right)^{sub_{rob}}\right]^{1/sub_{rob}},
\end{aligned}$$

where the elasticities of substitution satisfy $sub_{k,l}, sub_{sk} < 0$ and $sub_{rob} > 0$. $\tilde{x}_t^{rob}$ represents the exogenously given, potentially time-varying productivity of automation technologies/robots.

In every period, the representative firm maximizes its profits $Y_t - W_t^{nr}\, N_t^{w,nr} - W_t^{ro}\, N_t^{w,ro} - r_t^k\, K_{t-1} - r_t^{k,rob}\, K_{t-1}^{rob}$ with respect to the factor inputs, which determines the corresponding factor demand:

$$\begin{aligned}
W_t^{nr} =& \alpha\cdot\left(\frac{Y_t}{\tilde{n}_t}\right)^{(1-sub_{k,l})}\cdot\left(1-\alpha^{sk}\right)\cdot\left(\frac{\tilde{n}_t}{N_t^{w,nr}}\right)^{(1-sub_{sk})} \\
W_t^{ro} =& \alpha\cdot\left(\frac{Y_t}{\tilde{n}_t}\right)^{(1-sub_{k,l})}\cdot\alpha^{sk}\cdot\left(\frac{\tilde{n}_t}{rob_t}\right)^{(1-sub_{sk})}\cdot\alpha^{rob}\cdot\left(\frac{rob_t}{N_t^{w,ro}}\right)^{(1-sub_{sk})}, \\
r_t^{k,rob} =& \alpha\cdot\left(\frac{Y_t}{\tilde{n}_t}\right)^{(1-sub_{k,l})}\cdot\alpha^{sk}\cdot\left(\frac{\tilde{n}_t}{rob_t}\right)^{(1-sub_{sk})}\cdot\left(1-\alpha^{rob}\right)\cdot\left(\frac{rob_t}{\tilde{x}_t^{rob}\cdot K_{t-1}^{rob}}\right)^{(1-sub_{sk})}\cdot\tilde{x}_t^{rob},
\end{aligned}$$

and

$$r_t^k = (1-\alpha)\cdot\left(\frac{Y_t}{K_{t-1}}\right)^{(1-sub_{k,l})}. \tag{17}$$

2.5 Fiscal policy

The government issues one-period debt B_t and levies lump-sum taxes to finance a given stream of consumption G_t. The flow government budget constraint is

$$B_t = R_{t-1}B_{t-1} + G_t - T_t, \tag{18}$$

where $T_t = T_t^{ro} + T_t^{nr} = (N_t^{w,ro} + N_t^{w,nr})\cdot T_t^w$. For simplicity, we follow Carvalho et al. (2016) and assume that the ratio between government spending and GDP is constant, $G_t = gY_t$. We also impose public debt to be a fixed share of GDP, $B_t = bY_t$.

2.6 Equilibrium

Given the dynamics for the exogenous demographic processes $n_t^{w,ro}$, ω_t, $\omega_t^{o,i}$ and γ_t^i, for $i \in \{ro, nr\}$, a competitive equilibrium for this economy is a sequence of quantities $\{A_t, B_t, Y_t, K_t, K_t^{rob}, I_t, I_t^{rob}, T_t\}$ and $\{C_t^{z,i}, \lambda_t^{z,i}, H_t^{z,i}, V_t^{z,i}\}_{i\in\{ro,nr\},z\in\{w,r\}}$, marginal propensities to consume $\{\xi_t^{z,i}, \Omega_t^i\}_{i\in\{ro,nr\},z\in\{w,r\}}$, prices $\{R_t, r_t^k, r_t^{k,rob}, W_t^i\}_{i\in\{ro,nr\}}$, and population shares $\Psi_t, s_t^{nr}, \Psi_t^{ro}$ and Ψ_t^{nr} such that:

1. Retirees and workers maximize utility subject to their budget constraints, taking market prices as given, as described in Sections 2.2 and 2.3.

2. Firms maximize profits, set markups and enter the market subject to their technology and entry costs, as outlined in Section 2.4,

3. The fiscal authority chooses a mix of debt and lump-sum taxes to satisfy its budget constrained of Section 2.5.

4. Prices are such that the markets for labor, capital and goods clear. In particular, the economy-wide resource constraint $Y_t = C_t + I_t + I_t^{rob} + G_t$ must hold.

As long as $n_t^{w,ro} > 0$, the economy is subject to ongoing exogenous growth. Hence, the balanced growth path, where all factors of production grow at the same rate, which leaves relative wages and capital returns constant, is defined by a detrended version of the model that expresses all unbounded variables, X_t, in terms of efficiency units per routine worker, i.e. $\tilde{X}_t = X_t/N_t^{w,ro}$.

2.7 Calibration

We calibrate our model to annual frequency. Individuals are born at the age of 20 and are assumed to retire at the age of 65 (on average). We assume that population grows at rate $n^{w,ro} = 0.4\%$ in the initial steady state. This corresponds to the Euro area average from 1960 to 2000 (see also Kara and von Thadden, 2016, and Schön and Stähler, 2019). The old age dependency ratio in the year 2000, which we take as our base year, is set to 26.4% according to OECD (2017) data.

Given that we target a share of non-routine-over-routine workers of 18% following Eden and Gaggl (2018), who base their calculations on Acemoglu and Autor (2011), this allows us to derive the transition probabilities ω, $\omega^{o,ro}$ and $\omega^{o,nr}$ in steady state. Assuming that $\gamma^{ro} = \gamma^{nr}$ (i.e. we ignore the possibility that routine and non-routine workers may have a different life expectancy), we can also derive the survival probabilities. The resulting values are summarized in Table 1.

Table 1: Baseline calibration

Variable/Parameter	Symbol	Value
Working-age population growth	n^w	0.0040
Old age dependency ratio	Ψ	0.2639
Share of skilled/unskilled workers	s^{sk}	0.1800
Probability to stay routine worker	ω	0.9198
Probability to become non-routine worker	$(1-\omega)\cdot(1-\omega^{o,ro})$	0.0602
Retirement probability of routine workers	$(1-\omega)\cdot\omega^{o,ro}$	0.0200

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Variable/Parameter	Symbol	Value
Retirement probability of non routine workers	$1-\omega^{o,sk}$	0.3325
Survival probability for retirees	$\gamma^{ro}=\gamma^{nr}$	0.7486
Discount rate	β	0.9346
Intertemporal elasticity of substitution	σ	0.5000
Government spending over GDP	$\bar{G}/\bar{Y}$	0.2000
Government debt over GDP	$\bar{B}/\bar{Y}$	0.6000
Production share of labor	α	0.6667
Composite share of non-routine labor	$1-\alpha^{sk}$	0.1016
Composite share of robots	$1-\alpha^{rob}$	0.3556
Substitution elasticity labor and capital	$sub_{k,l}$	-0.1000
Substitution elasticity non-routine and routine labor	sub_{sk}	-0.1000
Substitution elasticity labor and robots	sub_{rob}	0.5000
Traditional capital depreciation	δ^{k}	0.1000
Automation capital depreciation	$\delta^{k,rob}$	0.2000

Source: OECD (2017) for demographic variables. Remaining variables/parameters in line with the literature as described in the text.

The other parameters are fairly standard in the literature. We choose a labor share in production of 2/3, assume that traditional (automation) capital depreciates at an annual rate of 10% (20%) and set the elasticity of intertemporal substitution to $\sigma = 0.5$. The higher capital depreciation rate for robot capital is along the lines of Krusell, Ohanian, Rios-Rull, and Violante (2000). As discussed in Ferrero (2010), the somewhat low value of the elasticity of intertemporal substitution has become standard in this class of models since Auerbach and Kotlikoff (1987), which is consistent with estimates by Hall (1988) and Yogo (2004). Government spending represents 20% of GDP, while government debt corresponds to 70% of GDP (Kara and von Thadden, 2016). The individual discount factor β is set to almost 0.94 so that the real interest rate in the initial steady state equals 4%.

Turning to the production side, we assume that $sub_{k,l} = sub_{sk} = -0.1$, which implies an elasticity of substitution between capital and labor services as well as between non-routine and routine labor services (the latter including robots) near unity along the lines of Eden and Gaggl (2018). Regarding the substitutability between routine workers and robots, we follow Lin and Weise (2019) by setting $sub_{rob} = 0.5$. Targeting a traditional-over-robot-capital share of four, also in line with Lin and Weise (2019), and assuming no wage premium for non-routine workers in the initial steady state, this allows us to derive $\alpha^{rob} = 0.6825$ and $\alpha^{sk} = 0.8984$.[6] With these values at hand, it is computationally

[6] A positive wage premium would reduce α^{rob} and α^{sk}. Qualitatively, the results presented below

straightforward to solve for the initial steady state.

3 Analysis

Simulation design: We use our model to simulate the projected demographic trends for the Euro area as well as an increase in the productivity in automation technology. We simulate these changes simultaneously, but we also show results when each of the changes is simulated separately.

To be more precise, we assume that the population growth rate n^w falls from 0.004 in the initial steady state to -0.002 in the final steady state, which is the projected value stated by OECD (2017) after 2080. Hence, population in Europe is expected to shrink. To reach the new steady state, we assume that the process is AR(1): $n_t^w = \rho^{n^w} \cdot n_{t-1}^w + (1 - \rho^{n^w})\, n^w$, starting at $n^w = 0.004$ and moving to $n^w = -0.002$. We assume $\rho^{n^w} = 0.9$.

We also assume that the old age dependency ratio increases from the initial value of 26.4% to 62.6% in the new steady state, as projected to happen in the Euro area by 2080 (see OECD, 2017). We assume that this happens due to an increase in longevity, which again adjusts following an AR(1) process: $\gamma_t^i = \rho^\gamma \cdot \gamma_{t-1}^i + (1 - \rho^\gamma)\, \gamma^i$, where $i = \{ro, nr\}$ and $\gamma^{i,initial} = 0.7486, \gamma^{i,final} = 0.8910$ (given the values for n^w in the initial and the final steady state). Again, we assume that $\rho^\gamma = 0.9$ and do not differentiate between an increase in longevity for routine and non-routine workers.

Furthermore, we assume that the productivity of automation capital from 2000 to 2080 increases by a total of 25% (relative to 2000). The adjustment again takes place by means of an AR(1) process: $\tilde{x}_t^{rob} = \rho^{\tilde{x}^{rob}} \cdot \tilde{x}_{t-1}^{rob} + (1 - \rho^{\tilde{x}^{rob}})\, \tilde{x}^{rob}$, with $\rho^{\tilde{x}^{rob}} = 0.8$. It is difficult to assess whether an increase of 25% is very realistic. It is also not possible to derive from the literature what productivity gains are to be expected until 2080. Therefore, the productivity gain is assumed on an ad hoc basis. A larger (smaller) productivity gain in the field of automation technologies would boost (diminish) the effects outlined below accordingly.

For simplicity, we assume that, at the time of the structural changes, the economy is in its initial steady state, that the changes are unanticipated and that there are no future shocks in the economy. This allows us to isolate the effects of simulated changes from other shocks. We simulate the model in a non-linear manner and under perfect foresight.

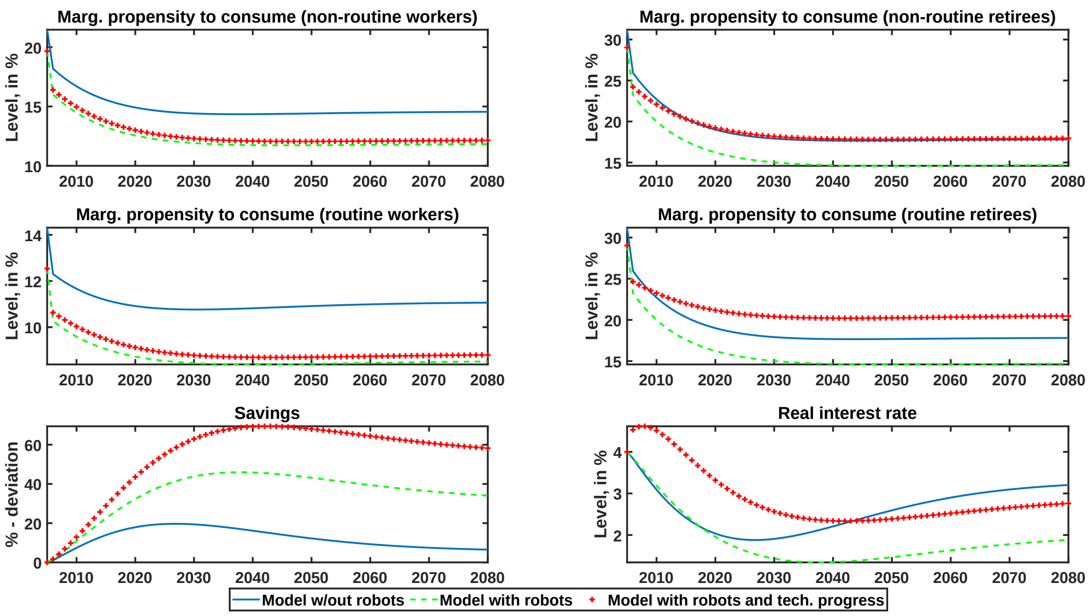
Results: In Figures 1 to 6, we summarize the findings of simulating population aging (i.e. a simultaneous increase in longevity and a fall n population growth) in our baseline model with automation capital (dashed greed lines) and compare these results to an analogous simulation in a model without automation capital (solid blue line).[7] Furthermore, we show the results of simulating productivity gains in automation technologies and population aging happening at the same time in a model with robot capital (crossed red lines). To save space, we relegate the graphs showing the simulations in which all changes are simulated separately to the appendix (Figures A.1 to A.9).

remain unchanged, however, and quantitative differences are relatively minor.

[7] The model is analogous to the one we present above. We simply assume that there is no automation technology available by setting $\alpha^{rob} = 1$ and $K_t^{rob} = r_t^{k,rob} = 0 \forall t$.

In Figure 1, we see that population aging increases savings and reduces the real interest rate, which is a familiar result in the literature (see, e.g., Carvalho et al., 2016; Papetti, 2019). A higher survival probability induces retirees to save more in order to finance consumption during a longer retirement period, captured by a fall in the marginal propensity to consume. Since workers become retirees with a certain probability at each point in time, which affects their continuation value, their savings also increase. Because the prolonged retirement period is still farther away, the impact on the marginal propensity to consume for workers is smaller than it is for retirees, and it is somewhat larger for routine households that it is for non-routine households. The latter is a result of the (labor) income losses of routine workers relative to non-routine workers, which we will explain in more detail below (see also Figure 4).

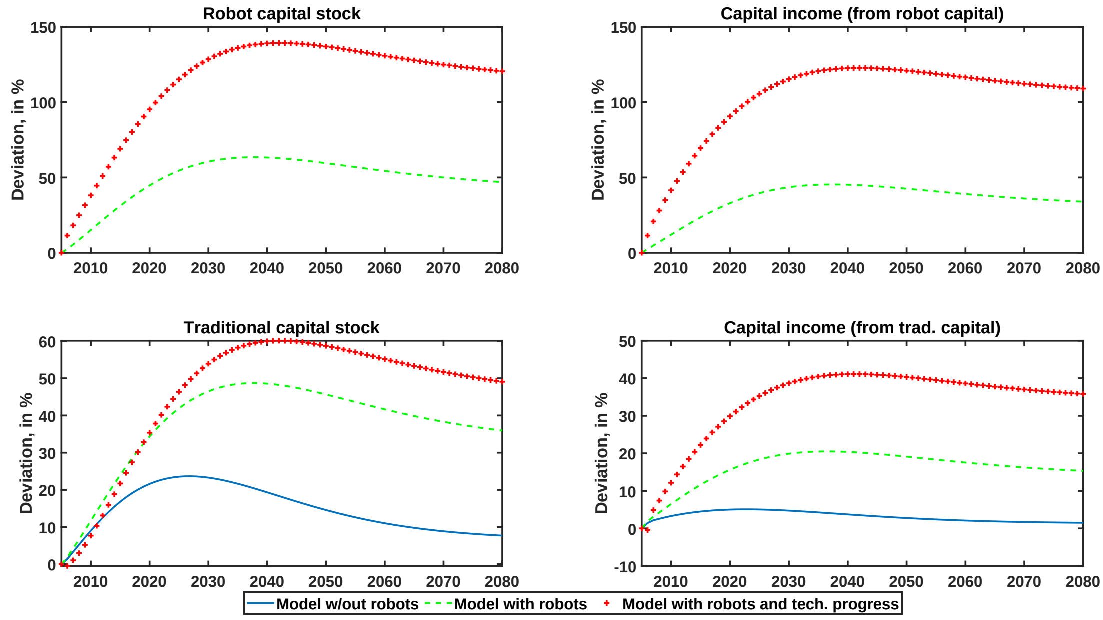
Figure 1: Consumption and savings behavior



Notes: Figure plots the simulated marginal propensities to consume for routine and non-routine workers and retirees, the percentage deviations of savings and the evolution of the real interest rate resulting from population ageing and productivity advances in automation technologies. It differentiates between simulating only aging in a model without robots (blue solid lines) and in a model with robots (green dotted lines) as well as simulating aging and technological progress simultaneously in a model with robots (red crossed lines).

Lower population growth also depresses the real interest rate because it augments the capital-labor ratio, which reduces the rental rate of capital and which, under the no-arbitrage assumption, must feed through to the natural real rate of interest. This effect is counteracted by the fact that the old age dependency ratio increases with falling population growth, and older people tend to have a higher marginal propensity to consume. However, the latter effect cannot overcompensate the former and, therefore, reduced population growth also increases savings (to a much lesser extent than increased longevity does, though; see Figure A.1 in the appendix and discussions in the literature such as Carvalho et al., 2016; Papetti, 2019).

Figure 2: Income from capital investment



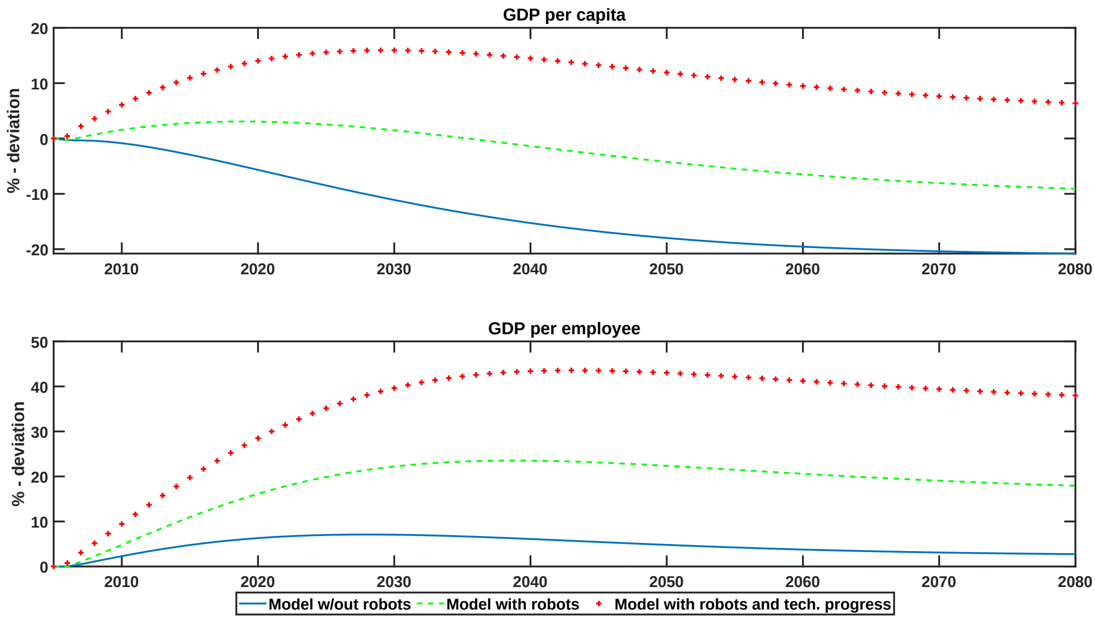
Notes: Figure plots the simulated changes in capital income resulting from population ageing and productivity advances in automation technologies. It differentiates between simulating only aging in a model without robots (blue solid lines) and in a model with robots (green dotted lines) as well as simulating aging and technological progress simultaneously in a model with robots (red crossed lines).

As we can see in Figure 1, the increase in savings is stronger in a model with automation technologies than in a model without. The reason is that aggregate output and income evolve more favorable in such a model (see Figures 2 and 3), which is due to the fact that the increased use of robots augments marginal productivity of other input factors (explained in more detail below). This difference is amplified if population aging and technological progress happen at the same time. The more favorable developments of output and income in a model with automation technologies overcompensate for the somewhat larger reduction in the marginal propensities to consume such that aggregate savings increase more (see Figure 1). The higher savings glut has a larger negative impact on the interest rate in the long run (solid blue line versus dashed greed line in Figure 1). If population aging and technological progress happen at the same time, the reduction in the real interest rate is mitigated because higher robot productivity increases the marginal product of labor and capital which, in turn, translates into a (relatively) higher real interest rate (crossed red line).[8]

[8] An increase in robot productivity has a strong positive effect on the interest rate on impact due to the increase in overall productivity which fosters output and income of households. Although households increase their marginal propensity to consume, aggregate savings rise. The reason is that the rise in output/income overcompensates the rise in consumption demand. As households increase their savings,

Although capital interest falls, capital income increases (see Figures 2). This is the result of the disproportionately strong increase in the capital stock (traditional and automation capital) which, in turn, is a result of the fact that using capital has become much cheaper for the firm due to the savings glut. The increase in output per employee (Figure 3) is a result of the higher capital-to-labor ratio. This increase in output per employee, however, is in general not sufficient to overcompensate for the fact that, with population aging, the share of active workers in the economy shrinks. Hence, output per capita tends to fall – unless the productivity increase (in automation technologies) is sufficient to overcompensate for this. In our simulation in which population aging and technological progress happen simultaneously, this is the case (see Figure 3); of course, this also depends on how much robot productivity increases.

Figure 3: Output



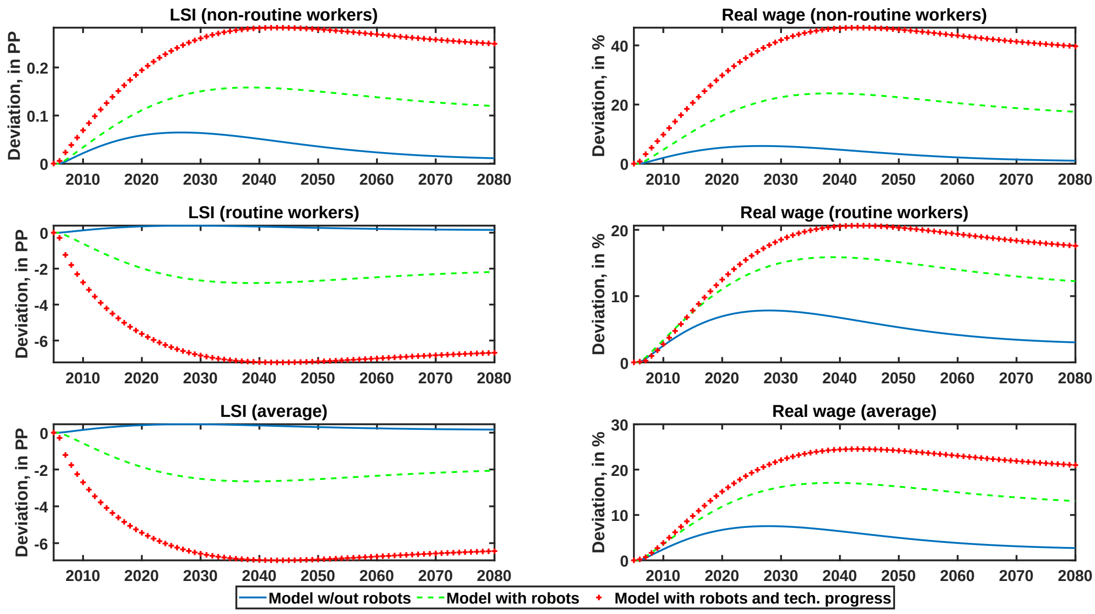
Notes: Figure plots the simulated changes in output per worker and output per capita resulting from population ageing and productivity advances in automation technologies. It differentiates between simulating only aging in a model without robots (blue solid lines) and in a model with robots (green dotted lines) as well as simulating aging and technological progress simultaneously in a model with robots (red crossed lines).

A common finding in the literature is that, because of population aging, real wages increase (see, among others, Aksoy et al., 2019; Carvalho et al., 2016). This is due to two effects. First, reduced population growth implies scarcity of labor, which generates upward pressure on real wages. Second, the higher capital-to-labor ratio, which we have

the real interest rate starts falling which, however, does not overcompensate for the rise in marginal productivity of capital. Hence, the real interest rate in the new steady state is above the initial steady-state value when automation technologies become more productive; see also Figures A.5 to A.9 in the appendix for a detailed presentation of such a simulation.

described above, increases the marginal productivity of labor and, thus, increases wages. As Figure 4 reveals, this is the case in our model, too.[9]

Figure 4: Wages and labor shares of income



Notes: Figure plots the simulated changes in wages and the labor share of income resulting from population ageing and productivity advances in automation technologies. It differentiates between simulating only aging in a model without robots (blue solid lines) and in a model with robots (green dotted lines) as well as simulating aging and technological progress simultaneously in a model with robots (red crossed lines).

Yet, there are some interesting observations we can make in our model. Without automation technologies (solid blue line in Figure 4), population aging leads to a wage increase for routine and non-routine workers of similar size (with a peak at 7.5% for routine versus almost 6% for non-routine workers around 2025). Both, aggregate as well as each type i-specific labor shares of income increases mildly (which is the result of a relatively large wage increase together with a relatively small increase in output per employee; see Figure 3).

If, however, routine workers can be substituted for by automation technologies/robots, there is a significant difference in wage developments. Wages for non-routine workers increase about 3.5 times as much as they do in a model without automation technologies, while the increase in wages for routine workers is a bit less than twice as high (dashed green line in Figure 4). Therefore, aging and the possibility to substitute non-routine workers can explain a rising skill premium and an increasing share of non-routine workers in the economy, as documented by Krusell et al. (2000), Cortes, Jaimovich, and Siu

[9]The introduction of endogenous individual labor supply, which increases with increasing wages, would not change this finding qualitatively.

(2017), Eden and Gaggl (2018), Lankisch, Prettner, and Prskawetz (2019) and Chen (2020), among others.[10]

The higher wage increase for non-routine workers is due to the fact that the increased use of robots fosters marginal productivity of non-routine labor services. This also holds for routine labor services which explains the higher wage increase. However, as cheaper robots substitute routine workers, this effect is significantly weaker than it is for non-routine workers. Given the relatively stronger increase in output, this translates into a fall in the labor share of income of routine workers as the rise in real wages falls short of the rise in output (per worker). The opposite is true for non-routine workers. As the former effect dominates in the aggregate, the economy-wide labor share of income falls. It is entirely borne by routine workers. All these effects are amplified when population aging and progress in robot productivity occur simultaneously.

How does all this translate into income, wealth and consumption inequality? Figure 5 aims to answer this question by showing the simulation-based Gini coefficients for labor income, asset wealth and per-capita consumption.[11] Given the explanations of the wage income developments above, it is clear that the inequality in labor income increases. It does so most when population aging and technological progress occur simultaneously. Wealth inequality increases relatively more when aging and technological progress occur at the same time (the amount of total assets held by non-routine workers increases by 20 percentage points). The reason is that, then, the differences in wages and thus lifetime labor income are amplified (see Figure 4) significantly, while the differences in the changes in the marginal propensities to consume are relatively small (Figure 1). Different developments in labor income and capital gains naturally imply different developments of consumption for which, as we can see in Figure 5, inequality increases, too. This is most relevant for the case in which population aging and advances in automation technologies happen simultaneously.

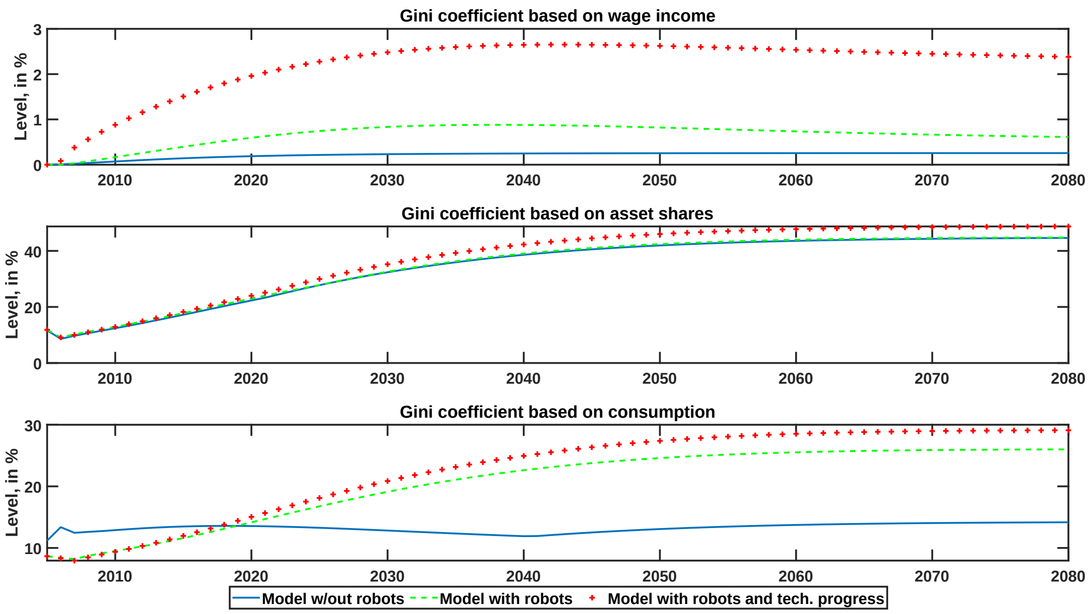
While this may not come as a surprise given the previous analysis, it is worthwhile having a closer look at the evolution of per-capita consumption, which we do in Figure 6. Whenever households realize that longevity increases and fertility declines, they reduce consumption and start saving to prepare for a longer life. This is already clear from the drop in the marginal propensities to consume (Figure 1), which translates into a drop in per-capita consumption of roughly 10% (20%) for workers (retirees) on impact. Thereafter, the evolution of per-capita consumption of routine and non-routine households diverges. The relative loss in wage income and capital gains for routine households implies that they reduce consumption further. For non-routine households, the reduction in consumption is dampened because of an increase in wage and capital income. We can observe in Figure 6 that, in all cases, consumption falls less (or even increases above the

[10] In our model, the fraction of non-routine goes up over the transition to the new steady state. However, this happens only mechanically due to fewer routine workers being born (see Section 2.1). Endogeneizing the worker type would strengthen this effect.

[11] Generally speaking, the results with respect to the Gini coefficient calculated on the basis of the model should not be overestimated. Besides fundamental criticism of the Gini coefficient (see Atkinson and Bourguignon, 2000, Cowell, 2000, Cowell and Flachaire, 2015, or Yitzhaki, 1998), only very few different households exist in our model. Moreover, these are also relatively homogeneous overall. For that reason, it is unclear whether the exact number of the Gini coefficient based on the model simulations has informative value at all. Nevertheless, it illustrates in a striking manner how the different developments in labor income, wealth and consumption could be presented in a generally recognized measure of inequality.

initial steady-state level for non-routine households) when population aging and technological progress occur at the same time.[12] The reason is that, because of the increase in the capital-to-labor ratio (Figure 2), capital gains are higher and the marginal productivity of workers increases. This fosters wage income. Hence, although inequality increases most in that scenario, actual losses in consumption per capita, relative to initial steady state, are smallest. Aggregate consumption per-capita (an average over all households) may even increase in this scenario (as does per-capita output; see Figure 3).

Figure 5: Inequality measures



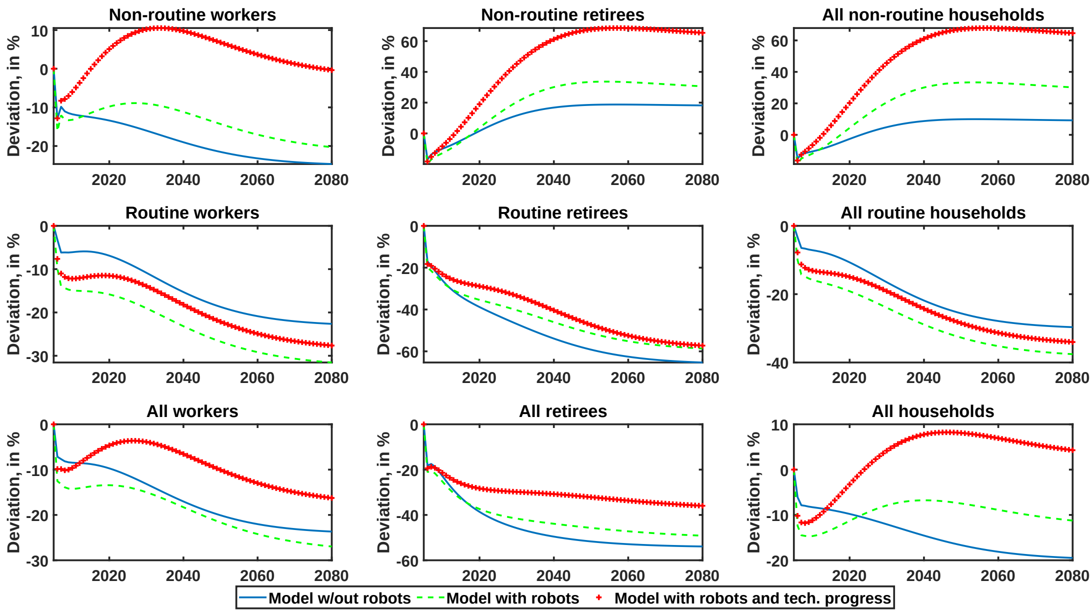
Notes: Figure plots the Gini coefficients based on the simulated evolution of labor income, shares of assets held by household types and per-capita consumption resulting from population ageing and productivity advances in automation technologies. It differentiates between simulating only aging in a model without robots (blue solid lines) and in a model with robots (green dotted lines) as well as simulating aging and technological progress simultaneously in a model with robots (red crossed lines).

In addition, there is a composition effect. Higher longevity clearly augments the share of retirees in the economy. Because of the fall in routine worker population growth, the share of non-routine workers to routine workers increases, too. And the share in routine retirees increase less than the share of non-routine retirees does. This means that, in the end, the share of people benefiting from technological progress rises due to the assumed population dynamics described in Section 2.1 (by construction). If we were to model endogenous decisions to become a non-routine worker, the share of beneficiaries could be increased even further.

[12]In a model without robots, in which capital gains are lower, losses in per-capita consumption are larger relative to the model with robots. This holds except for routine workers who have higher relative wage income losses in the model with robots. All the other types benefit (in relative terms) from higher capital gains in the model with robots.

Summarizing our findings, we can state that population aging tends to reduce output per capita and consumption. These losses can be mitigated by the existence of automation technologies, however. If, in addition, these technologies become (sufficiently) more productive, the losses will be reduced even more and can, in some cases, even turn into gains (see Figures 3 and 6). Hence, (progress in) automation technologies in our model reduce (or even overcompensate) aging-induced output and consumption losses. However, this comes at the cost of higher inequality. Wage differentials between routine and non-routine workers will increase (Figure 4), the share of wealth held by non-routine workers rises (Figure 5), and it is non-routine households who are potentially able to increase their consumption above initial steady-state levels, while routine households will lose. This implies an increase in consumption inequality (Figures 5 and 6). In terms of inequality, things could become even worse. In our model, we have assumed that routine and non-routine workers both benefit equally from robot capital gains (in general terms). If we were to assume that only non-routine workers are allowed to invest in automation capital, for example, inequality would rise even further.

Figure 6: Consumption per capita per group



Notes: Figure plots the simulated changes in consumption per capita per group resulting from population ageing and productivity advances in automation technologies. It differentiates between simulating only aging in a model without robots (blue solid lines) and in a model with robots (green dotted lines) as well as simulating aging and technological progress simultaneously in a model with robots (red crossed lines).

In terms of policy conclusions, our findings suggests that technological progress in automation helps to mitigate potentially negative effects of population aging, as all household types are, strictly speaking, better off in a world with (more productive) robots. To be more precise, per capita consumption increases with increasing robot productivity for all household types (see also Figure A.9 in the appendix). However, inequality rises as it is non-routine workers who will gain disproportionately. Whether or not this is something policy wants to address needs to be decided. Our model can provide a laboratory for analyzing upcoming policy proposals in future research to assess the implications of such distributional measures.

4 Conclusions

In this paper, we assess how population aging and progress in automation technologies affect the macroeconomy and inequality. We do so by means of a life-cycle model in which a representative firm produces a final good using routine and non-routine labor and capital. Routine labor can be substituted for by automation capital (e.g. robots).

We show that both, population aging and higher robot productivity, foster the increased use of robotics. Population aging decreases and technological progress in automation technologies increases output per capita in the long run. Technological progress can overcompensate for the aging-induced losses. However, labor income, wealth and consumption inequalities rise as a result. Hence, even when expected advances in automation technologies are able to mitigate or circumvent output losses in the aggregate, this comes at the cost of increased inequality.

Our analysis thus suggests that reaping the benefits from technological progress will require promoting inclusion and participation of those who are likely to lose. Our model seems suitable to serve as a laboratory for analyzing the economic costs and distributional revenues of upcoming policy suggestions to tackle the rise in inequality.

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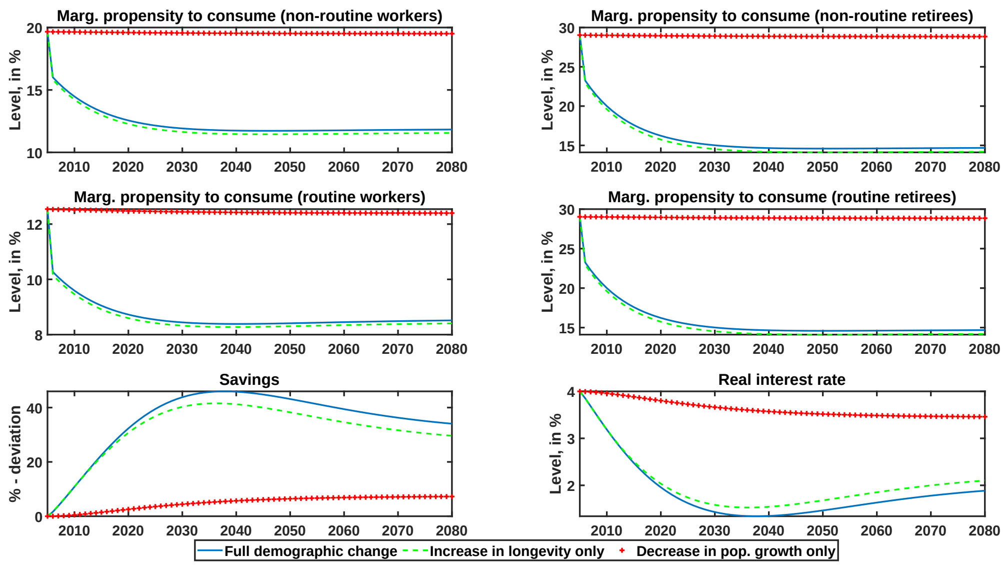
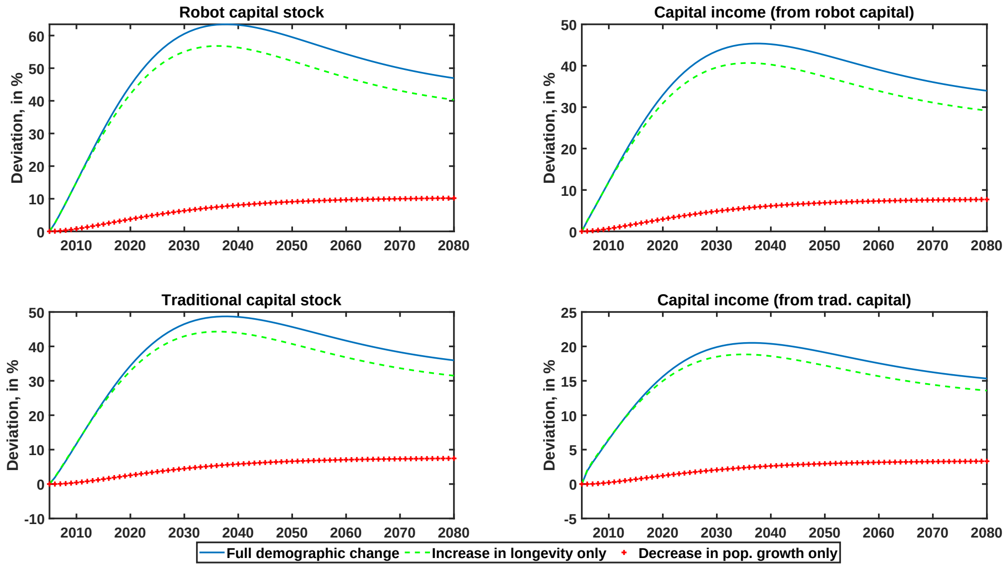
Appendix

Figure A.1: Consumption and savings behavior (only aging)



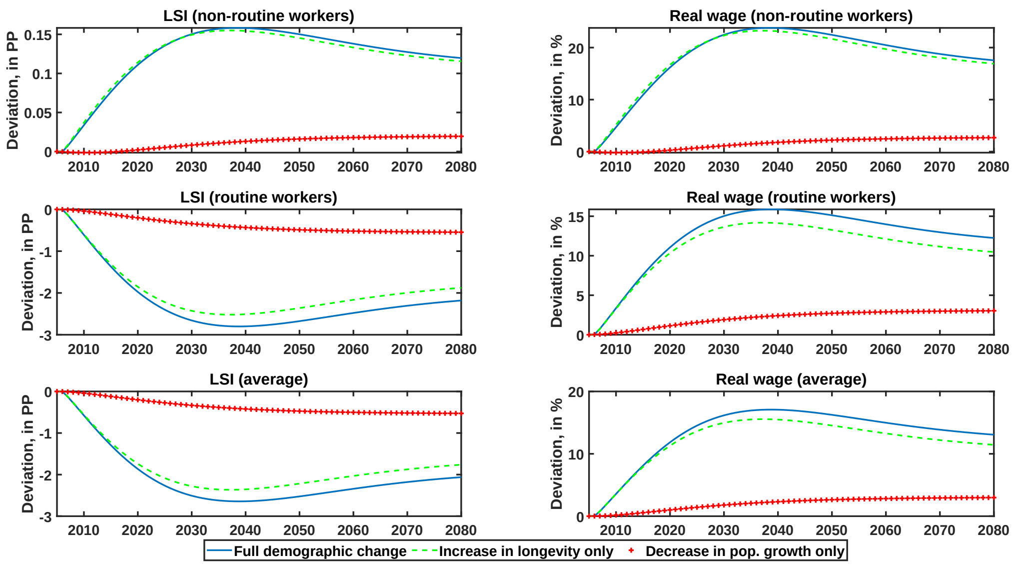
Notes: Figure plots the simulated marginal propensities to consume for routine and non-routine workers and retirees, the percentage deviations of savings and the evolution of the real interest rate resulting from population ageing in a model with robots.

Figure A.2: Income from capital investment (only aging)



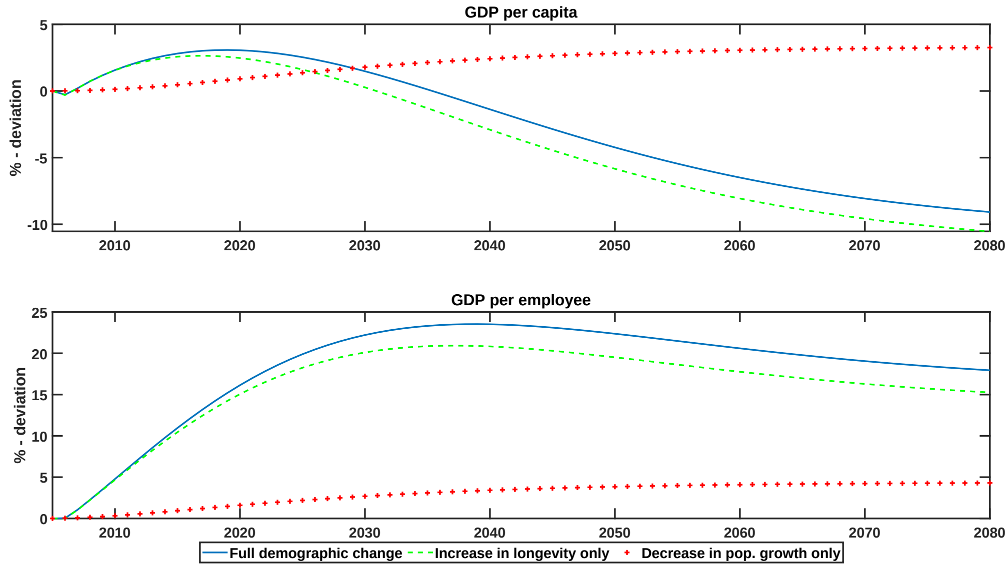
Notes: Figure plots the simulated changes in capital income resulting from population ageing in a model with robots.

Figure A.3: Wages and labor shares of income (only aging)



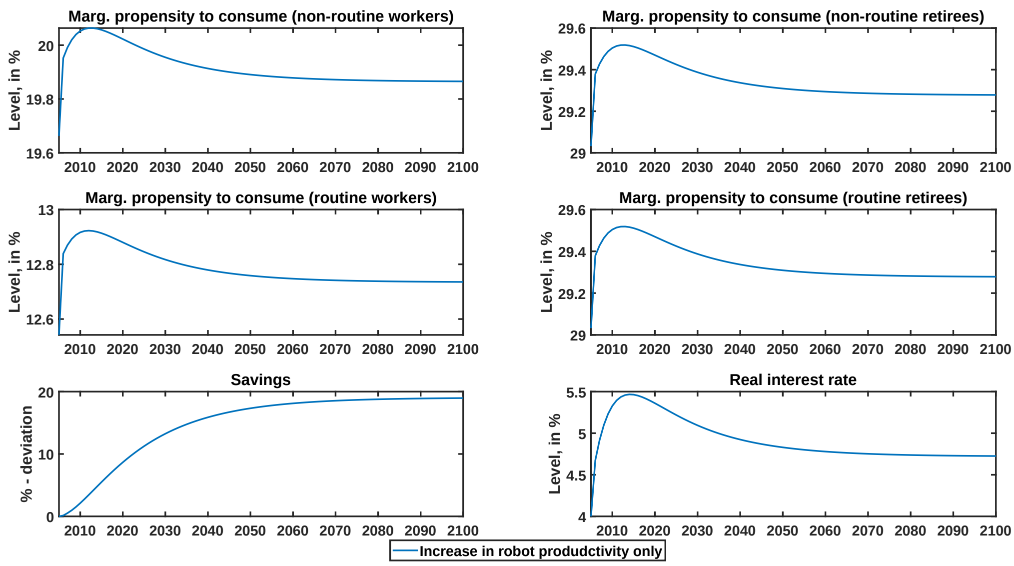
Notes: Figure plots the simulated changes in wages and the labor share of income resulting from population ageing in a model with robots.

Figure A.4: Output (only aging)



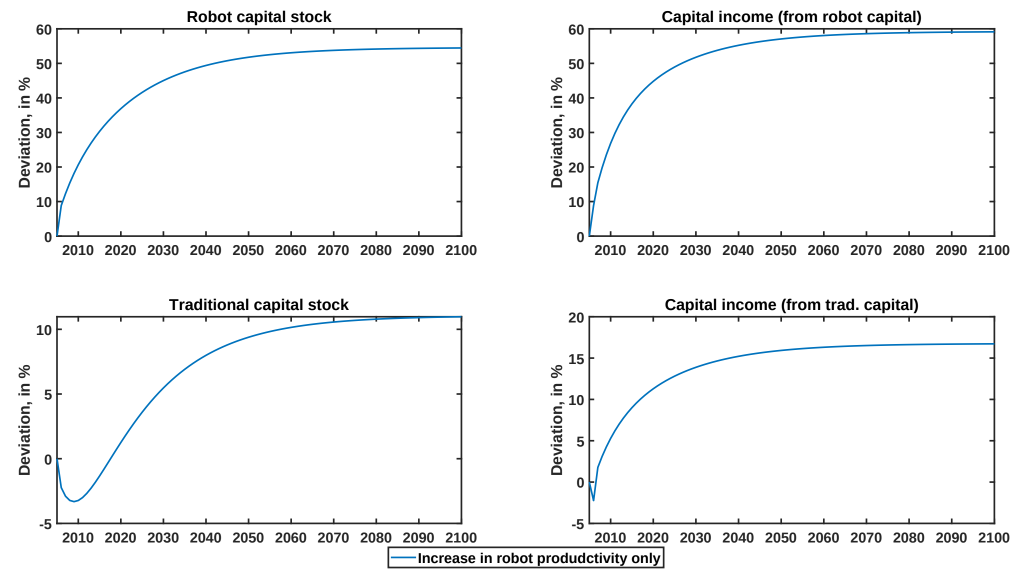
Notes: Figure plots the simulated changes in output per worker and output per capita resulting from population ageing in a model with robots.

Figure A.5: Consumption and savings behavior (only advances in robotics)



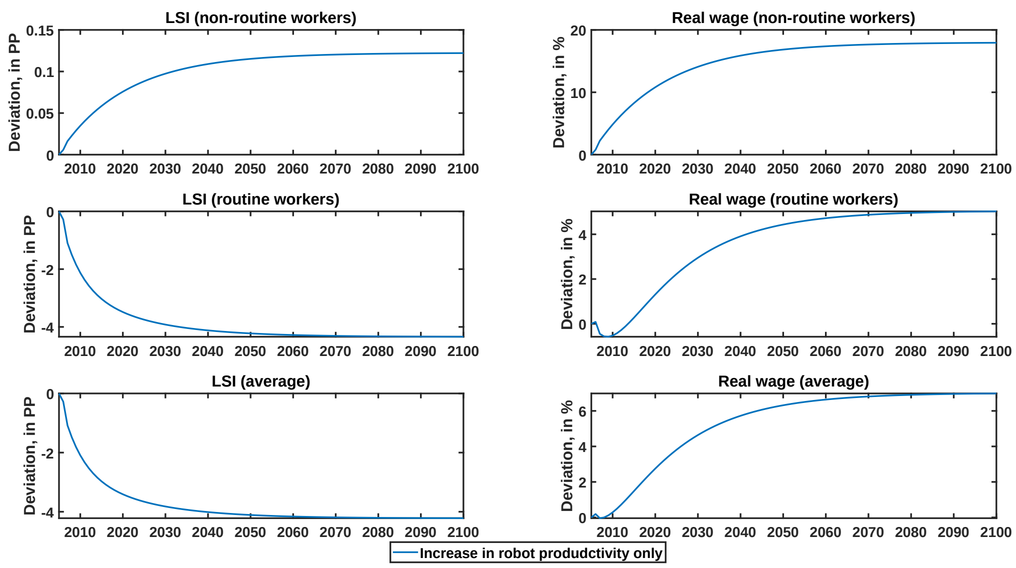
Notes: Figure plots the simulated marginal propensities to consume for routine and non-routine workers and retirees, the percentage deviations of savings and the evolution of the real interest rate resulting from technological progress in robotics.

Figure A.6: Income from capital investment (only advances in robotics)



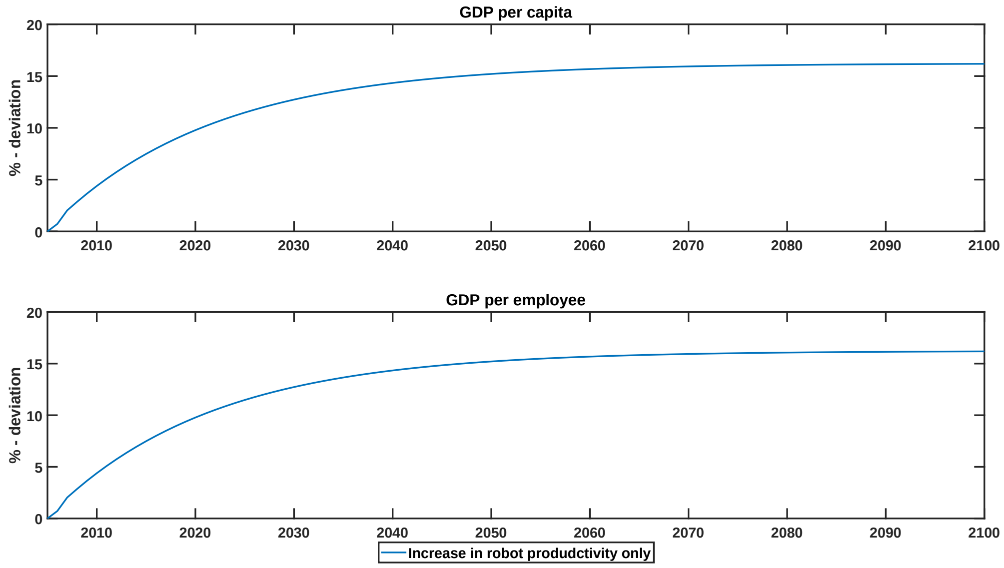
Notes: Figure plots the simulated changes in capital incomeresulting from technological progress in robotics.

Figure A.7: Wages and labor shares of income (only advances in robotics)



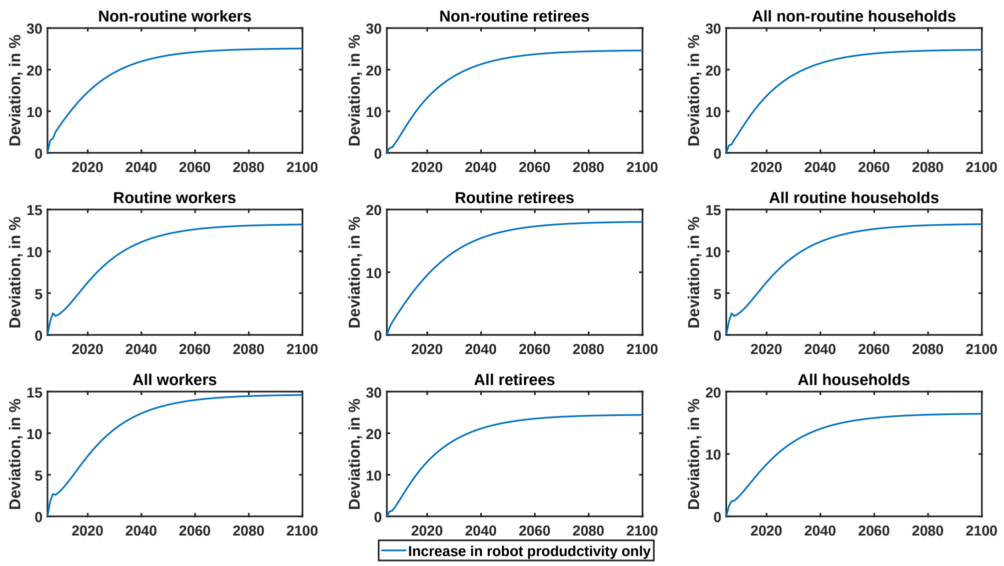
Notes: Figure plots the simulated changes in wages and the labor share of income resulting from technological progress in robotics.

Figure A.8: Output (only advances in robotics)



Notes: Figure plots the simulated changes in output per worker and output per capita resulting from technological progress in robotics.

Figure A.9: Consumption per capita per group (only advances in robotics)



Notes: Figure plots the simulated changes in consumption per capita (per household type) resulting from technological progress in robotics.