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DECLINING NATURAL INTEREST RATE IN THE US: THE PENSION SYSTEM MATTERS

by Jacopo Bonchi* and Giacomo Caracciolo†

Abstract

The natural interest rate is the level of the real interest rate compatible with potential output and stable prices. We develop a life-cycle model and calibrate it to the US economy to quantify the role of the public pension scheme for the past and future evolution of the natural interest rate. Between 1970 and 2015, the pension reforms mitigated overall the secular decline in the natural interest rate, raising it by around one percentage point and thus counteracting the downward pressure from adverse demographic and productivity patterns. As regards the future, we simulate the effects of the demographic trends expected between 2015 and 2060, combined with alternative pension reforms and productivity growth scenarios. We rank the different policy options according to a welfare criterion and study the implications for the natural interest rate. In terms of welfare, a reduction in the replacement rate outperforms an increase in the contribution rate under the "normal growth" scenario but the opposite is true under the "stagnant growth" scenario.

JEL Classification: E60, H55.

Keywords: natural interest rate, pensions, population ageing, secular stagnation, demography, social security.

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1 Introduction

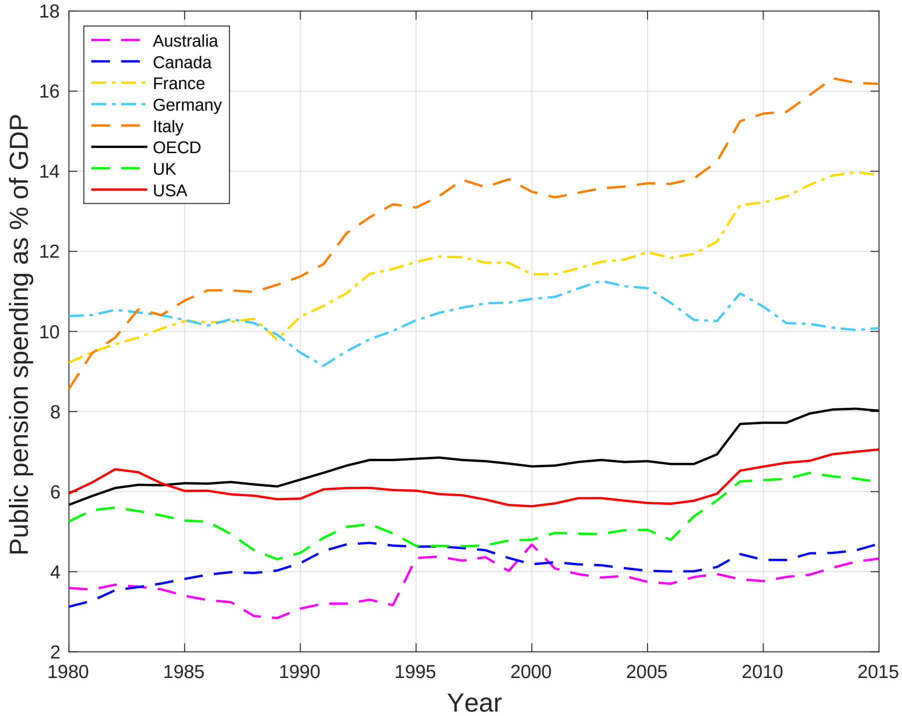
Based on the evidence of a sluggish recovery, a low inflation rate and policy rates at the zero lower bound, the idea of a "secular stagnation", formulated by Hansen (1939), has recently gained new momentum. The new theory of secular stagnation explains the declining trend in the US natural interest rate as the result of a widening gap between saving and investment and it puts forward several candidates as potential drivers of such phenomenon (Summers, 2014). The list of candidates includes, to name a few, population ageing, productivity slowdown, rising income inequality and the decline in investment goods prices. Among these, demographics and productivity stand out as the most quantitatively relevant (Gagnon et al., 2016; Eggertsson et al., 2019). The idea of a "natural" level of the real interest rate, the so-called r^*, consistent with the potential output and stable prices, is central to monetary policy. When the natural interest rate stabilizes at very low or even negative levels, as suggested by the recent estimates for the US economy (Laubach and Williams, 2016; Negro et al., 2017), the margins to cut the policy rate are greatly reduced, and the central bank could hit the zero lower bound (ZLB) more frequently. As more frequent ZLB episodes would imply deeper and prolonged recessions (Kiley and Roberts, 2017), it is crucial to understand the driving forces of the natural interest rate and whether their effect is going to vanish or persist in the future.

Despite the extensive analysis of many possible secular stagnation determinants, the existing literature has disregarded an economic institution that crucially affects the saving behavior: the pension system and its rules. This paper investigates the quantitative importance of the public pension system for the US natural interest rate in the last fifty years, and it carries out a prospective analysis of its future impact, in response to population ageing, under different policy and productivity growth scenarios. The omission of Social Security and its evolution over time in the literature on the drivers of the natural interest rate is notable for, at least, two reasons.

First, the size of the US public pension system, officially the Old-Age, Survivors, and Disability Insurance (OASDI) program, is not negligible, implying a potentially relevant impact on saving and the natural interest rate.[1] Figure 1 depicts US public

[1] The OASDI program operates under a pay-as-you-go (PAYG) basis providing benefits to retirees and disabled people. The current workers finance the benefits of the current retirees through payroll taxes, and the pension system keeps the financial resources in two trust funds, the Old-Age and Survivors Insurance Trust Fund (OASI) for retirement and the Disability Insurance Trust Fund (DI) for disability, which pay out effectively the benefits.

Figure 1: Public pension spending in the OECD countries
Source: OECD



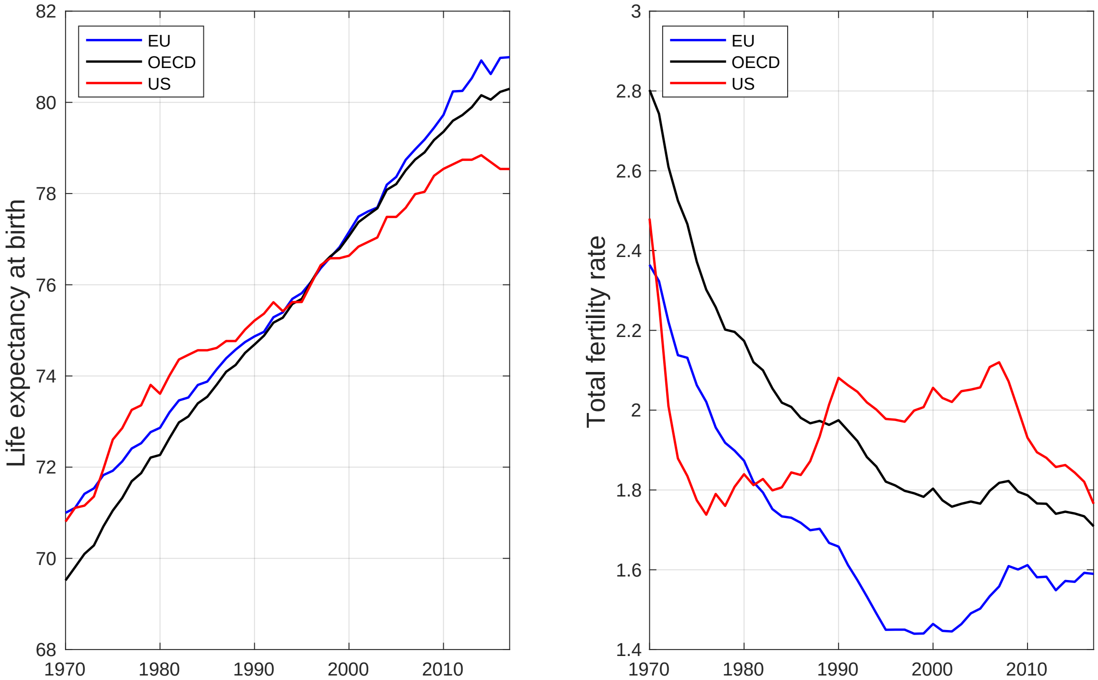
pension spending in terms of GDP, along with that of some OECD countries.

Second, the dimension of the US public pension system is expected to vary significantly in the future.The demographic transition towards an older society is at an earlier stage in the US than in other advanced countries, due to a delayed increase in life expectancy and a more muted decline in the fertility rate (Figure 2). As a consequence, the old-age dependency ratio (DR) has been more stable, mitigating the pressure on the budget of the pension system. However, the DR between people aged 65 and over and those aged 20-64 is expected to increase in the future, forcing the US government to speed up the reform process.[2][3] Indeed, a higher DR threatens the financial sustainability of the public PAYG schemes, because an ever-smaller working population would finance the pension benefits of more retirees.

[2]Most of the advanced countries have already implemented pension reforms to contain expenditure and increase revenues, mainly through changes in the replacement rate, the retirement age and the contribution rate (OECD, 2017). Although the US has put in place some minor reforms, the major pension reform, the so-called "Simpson-Bowles" plan, was never adopted (OECD, 2013).

[3]The US DR did not increase markedly between 1975 and 2015 (from 19.7% to 24.6%), but it will rise to 40.3% over the period 2015-2050 (OECD, 2017). Consequently, the OASI will exhaust in 2034 (2019 Annual Report of the Board of Trustees of the OASI and DI), and the deterioration in the funding position of the OASI will presumably call for substantial pension reforms.

Figure 2: Demographic trends
Source: World Bank



We aim to identify and measure the quantitative impact of the public pension system and its reforms on the natural interest rate, in the past and the future. To that aim, we first develop an overlapping generations (OLG) model with three generations for illustrative purposes. Although highly stylized, the model explains the relationship between a PAYG pension scheme and the natural interest rate. Furthermore, it clarifies the interaction between demographic changes and pension reforms, providing clear theoretical insights to understand the quantitative impact of the pension system on the natural interest rate under different demographic and technological conditions. As a result, the toy model shows that, following the same demographic shock, some types of pension system adjustments mitigate the direct effect of the shock on the equilibrium interest rate, while some others amplify it.

We then employ a more realistic quantitative life-cycle model, which is calibrated to the US economy. Specifically, we run two quantitative exercises. Firstly, we decompose the decline in the natural interest rate between 1970 and 2015 and we examine the role of the pension system and its reforms. On the one hand, simply accounting for the pension system, even without considering its changes over time, mitigates the impact of the forces putting downward pressure on the natural interest rate. On the other hand, the adjustments in the US pension system have prevented the natural interest rate from dropping further by around 1%, counteracting the negative effect of demographic and technological trends. The last result is due to the past evolution of the US pension scheme, which has become more generous in terms of replacement rate in the last fifty years.

Secondly, we simulate the demographic changes predicted by the United Nations for the US population between 2015 and 2060 and we study the expected evolution of the natural interest rate implied by alternative pension reforms along the transition. Our analysis focuses deliberately on the case in which the real interest rate is lower than the economy's growth rate g, due to a falling r^*. While demographic trends are slow-moving and thus easily predictable, the evolution of productivity is an object of speculation. Consequently, we compare two different scenarios: one, named "stagnant growth", in which the rate of productivity growth remains at the 2015 low level until 2060, and another one of "normal growth" in which productivity grows at 2% per year.

Our results indicate that the future natural interest rate is subject to high variability depending on the scenario-reform combination, with its long run value ranging between +45 to -160 basis points relative to the starting point in 2015. In particular, it always decreases with "stagnant growth", while it always increases with "normal growth", for a given public debt-to-GDP ratio. More importantly, the ranking among the different pension adjustments, based on a welfare criterion, depends on the evolution of productivity, and it is driven by the implied effect on the natural interest rate, r^*. In particular, a reduction in the replacement rate outperforms, in terms of welfare, an increase in the contribution rate in the "normal growth" scenario and vice versa in the "stagnant growth" case. This result goes hand-in-hand with the fact that the reform of the replacement rate mitigates the fall in r^* as much as the reform of the contribution rate with "normal growth", but it greatly amplifies the fall in r^* with "stagnant growth".

Related literature

Our contribution lies in the intersection between two strands of the economic literature. The first one concerns secular stagnation and the historical decline in the natural interest rate (Ikeda and Saito, 2014; Summers, 2014; Gordon, 2015; Carvalho et al., 2016; Gagnon et al., 2016; Kara and von Thadden, 2016; Cooley and Henriksen, 2018; Barany et al., 2018; Eggertsson et al., 2019; Rachel and Summers, 2019; Auclert et al., 2020; Bielecki et al., 2020; Papetti, 2020). The second one, less recent, regards the effects of PAYG pension system reforms (de Nardi et al., 1999; Börsch-Supan et al., 2006; Krueger and Kubler, 2006; Attanasio et al., 2007; Krueger and Ludwig, 2007). The empirical phenomena that motivate, and so connect, the two are population ageing and the evolution of technology over time. We contribute to the literature on the drivers of the historical decline in r^* by studying the implications of the pension reforms implemented in the US in response to demographic trends experienced in the past and expected in the future. Our analysis distinguishes itself from the second strand as we investigate PAYG reforms in a secular stagnation environment featuring $r < g$. By focusing on a dynamically inefficient economy, our work emphasizes how the implicit return of the PAYG asset, which is larger than the real interest rate, influences the desirability of different pension adjustments forced by demographic changes. Although $r < g$ has often been regarded as a purely theoretical case (Abel et al., 1989), the recent evidence by Geerolf (2018) and Blanchard (2019) proves that it is a real possibility for the advanced economies, including the US, especially if the declining trend in r^* will persist in the future.

Our work is very close to Attanasio et al. (2007) and Krueger and Ludwig (2007), who study the impact of alternative pension reforms, aimed at restoring the sustainability of the PAYG system in response to demographic trends, on prices and welfare. We depart from their approach as we examine a closed, dynamically inefficient, economy. Carvalho et al. (2016) and Kara and von Thadden (2016) adopt a "perpetual youth" model à la Gertler (1999), in which the probability of dying is not age-specific, to study the effect of pensions and demographics on interest rates. By employing this framework, Carvalho et al. (2016) show that the pension system and its reforms did not counteract significantly the declining interest rates in the advanced economies. In contrast, using a quantitative life-cycle OLG model à la Auerbach and Kotlikoff (1987), in which the probabilities of retiring and dying are age-dependent allowing for a more realistic population age structure, we show that the pension system and its reforms have mitigated the decline in the US interest rates by around 1%. Rachel and Summers (2019) reach a similar conclusions using econometric estimates as well as two general equilibrium models, calibrated to the bloc of the industrialized economies. In their findings, fiscal policy, including the increasing generosity of PAYG schemes, substantially mitigated the effects of the savings glut. Our life-cycle model is closely connected to the one proposed in Eggertsson et al. (2019). However, we augment it with a realistic representation of the US pension system, proving that pensions matter for the quantitative determination of the natural interest rate and its drivers, which have a more muted impact compared to the original findings in Eggertsson et al. (2019).

The remainder of the paper is organized as follows: Section 2 shows the main theoretical mechanisms at work in a simple three-period OLG model; Section 3 develops a quantitative life-cycle model, which is used in Section 4 and 5 to run our quantitative experiments; Section 6 concludes.

2 Theoretical model

In this section, we first illustrate a stylized deterministic three-period OLG model that accounts for the determinants of saving over the life-cycle. Then, we show theoretically how demographic changes and pension reforms interact in the determination of the natural/equilibrium interest rate through the saving behavior.[4]

2.1 Setup

We study an endowment economy with three overlapping generations and a government running a PAYG pension system. The size of each generation is N_t^i with $i = y, m, o$ and the ratio between the young and middle generation is $(1+n) = \frac{N_t^y}{N_t^m}$, where n is also the growth rate of the total endowment. Young people borrow up to the exogenous debt limit D by issuing a one-period risk-free bond, denoted by a_t^y, which pays the real return r_t. Middle-aged agents receive the positive endowment Y, pay the contribution to the pension system T, consume and save for retirement by investing the real resources a_t^m in bonds. The old generation consumes the private pension from its investment in bonds and the public pension from its contribution to the PAYG system. The public pension is a fraction ν, replacement rate, of Y. The representative household's maximization

[4]Demographics affects the natural interest rate through several channels (Carvalho et al., 2016; Gagnon et al., 2016; Eggertsson et al., 2019). A longer life extends the retirement period, inducing workers to accumulate more saving and thus depressing the natural interest rate. Lower fertility also puts downward pressure on the natural rate, because a shrinking labor force increases the capital-to-labor ratio decreasing the marginal product of capital, and the relative abundance of the capital factor implies less investment. These effects are only partially mitigated by the positive impact of a larger fraction of retirees, who consume more and save less than workers. In this section, we replicate only the effect of demographics working through an extended retirement period, because this is the channel most closely connected to the pension system. However, this should be interpreted as a stylized representation of all the effects just outlined, whose overall impact on the natural interest rate is negative and which are in any case at work in the quantitative model of Section 3.

problem is[5]

$$\max_{c_{t+1}^m, c_{t+2}^o} \lambda^y \ln c_t^y + \beta\lambda^m \ln c_{t+1}^m + \beta^2 \lambda^o \ln c_{t+2}^o$$

s.t.

$$\lambda^y c_t^y = \lambda^y a_t^y = \frac{\lambda^m D}{1 + r_t} \quad (1)$$

$$\lambda^m c_{t+1}^m = \lambda^m Y - (1 + r_t)\, a_t^y - \lambda^m a_{t+1}^m - \lambda^m T \quad (2)$$

$$\lambda^o c_{t+2}^o = (1 + r_{t+1})\, \lambda^m a_{t+1}^m + \lambda^o \nu Y. \quad (3)$$

The household's utility, discounted at the rate β, is given by the real consumption in each stage of life, c_t^y, c_{t+1}^m and c_{t+2}^o, and it includes the length of youth λ^y, middle age/working life, λ^m, and old age/retirement, λ^o. This lifetime utility representation distinguishes the sub-period/yearly utility in each stage of life and the length of each stage of life (Philipson and Becker, 1998).[6] All variables are, accordingly, sub-period/yearly variables and need to be multiplied for the relevant λ to obtain their aggregate counterpart.[7] The optimality condition for the household's problem is the Euler equation

$$\frac{1}{c_t^m} = \beta\,(1 + r_t)\, \frac{1}{c_{t+1}^o}. \quad (4)$$

Young and middle-aged households trade risk-free assets in the credit market. This market is in equilibrium when the demand from the young generation equals the supply from the middle one, given the different size and length of the generations:

$$(1 + n)\, \lambda^y a_t^y = \lambda^m a_t^m. \quad (5)$$

Combining equation (1) and the left-hand side of (5) yields the total demand for credit D_t^c, namely

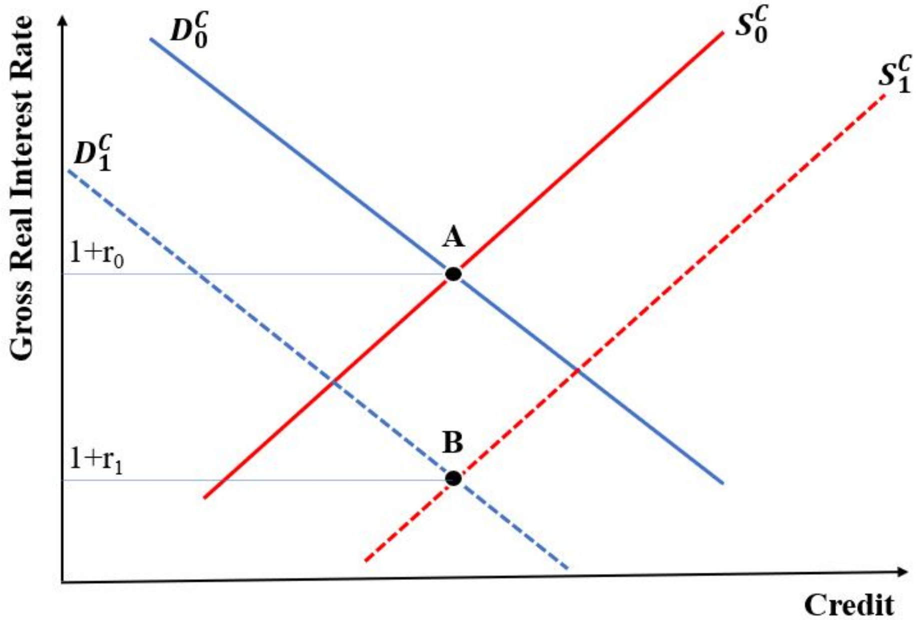
$$D_t^c = \left(\frac{1 + n}{1 + r_t}\right) \lambda^m D. \quad (6)$$

[5]The borrowing constraint in equation (1) is binding because $D < \frac{1}{1+\beta(\lambda^m+\beta\lambda^o)} \left[\lambda^m (Y - T) + \frac{\lambda^o \nu Y}{(1+r_t)}\right]$.

[6]In the original interpretation of Philipson and Becker (1998), the sub-period/yearly utility measures the quality of life, while the length of generations measures the quantity of life. Given our utility function and no discounting within working life and within retirement period, the consumption in each sub-period is the same during both working life and retirement.

[7]For example: Y is the endowment received in each sub-period of middle age, while $\lambda^m Y$ is the total endowment. Moreover, the debt limit in (1) is multiplied by λ^m because an endowment received for a longer period improves the ability to repay debt, relaxing the borrowing constraint. Finally, $\lambda^y + \lambda^m + \lambda^o \leq 3$, where $\lambda^y = 1$ and $\lambda^o \in (0, 1)$.

Figure 3: Credit Market Equilibrium



Instead, we derive the total credit supply/saving

$$S_t^c = \lambda^m a_t^m = \lambda^m \left[\frac{\beta \lambda^o}{\lambda^m + \beta \lambda^o} (Y - D - T) - \left(\frac{1}{\lambda^m + \beta \lambda^o} \right) \frac{\lambda^o \nu Y}{(1 + r_t)} \right], \tag{7}$$

which depends on the length of middle age/working life and on the sub-period credit supply/saving a_t^m, by using (1), (2), (3), and (4). The effect of the PAYG pension scheme on saving is twofold. First, the pension scheme decreases disposable income and thus saving, for a given propensity to save, by levying T. Second, it provides an income at old age, νY, that induces the household to save less by changing its propensity to save. The negative effect of the PAYG scheme on saving reflects on the gross equilibrium real interest rate,

$$1 + r = \frac{(\lambda^m + \beta \lambda^o)(1 + n) D + \lambda^o \nu Y}{\beta \lambda^o (Y - D - T)}, \tag{8}$$

which would be lower without a pension scheme, that is for $T = \nu = 0$. As depicted in Figure 3, the credit demand D_t^c relates negatively to $1 + r$ in (6), while the credit supply/saving (7) relates positively to the real interest rate.[8] Furthermore, a reduction

[8]The relationship between saving and the real interest rate relies on the effect of a higher $1+r$ on the discounted value of future pension benefits. This relationship would not be necessarily positive with

in the credit demand that shifts the corresponding curve downward, from D_0^C to D_1^C in Figure 3, results in a lower equilibrium interest rate. The same happens for an increase in the supply of saving, which shifts the credit supply curve downward, for example, from S_0^C to S_1^C in the figure. On the contrary, an increase in the credit demand and a decrease in saving would shift the corresponding curve upward, increasing the real interest rate.

One last equation closes the model, the PAYG pension scheme budget constraint

$$N_t^m \lambda^m T = N_t^o \lambda^o \nu Y. \tag{9}$$

The left-hand side (LHS) corresponds to the total contributions to the pension system, while the right-hand side (RHS) is the total expenditure for pension benefits. On the RHS, an increase in λ^o causes a higher expenditure for pensions because of a longer retirement, while a lower fertility, $1+n = \frac{N_t^m}{N_t^o}$, implies fewer middle-aged people relative to retirees and so less contributions in aggregate.

2.2 Demographics, pension reforms and the natural interest rate

We study the effects of demographics on the real interest rate, starting from an economy where there is no pension system, i.e., $T = \nu = 0$. Then, we introduce the PAYG scheme and examine how the same demographic change affects r through alternative pension reforms. As the purpose of this section is illustrative, we focus exclusively on a permanent change in the duration of old age λ^o due to higher life expectancy, which is the quantitatively most relevant demographic phenomenon taking place in the US. As the credit demand, given by equation (6), is independent of λ^o, it is sufficient to study the impact of λ^o on credit supply S_t^c to predict the implied change in the equilibrium interest rate. Starting from the definition $S_t^c = \lambda^m a_t^m$ in equation (7) and differentiating with respect to λ^o, we get[9]

$$\frac{\partial S_t^c}{\partial \lambda^o} = \frac{\partial \lambda^m}{\partial \lambda^o} a_t^m + \left[\frac{\partial a_t^m}{\partial \lambda^o} + \frac{\partial a_t^m}{\partial \lambda^m} \frac{\partial \lambda^m}{\partial \lambda^o} \right] \lambda^m. \tag{10}$$

different preferences. Notwithstanding, we view the case considered as the most relevant empirically, as Eggertsson et al. (2019).

[9]Note that $\frac{\partial \lambda^m}{\partial \lambda^o} \neq 0$ only when the government adjusts the retirement age in response to any change in λ^o.

In absence of the PAYG scheme, the effect of a higher life expectancy at old age is given by

$$\left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{No-PAYG} = \lambda^m \left[\frac{\beta\lambda^m}{(\lambda^m+\beta\lambda^o)^2}(Y-D)\right] > 0. \tag{11}$$

A longer retirement increases savings via a higher propensity to save, and this, in turn, translates in a lower equilibrium interest rate. For a given stock of wealth $(1+r_t)\,\lambda^m a_t^m$, a higher λ^o reduces consumption in each sub-period of retirement in (3), inducing middle-aged households to save more in each sub-period of working life. Demographic factors, as well as affecting the incentives to save, carry important consequences for the pension system through the dependency ratio, $DR = \frac{\lambda^o N_t^o}{\lambda^m N_t^m}$. As a result of longer life expectancy, which causes higher λ^o, and/or lower fertility $1+n = \frac{N_t^m}{N_t^o}$, the DR increases, undermining the financial sustainability of the public pension system. The government can restore it by varying the policy parameters ν, T, λ^m and λ^o.

2.2.1 Reform of the replacement rate

If the government adjusts ν to offset the fiscal imbalance generated by demographic phenomena, we get

$$\left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{Adjust-\nu} = \left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{No-PAYG} + \frac{\beta\lambda^m}{(\lambda^m+\beta\lambda^o)^2}\left(\frac{1+n}{1+r}-1\right)\lambda^m T > 0, \tag{12}$$

which is always positive.[10] The replacement rate falls in response to an increase of λ^o. Hence, lifetime income and old-age consumption decrease, forcing middle-aged households to build up more saving each sub-period. The reform of the replacement rate, induced by a longer life expectancy, amplifies the original effect of a higher λ^o on saving, as shown by the last term on the RHS of the equation. This term also reveals that in the presence of dynamic inefficiency, i.e., $r < n$, the credit supply response to a

[10] Indeed, it can be alternatively written as

$$\left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{Adjust-\nu} = \lambda^m \left\{\frac{\beta\lambda^m}{(\lambda^m+\beta\lambda^o)^2}\left[(Y-D-T)+\left(\frac{1+n}{1+r}\right)T\right]\right\},$$

where $(Y-D-T)>0$ because the supply of saving from middle-aged households has to be positive in presence of a PAYG. Only the term $\lambda^m\left[\frac{\beta\lambda^m}{(\lambda^m+\beta\lambda^o)^2}\left(\frac{1+n}{1+r}\right)T\right]$ regards the reform of the replacement rate, while the term $-\lambda^m\left[\frac{\beta\lambda^m}{(\lambda^m+\beta\lambda^o)^2}T\right]$, which does not enter $\left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{No-PAYG}$, arises because of the presence of the pension scheme.

change in ν is even stronger, because the return of the pension system is higher than the return of the risk-free bond for each unit invested. To conclude, the endogenous decline in ν puts further downward pressure on the equilibrium real interest rate through the increase in saving.

2.2.2 Reform of the contribution

When, instead, the contribution to the pension scheme, T, changes in response to adverse demographic trends, we obtain

$$\left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{Adjust-T} = \left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{No-PAYG} - \frac{\nu Y}{1+n}\left[\frac{\beta\lambda^m\lambda^o}{(\lambda^m+\beta\lambda^o)^2} + \frac{\beta\lambda^o}{\lambda^m+\beta\lambda^o} + \frac{1+n}{1+r}\right], \tag{13}$$

which is necessarily lower than $\left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{No-PAYG}$. A larger λ^o calls for an increase in taxes, T when the replacement rate ν is unchanged. An increase in T incentivizes the agent to optimally reduce savings, because the pension scheme pays the same benefit νY and the decline in disposable income, $Y - D - T$, reduces the resources available for consumption at middle-age. Overall savings S_t^c will increase or decrease depending on whether the incentive to save due to a longer retirement period, in red, is stronger than the disincentive implied by the pension system adjustment. This reform counteracts the change in credit supply caused by demographic phenomena, mitigating the downward pressure on the equilibrium interest rate r.

2.2.3 Reform of the retirement age

The reform of the retirement age (RA) alters the duration of working life and retirement, λ^m and λ^o, so that their ratio returns to the level before the demographic change. This fully neutralizes the impact of ageing on the pension scheme budget constraint:

$$\frac{\lambda^m}{\lambda^o} = \frac{\nu Y}{T(1+n)}. \tag{14}$$

This reform implies that the term $\left[\frac{\partial a_t^m}{\partial \lambda^o} + \frac{\partial a_t^m}{\partial \lambda^m}\frac{\partial \lambda^m}{\partial \lambda^o}\right]$ in equation (10) equals 0 because a_t^m only depends on the ratio $\frac{\lambda^m}{\lambda^o}$ that remains constant. Therefore,

$$\left(\frac{\partial S_t^c}{\partial \lambda^o}\right)^{Adjust-RA} = \frac{\lambda^m}{\lambda^o} a_t^m > 0, \tag{15}$$

where we have implicitly assumed that the agent earns Y for each extra sub-period of working life. The reform of the RA neutralizes the effect of ageing on the supply of savings per sub-period a_t^m due to an extended retirement period, (11), which disappears in equation (15). However, the overall effect, direct and indirect through pensions, of λ^o on S_t^c is positive because middle-aged agents save for more sub-periods, increasing the total credit supply. Moreover, the variation in λ^m also increases credit demand (1) putting upward pressure on r, therefore we cannot determine unambiguously the impact of this reform on the equilibrium real interest rate. We now carry out a quantitative analysis that, among the other things, can disentangle the net effect of the reform to the RA on r.

3 Quantitative model

We develop a medium-scale life-cycle model to study the quantitative importance of the pension channels, investigated theoretically in Section 2, for the past and future evolution of the natural interest rate. The proposed theoretical framework draws on the model in Eggertsson et al. (2019), with two substantial deviations. First, a public PAYG pension system is explicitly modeled; second, a simple form of within-cohort heterogeneity is introduced: only a fraction $\psi < 1$ of households for each cohort participates to the scheme. These innovations allow accounting for the effect of pensions on households' saving decisions and better capture the specifics of the OASDI program in the data.

In the remainder of this section, we briefly sketch out the behavior of households, firms, and government. We put all the equations characterizing the model in the Appendix A, together with the definition of the competitive equilibrium and the outline of the solution method.

3.1 Households

Households enter the economy and have kids at age 26, and they participate to the labor market until their retirement at age RA. They die certainly at the maximum possible age of J, which is 81 years, but they face a positive probability of dying even before age J. The population growth depends on the fertility rate of every family, f_t. A representative household i aged j gets utility from consumption, $c_t(i,j)$, and from the bequest left to each descendent, $x_t(i,j)$. The utility functions from consumption and bequests, $u(.)$ and $v(.)$, are CRRA, and they are discounted at the rate β, multiplied by the age-dependent survival probability s^j. The elasticity of intertemporal substitution is ρ, while the strength of the bequest motive is measured by the parameter μ. Households leave bequests only at age J and receive inheritances, $q_t(j = 57)$, one period after the death of their parents[11]. Therefore, a household i entering the economy at time t maximizes the lifetime utility

$$U_t(i) = \sum_{j=26}^{J} s^j \beta^j u\big(c_{t+j-1}(i,j)\big) + s^J \beta^J \mu v\big(x_{t+J-1}(i,J)\big)$$

[11]Formally, $x_t(i,j) = 0 \quad \forall j \neq J$ and $q_t(j) = 0 \quad \forall j \neq 57$. As shown in the Appendix A.1, we assume that inheritances q_t do not depend on the index i, i.e., they are the same for participants and non-participants to the pension system of the same age.

subject to the budget constraints

$$c_t(i,j)+\xi_t a_{t+1}(i,j+1) = (1-\tau_t^b-\tau_t^w \mathbf{1}_{i\in\Psi_t})w_t hc(j)+\Pi_t(j)+[r_t^k+\xi_t(1-\delta)]\Big[\frac{a_t(i,j)}{s(j)}+q_t(j)\Big]$$

$$c_t(i,j)+\xi_t a_{t+1}(i,j+1)+f_{t-j+26}(26)x_t(i,j) = p_t^b(j)\mathbf{1}_{i\in\Psi_t}+[r_t^k+\xi_t(1-\delta)]\Big[\frac{a_t(i,j)}{s(j)}+q_t(j)\Big].$$

The first constraint holds for $26 \leq j \leq RA$, when the household is young and active in the labor market, while the second one holds for $RA < j \leq J$, when the household is old and retired. Households supply inelastically their labor endowment for the labor income $w_t hc(j)$, where w_t is the real wage and $hc(j)$ is the age-dependent labor efficiency level. A proportion τ^b of the labor income is paid in form taxes to finance government expenditure, while τ^w is the contribution rate to the public pension system. The indicator function $\mathbf{1}_{i\in\Psi_t}$ is a dummy that takes value 1 only when $i \in \Psi_t$, i.e., if the household i participates to the public pension scheme, and it is 0 otherwise.[12] The use of the latter in the two budget constraints indicates that the pensions contributions/benefits are paid/received only by participants. Young households also earn firms' profits $\Pi_t(j)$, which are distributed proportionally according to gross labor income.

Agents can save to smooth consumption over their lifetime by purchasing one-period assets, $a_t(i,j)$, in the form of physical capital or risk-free bonds. The exogenous price of capital in consumption units is ξ_t, while the return on capital, which depreciates at the rate δ, is r_t^k. Young households can also borrow, but they face a borrowing limit of the form $a_t(i,j)(1+r_t) \geq D_t(j) = d_t w_t hc(j)$, where $0 \leq d_t \leq 1$.[13] Finally, all households insure against the idiosyncratic risk of death before age J by participating to annuity markets, as in Ríos-Rull (1996). Therefore, involuntary bequests are shared among the surviving members of the same cohort, as expressed by the term $\frac{a_t(i,j)}{s(j)}$ in the two budget constraints. After retirement, individual income is the proceedings from the investment decisions, and, for the public pension scheme participants, the pension benefit $p_t^b(j)$.

[12] Ψ_t is the set of pension scheme participants at time t. The size of Ψ_t is $\psi_t \sum_{j=26}^{J} N_t(j)$, as a constant fraction ψ_t of each cohort j participates to the public pension system .

[13] For a no-arbitrage condition, the return from risk-free bonds equals that from capital investment: $1+r_t = [r_t^k+(1-\delta)\xi_t]/\xi_{t-1}$. As regards the borrowing constraint, it is expressed on asset accumulation, unlike that in equation (1) of the theoretical model. Moreover, $D_t(j)$ grows at the rate of productivity growth (due to w_t) and the household's earning potential over the life-cycle (due to $hc(j)$).

3.2 Firms

The supply side of the economy is very rich, but it boils down to a few equations. For all details and derivations, see Appendix A.2. The aggregate production function is CES

$$Y_t = \left[\alpha(A_k K_t)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)(A_{l,t}L_t)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}},$$

where Y_t is aggregate output, σ is the elasticity of substitution between inputs, $A_{l,t}$ is a labor-augmenting technological process growing at the exogenous rate g_t, and A_k is the capital productivity that is constant over time. Aggregate labor is the sum of the labor productivity of each cohort weighted by its mass, $L_t = \sum_{j=26}^{J} N_t(j)hc(j)$.[14] Moreover, employers contribute to the pension system, along with their employees, and their tax rate is τ_t^f. However, not all workers participate to the pension system, so the total contribution of firms is $\psi_t\tau_t^f w_t L_t$. Aggregate capital K_t evolves over time according to the law of motion $K_{t+1} = (1-\delta)K_t + \frac{I_t}{\xi_t}$, where I_t is aggregate investment and ξ_t is the price of investment goods. Finally, the returns to capital and labor are, respectively

$$r_t^K = \frac{\theta_t - 1}{\theta_t}\alpha A_k^{\frac{\sigma-1}{\sigma}}\left(\frac{Y_t}{K_t}\right)^{\frac{1}{\sigma}},$$

$$w_t = \frac{1}{1+\psi_t\tau_t^f}\frac{\theta_t-1}{\theta_t}(1-\alpha)A_{l,t}^{\frac{\sigma-1}{\sigma}}\left(\frac{Y_t}{L_t}\right)^{\frac{1}{\sigma}},$$

where $\theta_t > 1$ is the elasticity of substitution across final good varieties.

3.3 Government

The government budget constraint is

$$B_{t+1} = (1+r_t)B_t + G_t - G_t^p - T_t,$$

where G_t is the public expenditure, G_t^p is the pension surplus, B_t denotes public debt, and labor income taxes are $T_t = \tau_t^b w_t L_t$. On the balanced growth path, we assume that the government debt-to-output ratio is constant and the tax rate τ^b varies to keep the government budget balanced.[15]

[14] After RA, $hc(j) = 0$.

[15] This assumption implies that whenever $G_t^p < 0$, the tax burden imposed by the pension deficit falls on all working households, including those not covered by the public pension scheme. Similarly, if

3.4 Pension system

The pension system plays a central role in our quantitative model, and we tailor it to replicate the salient features of the US public pension system, the OASDI program. While a fraction of households, $\psi < 1$, participates to the public pension system, contributing the tax rate τ^w when working and receiving the pension $p_t^b(j)$ once retired, the remaining fraction of households does not, $\tau^w = p_t^b(j) = 0$. The budget constraint of the pension system is

$$G_t^p = \psi \tau_t^p w_t \sum_{j=26}^{RA} N_t(j) hc(j) - \sum_{j=RA+1}^{J} N_t(j) p_t^b(j), \tag{16}$$

where $\tau_t^p = \tau_t^w + \tau_t^f$ is the total contribution rate from workers and employers. The first term on the RHS is the total contribution from working households, while the second term is the total expenditure for pensions benefits to retirees. Equation (16) is the equivalent of (9) in the theoretical model. However, now the pension budget is not necessarily balanced. The variable G_t^p denotes the pension system surplus or deficit, depending on whether the total contributions exceed the total benefits or vice versa. This new assumption allows for more precise calibration of the model to the OASDI program, which has run a surplus over the last decades but it is expected to undergo deterioration of its financial conditions due to population ageing.

The financial balance of the pension system crucially depends on how the policy parameters, τ_t^p, RA, and the replacement rate ν_t, adjust to the demographic pattern. The individual pension benefit of a retiree aged j is:

$$p_t^b(j) = \nu_t \phi(RA, FRA) \frac{w_{t-j+60}}{35} \sum_{z=RA-35+1}^{RA} hc(z). \tag{17}$$

Our calculation of the pension benefit, which is a fraction ν_t of the average gross labor income, follows the US Social Security regulation closely. A detailed account of the computation procedure can be found in Appendix A.3. In short, the US Social Security Administration computes the pension benefits according to the Primary Insurance Amount (PIA), which considers only the average labor earnings of the top 35 years of contribution, defined as Average Indexed Monthly Earnings (AIME). Monthly earnings are indexed relative to the average wages of the indexing year, the year in which the

$G_t^p > 0$, the pension surplus is shared across all working households.

contributor turns 60. We calculate the AIME by averaging the gross labor earnings of the last 35 years of work because, given the calibration, they correspond to the top 35 years of earnings. On the other hand, we index individual wages relative to the economy-average wage in the year in which the agent turned 60, i.e., w_{t-j+60}. As the US regulation applies a penalty to benefits in case of early retirement, the function $0 < \phi(RA(i), FRA) \leq 1$ gives the penalty, in terms of replaced contributions, if the individually chosen retirement age $RA(i)$ is lower than the full retirement age FRA.

Table 1: Calibration

Parameters	Symbol	1970 value	2015 value	
Parameters estimated directly from the data				Source
Mortality profile	s_j			US mortality tables, CDC
Income profile	hc_j			Gourinchas and Parker (2002)
Total fertility rate	n	2.8	1.88	UN fertility data
Productivity growth	g	2.02%	0.65%	Fernald (2012)
Government spending (percent of GDP)	G	21.3%	21.3%	CEA
Public debt (percent of GDP)	b	42%	118%	Flow of Funds
Retirement age	RA	63	65	US Census Bureau
Replacement rate	ν	32.3%	40.8%	US Social Security
OASDI program coverage		90%	96%	US Social Security
Pension contribution rate	τ^p	8.4%	12.4%	US Social Security
Parameters taken from the literature				Source
Elasticity of intertemporal substitution	ρ	0.75	0.75	Gourinchas and Parker (2002)
Capital/labor elasticity of substitution	σ	0.6	0.6	Antras (2004)
Depreciation rate	δ	12%	12%	Jorgenson (1996)
Price of investment goods	ξ	1.3	1	Fernald (2012)
Parameters calibrated matching some data moments				
Rate of time preference	β	0.96	1.005	
Borrowing limit (percent of annual gross labor income)	d	9.52%	50.22%	
Bequests parameter	μ	55.06	9.12	
Retailer elasticity of substitution	θ	8.6	4.89	
Capital share parameter	α	0.19	0.24	
Data moments				Source
Natural rate of interest		2.62%	-1.47%	FED
Investment-to output ratio		16.8%	15.9%	NIPA
Consumer-debt-to-output ratio		4.2%	6.3%	Flow of Funds
Labor share		72.4%	66%	Elsby et al. (2013)
Bequests-to-output ratio		3%	3%	Hendricks (2002)

4 The natural interest rate in the past

We employ our quantitative model to study the importance of several determinants of the declining trend, between 1970 and 2015, in the US natural interest rate. We emphasize the role of the pension system and its interaction with demographic and productivity changes, because we aim to verify whether the pension system matters for the past pattern of the natural interest rate. Our *positive* analysis consists of comparative statics between balanced growth path-stationary equilibria, and we assume a zero output gap in 2015 so that the *natural* and *real* interest rates coincide, at -1.47%, and the two terms can be used interchangeably.[16]

As we have drawn on the life-cycle model of Eggertsson et al. (2019) for the construction of our quantitative framework and augmented it with a realistic pension system, we treat their model as a benchmark to highlight the specific effect of the pension system on the natural interest rate. Moreover, as our calibration procedure follows closely that in Eggertsson et al. (2019), we focus only on the calibration of the parameters governing the pension system, referring the reader to that paper for further details. Table 1 summarizes our calibration. The first set of parameters, including pension parameters, are directly estimated from data. We take the second set of parameters from the related literature. We internally calibrate the parameters in the third set to match some key moments in data by minimizing a quadratic loss function.

The US Social Security regulation established that the FRA was around 66 years in 2015, but early retirement was possible at 62 years. To take into account the effect of early retirement, we calibrate the effective RA at 65, which is slightly lower than 66 and is consistent with Eggertsson et al. (2019). Regarding 1970, we opt for a more conservative calibration of the RA, 63 years, against the average RA of roughly 65 years for men (US Census Bureau).[17] However, we perform a robustness check in Appendix B.1, where we assume a higher RA in 1970, 64 years, and so a lower variation in the RA over the period 1970-2015. Given our calibration of the RA in 1970 and 2015, our formula for calculating the pension benefits, (17), implies a reduction of 13.3% of the

[16] Although there are several and different estimates of the US's output gap after the Great Recession; we base our assumption of zero output gap on Stock and Watson (2012).

[17] In 1970, there was a large fraction of women excluded from the official labor force. Although data on the average retirement for men are available, average statistics can be misleading because of a left-skewed distribution. Moreover, the so-called survivorship bias and the decision to retire early of sick people significantly affect the data. These are the considerations motivating our conservative calibration for the RA in 1970.

replacement rate for early retirement in 1970 and 6.66% in 2015.

The contribution rate for the OASDI in 1970 was 4.2% of the gross labor income for both employer and employee, while it was 6.2% in 2015. Hence, $\tau^p = \tau^w + \tau^f$ is 8.4% in 1970 and 12.4% in 2015. We calibrate the replacement rate using the US Social Security Administration data on the medium earner's pension benefit, whose net replacement rate was around 32.3% in 1970 and approximately 40.8% in 2015.[18] The positive variation in the replacement rate is a sign that the program experienced an increase in its generosity over the period considered. Hence, we expect it to have mitigated the secular fall in the natural interest rate. Such reform seems to respond more to pension adequacy considerations rather than to the problem of pension funding. In the last fifty years, the US population has experienced adverse demographic dynamics, which were less pronounced than those of other advanced economies. Consequently, the financial sustainability of the public pension scheme was overall less of a pressing concern. Finally, the OASDI program underwent a substantial expansion in terms of coverage, as documented in the historical accounts of the US Social Security Administration. While in 1970 Social Security involved around 90% of civilian workers, this proportion increased to 96% in 2015.

[18]Data available at https://www.ssa.gov/oact/NOTES/ran9/index.html.

Table 2: Decomposition of the decline in the natural interest rate

Forcing variable	Our results	EMR (2019)
Total real interest rate variation	-4.09%	-4.02%
Single effect		
Mortality rate	-0.64%	-1.82%
Total fertility rate	-0.38%	-1.84%
Productivity growth	-1.44%	-1.90%
Government debt (percent of GDP)	+0.99%	+2.11%
Relative price of investment goods	-0.27%	-0.44%
Replacement rate	+0.50%	-
Retirement age	+0.44%	-
Contribution rate	-0.05%	-
Coverage	+0.16%	-
Combined effect		
All pension adjustments	+1.10%	-
Mortality + Fertility	-0.99%	-
Mortality + Fertility + Replacement rate	-0.71%	-
Mortality + Fertility + Retirement age	-0.59%	-
Mortality + Fertility + Contribution rate	-1.02%	-
Mortality + Fertility + Coverage	-0.90%	-
Mortality + Fertility + all pension adjustments	-0.21%	-
Demographics + pension adjustments + productivity slowdown	-1.90%	-
Demographics + productivity slowdown	-2.69%	-

4.1 Results

We decompose the decline in the US natural interest rate, denoted by r^* hereafter, among all its potential drivers through the following procedure. We treat 1970 and 2015 as two balanced growth path-stationary equilibria, and we calibrate our quantitative model accordingly. We first take the 2015 stationary equilibrium. Then, we shock, one at a time, the parameters associated with the drivers of r^* assigning them the value they take in the 1970 equilibrium, keeping all the other parameters constant. Finally, we interpret the implied variation in the real interest rate as the single driver's effect on the evolution of r^* over 1970-2015. If the implied variation is positive, the driver's effect is negative and vice versa for a negative variation. The top part of Table 2 shows the results of our decomposition for the single drivers, that is the "single effect". Our quantitative model accounts for the full decline of -4.09 percentage points, from 2.62% in 1970 to -1.47% in 2015, in r^*. In particular, it delivers three key results.

First, the public pension scheme matters, in a *static* sense (i.e. absent any pension adjustment over time) to quantify the impact of all the potential drivers of the decline in r^*, as accounting for it determines a different calibration of the model parameters. The decrease in the mortality and fertility rates, the productivity slowdown, and the surge in government debt still qualify as the main drivers of the past pattern of the natural interest rate. But their quantitative impact falls greatly in absolute value, compared to Eggertsson et al. (2019), once the model accounts for the pension system and its evolution between 1970 and 2015. Taking as an example the demographic phenomena, the fall in the mortality rate has negatively impacted the natural interest rate just by 64 basis points, against the 182 basis points originally obtained in Eggertsson et al. (2019). The drop in the total fertility rate pushes r^* down by 38 basis points, while the original effect was -184 basis points. The first quantitative finding derives from the pension system's ability to absorb savings and raise the natural interest rate, as well as its implications for the calibration of the model.

In this sense, we interpret the discrepancies in results relative to Eggertsson et al. (2019) as a consequence of the role of the public PAYG system for the saving behavior and its differences, as an asset, with respect to the bonds and capital in the model. Contributing to the pension scheme reduces disposable income and crowds out private savings and bequests. Moreover, the PAYG entitlement offers a different type of insurance relative to the other assets in the model. Its overall return increases with the individual household's life span, favoring/hurting those that, ex-post, die later/earlier than the economy life-expectancy at birth. Instead, the assumption of perfect annuity markets for private savings grants intra-cohort insurance against the age-specific risk of death.

Second, the pension system matters, in a *dynamic* sense, because the effect of the observed pension reforms on the natural interest rate is positive and quantitatively significant. As well as to measure the single driver's impact on the pattern of r^*, we also consider several drivers simultaneously, that is the "combined effect", such as all the pension reforms implemented. The bottom part of Table 2 shows that the changes to replacement and contribution rates, RA, and coverage have counteracted the downward pressure of the other forces on r^*, raising the natural interest rate by approximately 1% overall.

When we consider every single reform in the top part of Table 2, the change in the replacement rate plays the most significant role. This result is not striking because the replacement rate has increased from 32.3% to 40.8%, over the period under investigation, discouraging private savings and increasing r^* by 0.5 percentage points. The quantitative impact of a higher RA is similar, +0.44 percentage points, and this is because each household spends a slightly larger fraction of her lifetime working and needs fewer savings to support the same amount of consumption at old age.[19] In Appendix B.1, an alternative calibration of the model featuring a lower increase in the RA confirms this result qualitatively (the sign). However, the alternative calibration points to a smaller quantitative impact of a higher RA on r^*, +12 basis points, while the overall effect of all pension reforms is still significantly high, +0.77 percentage points. Finally, the effect of a higher coverage on the natural interest rate is small, but not negligible. At the same time, the impact of the pension contributions is very close to 0 because the change in τ^p is marginal.

Third, the pension system matters for the evolution of the natural interest rate because of its *dynamic* interaction with demographic and technological trends. In the bottom part of Table 2, we measure first the simultaneous effect of pension reforms and changes in the fertility and mortality rates; then, we also consider the slowdown in productivity that occurred between 1970 and 2015. Demographics alone explains a fall in r^* of about one percentage point, which becomes -2.7 percentage points if we take into account also the productivity change. When we consider all the pension reforms in

[19] *Ceteris paribus*, a higher RA increases the aggregate labor supply, $L_t = \sum_{j=26}^{J} N_t(j)hc(j)$ for positive levels of labor productivity around RA. Given the CES technology, a larger L_t increases r_t^K for the same amount of capital.

conjunction with both demographic shocks, the real interest rate drops just by 21 basis points, while the fall is -190 basis points if we add the productivity decline. Again, the single pension reforms that drive these results are the reform to the replacement rate and the RA.

To summarize, our quantitative results highlight a positive effect of the US pension system on the *past* evolution of the natural interest rate. The capacity of the public pension scheme to exert upward pressure on r^* is particularly significant because it counteracts the downward pressure from adverse demographic and technological trends. Notwithstanding, the positive effect relies mainly on the increase in the replacement rate possible because of more favorable demographic trends than in other advanced economies. In the future, more adverse demographic patterns resulting in a higher DR could make a further increase in the replacement rate highly costly, and demographics itself could become so pronounced to push r^* further down. The *future* evolution of the natural interest rate is at the center of the next section.

5 The natural interest rate in the future

We use the same model of the previous section for a prospective analysis, in which we simulate the future demographic dynamics under two opposite productivity scenarios to evaluate the impact of different pension reforms on r^* and welfare. Specifically, we structure our *normative* exercise as follows.

We simulate the US economy's transition dynamics in response to the future demographic trends, estimated by the UN between 2015 and 2060, taking as a starting point the 2015 stationary equilibrium. In 2016, the economy is shocked unexpectedly by changes in mortality, fertility, and production growth. From 2016 onward, agents have perfect foresight of the evolution of productivity, pension adjustments and demographic variables, which return constant after 2060, when the economy starts to converge to a new stationary equilibrium.[20] Moreover, we inform the model with the available estimates of demographic trends between 2015 and 2060, including year-by-year age-dependent survival probabilities and fertility rates. This setting allows us to study the natural interest rate and the welfare of all the generations involved in the transi-

[20] All agents older than 26 years are surprised by the shocks in 2016, and they revise their optimal decisions of consumption and saving over the life-cycle. Instead, cohorts entering the economy after that have full information on the evolution of prices and pension benefits, and they make their decisions accordingly.

tion under two productivity scenarios and subject to four alternative pension reforms. Therefore, we can identify which policy could earn the strongest political consensus, and form an expectation of the most likely time path of the real interest rate in two opposite scenarios regarding future productivity.

We compare a scenario in which the labor productivity growth, g_t in our quantitative model, constantly grows at the 2015 level, 0.65%, with one in which it permanently grows at 2.02%, the average growth rate of the real GDP in the postwar period. We refer to the first scenario as "stagnant growth" and the second one as "normal growth". As we still assume the real and natural interest rates coincide and are negative, we account explicitly for the economic context where the real interest rate is lower than the economy's growth rate, $r^* < g+n$, where n is the population growth rate. We view this environment as the most likely for the US economy in the future, given the past pattern of r and g (Blanchard, 2019).[21]

The pension reforms under investigation are an increase in the tax rate τ^p, a decrease in the replacement rate ν, an increase by one year of the effective RA, and a debt-financed deficit of the pension system. For each pension reform, we shock the corresponding parameter keeping constant the other pension parameters.[22] The last reform allows the government to issue bonds to finance the increase in pension spending due to unfavorable demographics. Instead, the first three reforms alter the balance between expenditures and revenues of the pension system, which is expected to run a deficit in the future due to demographic changes and the resulting higher DR. In any case, we neutralize the impact of these three reforms on the consolidated government budget through an automatic adjustment of the payroll tax rate, τ^b. Therefore, the debt-to-GDP ratio, denoted by $\frac{B}{Y}$, remains constant at the 2015 level, 118%. This assumption matters for the expected evolution of r^* in the future, but not for the welfare ranking of reforms across productivity scenarios. We show this in Appendix C.2, where we conduct an alternative exercise with constant payroll tax rate, set at the 2015 level, and an endogenous debt-to-GDP ratio.

[21] Although the increase in the US public debt prompted by the COVID-19 pandemic may raise the natural interest rate, this effect could be offset by the negative impact of the pandemic shock itself (Jorda et al., 2020). In any case, it is very hard to foresee the higher public debt reversing the historical downward trend in the US natural interest rate.

[22] Apart from the change in the age of retirement, we assume that the effective RA remains at 65 years for the other pension reforms. Notwithstanding, given the automatic adjustment of the FRA to life expectancy in the US legislation, we impose that the penalty associated with early retirement increases as FRA reaches 67 years.

5.1 Calibration

According to the UN *medium variant* projections, life expectancy at birth will increase from 78.7 years in 2015 to 85.3 years in 2060. We replicate the positive longevity shock as a gradual increase in the age-dependent survival probabilities, $[s(j)]_{j=26}^{J-1}$. The UN also predicts that the US total fertility rate will increase, from 1.875 to 2.017 children per woman, in the same period. The combined effect of longevity and fertility causes a variation in the DR from around 42% in 2015 to 50% in 2060.

Compared to the last section exercise's, we slightly modify the calibration to capture the quantitative impact of ageing on pension expenditure. More precisely, agents can now reach a higher maximum age that is $J = 90$.[23] Moreover, we assume that the pension system covers all the population, $\psi = 1$, starting from 2015 and during the transition. This assumption, which simplifies the analysis, is realistic because the coverage of the US pension system was very close to 100% in 2015. We calibrate all the other parameters in the same way outlined in Section 4.[24]

5.2 Results

5.2.1 Stationary equilibrium and transition dynamics

Table 3 displays the main variables and pension parameters in the initial and in the new stationary equilibrium, distinguishing the two productivity scenarios considered. With "stagnant growth", identified by grey columns in the table, r^* is lower than the initial equilibrium in 2015. In contrast, with "normal growth", denoted by white columns, it is higher than the -1.47% value, but still negative. The only exception is the case of a debt-financed deficit of the pension system, which always produces the lowest r^*. Although the government finances the pension deficit by issuing public debt, its refinancing cost is ever lower, along the transition, because $r^* < g + n$. As a consequence, the debt-to-GDP ratio, $\frac{B}{Y}$, falls dramatically, and a lower $\frac{B}{Y}$ reduces r^* given the relative abundance of savings over assets.

[23] As agents leave bequests at age J and have children at age 26, increasing the maximum age from 81 to 90 implies that households receive their inheritance at age 66 and not at age 57.

[24] However, our new calibration affects some parameters, β, d and μ, which are obtained by minimizing a loss function of some relevant data moments. In Appendix C.1, Table 5 displays the new values of these parameters for the 2015 stationary equilibrium. Although different from our original calibration, these values are even closer to the prevailing ones in the related literature. See, for example, Ríos-Rull (1996) for estimates of the discount factor and Kaplan (2012) for those of the borrowing limit as a fraction of labor income, d.

Table 3: Main variables and pension parameters with "stagnant" vs. "normal" growth

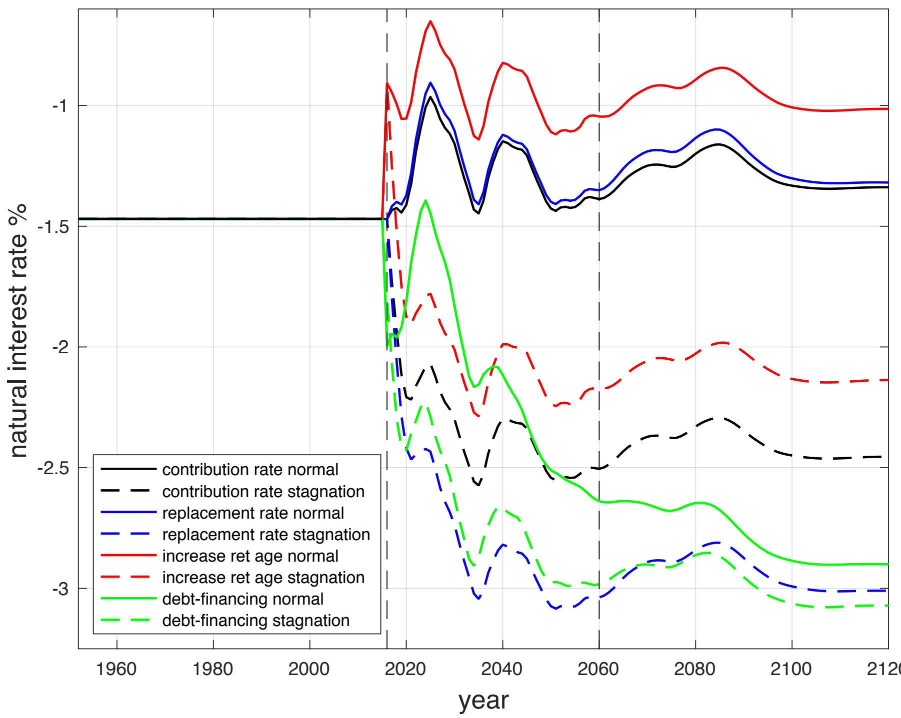
	2015	New stationary equilibrium							
Type of reform	/	contribution rate		replacement rate		retirement age		debt-financing	
Scenario	/	stagnation	normal	stagnation	normal	stagnation	normal	stagnation	normal
r^*	-1.47%	-2.46%	-1.34%	-3.02%	-1.33%	-2.14%	-1.02%	-3.07%	-2.9%
τ^p	12.4%	15.3%	12.3%	12.4%	12.4%	12.4%	12.4%	12.4%	12.4%
τ^b	33.27%	28.53%	27.98%	26.99%	28.02%	31.78%	28.71%	33.27%	33.27%
ν	40.8%	40.8%	40.8%	33.09%	41.05%	40.8%	40.8%	40.8%	40.8%
ϕ	93.3%	86.6%	86.6%	86.6%	86.6%	93.3%	93.3%	86.6%	86.6%
RA	65	65	65	65	65	66	66	65	65
DR	42.4%	46.9%	46.9%	46.9%	46.9%	43.5%	43.5%	46.9%	46.9%
$\frac{B}{Y}$	118%	118%	118%	118%	118%	118%	118%	57.7%	6.67%

More importantly, the natural interest rate varies greatly depending on the pension reforms implemented, even in the same productivity scenario. In general, r^* in the new long run stationary equilibrium ranges from +45 (normal growth and retirement age) to -160 basis points (stagnant growth and debt-financing) relative to the -1.47% level observed in 2015. In particular, in the pessimistic scenario of "stagnant growth", the pension reform that decreases the replacement rate exacerbates the fall in r^* triggered by demographic forces. On the contrary, the alternative reform that increases the contribution rate mitigates the fall in the natural interest rate. This result is consistent with the predictions of the theoretical model in Section 2. Finally, adjusting the effective retirement age (be it the result of a regulatory change or an endogenous behavioral response not explicitly modeled here) minimizes the impact of ageing on r^* by rebalancing the DR. Instead, in the "normal growth" scenario, the reforms to replacement and contribution rates imply very similar levels of the natural interest rate, and the change in the RA determines its largest increase.

We now investigate the entire time path of the natural interest rate along the transition, plotted in Figure 4. In the figure, full lines correspond to the "normal growth" case and dashed lines to "stagnant growth".

Keeping in mind r^* is not an explicit objective of the Social Security Administra-

Figure 4: Natural interest rate along the transition



tion, we can interpret the distance between the full and dashed lines of the same color as a measure of the "stability", associated with each pension reform, for the dynamics of r^*. The more stable pension adjustments produce a similar path of the natural interest rate independently of the productivity scenario. Hence, they correspond to a small vertical distance between full and dashed lines. "Debt financing", though it delivers the largest fall in r^*, generates somewhat similar natural interest rate paths (green lines) in both the productivity scenarios. More interestingly, the reform of the replacement rate, corresponding to the blue curves, brings about an evolution of the natural interest rate almost identical to the change of the contribution rate, identified by black lines, with "normal growth". However, the former has a stronger negative impact on r^* than the latter with "stagnant growth". This stark difference between the two reforms across productivity scenarios points to a change in the replacement rate as the least "stable" reform for the dynamics of r^*. Though this intuition is intriguing, we can draw robust conclusions about the alternative pension reforms' desirability only through an explicit welfare analysis.

5.2.2 Welfare analysis

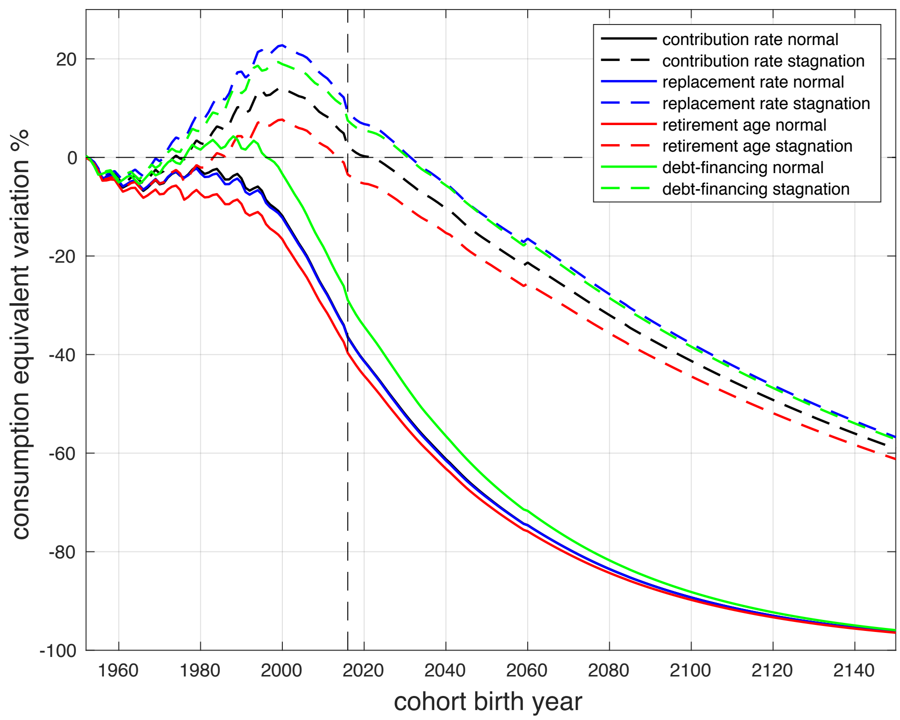
The analysis of the transition dynamics allows us to determine the impact of the pension reforms on the welfare of the generations, which are alive during the convergence. Our welfare criterion is the lifetime utility of the generation aged 26 at time t under the policy adjustment $z = rr, cr, ra, df$ and the productivity growth scenario $i = n, s$. For the sake of comparability, we report the results in terms of consumption equivalent variation (CEV) relative to the benchmark welfare level, which is

$$U^B = \sum_{j=26}^{J} s^j \beta^j u\big((1 + CEV^{z,i})c^{z,i}_{t+j-1}(j)\big) + s^J \beta^J \mu v\big(x^{z,i}_{t+J-1}(j)\big).$$

A *positive* CEV corresponds to a *welfare-reducing* reform-productivity combination because a positive consumption compensation is necessary to deliver the benchmark level of welfare. Vice versa, a *negative* CEV corresponds to a *welfare-enhancing* reform-productivity combination. We first take, as a benchmark for welfare, the lifetime utility of the generation dying in 2015, the year before the transition. This is the generation aged 26 in 1952, and, by using this benchmark, we can identify the role of productivity growth for welfare.

Figure 5 plots the CEV of welfare when the benchmark level is the lifetime utility of the generation entering the economy in 1952. The figure highlights how the "stagnant" productivity scenario imposes welfare losses, denoted by a positive CEV, for the generations entering the labor markets between 1970 and 2030, as opposed to the welfare gains, i.e. the negative CEV values, implied by the "normal" productivity growth. Once again, "debt-financing" represents an important exception because the associated CEV turns positive for the generations aged 26 between 1975 and 1995, even in the more optimistic productivity scenario. Moreover, the welfare ranking among the different reforms does not necessarily coincide in the two productivity cases. While, in the presence of normal growth, the reform to the replacement rate outperforms in terms of welfare the reform to the contribution, and even more the debt-financed pension deficit, with stagnant growth, the former turns out to be the most detrimental. Finally, an increase in the effective retirement age always emerges as the best policy option by taking our welfare criterion. By comparing Figures 4 and 5, we observe that the pension adjustments associated with the largest drops in the natural interest rate correspond to the ones related to the largest welfare losses, except for "debt-financing". This result relies on the fact that *the natural interest rate is a sufficient metric for welfare* in our

Figure 5: CEV relative to the welfare of the generation born in 1952



quantitative model, because it crucially affects the return from investment and so the gap between r^* and the economy growth rate $g + n$: the lower r^*, the larger the gap between r^* and $g + n$ and the lower welfare.

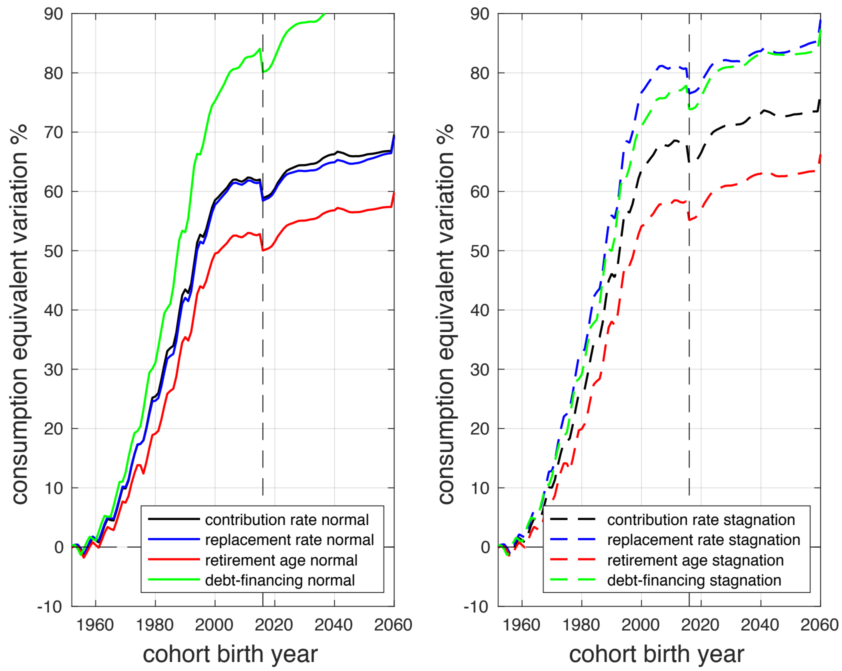
Now, we perform a different computation in which the benchmark for welfare is the lifetime utility that generations would enjoy if demographic variables stayed constant at their 2015 level. This alternative measure of the benchmark welfare, U^B, allows us to examine the welfare costs due to population ageing. Figure 6 plots the CEV with this different definition of U^B. The results in terms of ranking among alternative pension reforms are analogous to the ones obtained in Figure 5.

6 Conclusions

The paper investigates whether the US public pension system and its reforms play a significant role in determining the "natural" interest rate, r^*, consistent with the potential output and stable prices.

We have introduced a realistic representation of the US OASDI program into a medium-scale OLG model to decompose quantitatively, among its drivers, the historical

Figure 6: CEV relative to welfare without ageing



decline in r^*. We have found that the pension system matters quantitatively. The presence of a public pension scheme reduces *per se* the relative impact of all the potential drivers of the declining r^* between 1970 and 2015. Furthermore, our positive exercise shows that the combined effect of all past pension reforms was to raise approximately 1% the natural interest rate, counteracting the downward pressure of demographic and technological trends.

We have then explored how different pension adjustments, adopted in response to the projected demographic trends over the next 40 years, may affect the US natural interest rate and welfare, comparing two alternative scenarios for the productivity path. This *normative* exercise portrays an economic environment in which the real interest rate is lower than the economy's growth rate, i.e. $r^* < g + n$.

In both productivity scenarios, raising the effective retirement age leads to the best outcome according to our welfare criterion. The worst outcome results from a debt-financed pension deficit. However, we do not emphasize this result because it relies on the assumption of exogenous labor supply. More importantly, the ranking between two of the other policy options, i.e., changing the replacement rate vs. changing the contribution rate, depends on the productivity growth rate. When productivity growth is weak, an increase in pension contributions is preferable over reducing the replacement rate, while such a conclusion is reversed in the case of normal growth.

This is an interesting finding because the US government has not updated the contribution rate since 1990.[25] Future pension adjustments, imposed by population ageing, could accordingly happen through a lower replacement rate or a higher debt-financed pension deficit, as the full retirement age is linked to life-expectancy and the effective retirement age is already high. These pension adjustments could lead, according to the predictions of our quantitative model, to significant welfare losses for the present and future generations, especially if future productivity will remain low. We conclude by discussing some possible extensions of the present analysis that could reinforce our results.

First, we should explicitly consider the case of endogenous labor supply to evaluate how the intertemporal allocation of labor and distortionary taxation could affect welfare, when different pension reforms, in particular a change in retirement age, are implemented.

Second, extending our framework to open economy would account for the different timing of demographic transition in the advanced economies. In any case, this assumption would not alter the main conclusions derived in the closed economy framework. In an open economy, as shown by Attanasio et al. (2007) and Krueger and Ludwig (2007), the impact of ageing on the natural interest rate is even greater, emphasizing the differential effect of alternative pension reforms on r^*. Moreover, though the impact of alternative pension adjustments on welfare is more muted, this effect is symmetric across pension reforms, without altering the ranking identified in our normative analysis.

Third, the growing literature on monetary and fiscal policy interactions in heterogeneous agents models has emphasized the importance of heterogeneity, not only for inequality-related issues but also for the aggregate response of the economy to different shocks. As the US public pension system features a significant degree of redistribution from high earnings workers towards low earnings workers, we could extend our quantitative model to account for this intra-generational heterogeneity.

Finally, our setup does not involve any friction that may prevent the output from reaching its efficient level. Although not explicitly modeled here, an inflation target around 2% may not be sufficient, even at the zero lower bound, to sustain a full-employment equilibrium entailing a negative natural interest rate. Therefore, the

[25] Data available at https://www.ssa.gov/OACT/ProgData/taxRates.html.

possibility of future low productivity, combined with ageing, threatens the ability of the monetary authority to stabilize the economy, due to the presence of the zero lower bound. Future research could investigate the role of the pension system in an ageing society, when stagnation implies a systematic output gap because of a binding effective lower bound.

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Appendices

A Quantitative model

A.1 Households

Demographics

Households die certainly at age $J = 81$, but each period they face a positive probability to die $1 - s_t(j)$, where $s_t(j)$ is the survival probability between age j and $j + 1$. The age-specific probabilities $[s_t(j)]_{j=26}^{J-1}$, along with the fertility rate f_t, determine the DR between workers and retirees. Indeed, given $N_t(j)$ households aged j at time t, there will be $N_{t+1}(j + 1) = s_t(j)N_t(j)$ households aged $j + 1$ at time $t + 1$, while the total population at time t is $N_t = \sum_{j=26}^{J} N_t(j)$. The population entering the economy at time t is given by the population of their parents times the fertility rate of the parents, $N_t(26) = N_{t-25}(26) * f_{t-25}(26)$. In what follows, we study a stationary equilibrium in which the total fertility rate and the survival probabilities do not depend on time. In this equilibrium, f determines the population growth rate n through the equation $n = f^{\frac{1}{25}} - 1$, and $(1+n)$ is the ratio between the size of the newborn generation and that of the previous period. Moreover, the relationship $N(j + 1) = s(j)N(j)/(1 + n)$ holds for $j \in [26, J - 1]$ and a given $N(26)$. We normalize $N(26)$ such that total population equals 1 and so the mass of each cohort is also the corresponding share of the overall population, $N(j)/N$.

Utility

Utility from consumption and from bequests share the CRRA functional form and the same intertemporal elasticity of substitution ρ:

$$u\left(c_t(i,j)\right) = \frac{c_t(i,j)^{1-\frac{1}{\rho}}}{1-\frac{1}{\rho}}$$

$$v\left(x_t(i,J)\right) = \frac{x_t(i,J)^{1-\frac{1}{\rho}}}{1-\frac{1}{\rho}}.$$

Bequests

A fraction $0 \leq \psi_t \leq 1$ of households at each age is covered by the public pension system. The remaining $(1-\psi_t)$ is not and builds value for old-age consumption via private savings uniquely. Therefore, these two types of agents make different consumption/savings decisions over their lifetime and leave different amount of bequests to their descendants. For the sake of simplicity, we assume that participants and non-participants of each cohort pool together their bequests so that their offspring receives the same inheritance. It follows that:

$$q_{t+1}(j=57) = \frac{N_t(J)}{N_{t+1}(57)} f_{t-J+26} \left[\psi_t x_t(i \in \Psi_t, J) + (1-\psi_t)\, x_t(i \notin \Psi_t, J)\right],$$

where Ψ_t is the set of participants to the public pension system at time t.

A.2 Firms

Three types of firms populate the economy's supply side: final goods firms, intermediate goods firms, and capital goods firms.

Final goods firms

Final goods firms operate in a regime of monopolistic competition. They purchase intermediate goods y_t^m at the price p_t^{int}, and transform them in differentiated final goods via a linear production function, $y_t^f(i) = y_t^m$. The different varieties are combined with a CES aggregator

$$Y_t = \left[\int_0^1 y_t^f(i)^{\frac{\theta_t - 1}{\theta_t}} di\right]^{\frac{\theta_t}{\theta_t - 1}},$$

where Y_t is aggregate output and $\theta_t > 1$ is the elasticity of substitution across different varieties. The final good producer sets the price $p_t(i)$ in each period, solving the maximization problem:

$$\max_{p_t(i)} \frac{p_t(i)}{P_t} y_t^f(i) - \frac{p_t^{int}}{P_t} y_t^m$$

s.t.

$$y_t^f(i) = y_t^m = Y_t \left(\frac{p_t(i)}{P_t}\right)^{-\theta_t},$$

where $P_t = \left[\int_0^1 p_t(i)^{1-\theta_t} di \right]^{\frac{1}{1-\theta_t}}$ is the economy's price level. The constraint in the maximization problem represents the demand curve of the differentiated final good. The solution of the problem above implies that the price is set charging a mark-up over the marginal cost:

$$\frac{p_t(i)}{P_t} = \frac{\theta_t}{\theta_t - 1} \frac{p_t^{int}}{P_t}.$$

As the intermediate good is homogeneous, all final goods producers set the same price, $p_t(i) = P_t$. Hence,

$$\frac{p_t^{int}}{P_t} = \frac{\theta_t - 1}{\theta_t}$$

and aggregate profits are $\Pi_t = \frac{Y_t}{\theta_t}$. These profits are distributed among households in proportion to their labor income:

$$\frac{Y_t}{\theta_t} = \sum_{j=26}^{J} N_{j,t} \Pi_{j,t}$$

Finally, it is worth noting that, by using $p_t(i) = P_t$ in the demand for the differentiated final good i, we get

$$y_t^f(i) = y_t^m = Y_t$$

Intermediate goods firms

The intermediate goods sector is perfectly competitive. The firms in this sector employ labor and capital as inputs and they have a CES production technology

$$Y_t = \left[\alpha (A_k K_t)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)(A_{l,t} L_t)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}.$$

σ is the elasticity of substitution between factors, $A_{l,t}$ is a labor-augmenting technological progress growing, exogenously, at rate g_t, A_k is capital productivity (assumed to be constant over time) and aggregate labor is defined as the sum of the labor productivity of each cohort weighted by its mass, $L_t = \sum_{j=26}^{J} N_t(j) hc(j)$. Intermediate goods firms also contribute to the pension scheme paying a tax τ_t^f on each unit of labor involved in the scheme. The problem faced by the intermediate producer is

$$\max_{L_t, K_t} \quad \frac{p_t^{int}}{P_t} Y_t - (1 + \psi_t \tau_t^f) w_t L_t - r_t^K K_t.$$

It follows that labor and capital are remunerated at their marginal products:

$$w_t = \frac{1}{1+\psi_t \tau_t^f} \frac{p_t^{int}}{P_t} (1-\alpha) A_{l,t}^{\frac{\sigma-1}{\sigma}} \left(\frac{Y_t}{L_t} \right)^{\frac{1}{\sigma}}$$

$$r_t^K = \frac{p_t^{int}}{P_t} \alpha A_{k,t}^{\frac{\sigma-1}{\sigma}} \left(\frac{Y_t}{K_t} \right)^{\frac{1}{\sigma}}$$

Capital goods firms

In a perfectly competitive investment-specific production sector, the composite final good is converted into capital goods, using a linear production function. The maximization problem of capital goods firms is

$$\max_{Y_t^K} \quad \xi_t K_t - Y_t^K$$

s.t.

$$K_t = z_t Y_t^K,$$

where z_t is the productivity in the investment-specific production sector and ξ_t is the price of capital goods. The capital stock evolves over time according to the following law of motion:

$$K_{t+1} = (1-\delta) K_t + \frac{I_t}{\xi_t}.$$

A.3 The pension benefit formula according to the OASDI progam

To replicate the main features of the OASDI program, in particular the pension benefits calculation, we follow the US Social Security regulation, which establishes that:

- pension benefits are computed according to the Primary Insurance Amount (PIA), which considers only the average labor earnings of the top 35 years of contribution to the scheme, defined as Average Indexed Monthly Earnings (AIME);
- monthly earnings are indexed relative to the average wages of the indexing year, which is the year in which the agent turns 60, to factor in wage growth;
- once the AIME is determined, the PIA is computed using some *bend points*, which are adjusted every year;

- a penalty to benefits is applied whenever agents retire before the full retirement age.

The bend points are some dollar amounts that, combined with some fixed percentages (in practice: 90%, 32%, and 15%), establish the implicit replacement rate, i.e., the fraction of average earnings are replaced by the pension benefits. The bend points for 2020 are \$960 and \$5785. Then, the PIA is the sum of the 90% from the first \$960 of the AIME, the 32% from earnings between \$960 and \$5,785, and the 15% of monthly earnings over \$5,785. Such calculation implies that poorer agents enjoy a larger fraction of their AIME as a pension transfer and that the program produces a redistribution from high to low earners. Figure 7 shows the evolution of the bend points over time.[26] Admittedly, given that the proposed model does not account for earnings heterogeneity, we fall short in capturing such redistribution. However, estimates from the Social Security Administration quantify the implicit replacement rates for medium earners of different cohorts during the periods under analysis.

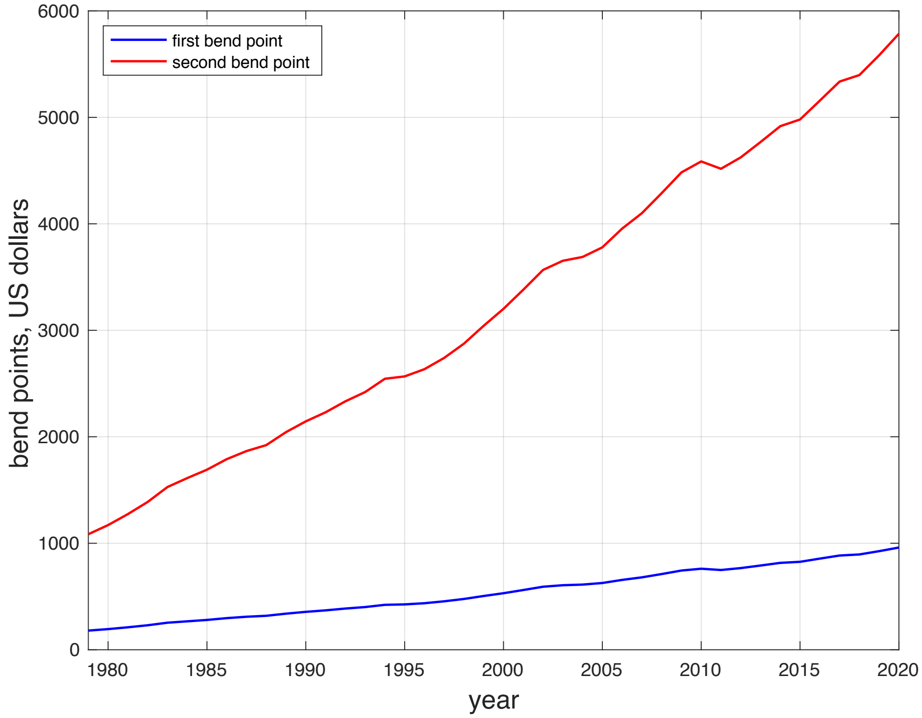
In our notation, the contribution rate is τ_t^p, and it is the sum of the employee and employer contribution rates, τ_t^w and τ_t^f, respectively. The effective retirement age is RA and the replacement rate is ν_t. The latter is the fraction of the average gross labor income (subject to the indexation mentioned above) earned during working age that each entitled retiree receives as a benefit. The individual pension benefit of a retiree i aged j at time t is

$$p_t^b(i,j) = \nu_t \phi(RA(i), FRA) \frac{1}{35} \sum_{z=RA(i)-35+1}^{RA(i)} \left(\frac{w_{t-j+60}}{w_{t-j+z}}\right) \big(w_{t-j+z}(i) hc(z)\big),$$

which states that the AIME is calculated averaging the gross labor earnings of the last 35 years of work before retirement age $RA(i)$ as, given the calibration, they correspond to the top 35 years of earnings during the working life. Secondly, individual wages are indexed with respect to the economy-average wage in the year in which agent i, aged j at time t, turned 60, i.e., w_{t-j+60}. Thirdly, the function $0 < \phi(RA(i), FRA) \leq 1$ gives the penalty, in terms of replaced contributions, applied whenever the individually chosen retirement age $RA(i)$ is lower than the full retirement age FRA. The penalty associated to early retirement is increasing in the months of work foregone with respect to the full retirement age. In particular, a pension *"benefit is reduced $\frac{5}{9}$ of one percent for each month before full retirement age, up to 36 months. If the number of months*

[26]Source: https://www.ssa.gov/oact/cola/bendpoints.html.

Figure 7: OASDI bend points over time



exceeds 36, then the benefit is further reduced $\frac{5}{12}$ *of one percent per month"*[27]. Finally, as the economy-average wage equals the individual wage in the same year, due to the assumption that each cohort is homogeneous in terms of gross labor income and choice of age of retirement, we have that $\forall i$:

$$w_{t-j+z}(i) = w_{t-j+z}$$

$$RA(i) = RA.$$

This implies that we can drop the identifier i from the pension benefit equation, which collapses to:

$$p_t^b(j) = \nu_t \phi(RA, FRA) \frac{w_{t-j+60}}{35} \sum_{z=RA-35+1}^{RA} hc(z).$$

[27] US Social Security Online, www.socialsecurity.gov

A.4 Competitive stationary equilibrium

The model features CRRA preferences and exogenous growth, given by population growth and labor-augmenting technological progress. Therefore, we adjust all the variables to solve for the stationary equilibrium of the model. This means that we need to divide all the aggregate variables need by $(1+g)^t(1+n)^t$, while we need to divide cohort variables, pension benefits and wages by $(1+g)^t$. Then, a stationary competitive equilibrium of this economy can be defined as the marginal return to capital r^K, the wage rate w, aggregate output Y, aggregate capital K, aggregate labor L, bequests given $x(i)$ and received q, the tax rates τ^w, τ^f and τ^b, the pension benefit p^b and the age profiles of consumption $[c(i,j)]_{j=26}^{J}$ and assets $[a(i,j)]_{j=26}^{J}$ $\forall i$ such that:

- lifetime utility is maximized subject to all period budget and borrowing constraints, given initial asset holdings $a(i,26)$, $\forall i$;
- total bequests given equal total bequests received;
- demographic phenomena follow the dynamics described in Appendix A.1;
- capital evolves over time according to its law of motion;
- final, intermediate and capital goods producers maximize their profits subject to their technological constraints and the relevant market structure, as described in Appendix A.2;
- the government satisfies its budget constraint;
- the pension benefit is computed according to the formula defined in Appendix A.3;
- asset markets clear, so that $\sum_i \sum_{j=26}^{J} N_j \xi a(i,j) = \xi K + b$.

A.5 Solution method

The solution of the stationary equilibrium and transition dynamics of the model requires standard numerical methods, given the large systems of non-linear equations. First of all, we need to re-scale the model for growth, so that it is stationary, as described in the previous subsection. Then, a standard algorithm is implemented. The iterative procedure we follow can be summarized in a series of steps:

1. guess a set of endogenous variables including aggregate capital K, bequests received q and the tax rate τ^b;

2. given these endogenous variables, calculate prices w and r^K, pension benefits p^b, profits Π and aggregate output Y;

3. solve households' lifetime utility maximization problem to retrieve the optimal age profile of consumption and assets, as well as bequests given;

4. update the guess for bequests received q, imposing the equality between total bequests given and received;

5. combine individual choices to determine the ex-post level of aggregate capital, taking into account the economy age structure;

6. calculate the ex-post tax rate τ^b that makes the government budget balanced;

7. verify convergence of aggregate capital to the iteration initial guess;

8. if convergence is not achieved yet, update the guess for the next iteration, determined as a linear combination of this iteration initial guess and ex-post aggregate capital, and repeat all the steps until convergence.

Whenever we solve for the stationary equilibrium, the initial guess consists of a single value for each of the following variables: K^*, q^* and τ^{b*}. Solving for the entire perfect foresight transition path is more complicated. It requires choosing a sufficiently large number of transition periods to ensure the convergence to a new stationary equilibrium (or balanced-growth path). Then, one needs to make a guess for the entire time path of K_t and τ_t^b. We solve the transition forward, which means that we solve the lifetime utility maximization problem for each generation involved in the transition taking into account the evolution of prices along her lifetime, starting from the generation that reaches age J in the first period of the transition. Her optimal bequests given x_t are used to determine the guess for the bequests received by their descendants in the next period, q_{t+1}.

One of the most delicate steps of the procedure is the one where we compute the optimal path of consumption and savings over the life-cycle, because of the presence of borrowing constraints. We employ the Matlab routine *fzero*, which implements root-finding algorithms for one-dimensional functions. Starting from the assumption of households entering the economy with zero assets, i.e., $a_t(i, 26) = 0$, our standard procedure entails making a guess of first-period consumption $c_t(i, 26)$. Next, we verify that the implied last period consumption level $c_{t+J-25}(i, J)$ is consistent with the optimality condition that, at age J, the household is indifferent between consuming and leaving as bequest one extra unit of value. Between age 26 and J, consumption and asset holdings are determined using the Euler equations and the budget constraints. Nonetheless, given the calibrated age profile of labor productivity, borrowing constraints are likely to be binding in the first periods of the working life. Then, for those periods where the borrowing constraints are not satisfied, the Euler equations cannot be exploited. Whenever our standard procedure generates levels of asset holdings below the borrowing limit for some period, we assume that the agent starts that period of her life exactly with the debt limit as asset position and solve a shorter problem involving the remaining years until age J. For example, if the individual maximization problem hits a borrowing constraint at age 30, we repeat our standard procedure for the life span 30-to-J and verify that no more borrowing constraints are not satisfied. If this is the case, we proceed to solve the problem for the life span 26-to-29, imposing as a final condition for assets at age 30 the corresponding borrowing limit. If instead, other borrowing constraints for the 30-to-J problem are not satisfied, we attempt to solve the problem for the life span 31-to-J and so on.

A.6 The age profile of labor productivity

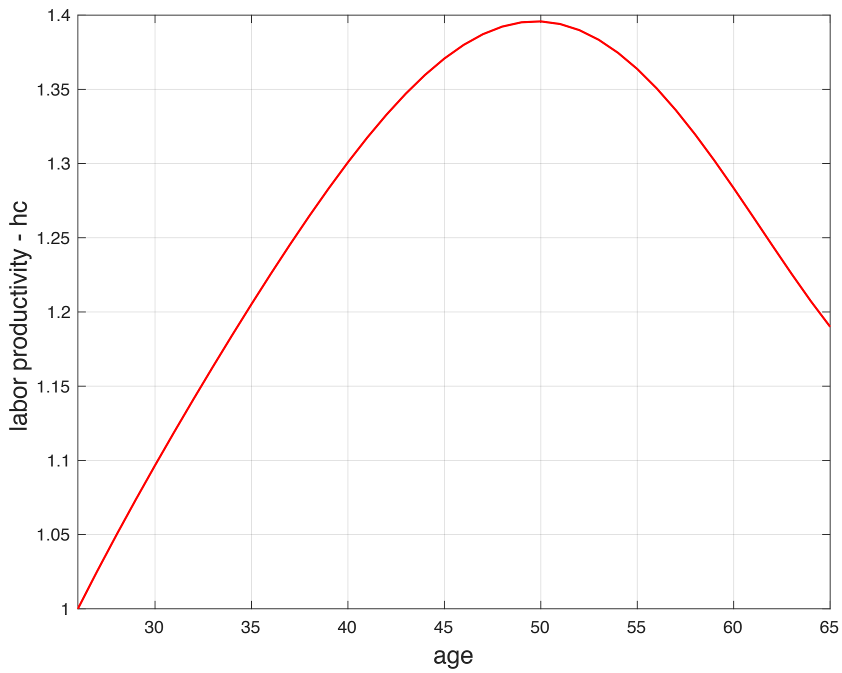
Our calibration for the age profile of labor productivity hc takes the same values as in Eggertsson et al. (2019). In their paper, hc is obtained matching the earnings profile estimated from the data by Gourinchas and Parker (2002). Figure 8 plots it by age, revealing the typical inverted U-shape.

B The natural interest rate in the past

B.1 Alternative calibration of the retirement age

Here, we perform a robustness check by making an alternative assumption about the increase of the RA over 1970-2015. We do that because the information on the median/average effective RA is subject to measurement issues in the data. In particular, the so-called *survivorship bias* affects the available data, and there is substantial con-

Figure 8: Age profile of labor productivity



fusion, as well as historical heterogeneity, on the effective RA of women and men.

Specifically, we repeat the same decomposition exercise of Section 4 under the assumption that the increase in the effective RA is one year, from 64 to 65, between 1970 and 2015. As a consequence, the reduction in benefits due to early retirement is 6.66% in 1970. The other parameters governing the pension system are at their baseline calibration: the overall contribution rate is 8.4% in 1970 and 12.4% in 2015; the coverage of the pension scheme is 90% in 1970 and 96% in 2015; the implicit replacement rate for the average worker is 32.3% in 1970 and 40.8% in 2015. We report the results of the alternative calibration of the RA in Table 4. For the sake of exposition, we report only the results regarding the pension parameters, and we do not report those regarding all the other drivers of r^*, which are substantially unchanged compared to the baseline exercise.

A more modest increase in the effective RA generates a smaller mitigation effect of the pension system on the fall in the natural interest rate. However, the overall result regarding the positive impact of the pension system, and all its reforms, on r^* is unaffected by our alternative calibration of the RA in 1970. Indeed, all the pension reforms jointly still increase significantly, by +0.77 percentage points, r^* and substantially mitigate the decline in r^* triggered by demographic and productivity

Table 4: Decomposition of the decline in the natural interest rate - Robustness check

Forcing variable	Δ in r
Total interest rate variation	-4.09%
Retirement age	+0.12%
All pension adjustments	+0.77%
Mortality + Fertility + Retirement age	-0.85%
Mortality + Fertility + all pension adjustments	-0.48%
Demographics + pension adjustments + productivity slowdown	-2.20%

trends.

C The natural interest rate in the future

C.1 Calibration

Table 5 reports the values of the parameters that are set to match some data moments in our calibration procedure. β, d and μ change with the new calibration of Section 5, while we calibrate θ and α in the same way of Section 4.

Table 5: Calibration

Parameters calibrated matching data moments	Symbol	2015 value
Rate of time preference	β	1.005
Borrowing limit (percent of annual gross labor income)	d	35.49%
Bequests parameter	μ	38.43
Retailer elasticity of substitution	θ	4.89
Capital share parameter	α	0.24

C.2 Endogenous debt-to-GDP ratio

We perform an exercise in which, during the transition, the government does not adjust the tax rate τ^p, to neutralize the impact of ageing, productivity, and pension reforms on the public debt-to-GDP ratio, $\frac{B}{Y}$. We accordingly keep τ^b at its initial level, 33.27%, and $\frac{B}{Y}$ is determined endogenously. It follows that in the long run, not only each scenario-reform combination leads to different levels of the natural interest rate, r^*, but also different values of $\frac{B}{Y}$. Moreover, the natural interest rate falls deeper in negative territory in both productivity scenarios because the debt dynamics imply a significant reduction in $\frac{B}{Y}$, as reported in Table 6. Unsurprisingly, a 1-year increase in the effective retirement age is the pension reform that mitigates the most the impact of ageing on r^*, while a change in the contribution rate and a change in the replacement rate bring about similar values for r^* in the "normal growth" scenario, but very different ones in the "stagnant growth" scenario. The path of the natural interest rate over time is depicted in Figure 9.

Turning to the welfare analysis along the transition, nothing changes substantially compared to our exercise with constant debt-to-GDP ratio, as depicted in Figures 10 and 11. The ranking among pension reforms in each scenario is the same as in the exercise described in the main text. A change in retirement age is always the best pension reform in terms of welfare. In contrast, the reform to the contribution rate and that to the replacement rate produce very similar CEV levels in the "normal growth" scenario. Still, their effect on welfare diverges significantly in the "stagnant growth" scenario.

Table 6: Main variables and pension parameters with "stagnant" vs. "normal" growth

	2015	New stationary equilibrium					
Type of reform	/	contribution rate		replacement rate		retirement age	
Scenario	/	stagnation	normal	stagnation	normal	stagnation	normal
r^*	-1.47%	-3.66%	-2.89%	-4.36%	-2.87%	-2.7%	-2.56%
τ^p	12.4%	15.29%	12.3%	12.4%	12.4%	12.4%	12.4%
τ^b	33.27%	33.27%	33.27%	33.27%	33.27%	33.27%	33.27%
ν	40.8%	40.8%	40.8%	33.09%	41.05%	40.8%	40.8%
ϕ	93.3%	86.6%	86.6%	86.6%	86.6%	93.3%	93.3%
RA	65	65	65	65	65	66	66
DR	42.4%	46.9%	46.9%	46.9%	46.9%	43.5%	43.5%
$\frac{B}{Y}$	118%	12.2%	7.5%	2.37%	7.8%	67.2%	10.1%

Figure 9: Natural interest rate along the transition

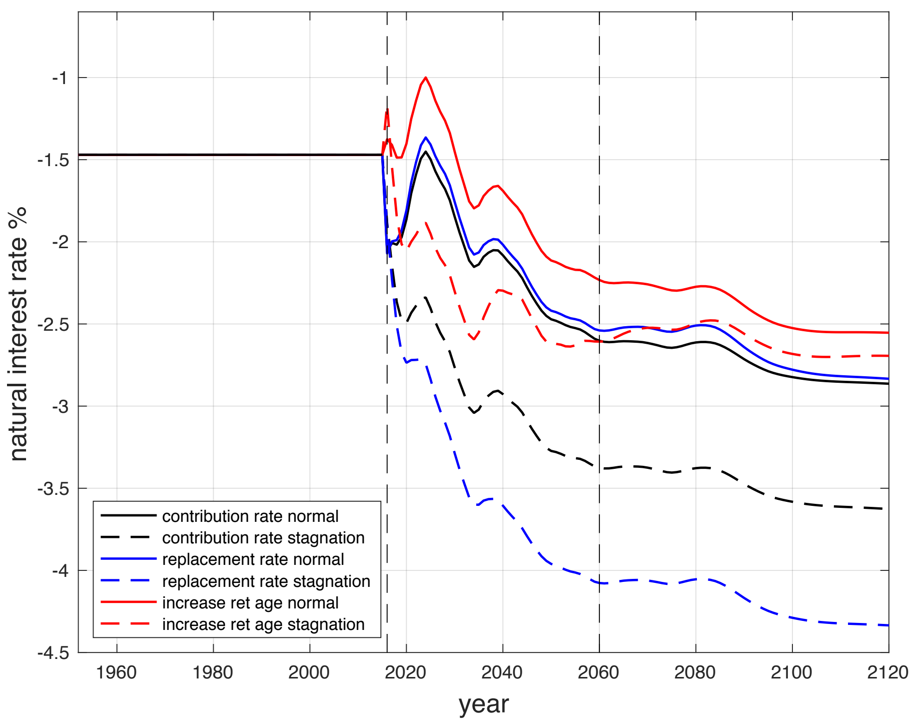


Figure 10: CEV relative to the welfare of the generation born in 1952

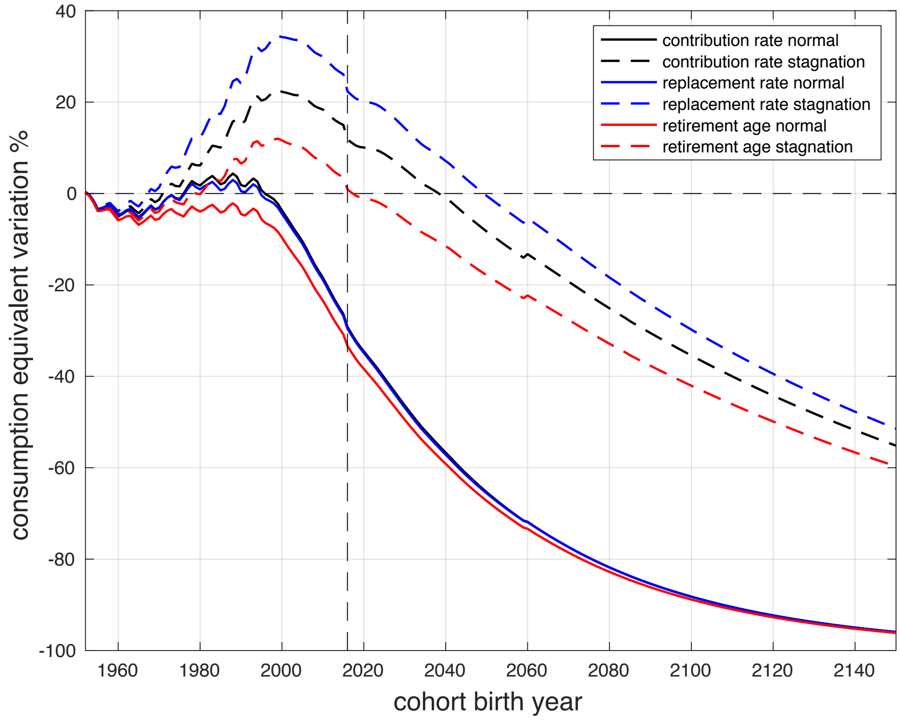
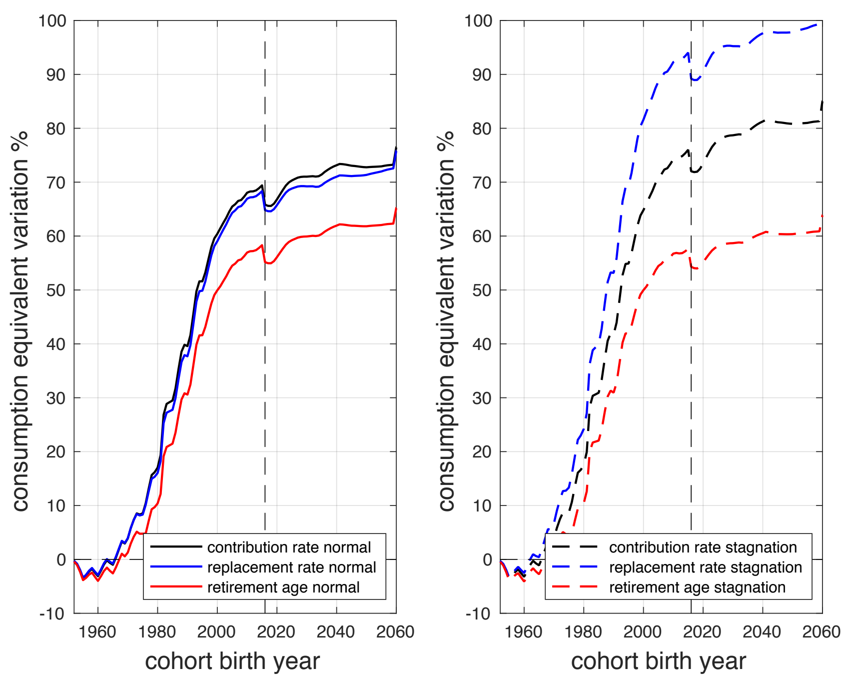


Figure 11: CEV relative to welfare without ageing



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