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Abstract

We study the role of endogenous healthcare choices by households to extend their expected lifetimes on economic growth and welfare in a decentralized overlapping generations economy with the realistic feature that households' savings are held in annuities. We characterize healthcare spending in the decentralized market equilibrium and its effects on economic growth. We then identify the moral-hazard effect in healthcare investments when annuity rates are conditioned on average mortality and explain the conditions under which it will lead to over-investment in healthcare. Moreover, we specify the general equilibrium effects and macroeconomic repercussions associated with this moral-hazard effect. Calibrating our model to OECD data, we find that the moral-hazard effect may be substantial and implies sizeable welfare losses of approximately 1.5%. At a more general level, our study suggests that welfare improvements from longevity increases may be quite lower than sometimes assumed when considered in planner economies.

Keywords: annuities, economic growth, endogenous longevity, healthcare expenditures, healthcare technology, moral hazard, pension systems, welfare analysis.

JEL Classification: O40, I10, J10

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1 Introduction

In recent decades, nearly all countries have experienced a substantial increase in human longevity. At least in the developed world, higher expected lifetimes have been accompanied by a significant increase in healthcare expenditures. For example, life expectancy in the U.S. rose from 69.8 to 78.6 years between 1960 and 2010, while health expenditures, as a share of GDP, surged from 5.2% to 16.4% (according to OECD data).

How does this increased longevity translate into welfare gains? While the existing literature has approached this question by suggesting extended welfare measures that include longevity, varying exogenous longevity in growth models and discussing endogenous healthcare choices in macroeconomic social planner models, this paper introduces a new perspective. We develop and analyze an endogenous growth model in which longevity is endogenously determined by households' demand for healthcare services in a decentralized market economy.[1] This perspective allows us to study the general equilibrium effects and macroeconomic repercussions on economic growth – and, consequently, the comprehensive welfare effects – of individual healthcare choices.

As we will show, these individual healthcare choices are not necessarily efficient. We particularly focus on an effect that – while important and most likely involving substantial macroeconomic repercussions – has not yet received much attention in the macroeconomic literature: the moral-hazard effect in healthcare investments arising from annuities. Its importance arises from the fact that nearly all social security systems crucially depend on (mandatory) annuitization, where the annuity premium is not conditional on individual healthcare choices, but only on average mortality rates. As "Public annuity programs are thus large and growing: in OECD countries they constitute about one-tenth of the gross domestic product, make up more than three-quarters of all social insurance, and have contributed to a quarter of the growth in total public expenditures since 1960" (Philipson and Becker, 1998, p. 552), the properties of annuities have recently received considerable attention (e.g., Hosseini, 2015 focuses on adverse selection, while Reichling and Smetters, 2015 consider the role of mortality-related medical costs). While Davies and Kuhn (1992) and Philipson and Becker (1998) provide seminal microeconomic (partial equilibrium) analyses of the moral-hazard effect of longevity-increasing healthcare investments, we are, to the best of our knowledge, the first to examine the general equilibrium effects and its macroeconomic repercussions.

In addition, we use our model to discuss the role of technological progress in healthcare technology for economic growth and welfare. Finally, we calibrate our model using OECD data to appreciate the size of the growth and welfare effects associated with moral hazard in healthcare spending, as well as the effects of technological improvements in the healthcare sector.

From a methodological perspective, our model combines the household side of overlapping generations perpetual youth models in the tradition of Blanchard (1985) with the production side of an endogenous growth model in the style of Romer (1986) amended by a healthcare sector. We

[1] There is a substantial empirical literature on the relationship between health expenditures and life expectancy that argues that expected lifetime is not given per se but can be influenced by investments in healthcare, such as improving sanitation, buying medication and inoculations, consulting a physician, etc. (Lichtenberg, 2004; Cutler et al., 2006; Hall and Jones, 2007; Caliskan, 2009).

first demonstrate the existence of a unique market equilibrium in the steady-state economy and discuss the general equilibrium and growth effects of varying healthcare sector sizes. Then, we characterize and solve the problem of a social planner maximizing the sum of individual lifetime utilities to identify three inefficiencies in the decentralized market equilibrium: the standard learning-by-investing externality (Romer, 1986), a spillover effect of healthcare investments on the productivity of consumption good production and the moral-hazard effect associated with annuities with returns that are conditioned on average mortality.

We then show how the sign and size of the moral-hazard effect in healthcare investments depends on the relative changes in the households' expected consumption paths and expected lifetime wealth. In the steady-state equilibrium, the result ultimately depends on the difference in the growth rate of individual household consumption and the growth rate of the economy as a whole. The difference between the two growth rates originates from the finite lifetimes of the individuals, thereby leading to the corresponding generations turnover term in the growth rate of the economy. We show that if the consumption growth rate of the household is positive and larger than the growth rate of the economy, then individuals over-invest in healthcare in the decentralized market equilibrium with annuities conditioned on average mortality rather than individual health status.

What are the macroeconomic implications of over-investment in healthcare? On the one hand, when households live longer, their propensity to consume out of expected lifetime wealth declines, as saving for old age becomes more valuable. This increases the economy's growth rate. On the other hand, shifting labor from the more capital-intensive consumption good production into the healthcare sector reduces the marginal return on capital. A lower interest rate decreases incentives to save and, as a consequence, implies lower economic growth. We show that the first direct and positive effect of higher longevity on economic growth dominates if the healthcare sector is rather small; however, given a larger health sector, the indirect and negative effect, working through the change in the interest rate, prevails. Accordingly, the households' welfare is affected by over-investments in healthcare, not only by an imbalance between the enjoyment of a longer life and its associated direct healthcare costs, as emphasized in the microeconomic literature, but also by changes to the return on the underlying fundamental of the annuities, i.e., the return on capital, as well as the wage rate and the economy's growth rate.

While the theoretical rationale for the importance of examining the general equilibrium effects and macroeconomic implications of moral hazard associated with annuities unconditioned on individual healthcare investment is conclusive, are the implications also quantitatively significant? Calibrating our model to OECD data, we argue that they are. We find overall welfare losses due to overspending in healthcare of approximately 1.5%. Decomposing the overall welfare effect into its different components, we find that the direct impacts due to individual household behavior are rather small while the general equilibrium effects and the effect on the economy's growth rate dominate.

Finally, we investigate the implications of technological improvements in the healthcare sector. We consider two different types of healthcare improvements. The first type decreases baseline mortality, which is independent of individual investments in healthcare. One could think of improvements in the sanitary infrastructure or behavioral changes such as reduced smoking. The second type increases the marginal productivity of healthcare expenditures. Examples include better medication or therapeutic breakthroughs, such as new diagnostic tools or surgeries.[2] We show that in our model framework, both types of health technology improvements increase households' healthcare investments. The resulting increased life expectancy exerts a direct positive effect on the economy's growth rate via a higher incentive to save. However, an associated increase in healthcare spending will have the indirect negative effect of reducing the interest rate. Similar to the growth consequences of overspending in healthcare due to moral hazard with unconditioned annuities, as discussed previously, technological improvements in health increase the growth rate when the healthcare sector is very small but have negative growth effects when the healthcare sector is sufficiently large. To illustrate the welfare effects from improved technology, we calibrate our model such that it reflects the increase in healthcare investments in the average OECD country between 1980 and 2005. While our numerical calculations suggest a substantial welfare gain of approximately 4.5% due to better healthcare technology, we also find that the moral-hazard effect becomes larger if the healthcare technology improves. Thus, our analysis of the macroeconomic repercussions of moral hazard due to unconditioned annuity claims suggests that welfare benefits due to increased longevity may be lower than is often suggested.

The remainder of the paper is organized as follows. In the next section, we relate our paper to the existing literature. In Section 3, we introduce the model and provide a detailed discussion of the household's maximization problem with respect to healthcare. In Section 4, we characterize the market equilibrium and derive the dynamics of the aggregate economy. We identify the inefficiencies in the decentralized market equilibrium in Section 5 by analyzing the social planner's solution. In addition, we explain in detail the moral-hazard effect in healthcare spending due to annuities when their return is not conditioned on the individual household's health status. We discuss the role of technological progress in healthcare technology in Section 6 before we provide a numerical simulation of the size of the welfare effects by calibrating our model to OECD data in Section 7. Finally, we discuss several aspects of our model in relation to the real world in Section 8 and conclude in Section 9. The proofs of all propositions are relegated to the Appendix.

2 Related Literature

Our main contribution is to develop an endogenous growth model with endogenous lifetime, in which households determine their healthcare investments in a decentralized market economy. This innovation provides us with the tools to analyze the general equilibrium effects and macroeconomic repercussions of distortions in healthcare investments due to annuitized wealth, as identified in the microeconomics literature. Thus, our paper is related to the following strands of the literature.

[2] Our model emphasizes that increases in healthcare expenditures and longevity are driven primarily by the availability of better healthcare technologies, a view supported, for example, by Newhouse (1992), Cutler et al. (2006), Suen (2006) and Fonseca et al. (2009).

In a model that has similarities with our framework, Kuhn and Prettner (forthcoming) examine the channels through which an expanding healthcare sector affects economic growth and welfare. They build on the R&D-based endogenous growth model with horizontal innovation of Prettner (2013) by adding a productive healthcare sector. They find that R&D increases in response to healthcare investments due to a general equilibrium effect that reduces the interest rate and, thus, facilitates financing additional research projects. This positive growth effect may outweigh the negative effect of diverting labor from final goods production when the healthcare sector is small, but for larger health sectors, economic growth will decline in response to higher healthcare investments. In this paper, we find a similar growth reaction to an expanding healthcare sector in a model in which growth is driven by capital accumulation. However, the broader mechanism in our model could be interpreted as resulting from a more detailed underlying production side that explicitly includes R&D activities. The main difference between our paper and Kuhn and Prettner (forthcoming) is our endogenous modeling of individual households' healthcare choices that allows us to endogenously determine the size of the healthcare sector and the households' life expectancies. This innovative feature also distinguishes our paper from a large body of other papers considering the growth effects of exogenous variations in longevity, including Kalemli-Ozcan et al. (2000); Azomahou et al. (2009); de la Croix and Licandro (1999); Boucekkine et al. (2002); Echevarría and Iza (2006) and Irmen (forthcoming).[3]

Chakraborty (2004), Chakraborty and Das (2005), Bhattacharya and Qiao (2007) and Leung and Wang (2010) analyze a neoclassical growth model with endogenous longevity, which is determined by either household or government investments in health. While savings and healthcare expenditures compete for the same resources, they are complements in equilibrium. Thus, higher economic development is accompanied by a longer average lifetime. Combining endogenous growth with endogenous longevity, van Zon and Muysken (2001) and Aísa and Pueyo (2006) find non-monotonic relationships between longevity and growth. In these papers, longevity is endogenous but determined via aggregate spending in healthcare by a government or a social planner. In contrast, we develop an endogenous growth model, in which each household's average life expectancy directly depends on the household's investments in healthcare. Jones (forthcoming) develops a growth model with R&D in both the consumption goods sector and the healthcare sector and considers the optimal allocation of investment resources from a planner's perspective in an infinitely lived agent framework neglecting any externalities. Our paper, by contrast, purposefully includes several realistic features, such as a population structure with overlapping generations and old-age retirement saving in annuities that reflects the properties of typical social security systems to examine their effects on endogenous healthcare

[3]More remotely, our paper is also related to the literature on demographic transitions and the literature on the growth effects of epidemics such as AIDS. The former analyzes the relationship among fertility, mortality and growth. Longevity is either exogenous (Doepke, 2004; Soares, 2005; Hashimoto and Tabata, 2010; Prettner, 2013), endogenously determined via an externality of aggregate variables such as average income or human capital (Blackburn and Cipriani, 2002; Kalemli-Ozcan, 2002; Lagerloef, 2003; Cervellati and Sunde, 2005; Hazan and Zoabi, 2006) or endogenously determined by the healthcare investments of the parents (de la Croix and Licandro, 2013). Within the latter, Young (2005) concludes that the AIDS epidemic in South Africa, despite being a humanitarian disaster, has rather positive effects on long-run growth. Bell et al. (2006) and Bell and Gersbach (2009) are less optimistic and emphasize that epidemics may lead to poverty traps.

choices and economic growth.

A central focus of our paper is on the moral-hazard effect in healthcare spending associated with old-age-mortality-contingent claims such as annuities that are conditioned on average mortality rather than the individual household's health status. This moral-hazard effect is identified in partial equilibrium frameworks by Davies and Kuhn (1992), Philipson and Becker (1998), Sheshinsky (2008) and Kuhn et al. (2015), but – to the best of our knowledge – we are the first to examine how it percolates through the economy. We argue that this is of utmost importance, as on the one hand, healthcare expenditures represent a substantial fraction of GDP, with corresponding implications on the aggregate economy, and on the other hand, old-age saving is, to a large extent, held in annuities. It is also for these two reasons that Reichling and Smetters (2015) study optimal annuitization with correlated medical costs. As large shares of retirement wealth are held in mandatory annuities, Hosseini (2015) examines the welfare benefits of this obligation by avoiding adverse selection in the annuity market. We emphasize that such mandatory annuities entail another distortion, namely the moral-hazard effect in healthcare spending, which we focus on in our paper, with particular emphasis on its general equilibrium effects and macroeconomic repercussions. While the macroeconomic implications of unfairly priced annuities relative to fairly priced annuities are studied in Heijdra and Mierau (2012), we shift the focus to the macroeconomic implications of annuities when healthcare spending and longevity are endogenous. Taking the moral hazard effect of annuities on healthcare spending into account together with several other factors, Zhao (2014) recently argued that the expansion of social security can explain a large part of the surge in healthcare spending over the last few decades. Rather than quantifying the effects of expanded social security on healthcare spending, our focus lies on the effects of healthcare spending on the aggregate economy.

Finally, our paper relates to the literature on the welfare consequences of increased longevity, for example, Becker et al. (2005) and Jones and Klenow (2010). As in these papers, we employ the utility of a representative individual to derive a welfare measure that includes human longevity. However, we use a comprehensive general equilibrium framework, which is absent from those models. This allows us to identify further channels through which longevity affects welfare.

3 The Model

The model comprises a continuum of households. As in Blanchard (1985), households born at time $s \in (-\infty, \infty)$ face a hazard rate $p(s)$ of dying that is constant throughout the lifetime of each household. In our model, however, the hazard rate may vary across households from different cohorts, as it is determined by the level of medical treatment that the household receives throughout its lifetime. At any time t, a new cohort is born. We abstract from household fertility decisions and assume that cohort size grows at the constant and exogenously given rate ν.[4] We normalize the cohort size at time $t = 0$ to unity.

[4]The parameter ν can be mapped onto the economy's fertility rate, which specifies the average number of children born by each woman (or by our abstract genderless individual). The fertility rate is independent of the size of the actual population.

There are two production sectors in the economy: the consumption good sector and the healthcare sector. We assume that both sectors operate under perfect competition. In addition, there is a financial sector comprising competitive insurance providers offering annuities. A central aspect of the paper is the discussion of the implications of annuity premia being (un-)conditioned on individual households' mortality rates.

3.1 Healthcare sector

We consider a representative firm in the healthcare sector that provides medical treatment by solely employing labor.[5] Without loss of generality, we assume that one unit of labor produces one unit of medical treatment. Assuming a competitive healthcare sector, medical treatment will be offered at the marginal cost $w(t)$. We further assume that households choose a level of medical treatment $h(s)$, which is fixed over the entire lifetime and determines the hazard rate of dying $p(s)$ via a healthcare technology $H\big(h(s)\big)$:

$$p(s) = H\big(h(s)\big) \equiv p_{max} - \psi[h(s)]^{\beta} \ . \tag{1}$$

Without medical treatment ($h = 0$) households face the hazard rate $p(s) = p_{max}$ of dying. The hazard rate $p(s)$ decreases with (weakly) diminishing returns in the level of medical treatment $h(s)$, the degree of which is determined by the parameter $\beta \in (0, 1)$. While we preclude a linear healthcare technology with $\beta = 1$ in our definition, we will refer to the linear case whenever this yields interesting additional results. The parameter $\psi < p_{max}$ reflects the productivity of (a given level of) healthcare investment and may be interpreted as the quality level of the health system or the state of the art in medical treatment. It denotes the maximum amount by which a household could reduce its hazard rate against p_{max} by spending all wage income on healthcare. While p_{max} reflects, for example, the sanitary infrastructure of the economy, ψ increases with the human capital of physicians, the efficiency of hospitals and so forth.

The specification of the healthcare technology (1) implies that improvements in the healthcare technology may come in two qualitatively different ways. First, the maximal hazard rate p_{max} may decrease, implying that all households, independent of their levels of healthcare spending, experience a lower hazard rate of dying. In fact, a decrease in p_{max} offers higher life expectancy for free (at least for the individual household). Historical examples in this respect include new knowledge about germ theory leading to better hygienic standards and a change in personal behavior. We also interpret the introduction of most vaccines and drugs as a decrease in p_{max} because these drugs are usually not very expensive. As an example, consider penicillin,

[5]Health systems are traditionally highly labor-intensive. According to OECD (2015a), the health sector is a highly labor-intensive sector, although capital has become a more important production factor in health services in recent decades. "On average, OECD countries invested around 0.45% of their GDP in 2013 in terms of capital spending in the health sector. This compares with 8.9% of GDP on average across the OECD for current spending on healthcare services and medical goods." (OECD, 2015a, p. 174). There is also a literature that empirically demonstrates that due to the healthcare sector's high labor intensity, costs for healthcare services will increase strongly in response to increases in labor productivity in other sectors, for example, due to technological progress or capital accumulation (Hartwig, 2008; Bates and Santerre, 2013). This phenomenon is often referred to as Baumol's cost disease. Our model also reflects this feature.

which led to substantial declines in mortality in the last century. Second, the state of the art in medical treatment ψ may increase, implying that the same amount of healthcare spending leads to a higher life expectancy. However, only households with positive healthcare spending benefit from the improved healthcare technology. Consider improvements such as magnetic resonance imaging, coronary heart bypass grafting, and transplantation.[6]

3.2 Consumption good production

We consider a representative firm in the consumption good sector that produces a homogeneous consumption good via a Cobb-Douglas production technology $Y(t) \equiv K(t)^{\alpha}\big(A(t)L^F(t)\big)^{1-\alpha}$, where $\alpha \in (0,1)$ and $K(t)$ and $L^F(t)$ denote the aggregate amount of capital and labor employed in consumption good production, respectively. $A(t)$ denotes total factor productivity (TFP), respectively the technological level of the economy, regarding consumption good production and is taken as given by the representative firm. Capital depreciates at a constant rate δ. Profit maximization of the representative firm yields factor prices equal to their marginal productivities:

$$r(t) = \alpha\big(A(t)L^F(t)/K(t)\big)^{1-\alpha} - \delta \;, \tag{2a}$$

$$w(t) = (1-\alpha)A(t)^{1-\alpha}\big(K(t)/L^F(t)\big)^{-\alpha} \;. \tag{2b}$$

We specify total factor productivity $A(t)$ as follows:

$$A(t) \equiv \frac{K(t)}{L^F(t) + (1-\eta)L^H(t)}, \qquad \eta \in [0,1), \tag{3}$$

where $L^H(t)$ represents labor employed in the healthcare sector, reflecting total healthcare expenditures in the economy at time t. Our specification implies a standard "learning-by-doing" or "learning-by-investing" externality similar to Romer (1986), where the factor productivity depends on aggregate capital per worker $K(t)/L^F(t)$.[7] The term $(1-\eta)L^H(t)$ captures the importance of a healthy workforce for productivity. According to (3), consumption good production is more productive the higher aggregate healthcare expenditures are. The magnitude of this spillover effect from health is reflected by the parameter η. The larger η is, the greater the importance of healthcare for TFP, while the effect vanishes altogether when $\eta = 0$. We assume $\eta \in [0,1)$. For $\eta = 1$, re-assigning labor from consumption good production into the healthcare sector would have no effective costs in terms of consumption good output, and $\eta > 1$ would even imply that the reduction of output by a marginal decrease in the work force in consumption good production will be overcompensated by the corresponding marginal increase

[6]Although it makes perfect sense to conceptually distinguish the two different channels of improvements in the healthcare technology, we wish to emphasize that most real-world improvements simultaneously affect p_{max} and ψ. For example, knowledge about germ theory led to better hygienic standards not only in every day life, thereby decreasing p_{max}, but also in medical treatment, which increased ψ.

[7]Romer (1986) assumes that $A(t) \equiv K(t)$. Specifying TFP to depend on capital per worker allows us to avoid a strong scale effect in the economy's growth rate. The specification is similar to that introduced by Frankel (1962).

of labor in healthcare services, thereby even increasing output in the manufacturing sector. As this is rather unrealistic, we restrict parameter values to $\eta < 1$. However, we provide the results for the special case of $\eta = 1$ whenever insightful.[8]

3.3 The financial sector

The financial sector of the economy comprises a representative, fully competitive insurance firm offering actuarial notes as in Yaari (1965). An actuarial note is a "note that consumers can buy or sell and that stays on the books until the consumer dies, at which time it is automatically cancelled" (Yaari, 1965, p. 140). A household buying an actuarial note is effectively buying an annuity that pays a return a. With respect to the annuities' returns, we distinguish two cases.

In the first case, the insurance company can learn, at no cost, the average probability of dying $p(s)$ of each cohort but will not be able to observe individual households' healthcare investments. Consequently, annuity payments may depend on the cohort and will hence be written as a function of time t and cohort birth date s: $a(t, s)$.[9] Throughout the paper, we refer to this case as annuity claims that are unconditioned on healthcare expenditures or simply unconditioned annuities.

In the second case, the insurance company can observe healthcare investments and individual households' resulting hazard rates of dying. This allows the insurance company to condition the annuity rate on the healthcare investments of individual households, and we can write $a(t, h)$, where h reflects the household's level of healthcare spending. While this scenario is unrealistic, it provides an important benchmark scenario in which moral hazard with respect to healthcare investments is absent.[10] We call this case annuity claims conditioned on healthcare investments or, for short, conditioned annuities.

In our standard model framework, we assume that insurance companies can only observe average cohort mortality rates, while we consider the case of annuity claims conditioned on individual households' healthcare investments in Section 5.3.

[8] We incorporate the possibility of an effect of health on manufacturing productivity as a spillover effect in our model for two reasons. First, there are indications of such a spillover effect in the literature (see, e.g., Isaksson, 2007). Second, in our analysis, we focus on the households' incentives to invest in healthcare to extend their expected lifetime rather than to increase their labor productivities to obtain higher wages. When the spillover effect is fully internalized, the households would be able to privately reap the productivity increases from their healthcare investments, which can be interpreted as increasing their wage rates. While this by itself adds another motive to invest in healthcare, the households would never invest in their health without an additional longevity benefit if $\eta < 1$.

[9] As we consider large cohort sizes (technically represented by a continuum of households in each cohort), such that insurance companies can offer risk-free annuities, perfect competition among insurance companies will lead to fair annuity payments $a(t, s) = r(t) + p(s)$.

[10] We are aware that there exist so-called 'enhanced annuities' that pay a higher rate if the annuitant is overweight or smokes regularly (which is self-certified). However, this conditionality of the return depends on some negative health behaviors and serious conditions but does not account for positive measures to improve health and longevity.

3.4 The households' optimization problems

Households exhibit identical ex ante preferences and face equal hazard rates for the same levels of medical treatment. Households born at time s maximize expected discounted lifetime utility derived from consumption:

$$U(s) \equiv \int_s^{\infty} V\big(c(t,s)\big) \exp\left[-\big(\rho + p(s)\big)(t-s)\right] dt \ , \tag{4}$$

where $V\big(c(t,s)\big)$ denotes the instantaneous utility derived from consumption $c(t,s)$ at time t of the household born at time s, and ρ is the constant rate of time preference. We impose standard curvature properties on the instantaneous utility function ($V' > 0$ and $V'' < 0$), as well as the Inada conditions $\lim_{c\to 0} V'(c) = \infty$ and $\lim_{c\to\infty} V'(c) = 0$. Our definition of lifetime utility (4) normalizes instantaneous utility of being dead to zero. Hence, we additionally assume a utility representation with $V(c) > 0$ for all $c > 0$, which avoids the possibility of households wishing to be dead rather than alive.[11] At any time when alive, each household is endowed with one unit of labor that is supplied inelastically to the labor market at wage $w(t)$. In addition, households may save and borrow assets $b(t,s)$ at the interest rate $r(t)$. Households are born without assets and may contract against the risk of leaving unanticipated bequests on a perfectly competitive life insurance market, as described previously. In line with Philipson and Becker (1998) and Eeckhoudt and Pestieau (2008), among others, we assume that households take $a(t,s)$ as given and will contrast it with the case in which insurance companies can condition the annuity premia on a household's health status in Section 5.3. As negative bequests are prohibited, households hold their entire wealth in fair annuities. Denoting the costs of healthcare by $M\big(h(s)\big)$, the household's budget constraint reads

$$\dot{b}(t,s) = a(t,s)b(t,s) + w(t) - c(t,s) - M\big(h(s)\big) \ , \qquad t \geq s \ , \tag{5}$$

with $b(s,s) = 0$. Inserting $M\big(h(s)\big) = h(s)w(t)$ into the household's budget constraint (5) yields the following:

$$\dot{b}(t,s) = a(t,s)b(t,s) + \big(1 - h(s)\big)w(t) - c(t,s) \ . \qquad t \geq s \ . \tag{6}$$

Thus, we can interpret the level of medical treatment $h(s)$ as the fraction of labor income that a household spends throughout its entire life on healthcare services. This implies that $h(s) \in [0,1]$, as households are born without assets and must not be indebted when dying.

Households maximize expected intertemporal utility (4) subject to conditions (6) and $b(s,s) =$

[11] Rosen (1988) showed that optimal investments in healthcare crucially depend on two characteristics of the instantaneous utility function: (i) the intertemporal elasticity of substitution and (ii) the difference in instantaneous utility between being alive and dead. One way to ensure positive utility levels is to employ an instantaneous utility function with an intertemporal substitution elasticity $\sigma > 1$. Rosen (1988), Hall and Jones (2007) and Becker et al. (2005) use $V\big(c(t,s)\big) = c(t,s)^{1-\frac{1}{\sigma}}/(1-1/\sigma) + \lambda$ with some positive constant λ. This allows them either to employ intertemporal substitution elasticities of $\sigma < 1$ (Hall and Jones, 2007) or to calibrate the model to different values of a statistical life without changing the intertemporal elasticity of substitution (Becker et al., 2005; Hall and Jones, 2007). In our equilibrium analysis, we will use the functional form (11) representing homothetic preferences, which allow for a balanced-growth path: $V\big(c(t,s)\big) = c(t,s)^{1-\frac{1}{\sigma}}/(1-1/\sigma), \quad \sigma > 1$.

0 by choosing an optimal level of medical treatment $h(s)$ and an optimal consumption path $c(t,s)$. As detailed in the Appendix, the necessary conditions for the household's optimum are summarized by the standard consumption Euler equation:

$$\dot{c}(t,s) = -\frac{V'(c(t,s))}{V''(c(t,s))}[a(t,s) - (\rho + p(s))], \tag{7}$$

and by the necessary condition for optimal healthcare spending

$$\begin{aligned} &-\int_s^\infty V(c(t,s))H'(h(s))(t-s)\exp[-(\rho+p(s)))(t-s)]dt \\ &= \int_s^\infty V'(c(t,s))w(t)\exp[-(\rho+p(s))(t-s)]dt\ . \end{aligned} \tag{8}$$

These two conditions, together with the budget constraint (6), the initial condition $b(s,s) = 0$ and the transversality condition for the stock of assets $\lim_{t\to\infty} b(t,s)\exp\left[-a(s)(t-s)\right] = 0$, characterize the households' optimal choices. The left-hand side of condition (8) represents the additional utility derived from the increment in expected lifetime associated with a marginal increase in healthcare spending. The right-hand side reflects the marginal costs of such a higher expected lifetime, namely less consumption due to higher healthcare expenses. As the instantaneous utility function satisfies the Inada conditions, as does the health-production function for $h(s) \to 0$, the optimal amount of $h(s)$ will be an interior solution on $(0,1)$.[12] Note that $h(s) = 1$ is precluded, as this would imply that the household spent its entire labor income on healthcare, leading to zero consumption at all times it is alive. In this case, the marginal costs in terms of consumption would be infinite while the expected marginal benefit of healthcare expenditures is bounded from above.

4 Decentralized Market Equilibrium and Dynamics

We now analyze the decentralized market equilibrium. We will demonstrate the existence and uniqueness of the decentralized market equilibrium in the steady state. Then, we discuss the resulting steady-state dynamics of the economy. We conclude with results on the effects of an enlarged health sector on the equilibrium prices and the economy's growth rate. These insights will be important for the subsequent discussions on the growth and welfare consequences of moral hazard in health spending and the effects of improvements in the healthcare technology.

We begin by introducing aggregate household variables per capita derived by integrating over all living individuals and dividing by the population size of the economy:

$$z(t) \equiv \frac{\int_{-\infty}^t z(t,s)N(t,s)\,ds}{N(t)}\ , \tag{9}$$

where $z(t)$ and $z(t,s)$ denote aggregate per capita, respectively individual household, variables and $N(t,s) = \exp[\nu s]\exp[-p(s)(t-s)]$ reflects the size of the cohort born at s at time t. Abusing

[12]If the health-production function had a finite slope at $h = 0$, the corner solution $h = 0$ might occur.

notation slightly, we obtain the population size at time t and hence the labor supply at t by $N(t) = \int_{-\infty}^{t} N(t,s)ds$.

The economy consists of five markets: the labor market, the capital market, the consumption good market, the market for annuities and the market for healthcare. Accordingly, an equilibrium in this economy is defined as follows:

Definition 1 (Market equilibrium)
A market equilibrium is an allocation $\{\{c(t,s), b(t,s), h(s)\}_{s=-\infty}^{\infty}, K(t), L^F(t), L^H(t)\}_{t=-\infty}^{\infty}$ *and prices* $\{p_c(t) = 1, w(t), r(t), \{a(t,s)\}_{s=-\infty}^{\infty}\}_{t=-\infty}^{\infty}$ *such that profits of the firms (consumption good, healthcare, annuity) and utilities of the households are maximized and all markets clear at any time* t*, i.e.:*

$$K(t) = \int_{-\infty}^{t} b(t,s)N(t,s)ds \quad \textit{(capital market)}\ , \tag{10a}$$

$$L^F(t) + L^H(t) = N(t) \quad \textit{(labor market)}\ , \tag{10b}$$

$$\int_{-\infty}^{t} h(s)N(t,s)ds = L^H(t) \quad \textit{(healthcare market)}\ , \tag{10c}$$

$$\int_{-\infty}^{t} (a(t,s) - r(t))b(t,s)N(t,s)ds = -\int_{-\infty}^{t} b(t,s)\dot{N}(t,s)ds \ \textit{(annuity market)}\ , \tag{10d}$$

$$\int_{-\infty}^{t} [c(t,s) + \dot{b}(t,s)]N(t,s)ds = Y(t) \quad \textit{(consumption good market)}\ . \tag{10e}$$

The left-hand side of the market clearing conditions reflects demand, while the right-hand side represents the supply of the respective good. Our focus will be on the economy's steady state. We refer to a steady state of the economy by the standard definition:

Definition 2 (Steady state)
The economy is in a steady state if consumption per capita, capital per capita and wages grow at constant rates and the interest rate is constant.

In our equilibrium analysis of the decentralized economy, we use the following functional form for the individuals' instantaneous utilities:

$$V\big(c(t,s)\big) \equiv \frac{c(t,s)^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}}\ , \quad \sigma > 1\ , \tag{11}$$

which allows for a balanced-growth path.

We are now in a position to establish the following result:

Proposition 1 (Unique Steady-state Equilibrium)
There exists a unique steady-state equilibrium in which

1. *all households choose the same level of healthcare* $\bar{h}$*, implying mortality rate* $\bar{p} = H(\bar{h})$*,*

2. *interest rate* $\bar{r}(\bar{h}) = \alpha \left[\frac{1-\bar{h}}{1-\eta\bar{h}}\right]^{1-\alpha} - \delta$*,*

3. *wage rate* $\bar{w}(\bar{h},t) = k(t)\frac{1-\alpha}{1-\bar{h}}\left[\frac{1-\bar{h}}{1-\eta\bar{h}}\right]^{1-\alpha}$*, and*

4. *insurance premium:* $\bar{p}$, *i.e.* $\bar{a}(\bar{h},\bar{p}) = \bar{r}(\bar{h}) + \bar{p}$.

The unique optimal interior level of healthcare expenditures in the steady-state equilibrium $\bar{h}$ *is implicitly given by the equation*

$$\frac{\sigma}{1-\sigma}\frac{H'(\bar{h})}{x(\bar{h},\bar{p})} - \frac{1}{(1-\bar{h})} = 0 \ , \tag{12}$$

with $x(\bar{h},\bar{p}) \equiv (1-\sigma)\bar{a}(\bar{h},\bar{p}) + \sigma(\rho+\bar{p})$.

The proofs of all propositions are given in the Appendix. The crucial step in the proof is to derive the households' optimal healthcare expenditures, provided that the economy is in steady state, and then to show that these healthcare expenditures lead to the presumed steady state. Uniqueness follows from the uniqueness of the prices and allocation for a given level of healthcare expenditures and the fact that given a constant interest rate and constantly growing wage rate, the households' healthcare investments are unique.

In the proposition and throughout the paper, we indicate steady-state values by a bar. Moreover, we will give both h and p as arguments if appropriate rather than just h, as this allows us to separate the effects of h via longevity p from other channels. It enables us to identify and clearly illustrate the different ways that healthcare investments affect the economy. In equation (12), we use the abbreviation $x(\bar{h},\bar{p}) \equiv (1-\sigma)\bar{a}(\bar{h},\bar{p}) + \sigma(\rho+\bar{p}) = \bar{r}(\bar{h}) + \bar{p} - \sigma(\bar{r}(\bar{h}) - \rho) > 0$,[13] which represents the household's propensity to consume out of expected lifetime wealth. Using the utility specification (11), the Euler equation (7) identifies the equilibrium growth rate of the household's consumption profile in steady state as $g_{hh}(\bar{h}) \equiv \sigma(\bar{r}(\bar{h}) - \rho)$. Consequently, the second way of writing $x(\bar{h},\bar{p})$ shows that the propensity to consume $x(\bar{h},\bar{p})$ reflects the difference between the return on annuities $\bar{r}(\bar{h}) + \bar{p}$ and the growth rate of the household's consumption $g_{hh}(\bar{h})$.

Note that $\dot{N}(t,s) = -p(s)N(t,s)$, and consequently, we obtain from (10d) the actuarily fair premium $a(t,s) = r(t) + p(s)$. Focusing on the steady state, in which the equilibrium interest rate is constant, we can neglect the time argument and write $\bar{a}(\bar{h},\bar{p})$. Moreover, as households are free to choose between working in the healthcare sector and working in consumption good production, each household must earn the same equilibrium wage $w(t)$, as given by equation (2b). Given the consumption good firm's capital demand, as given by (2a), the allocation and prices are determined via the households' supply of capital and demand for healthcare services.

4.1 Equilibrium dynamics

The following proposition characterizes the resulting steady state dynamics of the economy:

Proposition 2 (Steady state dynamics)
The dynamics of the aggregate economy in the steady-state equilibrium

[13] Note that $x(\bar{h},\bar{p}) > 0$ is necessary for the household's maximization problem to be well-defined.

(i) is characterized by:

$$\dot{c}(t) = \sigma\left[\bar{r}(h) - \rho\right]c(t) - x(\bar{h},\bar{p})(\bar{p}+\nu)k(t)\ , \tag{13a}$$

$$\dot{k}(t) = \left[\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu\right]k(t) - c(t)\ , \tag{13b}$$

(ii) is governed by a unique balanced-growth path growing at the following rate:

$$\begin{aligned}\bar{g}(\bar{h},\bar{p}) =& \frac{1}{2}\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu + \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\} \\ & - \frac{1}{2}\sqrt{\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu - \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\}^2 + 4x(\bar{h},\bar{p})(\bar{p}+\nu)}\ .\end{aligned} \tag{14}$$

Besides providing a precise description of the economy's balanced-growth path, Proposition 2 conveys two important insights. First, as on the balanced-growth path $\dot{c}(t)/c(t) = \dot{k}(t)/k(t) = \bar{g}(\bar{h},\bar{p})$, the first equation, showing the evolution of aggregate consumption per capita, reveals that the growth rate of the household's consumption profile must be higher than the economy's growth rate on the balanced-growth path. This is evident, as the first term of (13a) reflects g_{hh}, from which a second positive term is subtracted. This latter term, which is the difference in consumption levels at any time t between the households just born and the households just dying, reflects the underlying overlapping generations structure of the economy. Second, the economy's growth rate on the balanced-growth path is affected by the size of healthcare investments via two different channels: life expectancy $\bar{p}$ and the equilibrium interest rate $\bar{r}(\bar{h})$. In the following subsection, we examine how these two channels of changes in the size of the healthcare sector influence equilibrium prices and the economy's growth rate.

4.2 Equilibrium and growth effects of an expansion of the health sector

The following proposition states how a marginal increase in healthcare expenditures impacts the steady-state equilibrium and balanced-growth path of the economy:

Proposition 3 (Equilibrium and growth effects of healthcare investments)

(i) An increase in steady-state healthcare investments $\bar{h}$ increases the equilibrium wage rate and decreases the equilibrium interest rate.

$$\frac{d\,\bar{w}(\bar{h},t)}{d\,\bar{h}} > 0, \quad \text{and} \quad \frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}} < 0.$$

(ii) If $\alpha < 1/\sigma$, the growth rate of the economy increases with the interest rate, while the difference between the growth rate of the households' consumption profiles and the economy's growth rate decreases with the interest rate.

$$\frac{d\,\bar{g}(\bar{h},\bar{p})}{d\,\bar{r}(\bar{h})} > 0, \quad \frac{d\left(g_{hh}(\bar{h}) - \bar{g}(\bar{h},\bar{p})\right)}{d\,\bar{r}(\bar{h})} < 0.$$

(iii) If $\alpha < 1/\sigma$, the direct effect of a larger healthcare sector on the economy's growth rate is positive (via increased longevity), while the general equilibrium effect via the interest rate is negative.

$$\frac{d\,\bar{g}(\bar{h},\bar{p})}{d\,\bar{h}} = \underbrace{\frac{\partial \bar{g}(\bar{h},\bar{p})}{\partial \bar{p}}\frac{d\,\bar{p}}{d\,\bar{h}}}_{>0 \text{ dir. effect}} + \underbrace{\frac{\partial \bar{g}(\bar{h},\bar{p})}{\partial \bar{r}(\bar{h})}\frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}}}_{<0 \text{ indir. effect}}$$

An increase in healthcare increases the growth rate if the healthcare sector is sufficiently small and decreases the growth rate if the healthcare sector is sufficiently large.

A rise in healthcare expenditures re-assigns labor from consumption good production to the health sector. This contraction of labor supply in manufacturing increases the equilibrium wage rate. In turn, the marginal productivity of capital declines, as labor is shifted away from the more capital-intensive sector. Note that this characteristic also stems from our realistic assumption that the spillover effects of healthcare investments on the productivity of consumption good production cannot fully compensate for the output loss due to the decline in the workforce employed in the latter sector.

In part (ii), we examine what such a change in the interest rate implies for economic growth. In line with economic intuition, we find that an increase in the interest rate positively affects economic growth by increasing households' savings. Consequently, a lower interest rate due to higher healthcare expenditures implies a negative effect on economic growth. Moreover, the growth rate of the household's consumption profile is positively related to the interest rate. Hence, both the consumption growth rate of the households and the economy's growth rate decline in response to an expansion of the healthcare sector, and we find that the difference between the two growth rates widens as a result. That is, the economy's growth rate has a steeper slope in r than does the household's consumption growth rate. The qualifier $\alpha < 1/\sigma$ constitutes a sufficient but not necessary condition for the result to hold. In our case, the coefficient of relative risk aversion is between one and two, which implies an upper bound on the capital share in consumption good production of between 1/2 and one. Typical values for α range from 1/3 to 1/2 and do not challenge the condition.

Finally, part (iii) of Proposition 3 describes the growth effects of a larger healthcare sector, which operate via two channels: (i) longevity and (ii) the equilibrium effects due to changes in the interest rate. With respect to the former channel, we find that the propensity to consume declines when households expect to live longer. This implies an increase in savings and, thereby, exerts a positive effect on the economy's growth rate. This channel is represented by the term $x(\bar{h},\bar{p})(\bar{p}+\nu)$ (see Appendix A.5), which is sometimes referred to in the literature as the "generations turnover" term. The second channel via the interest rate has already been discussed in parts (i) and (ii) of the proposition.

The relative sizes of these two effects with opposite signs drive the last result stated in Proposition 3. When the healthcare sector is small, the increase in longevity from a marginal increase in healthcare spending is very high according to our specification of the health production function, but the effect on the interest rate is rather small and bounded from above.

Due to diminishing returns in health production, the direct effect of longevity and growth decreases when health investments are already substantial. However, shifting additional labor from manufacturing to healthcare implies huge costs in terms of capital productivity when only few households are employed in consumption-good production.

5 Inefficiency of the Market Equilibrium

Thus far, we have characterized the decentralized, steady-state market equilibrium and identified how increasing healthcare expenditures affect the equilibrium prices and the steady state dynamics of the economy. Yet, a central innovation in our model is that healthcare investments are endogenously determined by the households' choices on healthcare expenditures. In the following, we analyze whether these household choices are efficient and discuss the general equilibrium and macroeconomic consequences of such inefficiencies.

5.1 The Social Planner's Solution

To identify potential market failures associated with the households' choice of healthcare expenditures, we compare the decentralized equilibrium allocation to the allocation that a social planner maximizing utilitarian welfare would choose.[14] Welfare is defined as the weighted sum of the utilities of all households alive from time $t = 0$ to infinity. The social planner's weight on the lifetime utilities of different cohorts is equal to the time preference rates of the households. This implies that the lifetime utility of a household born at time s will be discounted to time 0 with the time preference rate $\rho^s = \rho$.[15]

Then the planner's problem is given by:

$$\begin{aligned}
\max_{\{\{c(t,s)\}_{t=0}^{\infty}, h(s)\}_{s=0}^{\infty}} & \quad \int_0^{\infty} \mathcal{V}(t) dt, \\
\text{where } \mathcal{V}(t) &= \int_{-\infty}^{t} V(c(t,s)) \exp[-(\rho + p(s))(t-s)] \exp[\nu s] \exp[-\rho^s s] ds, \\
\text{s.t. } p(s) &= H(h(s)), \\
N(t) &= \int_{-\infty}^{t} \exp[\nu s - p(s)(t-s)] ds, \\
L^H(t) &= \int_{-\infty}^{t} h(s) \exp[\nu s - p(s)(t-s)] ds, \\
L^F(t) &= N(t) - L^H(t),
\end{aligned}$$

[14] As our focus is on moral hazard originating from unconditioned annuities, we could simply identify their effect at the macro level by including annuities conditioned on individual household mortality in the decentralized equilibrium. While not trivial, we nevertheless solve the social planner's problem to be transparent with respect to all market inefficiencies and potential interactions of other inefficiencies with the moral-hazard effect. Moreover, it allows us to provide simulation results on the size of the moral-hazard effect with and without correction of the other market failures.

[15] For a discussion of the effects of the relationship between individual time preference rates and that of the social planner on the allocation of consumption across different age cohorts, see for example, Schneider et al. (2012).

$$
\begin{aligned}
C(t) &= \int_{-\infty}^{t} c(t,s)\exp[\nu s - p(s)(t-s)]ds, \\
\dot{K}(t) &= F(K(t), L^F(t), L^H(t)) - \delta K(t) - C(t),
\end{aligned}
$$

and initial conditions specifying $\{h(s)\}_{-\infty}^{s=0}$ and $K(0)$ and $N(0)$.

$\mathcal{V}(t)$ represents aggregate welfare at time t, i.e., the sum of instantaneous utilities of all households alive at time t. Despite assuming $\rho^s = \rho$, we include the planner's time preference rate ρ^s in the welfare specification for clarity of expression. The first constraint represents the healthcare technology, while the second reflects the economy's population size at time t by summing the still living individuals of all cohorts born at the different birth dates $s \leq t$. For reasons of comparability with the decentralized solution, the planner determines one unique level of healthcare $h(s)$ for the households in the cohort born at time s that is fixed throughout their lifetimes. Consequently, the demand for healthcare at time t, $L^H(t)$, sums the individual healthcare demands of all households alive at time t. The remaining share of the population works in the consumption good sector. The last two constraints specify aggregate consumption and the equation of motion of the aggregate capital stock.

The planner's problem cannot be solved directly with the standard approach via optimal control theory because of (i) the double integral in the objective function and (ii) the integral constraints, whereby the integrals cannot be eliminated by differentiation. Regarding issue (i), we split the problem into an "inner problem," in which the social planner allocates a given amount of consumption across all generations alive in a period t. Our assumption $\rho^s = \rho$ implies that it is optimal for the social planner to distribute consumption equally such that every household enjoys consumption $c(t,s) = \hat{c}(t) = C(t)/N(t), \forall s$. Inserting this into the objective function, we obtain the "outer problem" of finding the optimal path $C(t)$ and $h(t)$. This, however, does not eliminate issue (ii). Therefore, we solve the outer problem by setting up the Lagrangian and interchanging the order of integration of the constraints such that we are able to use the calculus of variations to derive necessary conditions for an optimum. The detailed solution to the planner's problem is provided in the Appendix. For the necessary conditions for a welfare maximum, we obtain the familiar expressions for the optimal path of consumption and capital:

$$
\begin{aligned}
\dot{\hat{c}}(t) &= -\frac{V'(\hat{c}(t))}{V''(\hat{c}(t))}\left(\frac{\partial F(K(t), L^H(t), L^F(t))}{\partial K(t)} - \delta - \rho\right), &\quad (15)\\
\dot{k}(t) &= F(k(t), l^H(t), l^F(t)) - \delta k(t) - \frac{\dot{N}(t)}{N(t)}k(t) - \hat{c}(t), &\quad (16)
\end{aligned}
$$

where $l^F(t) = \frac{L^F(t)}{N(t)}$ and $l^H(t)$ denote the shares of labor in manufacturing and healthcare, respectively. The main novelty of our approach lies in the characterization of the optimal levels of healthcare. We obtain the following necessary condition that the level of healthcare of any generation born at time $s \geq 0$ satisfies in the social planner's optimum:

$$
-\int_{s}^{\infty} V(\hat{c}(t))H'(h(s))(t-s)\exp[-(\rho + p(s))(t-s)]dt
$$

$$
\begin{aligned}
& -\int_s^\infty w^H(t)V'(\hat{c}(t))\exp[-(\rho+p(s))(t-s)]dt \\
= \quad & -\int_s^\infty V'(\hat{c}(t))\hat{c}(t)H'(h(s))(t-s)\exp[-(\rho+p(s))(t-s)]dt \\
& -\int_s^\infty w^H(t)V'(\hat{c}(t))h(s)H'(h(s))(t-s)\exp[-(\rho+p(s))(t-s)]dt \\
& +\int_s^\infty w(t)V'(\hat{c}(t))H'(h(s))(t-s)\exp[-(\rho+p(s))(t-s)]dt,
\end{aligned} \tag{17}
$$

where $w^H(t) = \frac{\partial F}{\partial L^F(t)} - \frac{\partial F}{\partial L^H(t)}$ reflects the effective marginal opportunity costs of an additional unit of labor in healthcare. We denote by $w(t)$ the marginal product of labor in the consumption good sector, which reflects the wage rate in the decentralized market equilibrium.[16] In addition to the planner's uniform distribution of consumption, conditions (15)–(17) reveal three differences from their counterparts in the decentralized market economy, which we discuss in the following.

5.2 Externalities in the Market Equilibrium

Comparing the social planner's solution to the decentralized market equilibrium, as defined in Definition 1, we identify three market failures: the "learning-by-investing" externality (Romer, 1986), a spillover effect of health on consumption good production and moral hazard in healthcare investments.

We identify the standard 'learning-by-investing' externality by comparing the consumption Euler equation of the social planner (15) with the household's (7) in equilibrium, where $a(t,s) = r(t) + p(s)$, according to equilibrium condition (10d). Consequently, the difference between the consumption path of the households in the decentralized equilibrium relative to that in the social planner's optimum originates from the difference in the return on capital: The social rate of return $\partial F(K(t), L^H(t), L^F(t))/\partial K(t) - \delta = \big(A(t)L^F(t)/K(t)\big)^{1-\alpha} - \delta$ is larger than the private return $r(t) = \alpha\big(A(t)L^F(t)/K(t)\big)^{1-\alpha} - \delta$ because firms take the technological level $A(t)$ of the economy as given, neglecting the positive spillovers that the employment of capital exerts on the economy's manufacturing output $Y(t)$ via an increase in the technological level.[17] As is well known, this leads to an inefficiently low level of asset holdings that could be corrected, for example, by subsidizing household savings.

[16] Specifically, writing $F(K(t), L^H(t), L^F(t)) = A(t)^{1-\alpha}K(t)^\alpha L^F(t)^{1-\alpha}$ with $A(t) = K(t)/(N(t) - \eta L^H(t))$, where we use the definition of $A(t)$ as in Section 3.2 and the fact that $N(t) = L^F(t) + L^H(t)$, we obtain for the partial derivative with respect to $L^F(t)$ the expression $\partial F/\partial L^F(t) = (1-\alpha)A(t)^{1-\alpha}K(t)^\alpha L^F(t)^{-\alpha}[= w(t)]$, while we obtain for the partial derivative with respect to $L^H(t)$, $\partial F/\partial L^H(t) = \eta K(t)/[N(t) - \eta L^H(t)]^2(1-\alpha)A(t)^{-\alpha}K(t)^\alpha L^F(t)^{1-\alpha}$. Consequently, we can write $w^H(t) = w(t)(1-\eta)N(t)/(N(t) - \eta L^H(t))$.

[17] Note that $\hat{c}(t)$ in the planner's solution reflects each household's consumption level at time t and, thus, also the level of aggregate consumption per capita. The two consumption levels would differ if the planner's intragenerational distribution of consumption were not uniform, as is the case in the decentralized economy, where the disparity between $c(t,s)$ and $c(t)$ reflects the difference between the high consumption levels of those dying at t and the low consumption levels of those born at t. As $\hat{c}(t)$ reflects aggregate consumption per capita, the law of motion of the aggregate per capita capital stock in the social planner's solution (16) is equivalent to that in the decentralized equilibrium, which can be derived by applying (9) to (5) while considering equilibrium condition (10a).

The other two inefficiencies are associated with healthcare expenditures. The two expressions on the left-hand side of equation (17) are familiar from the household's first-order condition (8). They reflect the additional utility obtained directly from a higher expected lifetime and the direct healthcare costs arising from higher labor input in the healthcare sector at the expense of labor in consumption good production. Comparing the social planner's optimality condition (17) and the household's first-order condition (8), we notice two important differences: First, there is a wedge between the social marginal costs of healthcare $w^H(t)$ and the private marginal costs of healthcare $w(t)$ that results from households' inability to directly reap the benefits of the positive spillover of health investments on productivity in manufacturing. Thus, healthcare investments in the decentralized economy are, ceteris paribus, lower than socially optimal. This market failure could be corrected by subsidizing healthcare investments in the amount of the difference between $w(t)$ and $w^H(t)$.

Second, the terms on the right-hand side of the social planner's optimality condition with respect to healthcare investments (17) do not appear in the corresponding first-order condition (8) of the household in the decentralized economy. This represents the moral-hazard effect with respect to healthcare spending, as households take annuity rates as given. This effect comprises three parts, as indicated by the three integrals on the right-hand side of (17). The first term represents the utility loss from lower consumption at each point in time, as consumption has to be spread out over a longer expected lifetime. The second term captures the additional costs of healthcare that accrue during the expected additional lifetime of the individual. Third, the additional expected lifetime also allows an individual to earn additional labor income, thereby increasing total labor wealth. Consequently, the sign of the moral-hazard effect depends on the relative sizes of the marginal losses due to lower consumption and increased healthcare expenditures and the marginal benefits from higher labor wealth. Although the sign of the moral-hazard effect is generally ambiguous, in the steady-state equilibrium, the moral-hazard effect leads to over-investments in healthcare, as we show below.

While we believe that, in reality, the two spillover effects of capital investment and healthcare investments on the economy's productivity in manufacturing are present and important in decentralized market economies, our focus in this paper is on the inefficiency resulting from moral hazard in healthcare spending when annuity rates are not conditioned on individual mortality rates, as in typical social security systems in most developed countries. Therefore, we now contrast the outcome of the decentralized equilibrium without conditioned annuities with its hypothetical counterpart when annuities conditioned on health status can be supplied by the insurance firm and, thus, no moral-hazard effect arises.

5.3 Market Equilibrium without Moral Hazard

We now assume that insurance companies can observe and condition annuity rates $a(t, h)$ on the individual household's healthcare investment. As a consequence, a household increasing its healthcare investments will face a lower annuity rate. As all households of the same cohort s face the identical optimization problem, all households of a given cohort s will choose the same level of healthcare investments $h(s)$. Thus, we can still represent the cohort born at time s by a representative household. To minimize notation, we again write the annuity rate as a function of s, $a(t,s)$, with the difference being that now $\partial a(t,s)/\partial h(s)$ is no longer zero but negative. Given fair annuity rates, as will arise in the market equilibrium with perfect competition, $\partial a(t,s)/\partial h(s)$ will amount to the marginal productivity of the healthcare technology $H'(h(s))$.

For the representative household's optimization problem, this implies that a marginal increase in healthcare investments affects the budget constraint not only via the direct costs but also via changes in the annuity rate. The household's forward budget constraint (see Appendix A.1) reveals that the household's lifetime consumption stream must be financed by the expected lifetime labor income:

$$b(s,s) = \int_s^\infty [c(t,s) - (1-h(s))w(t)] \exp\left[-\int_s^t a(t',s)dt'\right] dt. \tag{18}$$

A decline in the annuity rate $a(t,s)$ due to a reduction of $p(s)$ will increase the expected net present value of both the consumption stream to be financed and the wealth from lifetime labor income. This reflects the additional consumption needed for the additional expected lifetime and the extra labor income from an longer expected work life, resembling the respective expressions in the social planner's solution. Whether a decline in $a(t,s)$ places additional pressure on the budget constraint or relaxes it depends on the trajectories of consumption and wage rates over time t and, hence, on their initial values at birth date s and their growth rates over time t. Consequently, the sign of the effect depends on the equilibrium dynamics of the economy, which, as shown in Proposition 3, are also influenced by aggregate health expenditures.

To determine the sign and size of the moral-hazard effect, we begin by deriving the household's necessary conditions for a utility maximum. While the optimality conditions with respect to savings and consumption take the same form as presented in Section 3.4, the first-order condition with respect to healthcare (8) becomes the following:

$$\begin{aligned}
&-\int_s^\infty V(c(t,s))H'(h(s))(t-s)\exp[-(\rho+p(s)))(t-s)]dt \\
&-\int_s^\infty V'(c(t,s))w(t)\exp[-(\rho+p(s))(t-s)]dt \\
=&\quad -\int_s^\infty V'(c(t,s))\,c(t,s)\frac{\partial a(t,s)}{\partial h(s)}(t-s)\exp[-(\rho+p(s))(t-s)]dt \\
&\quad +\int_s^\infty V'(c(t,s))(1-h(s))w(t)\frac{\partial a(t,s)}{\partial h(s)}(t-s)\exp[-(\rho+p(s))(t-s)]dt\ .
\end{aligned} \tag{19}$$

The left-hand side of equation (19) is identical to the first-order condition when households take the annuity rate as given. The right-hand side of (19) presents the additional terms reflecting the consequences of health investments that reduce the annuity rate. It reflects the influence on the household's budget constraint, as discussed above, evaluated in terms of marginal utility. As noted above, given fair annuity rates $a(t,s) = r(t)+p(s)$ we obtain $\partial a(t,s)/\partial h(s) = H'(h(s))$, thereby resembling the right-hand side of the social planner's optimality condition for healthcare investments (17). Note that the difference from the social planner's necessary condition for healthcare investments is that the marginal costs of healthcare are higher than the social marginal costs due to the positive spillovers of healthcare onto consumption good production, which has not been internalized here.[18] As already conjectured, the expression on the right-hand side of (19) reveals that the sign of the first term is positive, while the sign of the second term is negative. Consequently, the effect of conditioned annuity contracts on healthcare investments is, in general, ambiguous. Relative to the solution in which annuity rates are taken as given, an individual will spend more (less) on healthcare if the additional labor income wealth exceeds (is smaller than) the additional consumption requirements.

We define the market equilibrium analogously to Definition 1, with the sole difference being that the insurance firm can now verify healthcare investments at the individual household level. Again, perfect competition in the financial sector ensures fair annuity rates.[19] In the following proposition, we show that when the households' utilities take the form as in (11), there exists a steady-state equilibrium with conditioned annuity contracts that is unique under a plausible condition.

Proposition 4 (Steady-state equilibrium without moral hazard)
Suppose that annuity rates can be conditioned on individual healthcare investments. Then, there exists a steady-state market equilibrium in which all prices are characterized as in Proposition 1, 2.–4., and all households invest the same amount in healthcare. The interior level of healthcare expenditures in the steady-state equilibrium $\bar{h}$ is implicitly given by the equation

$$\frac{\sigma}{1-\sigma}\frac{H'(\bar{h})}{x(\bar{h},\bar{p})} - \frac{1}{(1-\bar{h})} = -H'(\bar{h})\left(\frac{1}{x(\bar{h},\bar{p})} - \frac{1}{y(\bar{h},\bar{p})}\right). \tag{20}$$

The equilibrium is unique if $d\frac{x(\bar{h},\bar{p})}{y(\bar{h},\bar{p})}/d\bar{h} < 0$.

We employ the abbreviation $y(\bar{h},\bar{p}) = \bar{r}(\bar{h}) + \bar{p} - \bar{g}(\bar{h},\bar{p})$ to denote the difference between the equilibrium annuity rate $\bar{a}(\bar{h},\bar{p}) = \bar{r}(\bar{h}) + \bar{p}$ and the economy's steady-state growth rate. The condition for uniqueness of the steady-state equilibrium given in the proposition is a sufficient but not necessary condition. More generally, the steady-state equilibrium is unique if the increase in the relationship between the households' propensity to consume out of wealth and the difference between the annuity rate and the economy's growth rate with respect to $\bar{h}$ is sufficiently small. In the following, we assume a unique equilibrium.[20]

[18]When internalizing the healthcare spillover, the first-order condition (19) will resemble the social planner's optimality condition (17) with the difference being that the consumption path $\{c(t,s)\}_{t=s}^{\infty}$ differs from the social planner's solution due to the "learning-by-investing" externality and the social planner's uniform intra-temporal distribution of consumption across all generations alive (resulting from the pure time preference rate of the planner being identical to those of the households).

[19]Fair annuity rates result from perfect competition, as a lower than fair annuity rate leading to profits for an insurance firm can profitably be overbid by competitors. Offering higher than fair rates for some levels of healthcare spending means cross-subsidization is necessary from households with other healthcare levels. Cross-subsidization will not be possible, as other firms can profitably overbid the excessively low annuity rate at a particular healthcare spending level.

[20]Over the whole parameter range of the sensitivity analyses of our numerical illustration (see Section 7 and Appendices A.9 and A.10, we obtain unique equilibria.

The right-hand side of (20) collects the additional terms entering the first-order condition due to conditioned annuity claims and, thus, is the steady-state equivalent of the right-hand side of equation (19). In fact, computing the integrals using steady-state values, the right-hand side of (19) yields

$$-c(s,\bar{h},\bar{p})^{-1/\sigma}H'(\bar{h})\left[\frac{c(s,\bar{h},\bar{p})}{[x(\bar{h},\bar{p})]^2}-\frac{(1-\bar{h})w(s,\bar{h})}{[y(\bar{h},\bar{p})]^2}\right], \tag{21}$$

where $c(s,\bar{h},\bar{p})^{-1/\sigma}$ is the marginal utility of consumption at birthdate s and $-H'(\bar{h})$ denotes the increase in longevity and, simultaneously, the reduction in the annuity rate for a marginal increase in healthcare expenditures. The term in brackets is the difference between the additional consumption needed for the additional lifetime and the additional wealth in terms of labor income net of extra healthcare costs. Thus, the term in brackets echoes the increased pressure (or release of pressure) on the budget constraint (18) from a marginal increase in longevity increasing healthcare investments. The sign and size of this effect is determined by the difference between $x(\bar{h},\bar{p})$ and $y(\bar{h},\bar{p})$, which reflects the difference between the growth rate of the household's consumption profile $g_{hh}(\bar{h}) = \sigma(\bar{r}(\bar{h}) - \rho)$ and the growth rate of the economy in steady state $\bar{g}(\bar{h},\bar{p})$, as well as by the relationship between the level of initial consumption by the household $c(s,\bar{h},\bar{p})$ and the level of net labor income at date s $(1-\bar{h})w(s,\bar{h})$. In addition to $x(\bar{h},\bar{p})$ and $y(\bar{h},\bar{p})$, the equilibrium level of initial consumption $c(s,\bar{h},\bar{p})$ is also affected by the equilibrium interest rate and the economy's growth rate, as it depends on the household's net present lifetime wealth. As a consequence, both the size and sign of the moral-hazard effect in general equilibrium is ex ante ambiguous.

The solution to the household's utility maximization problem provides a link between the initial wage rate and initial consumption $c(s,\bar{h},\bar{p})$. In steady state, we obtain $c(s,\bar{h},\bar{p}) = (1-\bar{h})W(s,\bar{h},\bar{p})x(\bar{h},\bar{p})$, where $W(s,\bar{h},\bar{p}) = w(s,\bar{h})/y(\bar{h},\bar{p})$ denotes the net present value of the household's lifetime labor income. Inserting into (21) yields, after some transformations, the right-hand side in the household's first-order condition (20) in the steady-state equilibrium. This indicates that the sign of the moral-hazard effect is determined by the relationship between the growth rate of the household's consumption profile, which is part of $x(\bar{h},\bar{p})$, and the growth rate of the economy, as in $y(\bar{h},\bar{p})$. As we have shown, $g_{hh}(\bar{h}) > \bar{g}(\bar{h},\bar{p})$ and, consequently, $y(\bar{h},\bar{p}) > x(\bar{h},\bar{p})$, implying that the right-hand side of (20) is positive. Therefore, in the steady-state market equilibrium with conditioned annuity rates, households' healthcare spending is lower than in the steady-state equilibrium with unconditioned annuity rates. This result is summarized in the following proposition.

Proposition 5 (Over-investment in healthcare)
In the steady-state equilibrium with mortality contingent annuity claims, the households invest less in healthcare than in the steady-state equilibrium where annuity rates cannot be conditioned on individual healthcare investments.

6 Improvements in the Healthcare Technology

One central reason for the increase in healthcare spending is technological progress in the healthcare sector (Chernew and Newhouse, 2012). Therefore, we are interested in how improvements in the healthcare technology affect healthcare spending, the size of the moral-hazard effect, welfare and economic growth. While we examine these questions numerically in the next section, we now discuss theoretically how the aggregate economy is affected by changes in the healthcare technology.

Recall that the healthcare technology (1) exhibits two parameters that influence the hazard rate p of households. A decline in the parameter p_{max} reduces the hazard rate that households face without investments in healthcare. An increase in the parameter ψ increases the reduction of the hazard rate that is purchased for any given healthcare investment h. As stated in the following proposition, an improvement in the healthcare technology either via a decrease in p_{max} or an increase in ψ leads to higher equilibrium healthcare investments, independent of whether annuity rates are conditioned on healthcare expenditures. The resulting effect on economic growth depends, once more, on the size of the healthcare sector.

Proposition 6 (Improvements in the healthcare technology)
In the steady-state market equilibrium,

(i) the following conditions hold:

$$\frac{d\bar{h}}{dp_{max}} < 0 \; , \qquad \frac{d\bar{p}}{dp_{max}} > 0 \; ,$$
$$\frac{d\bar{h}}{d\psi} > 0 \; , \qquad \frac{d\bar{p}}{d\psi} < 0 \; ,$$

(ii) improvements in the healthcare technology increase the economy's growth rate if $\bar{h}$ is small and decrease it if $\bar{h}$ is sufficiently large.

In the special case of $\eta = 1$, improvements in the healthcare technology increase economic growth:

$$\frac{d\bar{g}(\bar{h},\bar{p})}{dp_{max}} < 0 \; , \quad \frac{d\bar{g}(\bar{h},\bar{p})}{d\psi} > 0 \; .$$

A better healthcare technology affects the equilibrium hazard rate of dying $\bar{p}$ in two ways. First, there is a direct effect. Ceteris paribus, a decrease in p_{max} or an increase in ψ lowers the hazard rate $\bar{p}$. Second, an improvement in the healthcare technology induces higher healthcare expenditures. This is also the case for a decrease in p_{max}, although p_{max} enters p in an additively separable way. The reason is that the marginal effect of a decrease in p is proportional to the discount factor $\exp[-p(t-s)]$. As a consequence, any decrease in p – for whatever reason – will trigger higher healthcare expenditures.[21] Note that in our model, the direct effect of a marginal decrease in p_{max}, reflected by the partial derivative $\partial p/\partial p_{max}$, is equal to one. A marginal increase in the productivity of healthcare spending ψ implies a direct effect of h^{β}. Because

[21] This is a standard feature of life-cycle models (see, e.g., Murphy and Topel (2006)).

$h^\beta < 1$, the increase in expected lifetime that comes for "free" is larger when p_{max} marginally declines compared to a marginal increase in ψ. As a consequence, if a marginal decrease in p_{max} and a marginal increase in ψ lead to the same reduction in the hazard rate of dying, the decline via the increase in the productivity of health spending ψ is accompanied by higher healthcare expenditures.

By increasing longevity for given healthcare investments $\bar{h}$, technological improvements in the healthcare sector increase the economy's growth rate. As better technology in the healthcare sector also increases health spending, it further involves the equilibrium and growth effects of an expansion of the healthcare sector, as discussed in Proposition 3. Therefore, relative to the results provided in Proposition 3, technological improvements in healthcare exert an additional positive, but limited in size, effect on longevity in addition to that operating through an increase in healthcare investments. Consequently, when the healthcare sector is small, technological improvements in the healthcare sector positively affect economic growth. However, the negative effects on economic growth stemming from a declining marginal productivity of capital, as labor is re-assigned to the healthcare sector, will dominate when the healthcare sector is sufficiently large. Thus, technological improvements in healthcare increase economic growth when the healthcare sector is small and decrease growth when the healthcare sector is large. In the special case in which the spillovers from healthcare on productivity in manufacturing are very large, i.e., $\eta = 1$, the costs in consumption good output from shifting labor from manufacturing to healthcare are fully compensated by the spillover on productivity. Then, only the positive effect on economic growth via increased longevity remains, as indicated in Proposition 6.[22]

7 Numerical Simulations

In the following, we illustrate our theoretical findings via a numerical simulation. To abstract from country-specific peculiarities in the healthcare system to the greatest extent possible, we calibrate our model to the OECD average of healthcare expenditures and life expectancy. Among all OECD countries for which data were available in 1980, average lifetime at birth increased from 73.1 years in 1980 to 79.4 years in 2005.[23] Over the same time horizon, the average healthcare spending as a percentage of GDP increased from 6.1% to 8.7% while GDP per capita grew at an average rate of 2.05%.

For all other parameters in our model economy, we choose plausible real-world values. For the intertemporal elasticity of substitution σ, we follow Murphy and Topel (2003), who suggest a value of $\varepsilon = (u'(c)c)/u(c) = 0.346$, which is also used by Becker et al. (2005). For our instantaneous utility function (11), this translates to $\sigma = 1.529$, which we round to $\sigma = 1.5$.

[22]It would also be interesting to know how the size of the moral-hazard effect is affected by improvements in the healthcare technology. However, from a theoretical perspective, the effect is ambiguous, and thus, the answer to this question depends on the values of the exogenous parameters of the model. We will, however, examine the change in the size of the moral-hazard effect in our numerical simulations in the next section.

[23]We average life expectancy at birth and healthcare expenditures for all OECD countries for which data are available both in 1980 and 2005. In particular, this excludes Chile, the Czech Republic, Estonia, Greece, Hungary, Israel, Italy, Luxembourg, Mexico, Poland, the Slovak Republic, Slovenia and Sweden. See also Appendix A.9 for details on the numerical illustration.

Symbol	Description	Value Range
ρ	Time preference rate	2%
σ	Intertemporal elasticity of substitution	1.5
ν	Growth rate of cohort size	0%
α	Value share of labor	$0.35 \dots \mathbf{0.5} \dots 0.65$
δ	Capital depreciation rate	$5\% \dots \mathbf{7.5\%} \dots 10\%$
η	Positive spillover of healthcare spending on TFP	$0 \dots \mathbf{0.15} \dots 0.3$
β	Curvature parameter of healthcare technology	$0.5 \dots \mathbf{0.75} \dots 1$
p_{max}	Hazard rate of dying without healthcare	Calibrated to match data
ψ	Marginal impact of healthcare spending on longevity	Calibrated to match data
h	Share of labor income spend on healthcare	Taken from data
T	Life expectancy	Taken from data

Table 1: Summary of the model parameters used in the numerical illustration. In cases of value ranges, a sensitivity analysis is employed, where the reference case is denoted in bold.

The utility discount rate is set to $\rho = 2\%$. Employing a broad definition of capital, we set the capital share $\alpha = 0.5$ and the capital depreciation rate $\delta = 7.5\%$. Yet, we also perform sensitivity analyses with α ranging between 0.35 and 0.65 and δ varying between 5% and 10%. In addition, we abstract from population growth, i.e., $\nu = 0$, as we employ data on GDP per capita.

Crucial parameters in our model are the positive externality from healthcare spending on total factor productivity measured by the spillover parameter η and the healthcare technology characterized by p_{max}, ψ and β. To calibrate our model to real-world data, we apply the following procedure. We fix η and β and then calibrate p_{max} and ψ to match observed lifetime expectancy and healthcare spending rates. Unfortunately, there is no easy way to observe the spillover parameter η and the curvature parameter β of the healthcare technology. As a consequence, we perform a sensitivity analysis with a broad value range for both parameters. For η, we employ a range between 0 and 0.3 and for β a range between 0.5 and 1, where we consider $\eta = 0.15$ and $\beta = 0.75$ as the reference scenario. Finally, we derive the level of healthcare expenditures h in our model by dividing observed healthcare expenditures as a percentage of GDP by $2(1-\alpha)$: On the one hand, h in our model is the share of labor income spent on healthcare rather than the share of total GDP. Assuming a labor share of $1-\alpha$, we divide the data on health expenditures per GDP by this number. On the other hand, not all health expenditures are effective in prolonging life. Assuming that half of the expenditures affect the individuals' life expectancy leads to the factor of $1/[2(1-\alpha)]$ given above. Table 1 summarizes our parameter calibration.

In line with our endogenous growth model, we assume that increases in average lifetime stem from the interplay of improvements in the healthcare technology and the endogenous choice of healthcare spending. This implies that the growth and interest rates of the economy depend on the healthcare technology and the healthcare expenditures. We now calculate these rates and the expected lifetime utility of an individual household in a steady-state economy in two different scenarios: (i) with the healthcare technology of 1985 and (ii) with the healthcare technology of 2005. To concentrate on the effects of the healthcare technology, we assume that all other

	Scenario (i) $T = 73.1\,[a]$ $h = 6.1\,[\%]$	Scenario (ii) $T = 79.4\,[a]$ $h = 8.7\,[\%]$
Regime (a)		
$p_{max}\,[\%]$	1.4420	1.3662
$\psi\,[\%]$	0.6028	0.6664
$r\,[\%]$	3.61	3.38
$g\,[\%]$	2.14	1.96
$\Delta U_{(i)\to(ii)}\,[\%]$	4.55	
Regime (b)		
$h\,[\%]$	5.54	8.04
$T\,[a]$	72.83	79.02
$r\,[\%]$	3.64	3.51
$g\,[\%]$	2.18	2.01
$\Delta U_{(i)\to(ii)}\,[\%]$	4.86	
Comparison regime (a) $\to$ (b)		
$\Delta U_{(a)\to(b)}\,[\%]$	1.29	1.58
$\Delta U_{direct}\,[\%]$	0.011	0.013
$\Delta U_{equil}\,[\%]$	-0.22	-0.27
$\Delta U_{growth}\,[\%]$	1.50	1.84

Table 2: Utility gains (compensating variation) for a hypothetical average OECD country from improvements in the healthcare technology and switching from an unconditioned to a conditioned annuity claims regime.

aspects of the economy, such as the consumption good production technology and the initial capital endowment per capita, are the same.[24] We analyze two different annuity regimes. In regime (a), we assume that annuity payments cannot be conditioned on healthcare choices, which we consider the status quo. As a consequence, we calibrate the healthcare technologies of 1985 and 2005 to match observed healthcare expenditures and life expectancy. In regime (b), which we consider the counterfactual scenario, we assume that annuity payments are conditioned on healthcare expenditures.

To compare the expected lifetime utilities of two individuals under two different scenarios, we calculate the compensating variation, i.e. the percentage increase in consumption that an individual under the first regime had to enjoy to experience the same expected lifetime utility as the individual would under the second regime. The difference ΔU in expected lifetime utilities is either due to the improvement in the healthcare technology if we compare scenarios (i) and (ii) or due to the moral hazard induced by unconditioned annuity claims if we compare scenarios (a) and (b).

The results for our reference specification are shown in Table 2. In scenario (i), the healthcare technology has been calibrated to resemble the life expectancy (73.1 years) and healthcare expenditures (6.1% of GDP) of the average OECD country in 1985, while in scenario (ii),

[24]Note, however, that steady-state population size depends on the expected lifetime, as the cohorts' initial sizes when born are fixed and constant.

the healthcare technology mimics the life expectancy (79.4 years) and healthcare expenditures (8.7% of GDP) of the average OECD country in 2005. Comparing the calibrated healthcare technologies, we observe that the hazard rate for mortality without healthcare treatment p_{max} has declined and the marginal productivity of the healthcare technology ψ has improved. This implies that in scenario (ii), individuals live – on average – longer than in scenario (i) even without any healthcare expenditures, and each percentage point of wage income spent on healthcare in scenario (ii) reduces mortality to a greater extent than in scenario (i). As a result of the improved healthcare technology, individuals spend a higher percentage of their wage income on healthcare in scenario (ii): h increases from 6.1% to 8.7%. This has implications for the steady-state equilibrium of the economy. The interest rate decreases from 3.61% to 3.38%, and the growth rate declines from 2.14% to 1.96%. Despite a lower interest and growth rate, the expected lifetime utility of individuals has increased by 4.55%.[25]

First, we now analyze what would have happened in scenarios (i) and (ii) if annuity claims were conditioned on healthcare expenditures while all other fundamentals of the economy (including the healthcare technology) remained unchanged. We find that steady-state healthcare expenditures in both scenarios decrease while the interest and growth rates increase. In scenario (i), healthcare investments are reduced from 6.1% to 5.54%, resulting in a lower life expectancy of 72.83 years (a decrease of approximately 3 months). However, the interest rate increases from 3.61% to 3.64%, and the growth rate rises from 2.14% to 2.18%. Similarly, healthcare expenditures in scenario (ii) decline from 8.7% to 8.04%, resulting in a decline in life expectancy from 79.4 to 79.02 years (a decrease of approximately 4.5 months). The interest rate increases from 3.38% to 3.51%, and the growth rate of the economy rises from 1.96% to 2.01%. Moreover, under regime (b) individuals benefit from an improvement in the healthcare technology: Expected lifetime utility increases by 4.86%.

Second, we compare regimes (a) and (b). We find that expected lifetime utility levels are higher under regime (b) with conditioned annuity claims. Individuals under regime (a) would have to enjoy a 1.29% (1.58%) higher consumption level throughout their entire lifetime in scenario (i) ((ii)) to reach the expected lifetime utility under regime (b). To understand how conditioned annuity claims affect the expected lifetime utility, we first write expected lifetime utility in the steady state as follows (see also Appendix A.9):

$$U(s) = \frac{\sigma}{\sigma - 1} c(s, \bar{h}, \bar{p})^{\frac{\sigma-1}{\sigma}} \frac{1}{\bar{x}(\bar{h}, \bar{p})} \ , \tag{22}$$

where $\bar{x}(\bar{h}, \bar{p})$ denotes the propensity to consume in the steady-state equilibrium and $c(s, \bar{h}, \bar{p})$ is a household's consumption at birth, which is given by

$$c(s, \bar{h}, \bar{p}) = W(s, \bar{h}, \bar{p}) \bar{x}(\bar{h}, \bar{p})(1 - \bar{h}) \ . \tag{23}$$

[25]Recall that according to our metric, an increase of 4.55% means that we had to give an individual in scenario (i) a consumption increase of 4.55% over the entire lifetime to enjoy the same expected lifetime utility as an individual in scenario (ii).

Differentiating with respect to the steady-state healthcare expenditures $\bar{h}$ yields the following:

$$\frac{dU(s)}{d\bar{h}} = U(s)\left\{\frac{\sigma-1}{\sigma}\left[-\frac{1}{1-\bar{h}} + \frac{d\bar{x}(\bar{h},\bar{p})/d\bar{h}}{\bar{x}(\bar{h},\bar{p})} + \frac{dW(s,\bar{h},\bar{p})/d\bar{h}}{W(s,\bar{h},\bar{p})}\right] - \frac{d\bar{x}(\bar{h},\bar{p})/d\bar{h}}{\bar{x}(\bar{h},\bar{p})}\right\} . \tag{24}$$

Thus, changes in steady-state healthcare spending $\bar{h}$ affect utility either via a change in the growth rate of individual consumption (last term) or via the initial consumption level at birth (first three terms), which itself depends on the direct costs and benefits of healthcare expenditures (first and second terms in brackets) and changes in the net present value of lifetime earnings $W(s,\bar{h},\bar{p})$ (third term in brackets).

We further decompose the difference in expected lifetime utility into three components. The first component ΔU_{direct} consists of all changes in expected lifetime utility on the microeconomic level of the individual due to a direct change in healthcare spending $\bar{h}$ or a corresponding change in the mortality rate $\bar{p}$. Thus, ΔU_{direct} is the difference in expected lifetime utilities due to switching from regime (a) to regime (b) if the individual's $\bar{h}$ changes from 6.1% (8.7%) to 5.54% (8.04%) and, as a consequence, the life expectancy decreases from 73.1 (79.8) to 72.83 (79.02) years but the wage, interest rate and the growth rate of the economy remain at regime (a) values. The second component ΔU_{equil} isolates the effect of changes in the equilibrium wage rate and interest rate but leaves the healthcare spending, the expected lifetime and the economy's growth rate at the levels of regime (a). The last component ΔU_{growth} elicits the difference in expected lifetime utilities that stems from the change in the economy's growth rate while leaving healthcare spending, life expectancy and wage and interest rates unchanged.[26]

We find that the direct effect at the individual household level of a change from the annuity regime (a) to regime (b) is positive. This is to be expected, as regime (b) eliminates the moral hazard incentive for individual households to over-invest in healthcare because they do not take into account the repercussions of higher healthcare spending, respectively higher life expectancy, on the equilibrium annuity rate. This effect is well understood and documented in the literature (see, e.g., Philipson and Becker, 1998). Yet, we find that this direct effect at the individual household level is very small (0.011% in scenario (i) and 0.013% in scenario (ii)).

The isolated effect on the wage and interest rate ΔU_{equil} is negative. This implies that with respect to wage and interest rates, households are better off under regime (a) with moral hazard than under regime (b) without moral hazard. The reason is that the wage rate increases with increasing healthcare spending, while the interest rate decreases (see Proposition 3 (i)). This leads to a higher net present value of lifetime earnings. In Appendix A.9, we show that the effect on the initial consumption level at birth, as given by equation (23), is unambiguously positive. However, the propensity to consume $\bar{x}(\bar{h},\bar{p})$ increases, and thus, the total effect on lifetime utility, as given by equation (22), is ambiguous. Over the whole range of our sensitivity analyses, we find that the positive effect on initial consumption outweighs the negative effect on

[26]Note that the decomposition of the total effect is somewhat arbitrary. We select this particular (hypothetical) decomposition to clearly distinguish among the different channels by which increased longevity impacts expected lifetime utility and to clearly identify the magnitude of each of these channels. Obviously, other decompositions of the different channels, for example incremental or hierarchical decompositions, are conceivable.

the growth rate of individual consumption, rendering the total effect of an increase in healthcare spending on lifetime utility positive. As healthcare investments are lower in regime (b), this leads to the observed decrease in expected lifetime utility of -0.22% in scenario (i) and -0.27% in scenario (ii).

Finally, a change in healthcare expenditures also affects the growth rate of the economy. According to Proposition 3 (iii), an increase in $\bar{h}$ leads to an increase in the growth rate for small values and to a decrease for high values of $\bar{h}$. ΔU_{growth} isolates the impact of a change in the growth rate on expected lifetime utility. We find that in both scenarios a switch from regime (a) to regime (b) reduces healthcare expenditures and increases the economy's growth rate. Accordingly, we observe an increase in expected lifetime utility of 1.50% in scenario (i) and 1.84% in scenario (ii). In fact, for both scenarios and throughout the whole range of our sensitivity analyses, we find that an increase in healthcare expenditures leads to a decrease in the growth rate and an according expected utility loss by reducing the net present value of lifetime income.

To check the qualitative and quantitative robustness of our reference simulation, we perform a series of sensitivity analyses, the results of which we discuss in detail in Appendix A.9. We find clear evidence that the moral hazard incentives of unconditioned annuity claims have a sizable effect on individual expected lifetime utility. Throughout the parameter range of our sensitivity analyses, we find that expected lifetime utility would increase by approximately between 1–3% if annuity claims could be conditioned on healthcare expenditures. Interestingly, the direct microeconomic effect of moral hazard in our model is rather small. In fact, the negative effect of moral hazard is predominated by a macroeconomic repercussion of healthcare expenditures on the economy's growth rate. In addition, we find that the negative effect of moral hazard is larger under a healthcare technology that resembles the average OECD country in 2005 compared to a healthcare technology consistent with the average OECD country in 1985. Thus, if healthcare technology continues improving, the negative effect of moral hazard due to unconditioned annuity claims may increase further in the future.

8 Discussion

In the following, we relate our model framework and the obtained results to the real world. First, the most important argument for the relevance of our analysis stems from the prevalence of unconditioned annuity claims throughout the developed world. In fact, the typical pension system within OECD countries rests on three pillars: The first pillar is a public pension system, the second is a funded system that recipients and employers pay into, and the third is voluntary privately funded accounts. Typically, the first two pillars comprise mandatory annuities. According to OECD data (OECD, 2015b), in 2011 public pension expenditures in the OECD amounted on average to approximately 10% of GDP and to 18% of total government spending. Between 1990 and 2011, the increase in public pension expenditures outpaced the increase in GDP by 28%. Furthermore, in 2014, mandatory social insurance contributions and mandatory private pension contribution rates for employees and employers for a private sector worker earning the average wage were approximately 20% (OECD, 2015b).

Rusconi (2008) provides an overview of the annuity markets and pension systems across OECD countries and classifies countries into two categories: (i) 'life-long annuity predominated' versus (ii) those predominated by 'alternative forms of income'. While a number of countries, such as Germany, the UK, the Netherlands and Italy, predominantly employ life-long annuities, some countries, such as the U.S., use predominantly 'alternative forms of income'. Nevertheless, even in the U.S., the average fraction of retirement wealth that is annuitized is approximately 50% for individuals older than 60 years, as reported in Hosseini (2015).

Depending on the country, the types of annuities in the pension system and those offered in the private market can differ. The OECD categorizes them into immediate, deferred and other annuities. Cannon and Tonks (2008) provide a good overview of different annuity types. In essence, they all share the central characteristics captured by the actuarial notes we employ in our analysis. Furthermore, the fair rate of return of the annuity depends on average individual longevity, but annuity contracts do not typically condition on health factors: The overwhelming share of annuitized wealth from the public pension system and mandatory second-pillar contributions does not condition on the health status of the annuitant. There are so-called 'enhanced annuities', which pay higher rates when a person has some particular health conditions or is a regular smoker. However, they only play a marginal role in overall annuitized retirement wealth and only condition on very specific health characteristics.

Second, in our model, we find that whether the moral-hazard effect in healthcare investments leads to over- or under-investment depends on whether the expected additional consumption exceeds the expected additional wealth for a marginal increase in the household's life expectancy due to increased healthcare investments. It is rather intuitive that a longer life implies financing a stream of consumption over a longer time horizon. Yet, it is less obvious how it might lead to higher expected labor income wealth, as in reality, the average person no longer works at the age of average life expectancy of approximately 80 years. However, life-extending healthcare measures not only play a role at the very end of life, but they also extend an individual's expected working life via three different channels: (i) later death during the regular working life, (ii) later or no early retirement based on health issues and (iii) fewer unemployment spells due to poor health. In fact, ill health was the most commonly cited reason for early retirement among both men and women according to several studies [27] In addition to the expected extension of the household's working life, the expected additional labor income wealth also depends on the wage rate. In our model, the positive spillover effect that health expenditures exert on consumption good production and, ceteris paribus, leads to higher wages captures that a healthier workforce is also more productive. In addition, the wage rate is affected by the growth rate of wages (which, in steady state, is also the growth rate of the economy). As we have shown, the growth rate of the economy is either positively or negatively affected by a marginal increase in healthcare

[27] See, for example, Disney et al., 2006 and the references therein. In addition, Dwyer and Mitchell (1999) report that men in poor health are expected to retire one to two years earlier. Further evidence for substantial effects of health on labor market participation are reported by Garcia-Gomez et al. (2010), van den Berg et al. (2010) and Brown et al. (2010).

investments, depending on the initial size of the healthcare sector.

Third, we have shown that in the steady-state equilibrium, the moral-hazard effect leads to over-investment in healthcare relative to the case in which annuity rates are conditioned on health status. A crucial assumption for this result is that either there is no spillover effect of health on aggregate productivity or it is not internalized. We show in Appendix A.10 that if the spillover effect is internalized, the moral-hazard effect may indeed lead to under-investment in healthcare. Internalizing the spillover effect is essentially a wage subsidy conditioned on healthcare spending. Households, anticipating this increase in wage associated with higher healthcare investments, thus have an additional motive to increase healthcare expenditures. If this wage increase is sufficiently large, then the increase in the wealth component in the budget constraint can be strong enough to overcompensate for the additional consumption to be financed. Then, the moral-hazard effect would lead to under-investment in healthcare.

To test the robustness of our over-investment result, we re-run our numerical simulation, as detailed in Section 7 and Appendix A.9, with the only difference being that we internalize the spillover effect of healthcare investments on consumption good production (see Appendix A.10). We find that there is an additional incentive to invest in healthcare, yet it is rather small. As a consequence, the result that households over-invest in healthcare remains robust throughout the whole parameter range of our sensitivity analyses. In fact, healthcare investments decrease slightly less when switching from regime (a) with unconditioned annuity claims to regime (b) under which annuities are conditioned on healthcare spending, and compared to the standard case without internalizing the spillovers of healthcare investments to consumption good production, the welfare losses decrease from 1.29% to 1.23% in scenario (i) and from 1.58% to 1.42% in scenario (ii). In Appendix A.9, we also simulate the scenario in which both the learning-by-investing externality and the health investment spillover are internalized. We find that this substantially increases the size of the welfare losses associated with the moral-hazard effect relative to the scenario in which neither of these two externalities are internalized.

Fourth, in our model, we assume that households inelastically supply one unit of labor as long as they are alive. Thus, we abstract from a retirement phase at the end of a household's lifetime. How would the explicit consideration of a retirement phase change our results concerning under- or over-investment in healthcare due to moral-hazard effects from unconditioned annuity claims? As outlined above, over-investment occurs if the costs to finance consumption over a longer life expectancy outweigh the increase in the net present value of expected lifetime labor income due to a marginal increase in healthcare expenditures. While a retirement phase has little impact on the need to finance consumption over a longer time horizon, it clearly limits the possibilities for increases in lifetime labor income.[28] As a consequence, we expect that, in reality, over-investment in health is even larger than suggested by our model.[29] Thus, we interpret the loss in

[28]Yet, it is certainly true that people in good health expecting to live longer might consider extending their working life if doing so were to positively affect their wealth. In fact, Kuhn et al. (2015) examine the relationship between the endogenous choices of healthcare and retirement age in a partial equilibrium analysis and find that moral hazard due to unconditioned annuities leads to both excessive healthcare expenditures and an excessive duration of the working life. In addition, the official retirement age might also increase with higher average life expectancy.

[29]This is particularly true if pension systems rely on unconditioned annuity claims. Zhao (2014) shows in a

expected lifetime utility due to moral hazard of 1–3%, as suggested by our numerical illustration in Section 7, as a conservative estimate. To better estimate the size of the moral-hazard effect, a quantitative exercise with richer detail on retirement and age-dependent mortality and health status over the life-cycle would be a desirable next step.

Finally, we note that our general model framework and the solution to the households' maximization problem for given prices and the social planner's solution do include preference specifications as suggested by Hall and Jones (2007). It is only with respect to the steady-state equilibrium that we employ an intertemporal elasticity of substitution larger than one. With an intertemporal elasticity of substitution smaller than one, the equilibrium dynamics would change such that the healthcare sector would grow either to dominate the entire economy, with consumption good production growing positively but more slowly, or to bring consumption growth to a halt, leading to a stationary economy without growth. Similarly, we would obtain equilibrium dynamics with an ever-growing healthcare sector if we included continuous technological improvements in healthcare (see, e.g., Jones, forthcoming). However, such changes to our model will not negate the channels identified in this paper through which endogenous healthcare expenditures affect the economy and the determinants of the sign and the size of the moral-hazard effect from annuities unconditioned on individual household mortality but would affect the dynamics of the economy and likely the quantitative results.

9 Conclusion

In this paper, we examined the role of households' endogenous healthcare choices to extend their expected lifetimes in economic growth and welfare in a decentralized, overlapping generations economy with the realistic feature that households' savings are held in annuities. While it is well known that annuities that do not fully condition their returns on individual households' health statuses induce moral-hazard effects in health spending, how this effect plays out in general equilibrium and the macroeconomic repercussions it implies for the economy's growth prospects have yet to be analyzed. This is the central focus of our analysis.

An increase in healthcare spending that causes households to live longer will reduce the equilibrium return on annuities. We find that this lowers the discount rate in the household's budget constraint on future consumption and future labor income, the latter of which is typically neglected in the literature. Another interpretation is that the increase in healthcare spending implies, on the one hand, that additional consumption needs to be financed for the increase in lifetime but, on the other hand, that additional income may also be earned during the additional lifetime. Neglecting the effect of healthcare spending on annuity rates by taking the latter as given leads households to over-invest in healthcare if the extra lifetime consumption exceeds the extra lifetime income and vice versa. We show that households will over-invest in the steady-state equilibrium. Under-investment may only occur if the health investment has an additional

quantitative general equilibrium neoclassical growth model calibrated to US data that one third of the increase in US healthcare expenditures between 1950 and 2000 can be attributed to the increase in social securities over the same time horizon.

large and positive (side-)effect of increasing the households' wage rates.

We further show that in macroeconomic terms, increased health investments boost economic growth when the healthcare sector is small but curtail growth when the healthcare sector is already sizable. The latter case additionally amplifies the neglect of the quality of life in terms of consumption in favor of the quantity of life resulting from over-investment in healthcare, as emphasized in the microeconomic literature. In fact, our simulations using OECD data suggest that the growth effect of over-investment in healthcare is negative. Moreover, we find that the welfare losses resulting from over-investment in healthcare are substantial and throughout various scenarios between 1–3%. In particular, the numerical results highlight the importance of the general equilibrium effects and, especially, the growth effects for the welfare impacts of the moral-hazard effect. In addition, our simulations suggest that while technological improvements in the healthcare sector involved large welfare gains over the last two decades with increases of approximately 5%, they also tended to increase the welfare losses from moral hazard in healthcare investments.

The policy implications that can be drawn from our analysis clearly indicate that attempts should be made to condition annuity payments in social security systems to a far greater extent on health status than is currently done. In practice this might be a difficult task in terms of measurement, and it might also be a contentious issue politically. Yet, the rewards in the event of success are sizable gains in expected lifetime utility.

This paper analyzes the complex interplay among endogenous longevity, endogenous economic growth and welfare in a model that abstracts from various issues that deserve further scrutiny. To be able to analytically investigate the aggregate economy, we employ a rather simplistic household model. Interesting extensions in this direction include age-dependent mortality, retirement decisions or endogenous fertility. At the level of the aggregate economy, we have shown that the decentralized market solution exhibits several externalities that call for government action. Augmenting the model with realistic features of national health systems would allow future researchers to examine their effects on growth and welfare and to evaluate potential policy interventions. Finally, we only considered exogenous improvements in the healthcare technology. Endogenizing these improvements is a further challenge for future research.

Appendix

A.1 Households' utility maximization problems

In this section we derive the households' necessary conditions for an optimum and show that they are also sufficient. We first derive the household's forward budget constraint and then use it to establish the first-order conditions. Finally, we show that the first-order conditions are also sufficient in the steady state.

Integrating the flow budget constraint (5) with respect to t and using the initial condition $b(s,s)=0$ and the transversality condition $\lim_{t\to\infty} b(t,s)\exp[-\int_s^t a(t',s)dt']=0$, we obtain the household's forward budget constraint:

$$b(t,s)=\int_t^\infty \left[c(t',s)-\big(1-h(s)\big)w(t')\right]\exp\left[-\int_t^{t'} a(t'',s)dt''\right]dt' \ . \tag{A.1}$$

Then, we can write the household's problem as

$$\begin{aligned}&\max_{\{c(t,s)\}_s^t,h(s)} \quad \int_s^\infty V(c(t,s))\exp[-(\rho+p(s))(t-s)]dt\\ &\text{s.t.} \quad b(s,s)=\int_s^\infty [c(t,s)-(1-h(s))w(t)]\exp\left[-\int_s^t a(t',s)dt'\right] dt \ .\end{aligned}$$

As $b(s,s)=0$, we can set-up the Lagrangian

$$\begin{aligned}\mathcal{L}=\int_s^\infty & V(c(t,s))\exp[-(\rho+p(s))(t-s)]\\ &-\lambda[c(t,s)-(1-h(s))w(t)]\exp\left[-\int_s^t a(t',s)dt'\right] dt \ .\end{aligned} \tag{A.2}$$

Taking the (Volterra) derivative with respect to $c(t,s)$, equating it with zero and solving for the Lagrange multiplier yields:

$$\lambda=V'(c(t,s))\exp\left[\int_s^t a(t',s)dt'-(\rho+p(s))(t-s)\right] \ . \tag{A.3}$$

Then, taking the derivative with respect to t of the logarithm of both sides of (A.3) yields the Euler equation, as shown in equation (7).

When the households take the annuity rate $a(t,s)$ as given, the derivative of the Lagrangian with respect to $h(s)$ together with equation (A.3) yields the first-order condition with respect to healthcare investments (8). In the case where annuity contracts are conditioned on healthcare investments, the households additionally consider the change in the annuity rate $a(t,s)=r(t)+p(s)$ when deciding on their healthcare levels. In this case the respective derivative of the Lagrangian combined with (A.3) gives the first-order condition for healthcare investments presented in equation (19).

The first-order conditions are not only necessary but also sufficient for an interior household optimum in the steady state. In case of annuity claims that are conditioned on healthcare expenditures the Lagrangian (A.2) is jointly concave in $c(t,s)$ and $h(s)$ in the steady state whenever the first-order conditions hold. As a consequence, any local extremum is a local maximum. As the Lagrangian is continuously differentiable this implies that there is only one local maximum, and, as corner solutions cannot be optimal, the local maximum is also the global maximum.

In case of unconditioned annuity claims we interpret the household problem as a two-step maximization problem. In the first step, we seek the optimal consumption paths in the steady state for a given healthcare expenditure $\bar{h}$. In the second step, we insert the optimal consumption paths in the household's lifetime utility function and maximize with respect to healthcare expenditures $\bar{h}$. Given the utility function (11), the Euler equation characterizing the household's optimal consumption path (7) reads

$$\frac{\dot{c}(t,s)}{c(t,s)} = \sigma\left[\bar{a}(\bar{h},\bar{p}) - \rho - \bar{p}\right] , \qquad t \geq s . \tag{A.4}$$

For given $\bar{h}$, saving and consumption by a household born at time s is uniquely characterized by the system of differential equations (6) and (A.4), the initial condition $b(s,s) = 0$ and the transversality condition for the stock of assets $\lim_{t\to\infty} b(t,s)\exp\left[-\bar{a}(\bar{h},\bar{p})(t-s)\right] = 0$. Under the assumptions that the propensity to consume out of wealth $x(\bar{h},\bar{p}) = (1-\sigma)\bar{a}(\bar{h},\bar{p}) + \sigma\big(\rho+\bar{p}\big) > 0$ and the long-run growth rate of wages $\bar{w}(\bar{h},t)$ is smaller than $\bar{a}(\bar{h},\bar{p})$,[30] we obtain for the optimal paths of consumption $c(t,s,\bar{h},\bar{p})$ and assets $b(t,s,\bar{h},\bar{p})$

$$c(t,s,\bar{h},\bar{p}) = c(s,\bar{h},\bar{p})\exp\left[\sigma\big(\bar{a}(\bar{h},\bar{p}) - \rho - \bar{p}\big)(t-s)\right] , \tag{A.5a}$$

$$b(t,s,\bar{h},\bar{p}) = \frac{c(t,s,\bar{h},\bar{p})}{x(\bar{h},\bar{p})} - \big(1-\bar{h}\big)W(t,\bar{h},\bar{p}) , \tag{A.5b}$$

$$c(s,\bar{h},\bar{p}) = x(\bar{h},\bar{p})\big(1-\bar{h}\big)W(s,\bar{h},\bar{p}) . \tag{A.5c}$$

where $W(t,\bar{h},\bar{p}) \equiv \int_t^\infty \bar{w}(\bar{h},t')\exp\left[-\bar{a}(\bar{h},\bar{p})(t'-t)\right]dt' = \bar{w}(\bar{h},t)/y(\bar{h},\bar{p})$ denotes the expected net present value of the household's future labor income at time t. As in steady state the wage rate grows at a constant rate $\bar{g}(\bar{h},\bar{p})$, we can write $W(t,\bar{h},\bar{p}) = \bar{w}(\bar{h},t)/y(\bar{h},\bar{p})$, where $y(\bar{h},\bar{p}) = \bar{a}(\bar{h},\bar{p}) - \bar{g}(\bar{h},\bar{p})$. Inserting the optimal consumption path into the household's lifetime utility function (4) and differentiating with respect to healthcare spending $h(s)$ yields:

$$FOC\big(\bar{h}\big) \equiv -\frac{c(s,\bar{h},\bar{p})^{1-\frac{1}{\sigma}}}{x(\bar{h},\bar{p})}\left[\frac{\sigma}{\sigma-1}\frac{H'\big(\bar{h}\big)}{x(\bar{h},\bar{p})} + \frac{1}{1-\bar{h}}\right] . \tag{A.6}$$

Then, the necessary condition for an interior household optimum is given by $FOC\big(\bar{h}\big) = 0$. Note that the corner solutions $\bar{h} = 1$ and $\bar{h} = 0$ cannot be optimal solutions. For $\bar{h} = 1$, consumption and lifetime utility would drop to zero, while both are positive for any value $\bar{h} \in [0,1)$. Regarding the corner solution $\bar{h} = 0$, we recall that $H'(\bar{h}) = -\beta\psi\bar{h}^{\beta-1}$ which will approach infinity when

[30] If these assumptions do not hold, the household's problem is not well defined. We shall see in Section A.4 that the condition that the long-run growth rate of wages $\bar{w}(\bar{h},t)$ is smaller than $\bar{a}(\bar{h},\bar{p})$ always holds in the market equilibrium.

$\bar{h} \to 0$. Thus, the benefits of a marginal investment in healthcare diverges while the costs in terms of lifetime utility stay finite. Hence only interior solutions $\bar{h} \in (0,1)$ can be optimal.

Taking the limits of $FOC(\bar{h})$ for $\bar{h} \to 0$ and $\bar{h} \to 1$, we obtain:

$$\lim_{\bar{h}\to 0} FOC(\bar{h}) = +\infty \ , \quad \lim_{\bar{h}\to 1} FOC(\bar{h}) = -\infty \ . \tag{A.7}$$

As $FOC(\bar{h})$ is continuously differentiable on $\bar{h} \in [0,1]$, there exists at least one $\bar{h}$, which is also a local maximum, that satisfies $FOC(\bar{h}) = 0$. However, there may be any odd number of $h(s) \in [0,1]$ that satisfy the first-order condition. To show that there exists a unique solution to $FOC(\bar{h}) = 0$ and, thus, the first-order condition is also sufficient for a household optimum, we re-arrange it to yield:

$$\psi[1 + h(s)(\beta + \sigma - 1)] = \frac{\sigma}{\sigma - 1} x_{max} h(s)^{1-\beta} \ , \tag{A.8}$$

where $x_{max} = (1-\sigma)\bar{a}(\bar{h},\bar{p}) + \sigma(\rho + p_{max})$ is the propensity to consume in case $\bar{h} = 0$. Thus, the first-order condition requires the intersection of a linear function with a power function, which can only have zero, one or two solutions $\bar{h} \in [0,1]$. As we already know that $FOC(\bar{h}) = 0$ can only have an odd number of solutions, this implies that $FOC(\bar{h}) = 0$ has a unique solution, which is also local maximum and, because corner solution cannot be optimal, is also the global maximum.

A.2 Social planner's welfare maximization problem

We consider a social planner that maximizes the welfare of all generations alive from time 0 to infinity. $\mathcal{V}(t)$ reflects aggregate welfare at time t and comprises the utilities of all persons alive at this time. The planner discounts the different generations' utilities with the rate ρ^s which we assume to be equal to the households' pure time preference rates ρ.[31]

$$\begin{aligned}
\max_{\{\{c(t,s)\}_{t=0}^{\infty}, h(s)\}_{s=0}^{\infty}} & \quad \int_0^\infty \mathcal{V}(t)dt, \\
\text{where } \mathcal{V}(t) &= \int_{-\infty}^{t} V\big(c(t,s)\big) \exp\left[-\big(\rho + p(s)\big)(t-s)\right] \exp[\nu s] \exp[-\rho^s s] ds, \\
\text{s.t. } p(s) &= H\big(h(s)\big), \\
N(t) &= \int_{-\infty}^{t} \exp[\nu s - p(s)(t-s)] ds, \\
L^H(t) &= \int_{-\infty}^{t} h(s) \exp[\nu s - p(s)(t-s)] ds, \\
N(t) &= L^F(t) + L^H(t), \\
\dot{K}(t) &= F(K(t), L^F(t), L^H(t)) - \delta K(t) - C(t),
\end{aligned}$$

[31] See, for example, Schneider et al. (2012) for a detailed discussion on the role of the relation of the households' time preference rates and the generational discount rate of the social planner.

$$C(t) \quad = \quad \int_{-\infty}^{t} c(t,s)\exp[\nu s - p(s)(t-s)]ds,$$

together with the initial conditions $\{h(s)\}_{-\infty}^{0}$ and $K(0) = K_0 > 0$.

In our context the planner's welfare maximization problem bears some particular difficulties that do not allow to use the standard set of tools from optimal control theory directly.[32] The first difficulty is that we have a double integral in the objective function: one integrating over time t and another over the households' birth-dates s. Second, we have integral constraints in the maximization problem that cannot be transformed into constraints without integrals via taking derivatives. The latter is mostly due to the assumption that healthcare investment decisions have to be taken at the beginning of an individual's life and adhered to throughout lifetime.

With respect to the double integral in the objective function, we can perceive the problem as one with two parts.[33] One part, the "inner problem", is concerned with maximizing welfare at each point in time t by choosing the intratemporal distribution of consumption $c(t,s)$ across the different cohorts of size $N(t,s)$ taking as given aggregate consumption $C(t)$ and the cohort sizes. The other part, the "outer problem", uses the optimal intratemporal distribution of consumption from the solution to the inner problem and determines the paths of aggregate consumption $C(t)$, aggregate capital $K(t)$ and the healthcare levels of the generations born at time t, and therefore the path of each cohort's size.

Using the definition of $N(t,s) = \exp[\nu s - p(s)(t-s)]$, we can re-write the social planner's objective function

$$\int_{0}^{\infty} \underbrace{\int_{-\infty}^{t} V\big(c(t,s)\big)N(t,s)\exp[(\rho-\rho^s)s]\,ds}_{\text{objective of inner problem}} \;\exp[-\rho t]\,dt. \tag{A.9}$$

We observe that the social planner's weight on the different generations' consumption at any time t, depends on the sizes of the generations and the difference between the households' time preference rate, ρ, and the generational weight of the social planner, ρ^s. As mentioned previously, we assume that $\rho^s = \rho$. In this case, the social planner optimally distributes consumption equally among all households alive in each period, i.e. $c(t,s) = \bar{c}(t)\ \forall s \le t$. A proof of this result will be provided upon request and can also be found – together with a general discussion of optimal intratemporal consumption profiles including the cases $\rho^s \neq \rho$ – in Schneider et al. (2012).

With this result of the inner problem, we now turn to the outer problem with the difficulty that the integrals in the constraints cannot be eliminated. The outer problem can be written as follows:

$$\max_{\{\{C(t)\}_{t=0}^{\infty},h(s)\}_{s=0}^{\infty}} \int_{0}^{\infty} V\big(\bar{c}(t)\big)N(t)\ \exp[-\rho t]\,dt$$

[32] Our approach to the problem is based on chapter 22 in Kamien and Schwartz (1991) and chapters 7.3 and 9.1 in Chiang (1992).

[33] This split is typically used in welfare analysis of continuous-time overlapping generations models (see, e.g., Calvo and Obstfeld (1988) or Schneider et al. (2012)).

$$
\begin{aligned}
\text{s.t. } p(s) &= H\big(h(s)\big),\\
N(t) &= N_0(t) + \int_0^t \exp[\nu s - p(s)(t-s)]ds,\\
L^H(t) &= L_0^H(t) + \int_0^t h(s)\exp[\nu s - p(s)(t-s)]ds,\\
N(t) &= L^F(t) + L^H(t),\\
K(t) &= K(0) + \int_0^t F(K(\hat{s}), L^F(\hat{s}), L^H(\hat{s})) - \delta K(\hat{s}) - C(\hat{s})\, d\hat{s},\\
C(t) &= \bar{c}(t)N(t).
\end{aligned}
$$

This problem differs from the initial statement of the planner's problem in two respects. First, we have included the solution to the inner maximization problem and we have written the constraints on the stock variables to isolate the part fixed by the initial conditions from the one that can be influenced by the control variables. Note that $N_0(t)$ is the number of households born before time 0 and still alive at time t. These cohort sizes cannot be influenced by the planners control $\{h(s)\}_0^\infty$ but are given via the initial condition $\{h(s)\}_{-\infty}^0$. Similarly for L_0^H, which characterizes the labor demand in healthcare by the individuals born before time 0.

We can now set up the Lagrangian:

$$
\begin{aligned}
\mathcal{L}^s = &\int_0^\infty V\left(\frac{C(t)}{N(t)}\right) N(t)\, \exp[-\rho t]dt\\
&+ \int_0^\infty \varphi(t)\left[N_0(t) - N(t) + \int_0^t \exp[\nu s - p(s)(t-s)]ds\right] dt\\
&+ \int_0^\infty \mu(t)\left[L_0^H(t) - L^H(t) + \int_0^t h(s)\exp[\nu s - p(s)(t-s)]ds\right] dt\\
&+ \int_0^\infty \gamma(t)\left[L^F(t) + L^H(t) - N(t)\right] dt\\
&+ \int_0^\infty \xi(t)\left[K(0) - K(t) + \int_0^t F(K(\hat{s}), L^F(\hat{s}), L^H(\hat{s})) - \delta K(\hat{s}) - C(\hat{s})\, d\hat{s}\right] dt
\end{aligned}
$$

The constraints in the Lagrangian, for example the one with μ as the Lagrangian multiplier, comprise a double integral that sums the healthcare labor employed at time t to satisfy the healthcare demand of all generations born after time 0 to time t. The outer integral sums the healthcare labor demand in each period t, weighted by the shadow price for healthcare labor, over the social planner's planning horizon from 0 to infinity. However, by the assumption that healthcare levels are decided upon at the beginning of life and fixed at this level from then onwards, the planner is less concerned about the aggregate healthcare labor costs at time t but rather about the entire healthcare labor costs of fixing a certain healthcare level at time t for the generation born at this point in time. To obtain these healthcare costs incurred by the generation born in t, we can exchange the order of integration in the respective constraints.

This allows us to re-write the Lagrangian as follows:

$$\mathcal{L}^s = \lim_{T\to\infty} \int_0^T H\big(C(t), h(t), K(t), N(t), L^H(t), L^F(t)\big)$$
$$+ \varphi(t)\,[N_0(t) - N(t)] + \mu(t)\,[L_0^H(t) - L^H(t)] + \gamma(t)\,\left[L^F(t) + L^H(t) - N(t)\right]$$
$$+ \xi(t)\,[K(0) - K(t)]\,dt$$

where

$$H\big(C(t), h(t), K(t), N(t), L^H(t), L^F(t)\big) =$$
$$V\left(\frac{C(t)}{N(t)}\right) N(t)\,\exp[-\rho t] + \int_t^\infty \varphi(s)\,N(s,t)\,ds + \int_t^\infty \mu(s)\,h(t)N(s,t)\,ds$$
$$+ \int_t^\infty \xi(s)\,\left[F(K(t), L^F(t), L^H(t)) - \delta K(t) - C(t)\right]\,ds\ .$$

We now approach the planner's problem with the tools from the calculus of variations, seeking the optimal paths of the variables $h(t), C(t), K(t), N(t), L^H(t)$ and $L^F(t)$. We indicate the optimal paths by a star and define the perturbations from the optimal paths by $z(t) = z^\star(t) + \varepsilon\, o_z(t)$. In this definition, z stands for the respective variable and o_z is an arbitrary function. For example, $C(t) = C^\star(t) + \varepsilon\, o_C(t)$ and similarly for the other control and state variables. In particular, we also define $T = T^\star + \varepsilon\Delta T$, which we need to derive the transversality conditions.[34] Both of our control variables $C(t)$ and $h(t)$ are bounded from below, as they must be non-negative.[35] However, corner solutions in the sense that $C(t) = 0$ or $h(t) = 0$ for at least some $t \in [0,\infty)$ cannot be optimal, as both marginal instantaneous utility and marginal healthcare productivity diverge for $C(t) \to 0$, respectively $h(t) \to 0$. As a consequence, we know that the social planner's optimum must satisfy the condition $\partial\mathcal{L}^s(\varepsilon)/\partial\varepsilon = 0$. Combined with some mathematical transformations, this yields the necessary conditions for a welfare maximum as depicted in equations (15) and (17).

We obtain the transversality conditions from the terms generated via the derivative of T with respect to ε:

$$\lim_{T\to\infty} H(T) = 0, \qquad \lim_{T\to\infty} \varphi(T)N(T) = 0, \qquad \lim_{T\to\infty} \mu(T)L^H(T) = 0, \qquad \lim_{T\to\infty} \xi(T)K(T) = 0\ .$$

A.3 Proof of Proposition 1

The proof comprises two steps: First we show that given a fixed level of healthcare spending of all households, $\bar{h}$, there is a unique equilibrium allocation supported by the prices stated in the proposition. Second, given these prices there exists a unique optimal choice of $\bar{h} \in (0,1)$ by the

[34]See, for example, Chiang (1992).

[35]Note that in the social planner problem $h(t)$, which indicates the healthcare spending of the cohort born at time t, is not bounded from above. In fact, as the social planner equally distributes aggregate consumption among all households alive, it is feasible to choose $h(t) > 1$ at least for some $t \in [0,\infty)$. However, aggregate healthcare spending $\int_{-\infty}^t h(s)N(t,s)ds$ must not exceed aggregate wage income $w(t)N(t)$. We do not have to explicitly check for this condition, as this would imply aggregate consumption to go to zero, which cannot be optimal because Inada conditions hold for the instantaneous utility function (11).

households.

Uniqueness of equilibrium prices given uniform healthcare investments

Assume that all households invest a share $\bar{h}$ of their labor income in healthcare. Then, the labor demand in the healthcare sector amounts to $L^H(t) = \bar{h} \int_{-\infty}^{t} N(t,s)\, ds = \bar{h}N(t)$. According to the labor market clearing condition, the supply of labor for consumption-good production is given by $L^F(t) = \big(1 - \bar{h}\big)N(t)$. This supply will only match the demand of the consumption-good production firms for the equilibrium wage rate given in Proposition 1, which reflects the marginal productivity of labor in consumption-good production at the point $\big(L^F(t), L^H(t)\big) = \big((1-\bar{h})N(t), \bar{h}N(t)\big)$.

With the unique split of labor between healthcare and consumption-good production, the marginal return on capital is then given by the interest rate, as stated in the Proposition. This expression can be derived from evaluating equation (2a) at the point $\big(L^F(t), L^H(t)\big) = \big((1-\bar{h})N(t), \bar{h}N(t)\big)$.

Next, we turn to the equilibrium in the annuity market. With all households choosing healthcare level $\bar{h}$, their hazard rate of dying will be $\bar{p} = H(\bar{h})$. This implies that $\dot{N}(t,s) = -\bar{p}N(t,s)$. Using this together with the constant interest rate $\bar{r}(\bar{h})$, as established previously, we can re-write the market clearing condition in the insurance market as

$$\int_{-\infty}^{t} a(t,s)b(t,s)N(t,s)ds = \int_{-\infty}^{t} (\bar{r}(\bar{h}) + \bar{p})b(t,s)N(t,s)ds. \tag{A.10}$$

It follows directly that the unique steady-state equilibrium annuity rate must be $\bar{a}(\bar{h},\bar{p}) = \bar{r}(\bar{h}) + \bar{p}$.

Finally, by virtue of Walras' law, also the consumption good market must clear given all other market clear. As already noted in the main text, we choose the consumption good as the numeraire. Consequently, for any given $\bar{h} \in (0,1)$ we obtain a unique market equilibrium supported by the prices provided in items 2–4 of Proposition 1.

Uniqueness of healthcare investments given equilibrium prices

We will now show that there is a unique household choice $\bar{h}$ given the previously derived equilibrium prices. Inserting the household's optimal consumption and saving paths as described by equations (A.5) into the necessary condition with respect to healthcare investments (8), we obtain the expression (12) in Proposition 1. As already discussed in Appendix A.1, the corner solutions $\bar{h} = 1$ and $\bar{h} = 0$ cannot be optimal solutions. As only an interior solution is possible, we can re-arrange (12) to yield

$$G(\bar{h}) := \frac{\sigma}{1-\sigma} H'(\bar{h})(1-\bar{h}) - x(\bar{h}, H(\bar{h})) = 0. \tag{A.11}$$

Note that regarding the second argument of x we used the definition $\bar{p} = H(\bar{h})$. We will now show that $G(\bar{h})$ is strictly decreasing in its argument, implying that there must be a unique $\bar{h}$ satisfying $G(\bar{h}) = 0$.

When taking the derivative $G(\bar{h})$ with respect to $\bar{h}$, we obtain

$$\frac{dG(\bar{h})}{d\bar{h}} = \frac{\sigma}{1-\sigma}H''(\bar{h})(1-\bar{h}) - \frac{\sigma}{1-\sigma}H'(\bar{h}) - \underbrace{(1-\sigma)\frac{d\bar{r}(\bar{h})}{d\bar{h}} - H'(\bar{h})}_{dx(\bar{h},H(\bar{h}))/d\bar{h}} . \tag{A.12}$$

The last summand in (A.12), $-H'(\bar{h})$ is the only one that is positive. However, since $\sigma > 1$ by assumption, it is smaller in magnitude than the second summand $-\frac{\sigma}{1-\sigma}H'(\bar{h})$ and consequently, we obtain $\frac{dG(\bar{h})}{d\bar{h}} < 0$. Therefore, there is a unique healthcare investment level $\bar{h}$ which maximizes the households utilities given the equilibrium prices as derived previously.

□

A.4 Proof of Proposition 2

In this section we will show that with the unique equilibrium prices and healthcare choices derived in the Proof of Proposition 1, the economy's steady state dynamics are governed by a unique balanced-growth path where aggregate consumption per capita and aggregate capital per capita grow at the same constant rate.

(i) Aggregate dynamics: To derive the aggregate system dynamics, we evaluate equation (A.5b) in the market equilibrium, aggregate according to equation (9) and differentiate with respect to t:

$$\dot{c}(t) = x(\bar{h},\bar{p})\left[\dot{k}(t) + (1-\bar{h})\dot{W}(t,\bar{h},\bar{p})\right] . \tag{A.13}$$

Recall that $W(t,\bar{h},\bar{p}) = \int_t^\infty \bar{w}(\bar{h},t')\exp[-(\bar{r}(\bar{h})+\bar{p})(t'-t)]\,dt'$ denotes the net present value of the household's future lifetime labor income in the steady-state equilibrium at time t. Evaluating the budget constraint in the market equilibrium and aggregating according to equation (9), we obtain

$$\dot{b}(t) = \left[r(\bar{h}) - \nu\right] b(t) + (1-\bar{h})\bar{w}(\bar{h},t) - c(t) . \tag{A.14}$$

Inserting $\dot{W}(t,\bar{h},\bar{p})$ and equation (A.14) into equation (A.13) yields equation (13a). We derive (13b) by inserting the equilibrium wage rate given in Proposition 1 into equation (A.14).

(ii) Balanced growth path: By contradiction, we prove that the dynamics of the economy is governed by a unique balanced-growth path (BGP) given a fixed healthcare level $\bar{h}$ implying a constant hazard rate $\bar{p}$.

We start by asserting two facts: First, there is a unique economically feasible ratio $c(t)/k(t)$ such that $\dot{c}(t)/c(t) \equiv g_c(t) = g_k(t) \equiv \dot{k}(t)/k(t)$. This follows from solving the equations of motion for $c(t)/k(t)$ given that $g_c(t) = g_k(t)$. As $x(\bar{h},\bar{p})(\bar{p}+\nu) > 0$ for all $\bar{p} > 0$, there is only one economically feasible solution (with $c(t)/k(t) > 0$)

$$\begin{aligned}\frac{c(t)}{k(t)} = \zeta \equiv & \frac{1}{2}\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu - \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\} \\ & + \frac{1}{2}\sqrt{\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu - \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\}^2 + 4x(\bar{h},\bar{p})(\bar{p}+\nu)} .\end{aligned} \tag{A.15}$$

Second, we observe in equations (13a) and (13b) that $g_c(t)$ is increasing in $c(t)/k(t)$ while $g_k(t)$ is decreasing in $c(t)/k(t)$.

Now suppose that $g_c(t) > g_k(t)$. According to the two facts above, this can only hold if $c(t)/k(t) > \zeta$. The condition $g_c(t) > g_k(t)$ then implies that $c(t)/k(t)$ further increases which in turn will increase the future gap between g_c and g_k, leading to $\lim_{t\to\infty} g_k(t) = -\infty$. By the same line of argument, the economy's dynamics imply for $g_k(t) > g_c(t)$ that $\lim_{t\to\infty} g_c(t) = -\infty$. As both cases yield economically infeasible solutions the only remaining possibility is $g_c(t) = g_k(t)$ implying $c(t)/k(t) = \zeta$. Since the latter ratio does not depend on time t and is unique, the economy must be on a unique BGP $g_c(t) = g_k(t)$ at all times. The BGP growth rate can be calculated by inserting (A.15) into $g_k(t) = \frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu - c(t)/k(t)$:

$$\begin{aligned}\bar{g}(\bar{h},\bar{p}) =& \frac{1}{2}\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu + \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\} \\ & - \frac{1}{2}\sqrt{\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu - \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\}^2 + 4x(\bar{h},\bar{p})(\bar{p}+\nu)}\ .\end{aligned} \tag{A.16}$$

After some minor manipulations, we obtain that the growth rate on the BGP, $\bar{g}(\bar{h},\bar{p})$, is positive if and only if $x(\bar{h},\bar{p})(\bar{p}+\nu) < \sigma(\bar{r}(\bar{h})-\rho)\big(\frac{\bar{r}(\bar{h})}{\alpha}+\frac{1-\alpha}{\alpha}\delta-\nu\big)$. Consequently, $\bar{g}(\bar{h},\bar{p}) < 0$ if $x(\bar{h},\bar{p})(\bar{p}+\nu) > \sigma(r(\bar{h})-\rho)\big(\frac{\bar{r}(\bar{h})}{\alpha}+\frac{1-\alpha}{\alpha}\delta-\nu\big)$ and $\bar{g}(\bar{h},\bar{p}) = 0$ if $x(\bar{h},\bar{p})(\bar{p}+\nu) = \sigma(\bar{r}(\bar{h})-\rho)\big(\frac{\bar{r}(\bar{h})}{\alpha}+\frac{1-\alpha}{\alpha}\delta-\nu\big)$.
□

A.5 Proof of Proposition 3

(i) Taking the derivative of the equilibrium interest rate yields

$$\frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}} = \alpha(1-\alpha)\left[\frac{1-\bar{h}}{1-\eta\bar{h}}\right]^{-\alpha}\frac{\eta-1}{(1-\eta\bar{h})^2} < 0\ . \tag{A.17}$$

Differentiating the equilibrium wage rate with respect to $\bar{h}$, we obtain

$$\frac{d\,\bar{w}(\bar{h},t)}{d\,\bar{h}} = w(\bar{h},t)\left[\frac{\alpha(1-\eta\bar{h}) + (1-\alpha)(1-\bar{h})\eta}{(1-\eta\bar{h})(1-\bar{h})}\right] > 0\ . \tag{A.18}$$

(ii) Aiming for concise yet clear notation, in the next two paragraphs we highlight the growth rates' dependence on the interest rate and on longevity while not explicitly indicating their dependence on $\bar{h}$. We can then re-write the steady state growth rate in the form

$$\bar{g}(\bar{r},\bar{p}) = z(\bar{r}) - \sqrt{z(\bar{r})^2 + m(\bar{r},\bar{p})} + g_{hh}(\bar{r})\ ,$$

where $z(\bar{r}) = \frac{1}{2}\left(\frac{\bar{r}}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu - g_{hh}(\bar{r})\right)$, $m(\bar{r},\bar{p}) = x(\bar{r})(\bar{p}+\nu)$ and $g_{hh}(\bar{r}) = \sigma(\bar{r}-\rho)$.

Taking the derivative with respect to $\bar{r}$, we obtain

$$\frac{d\,\bar{g}(\bar{r},\bar{p})}{d\,\bar{r}} = \frac{\partial\bar{g}(\bar{r},\bar{p})}{\partial z(\bar{r})}\frac{d\,z(\bar{r})}{d\,\bar{r}} + \frac{\partial\bar{g}(\bar{r},\bar{p})}{\partial m(\bar{r},\bar{p})}\frac{d\,m(\bar{r})}{d\,\bar{r}} + \frac{d\,g_{hh}}{d\,\bar{r}}\ , \tag{A.19}$$

where

$$
\begin{aligned}
\frac{\partial \bar{g}(\bar{r},\bar{p})}{\partial z(\bar{r})} &= 1-\frac{z(\bar{r})}{\sqrt{z(\bar{r})^2+m(\bar{r},\bar{p})}} > 0 \ , \\
\frac{d\,z(\bar{r})}{d\,\bar{r}} &= \frac{1}{2}\left(\frac{1}{\alpha}-\sigma\right) > 0 \quad \text{if} \quad \alpha < 1/\sigma \ , \\
\frac{\partial \bar{g}(\bar{r},\bar{p})}{\partial m(\bar{r},\bar{p})} &= -\frac{1}{\sqrt{z(\bar{r})^2+m(\bar{r},\bar{p})}} < 0 \ , \\
\frac{d\,m(\bar{r},\bar{p})}{d\,\bar{r}} &= (1-\sigma)(\bar{p}+\nu) < 0 \ , \\
\frac{d\,g_{hh}(\bar{r})}{d\,\bar{r}} &= \sigma > 0 \ .
\end{aligned}
$$

Note that if $z(\bar{r}) > 0$, the condition for $\frac{\partial \bar{g}(\bar{r},\bar{p})}{\partial z(\bar{r})} > 0$ reduces to $m(\bar{r},\bar{p}) > 0$, which must be the case as $x > 0$. From the signs of the different terms in $\frac{d\,\bar{g}(\bar{r},\bar{p})}{d\,\bar{r}}$, together with the assumption $\alpha < \frac{1}{\sigma}$, it follows that the steady state growth rate of the economy increases with the interest rate.

According to the previous paragraph, we obtain

$$
\frac{d\left(g_{hh}(\bar{r})-\bar{g}(\bar{r},\bar{p})\right)}{d\,\bar{r}} = -\frac{\partial \bar{g}(\bar{r},\bar{p})}{\partial z(\bar{r})}\frac{d\,z(\bar{r})}{d\,\bar{r}} - \frac{\partial \bar{g}(\bar{r},\bar{p})}{\partial m(\bar{r},\bar{p})}\frac{d\,m(\bar{r},\bar{p})}{d\,\bar{r}} \ . \tag{A.20}
$$

By virtue of the signs of the different derivatives, as derived above, we conclude that $\frac{d\,(g_{hh}(\bar{r})-\bar{g}(\bar{r},\bar{p}))}{d\,\bar{r}} < 0$.

(iii) For the direct effect of increased healthcare investments via higher life expectancy, which implies lower $\bar{p}$, we obtain

$$
\frac{\partial \bar{g}(\bar{r},\bar{p})}{\partial m(\bar{r},\bar{p})}\frac{d\,m(\bar{r},\bar{p})}{d\,\bar{p}}\frac{d\,\bar{p}}{d\,\bar{h}} > 0 \ , \tag{A.21}
$$

as

$$
\begin{aligned}
\frac{\partial \bar{g}(\bar{r},\bar{p})}{\partial m(\bar{r},\bar{p})}\frac{d\ m(\bar{r},\bar{p})}{d\ \bar{p}} &= -\frac{1}{\sqrt{z(\bar{r})^2+m(\bar{r},\bar{p})}}\big((\nu+\bar{p})+x(\bar{r},\bar{p})\big) < 0 \ , \\
\frac{d\ \bar{p}}{d\ \bar{h}} &= \frac{d\,H(\bar{h})}{d\,\bar{h}} = -\beta\psi\bar{h}^{\beta-1} < 0 \ .
\end{aligned}
$$

With respect to the indirect effect via the equilibrium interest rate, we know from (i) that $\frac{d\ \bar{r}}{d\ \bar{h}} < 0$ and from (ii) that $\frac{d\ \bar{g}(\bar{r},\bar{p})}{d\ \bar{r}} > 0$. Consequently, the indirect effect of an increasing healthcare sector on economic growth must be negative.

Inspecting the derivatives of $\bar{p}$ and $\bar{r}$ with respect to $\bar{h}$,

$$
\begin{aligned}
\frac{d\,\bar{p}}{d\,\bar{h}} &= \frac{d\,H(\bar{h})}{d\,\bar{h}} = -\beta\psi\bar{h}^{\beta-1} < 0 \ , \\
\frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}} &= \alpha(1-\alpha)\left[\frac{1-\bar{h}}{1-\eta\bar{h}}\right]^{-\alpha}\frac{\eta-1}{(1-\eta\bar{h})^2} < 0 \ ,
\end{aligned}
$$

we find that $\lim_{\bar{h}\to 0}\frac{d\,\bar{p}}{d\,\bar{h}} = -\infty$ and $\lim_{\bar{h}\to 1}\frac{d\,\bar{p}}{d\,\bar{h}} < 0$ but finite. By contrast, $\lim_{\bar{h}\to 0}\frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}} < 0$ but finite and $\lim_{h\to 1}\frac{d\,\bar{r}(\bar{h})}{d\,h}=-\infty$. The claim of the Proposition then follows from the limits $h\to 0$ and $h\to 1$ of both $\frac{d\bar{g}(\bar{r},\bar{p})}{d\bar{p}}$ and $\frac{d\bar{g}(\bar{r},\bar{p})}{d\bar{r}}$ being finite. This is the case as $\bar{p}$ and $\bar{r}(\bar{h})$ are finite and consequently the expressions $x(\bar{r},\bar{p})$, $z(\bar{r})$ and $m(\bar{r},\bar{p})$ must be finite, which implies that $\frac{d\bar{g}(\bar{r},\bar{p})}{d\bar{p}}$ and $\frac{d\bar{g}(\bar{r},\bar{p})}{d\bar{r}}$ are finite. □

A.6 Proof of Proposition 4

Existence of the equilibrium will be shown as follows. First, for any given level of $h<1$ we obtain an equilibrium in the labor market, capital market, the annuity market and the market for the consumption good with prices as given by Proposition 1. The equilibrium level of healthcare is pinned down by equation (20). As shown in the Proof of Proposition 5, for every h the function $\hat{G}(h)$ defined via (20),

$$\hat{G}(h)=\frac{\sigma}{1-\sigma}\frac{H'(h)}{x(h,H(h))}-\frac{1}{(1-h)}+H'(h)\left(\frac{1}{x(h,H(h))}-\frac{1}{y(h,H(h))}\right)$$

must be strictly lower than the function $G(h)$ representing the equilibrium condition on healthcare spending with unconditioned annuities,

$$G(h)=\frac{\sigma}{1-\sigma}\frac{H'(h)}{x(h,H(h))}-\frac{1}{(1-h)}.$$

We know from Proposition 1, that there is a unique $\bar{h}$ satisfying $G(\bar{h})=0$. At this $\bar{h}$, we must then have $\hat{G}(\bar{h})<0$. By continuity of $\hat{G}(h)$ and $\lim_{h\to 0}\hat{G}(h)\to\infty$, there exists a $0<\tilde{h}<\bar{h}$ satisfying $\hat{G}(\tilde{h})=0$. Note that $\lim_{h\to 0}\hat{G}(h)\to\infty$ follows from $\lim_{h\to 0}H'(h)\to-\infty$ and

$$\frac{\sigma}{1-\sigma}\frac{1}{x(h,H(h))}+\frac{1}{x(h,H(h))}-\frac{1}{y(h,H(h))}<0.$$

The interior solution $\tilde{h}$ constitutes a steady-state equilibrium in the economy with conditioned annuities.

Multiplying $\hat{G}(h)=0$ by $x(h,H(h))$ and $(1-h)$, with $h\in(0,1)$, and taking the derivative with respect to h yields

$$\begin{aligned}&\frac{1}{1-\sigma}H''(h)(1-h)-\frac{2-\sigma}{1-\sigma}H'(h)-(1-\sigma)\frac{d\,\bar{r}(h)}{d\,h}\\ -&\big(H''(h)(1-h)-H'(h)\big)\frac{x(h,H(h))}{y(h,H(h))}-H'(h)(1-h)\frac{d\,\frac{x(h,H(h))}{y(h,H(h))}}{d\,h}.\end{aligned}$$

We obtain uniqueness of $\tilde{h}$ if above's expression is negative. Given $\sigma<2$, all summands are negative except for the last one where the sign is determined by the sign of $d\,\frac{x(h,H(h))}{y(h,H(h))}/d\,h$. Hence, a sufficient condition for uniqueness is that $x(h,H(h))/y(h,H(h))$ declines in h. Unfortunately, we cannot generally show that this must be the case, as it depends on the particular parameter values. □

A.7 Proof of Proposition 5

The argument in this proof is that the additional term on the right-hand side of (20), which comes in when annuities are conditioned on healthcare investments, must be positive. This implies that the first-order condition with conditioned annuity rates is everywhere lower than that with unconditioned annuity rates. Consequently, any root of the first-order condition with conditioned annuity rates must be lower than that of its unconditioned annuity counterpart.

It is, thus, sufficient to show that

$$\begin{aligned} -H'(\bar{h})\left(\frac{1}{x(\bar{h},\bar{p})}-\frac{1}{y(\bar{h},\bar{p})}\right) &> 0\ , \\ \Leftrightarrow \quad y(\bar{h},\bar{p})-x(\bar{h},\bar{p}) &> 0\ , \\ \Leftrightarrow \quad \bar{g}(\bar{h},\bar{p})-g_{hh}(\bar{h}) &< 0\ . \end{aligned}$$

When transforming the first into the second condition, we used that $x(\bar{h},\bar{p}), y(\bar{h},\bar{p}) > 0$. Using the expression $\bar{g}(\bar{h},\bar{p}) = z(\bar{h}) - \sqrt{z(\bar{h})^2 + m(\bar{h},\bar{p})} + g_{hh}(\bar{h})$ as introduced in the Proof of Proposition 3, we obtain

$$\begin{aligned} \bar{g}(\bar{h},\bar{p})-g_{hh}(\bar{h}) = z(\bar{h})-\sqrt{z(\bar{h})^2+m(\bar{h},\bar{p})} &< 0 \\ \Leftrightarrow \quad m(\bar{h},\bar{p}) &> 0\ . \end{aligned}$$

As $m(\bar{h},\bar{p}) = x(\bar{h},\bar{p})(\bar{p}+\nu) > 0$, we conclude that $-H'(\bar{h})\big(\frac{1}{x(\bar{h},\bar{p})} - \frac{1}{y(\bar{h},\bar{p})}\big) > 0$, and hence there is over-investment in healthcare with unconditioned annuities. □

A.8 Proof of Proposition 6

(i) The equilibrium levels of healthcare expenditures are characterized by the first-order conditions (12) and (20). For the derivatives of the equilibrium healthcare level with respect to the technological parameters ψ and p_{max}, we obtain via the implicit function theorem

$$\frac{d\bar{h}}{d\chi} = -\frac{\frac{\partial FOC}{\partial \chi}}{\frac{\partial FOC}{\partial h}}, \tag{A.22}$$

where χ stands for either ψ or p_{max} and FOC for either the first-order condition in the case with unconditioned annuities (12) or the one with conditioned annuities (20).

We will now go through each of the four cases to determine the sign of the effect of improvements in the healthcare technology. Note that in each case, $\frac{\partial FOC}{\partial h} < 0$ according to the proof of the uniqueness of the steady-state equilibrium (see section A.1). Consequently, the sign of the derivatives of $\bar{h}$ with respect to the parameters z will be determined by the partial derivatives of the FOCs with respect to these parameters.

We start with the first order conditions in the case with unconditioned annuities, where the

FOC takes the form as in (12).

$$\frac{\partial FOC}{\partial \psi} = \frac{\sigma}{1-\sigma} \frac{\frac{\partial H'(\bar{h})}{\partial \psi} x(\bar{h}, \bar{p}) - H'(\bar{h}) \frac{\partial x(\bar{h},\bar{p})}{\partial \psi}}{x(\bar{h}, \bar{p})^2} .$$

With $\frac{\partial H'(\bar{h})}{\partial \psi} = -\beta \bar{h}^{\beta-1}$ and $\frac{\partial x(\bar{h},\bar{p})}{\partial \psi} = -\bar{h}^{\beta}$, we obtain $\frac{\partial FOC}{\partial \psi} > 0$ (note that $\sigma > 1$ and $H'(\bar{h}) < 0$) and consequently, $\frac{d\bar{h}}{d\psi} > 0$.

$$\frac{\partial FOC}{\partial p_{max}} = -\frac{\sigma}{1-\sigma} \frac{H'(\bar{h}) \frac{\partial x(\bar{h},\bar{p})}{\partial p_{max}}}{x(\bar{h}, \bar{p})^2} .$$

As $\frac{\partial x(\bar{h},\bar{p})}{\partial p_{max}} = 1$, we can conclude that $\frac{d\bar{h}}{dp_{max}} < 0$.

Now we turn to the case where annuities can be conditioned on healthcare investments and we use

$$\begin{aligned} FOC &= \frac{\sigma}{1-\sigma} \frac{H'(\bar{h})}{x(\bar{h}, \bar{p})} - \frac{1}{(1-\bar{h})} + H'(\bar{h}) \left(\frac{1}{x(\bar{h}, \bar{p})} - \frac{1}{y(\bar{h}, \bar{p})} \right) \\ &= \frac{1}{1-\sigma} \frac{H'(\bar{h})}{x(\bar{h}, \bar{p})} - \frac{1}{(1-\bar{h})} - H'(\bar{h}) \frac{1}{y(\bar{h}, \bar{p})} \end{aligned}$$

For the derivatives with respect to ψ and p_{max}, we obtain

$$\frac{\partial FOC}{\partial \psi} = \frac{1}{1-\sigma} \frac{\frac{\partial H'(\bar{h})}{\partial \psi} * x(\bar{h}, \bar{p}) - H'(\bar{h}) \frac{\partial x(\bar{h},\bar{p})}{\partial \psi}}{x(\bar{h}, \bar{p})^2} - \frac{\frac{\partial H'(\bar{h})}{\partial \psi} * y(\bar{h}, \bar{p}) - H'(\bar{h}) \frac{\partial y(\bar{h},\bar{p})}{\partial \psi}}{y(\bar{h}, \bar{p})^2} .$$

We have $\frac{\partial y(\bar{h},\bar{p})}{\partial \psi} = \frac{\partial \bar{p}}{\partial \psi} - \frac{\partial \bar{g}(\bar{h},\bar{p})}{\partial \bar{p}} \frac{\partial \bar{p}}{\partial \psi}$. As we show below under (ii), $\frac{\partial \bar{g}(\bar{h},\bar{p})}{\partial \bar{p}} < 0$. With $\frac{\partial \bar{p}}{\partial \psi} = -\bar{h}^{\beta}$, we infer $\frac{\partial y(\bar{h},\bar{p})}{\partial \psi} < 0$. It follows that $\frac{\partial FOC}{\partial \psi} > 0$ and $\frac{d\bar{h}}{d\psi} > 0$.

$$\frac{\partial FOC}{\partial p_{max}} = -\frac{1}{1-\sigma} \frac{H'(\bar{h}) \frac{\partial x(\bar{h},\bar{p})}{\partial p_{max}}}{x(\bar{h}, \bar{p})^2} + \frac{H'(\bar{h}) \frac{\partial y(\bar{h},\bar{p})}{\partial p_{max}}}{y(\bar{h}, \bar{p})^2} .$$

As $\frac{\partial \bar{p}}{\partial p_{max}} = 1$ and consequently $\frac{\partial y(\bar{h},\bar{p})}{\partial p_{max}} > 0$, we can conclude that $\frac{d\bar{h}}{dp_{max}} < 0$.

(ii) For the growth rate $\bar{g}(\bar{h}, \bar{p})$, we obtain

$$\frac{d\bar{g}(\bar{h}, \bar{p})}{d\psi} = \frac{\partial \bar{g}(\bar{h}, \bar{p})}{\partial \bar{p}} \frac{\partial \bar{p}}{\partial \psi} + \left[\frac{\partial \bar{g}(\bar{h}, \bar{p})}{\partial \bar{p}} \frac{d\,\bar{p}}{d\,\bar{h}} + \frac{\partial \bar{g}(\bar{h}, \bar{p})}{\partial \bar{r}(\bar{h})} \frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}} \right] \frac{d\,\bar{h}}{d\,\psi}. \tag{A.23}$$

The first summand reflects the direct effect of an increase of the productivity of healthcare investments without effects on healthcare spending. The second expression in brackets summarizes the effects of higher healthcare spending on economic growth multiplied by the increase in healthcare investments caused by the improvement in the healthcare technology. The direct effect of healthcare spending is positive and finite. To see this, recall from the Proof of Proposition 3 that $\frac{\partial \bar{g}(\bar{h},\bar{p})}{\partial \bar{p}} < 0$ and finite. Further we get $\frac{\partial \bar{p}}{\partial \psi} = -\bar{h}^{\beta} < 0$ if $\bar{h} > 0$ and with limit 0 for $\bar{h} \to 0$.

Regarding the second summand, we know that $\frac{d\,\bar{h}}{d\,\psi} > 0$ from part (i) in this proof. The term in brackets represents how the economy's growth rate responds to an increase in the healthcare sector, which is described in Proposition 3. As shown there, an increase in healthcare investments increases the growth rate at low levels of $\bar{h}$ but decreases it when $\bar{h}$ is sufficiently large, as $\lim_{\bar{h}\to 1} \frac{d\bar{r}(\bar{h})}{d\bar{h}} = -\infty$. Here we obtain that for $\bar{h}$ very close to zero, the first term representing the direct effect of healthcare improvements on the growth rate will vanish. Inferring from part (i) in this proof that $\frac{d\bar{h}}{d\psi}$ will not become 0, as $\bar{h}$ approaches 0, we conclude that the term in brackets imposes that the effect of an increase in ψ will be positive for $\bar{h}$ sufficiently small, but negative if $\bar{h}$ is sufficiently large.

We argue in a similar way regarding a change in p_{max}:

$$\frac{d\bar{g}(\bar{h},\bar{p})}{dp_{max}} = \frac{\partial\bar{g}(\bar{h},\bar{p})}{\partial\bar{p}}\frac{\partial\bar{p}}{\partial p_{max}} + \left[\frac{\partial\bar{g}(\bar{h},\bar{p})}{\partial\bar{p}}\frac{d\,\bar{p}}{d\,\bar{h}} + \frac{\partial\bar{g}(\bar{h},\bar{p})}{\partial\bar{r}(\bar{h})}\frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}}\right]\frac{d\,\bar{h}}{d\,p_{max}}\,. \tag{A.24}$$

The only difference is that $\frac{\partial\bar{p}}{\partial p_{max}} = 1$, which does not vanish for $\bar{h}$ approaching 0. This implies that there is also a positive direct effect of a decreasing p_{max} on the growth rate if $\bar{h}$ is small. But ultimately if $\bar{h}$ is sufficiently large, the overall effect of a decrease of p_{max} on the growth rate will turn negative. □

A.9 Details on the numerical simulations

We use OECD data on life expectancy at birth for the total population (females and males) and healthcare expenditures in % of GDP for the years 1980 and 2005. Data on GDP also stems from the OECD. We use GDP per capita at constant prices and constant purchasing power parity (OECD indicator HVPVOB) for the years 1980 to 2005. Out of the sample of all OECD countries we discard all countries for which any of this data is not available. The remaining sample consists of 21 OECD countries namely Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Iceland, Ireland, Japan, Korea, The Netherlands, New Zealand, Norway, Portugal, Spain, Switzerland, Turkey, UK and USA. To construct our "average" OECD country, we take the unweighted average for life expectancy at birth, healthcare expenditures in % of GDP and GDP per capita for both years 1980 and 2005. We then calculate the average growth rate of GDP per capita over these 26 years, which equals 2.05%.

In line with our endogenous growth model, we assume that increases in average lifetime stem from the interplay of improvements of the healthcare technology and the endogenous choice of healthcare spending. This implies that also the growth rate of the economy depends on the healthcare technology and the healthcare spending. In order to calibrate our steady state model to observed data of life expectancy and healthcare expenditures in 1985 and 2005, we employ the following procedure: Assume that from 1985 to 1997 the economy was in a steady state consistent with 1985 data and from 1998 to 2005 the economy experienced steady state growth consistent with 2005 data we calibrate a scaling parameter ϕ for the production function in our model such that the average growth rate of the economy over the 26 years equals the observed average GDP growth rate per capita of 2.05% per year.

For regime (a) for which we suppose that annuity claims cannot be conditioned on life expectancy and which we consider to be the observable status quo, we then calibrate the parameters p_{max} and ψ of the healthcare technology (1) by fixing η and β and assuming that observed healthcare expenditures in the steady-state equilibrium are given by equation (12) and observed lifetime expectancy is due to the healthcare technology and the healthcare expenditures. Given the observed healthcare expenditures and life expectancy, we also calculate the interest and the growth rates of the economy. Finally, we calculate the expected lifetime utility of an individual born at time $s = 0$ under regime (i) and (ii). To this end, we insert (A.5a), (A.5c), $\bar{a}(\bar{h}, \bar{p}) = \bar{r}(\bar{h}) + \bar{p}$ and $\bar{w}(\bar{h}, t) = w_0 \exp[\bar{g}(\bar{h}, \bar{p})t]$ into the household's expected utility function (4):

$$\bar{U}(k(0), \bar{h}, \bar{p}) = \frac{\sigma}{\sigma - 1} \left[\frac{\bar{w}(\bar{h}, 0)(1 - \bar{h})\bar{x}(\bar{h}, \bar{p})}{\bar{y}(\bar{h}, \bar{p})} \right]^{\frac{\sigma-1}{\sigma}} \frac{1}{\bar{x}(\bar{h}, \bar{p})} \; . \tag{A.25}$$

Comparing expected utilities between scenario (i) and (ii), we seek for the relative change in consumption θ at all times alive for which the household's expected utility in scenario (i) coincided with the household's expected utility in scenario (ii):[36]

$$\begin{aligned} &\frac{\sigma}{\sigma - 1} \left[(1 + \theta) \frac{\bar{w}(\bar{h}^{(i)}, 0)(1 - \bar{h}^{(i)})\bar{x}(\bar{h}^{(i)}, \bar{p}^{(i)})}{\bar{y}(\bar{h}^{(i)}, \bar{p}^{(i)})} \right]^{\frac{\sigma-1}{\sigma}} \frac{1}{\bar{x}(\bar{h}^{(i)}, \bar{p}^{(i)})} = \\ &\qquad \frac{\sigma}{\sigma - 1} \left[\frac{\bar{w}(\bar{h}^{(ii)}, 0)(1 - \bar{h}^{(ii)})\bar{x}(\bar{h}^{(ii)}, \bar{p}^{(ii)})}{\bar{y}(\bar{h}^{(ii)}, \bar{p}^{(ii)})} \right]^{\frac{\sigma-1}{\sigma}} \frac{1}{\bar{x}(\bar{h}^{(ii)}, \bar{p}^{(ii)})} \end{aligned} \tag{A.26}$$

Solving for θ yields

$$\theta = \frac{\bar{w}(\bar{h}^{(ii)}, 0)(1 - \bar{h}^{(ii)})\bar{y}(\bar{h}^{(i)}, \bar{p}^{(i)})}{\bar{w}(\bar{h}^{(i)}, 0)(1 - \bar{h}^{(i)})\bar{y}(\bar{h}^{(ii)}, \bar{p}^{(ii)})} \left[\frac{\bar{x}(\bar{h}^{(i)}, \bar{p}^{(i)})}{\bar{x}(\bar{h}^{(ii)}, \bar{p}^{(ii)})} \right]^{\frac{1}{\sigma-1}} - 1 \tag{A.27}$$

For regime (b) in which we suppose that annuity claims are contingent on life expectancy respectively healthcare expecnditures and which we consider the hypothetical regime, we employ the same healthcare technology employed under regime (a) and calculate the resulting healthcare expenditures in the steady-state equilibrium according to equation (20) and the corresponding expected lifetime. The steady state growth and interest rates follow from inserting $\bar{h}$ and $\bar{p}$ into $\bar{g}(\bar{h}, \bar{p})$ and $\bar{r}(\bar{h})$. Again we calculate the difference in lifetime utility betwenn scenario (i) and (ii) according to equation (A.27).

To compare regimes (a) and (b), we decompose the difference in lifetime utility in three parts. To this end, we first differentiate expected lifetime utility (A.25) with respect to $\bar{h}$. Taking into account that $\bar{w}(\bar{h}, 0) = k(0)\frac{1-\alpha}{1-\bar{h}} \left[\frac{1-\bar{h}}{1-\eta\bar{h}}\right]^{1-\alpha}$, $\bar{x}(\bar{h}, \bar{p}) = (1 - \sigma)\bar{r}(\bar{h}) + \bar{p} - \sigma\rho$ and $\bar{y} = \bar{r}(\bar{h}) + \bar{p} - \bar{g}(\bar{h}, \bar{p})$ we obtain:[37]

$$\frac{d\bar{U}(k(0), \bar{h}, \bar{p})}{d\bar{h}} = \left\{ \frac{\sigma - 1}{\sigma} \frac{1}{\bar{y}} \frac{d\bar{g}}{d\bar{h}} \right. \tag{A.28a}$$

[36] See also Jones and Klenow (2010), who use a similar approach.

[37] For presentational convenience we drop the arguments of $\bar{x}$, $\bar{y}$, $\bar{g}$ and $\bar{r}$.

$$+\left[\frac{\sigma-1}{\sigma}\left(\frac{1-(1-\alpha)\frac{1-\eta}{1-\eta\bar{h}}}{1-\bar{h}}-\left[\frac{1}{\bar{y}}+\frac{\sigma-1}{\bar{x}}\right]\frac{d\bar{r}}{d\bar{h}}\right)+\frac{\sigma-1}{\bar{x}}\frac{d\bar{r}}{d\bar{h}}\right] \tag{A.28b}$$

$$+\left[\frac{\sigma-1}{\sigma}\left(\left[\frac{1}{\bar{x}}-\frac{1}{\bar{y}}\right]\frac{d\bar{p}}{d\bar{h}}-\frac{1}{1-\bar{h}}\right)-\frac{1}{\bar{x}}\frac{d\bar{p}}{d\bar{h}}\right]\Bigg\} \ . \tag{A.28c}$$

Thus, the first line (A.28a) corresponds to changes in utility due to a change in $\bar{h}$ which stem from a change in the growth rate. The second line (A.28b) denotes changes in utility stemming from changes in the wage and interest rates, and the third line (A.28c) denote changes in utility corresponding to changes in mortality and the direct effect of higher healthcare spendings. We denote the effects in the third line as the direct microeconomic effects stemming from the individual behavior of the household, the effects in the second line as general equilibrium effects stemming from changes in the market equilibria of capital and labor and the first line as the growth effect induced by a change in the economy's growth rate.

Allowing for non-marginal changes in $\bar{h}$ we re-write equation (A.28) to yield:

$$\begin{aligned}\bar{U}(k(0),\bar{h},\bar{p})^{(ii)}-\bar{U}(k(0),\bar{h},\bar{p})^{(i)}=&\Bigg\{\frac{\sigma-1}{\sigma}\frac{1}{\bar{y}}\Delta\bar{g}\\&+\left[\frac{\sigma-1}{\sigma}\left(\frac{1-(1-\alpha)\frac{1-\eta}{1-\eta\bar{h}}}{1-\bar{h}}\Delta\bar{h}-\left[\frac{1}{\bar{y}}+\frac{\sigma-1}{\bar{x}}\right]\Delta\bar{r}\right)+\frac{\sigma-1}{\bar{x}}\Delta\bar{r}\right]\\&+\left[\frac{\sigma-1}{\sigma}\left(\left[\frac{1}{\bar{x}}-\frac{1}{\bar{y}}\right]\Delta\bar{p}-\frac{1}{1-\bar{h}}\Delta\bar{h}\right)-\frac{1}{\bar{x}}\Delta\bar{p}\right]\Bigg\} \ .\end{aligned} \tag{A.29}$$

Then, we obtain:

$$U_{direct}^{(ii)}-U_{direct}^{(i)}=\frac{\sigma-1}{\sigma}\left(\left[\frac{1}{\bar{x}}-\frac{1}{\bar{y}}\right]\Delta\bar{p}-\frac{1}{1-\bar{h}}\Delta\bar{h}\right)-\frac{1}{\bar{x}}\Delta\bar{p} \ , \tag{A.30a}$$

$$\Delta U_{equil}^{(ii)}-\Delta U_{equil}^{(i)}=\frac{\sigma-1}{\sigma}\left(\frac{1-(1-\alpha)\frac{1-\eta}{1-\eta\bar{h}}}{1-\bar{h}}\Delta\bar{h}-\left[\frac{1}{\bar{y}}+\frac{\sigma-1}{\bar{x}}\right]\Delta\bar{r}\right)+\frac{\sigma-1}{\bar{x}}\Delta\bar{r} \ , \tag{A.30b}$$

$$\Delta U_{growth}^{(ii)}-\Delta U_{growth}^{(i)}=\frac{\sigma-1}{\sigma}\frac{1}{\bar{y}}\Delta\bar{g} \ . \tag{A.30c}$$

By switching from regime (a) to regime (b), U_{direct} unambiguously increases. The reason is that in regime (b) the household chooses $\bar{h}$ such as to maximize U_{direct}. By definition, any deviation from this optimum can only result in lower expected lifetime utility levels. U_{equil} may either increase or decrease by a switch from regime (a) to regime (b). While the term in parenthesis in equation (A.30b), which equals the initial consumption at the time of birth, is unambiguously positive, the last term, denoting the growth rate of individual household consumption, is unambiguously negative. As a consequence the total effect may be either positive or negative. According to Proposition 6 (iii) U_{growth} increases by a switch from regime (a) to regime (b) for small levels of healthcare expenditures and increases for large levels. Expressing changes in utility according to equation (A.27) yields ΔU_{direct}, ΔU_{equil} and ΔU_{growth} as shown in Tables 2–4.

To check the qualitative and quantitative robustness of our baseline simulation, the results of which are shown in Table 2, we run a series of sensitivity analysis. In particular the spillover parameter η and the curvature parameter β of the healthcare technology cannot be observed directly, yet they may crucially influence the results. The spillover parameter η can be approximately interpreted as a reduction in the labor costs of healthcare due to productivity increases of increased longevity in the consumption good sector. While we do believe there are some positive spillovers from better healthcare to consumption production, for example, because employees are less often ill, we do not believe that these spillovers can be arbitrarily large.[38] As an educated guess we employ $\eta = 0.15$ in our baseline scenario and run a sensitivity analysis between 0 and 0.3. Table 3 shows the results. We observe that a variation in η has very little influence on the calibration of the healthcare technology and also hardly changes the steady state interest and growth rates. However, the utility gain from switching from scenario (i) to scenario (ii) and switching from regime (a) to regime (b) do modestly depend on the choice of η. We find that depending on the scenario and the parameter value of η eliminating moral hazard due to contingent annuity claims induces an expected lifetime utility gain between 1% and 2%. The parameter β of the healthcare technology determines the degree of diminishing returns to investments in healthcare. Table 4 shows the results of a sensitivity analysis were β covers the range between 0.5 and 1. We observe that for increasing β healthcare improvements between scenarios (i) and (ii) increasingly stem from changes in p_{max} and less and less from improvements in ψ. As a consequence, healthcare expenditures become more and more inefficient with respect to improving life expectancy. As a consequence, the reduction in healthcare expenditures and, thus, also the utility gain from switching between regime (a) and regime (b) becomes increasingly larger amounting to over 4% in the case of a linear healthcare technology ($\beta = 1$).

Changes in the depreciation rate of capital in the range of 5% to 10% shows very little impact on our results, as can be seen in Table 5. The main impact is on the expected lifetime utility gain by switching to the better healthcare technology (switch from scenario (i) to scenario (ii)). The impact on the expected lifetime utility by switching from regime (a) to regime (b), however, is rather modest. Values range, depending on the scenario and the parameter value of δ, between 1.41% and 1.85%. Finally, we run a sensitivity analysis over reasonable vales for the income share of capital α ranging between 0.35 and 0.65. As we employ data on healthcare expenditures in percentage of GDP but in our model healthcare expenditures are measured in percentage of labor income, an increase in α also increases the observed healthcare expenditures h. In order to match observed life expectancy, the calibration of the healthcare technology results in higher values of p_{max} and lower values of ψ for increasing capital income share α. However, the effects on interest and growth rates and the expected utility gain from switching to a better healthcare technology are very small. Depending on the scenario and the parameter value of α, the expected utility gains from eliminating moral hazard due to contingent annuity claims induces an expected lifetime utility gain between 0.87% and 1.90%.

To further scrutinize the moral-hazard effect of annuity claims that cannot be conditioned

[38] Recall that in our model a spillover parameter of $\eta = 1$ implies that shifting labor from production to healthcare is without any loss in consumption-good production, which is obviously an unrealistic assumption.

η	0	0.05	0.1	0.15	0.2	0.25	0.3
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4418, 1.3664)$	$(1.4419, 1.3664)$	$(1.4419, 1.3663)$	$(1.4420, 1.3662)$	$(1.4420, 1.3661)$	$(1.4421, 1.3660)$	$(1.4421, 1.3660)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.6015, 0.6678)$	$(0.6019, 0.6674)$	$(0.6023, 0.6669)$	$(0.6028, 0.6664)$	$(0.6032, 0.6659)$	$(0.6036, 0.6654)$	$(0.6041, 0.6649)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.62, 3.47)$	$(3.62, 3.47)$	$(3.61, 3.47)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.60, 3.48)$	$(3.60, 3.49)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.15, 1.95)$	$(2.15, 1.95)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.13, 1.97)$	$(2.13, 1.97)$	$(2.12, 1.98)$
$\Delta U_{(i)\to(ii)}$ [%]	3.01	3.52	4.03	4.55	5.08	5.62	6.16
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(5.56, 8.06)$	$(5.55, 8.06)$	$(5.55, 8.05)$	$(5.54, 8.04)$	$(5.54, 8.04)$	$(5.53, 8.03)$	$(5.53, 8.02)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.84, 79.03)$	$(72.83, 79.03)$	$(72.83, 79.02)$	$(72.83, 79.02)$	$(72.82, 79.01)$	$(72.82, 79.01)$	$(72.82, 79.00)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.65, 3.50)$	$(3.65, 3.51)$	$(3.64, 3.51)$	$(3.64, 3.51)$	$(3.63, 3.51)$	$(3.63, 3.52)$	$(3.62, 3.52)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.20, 2.00)$	$(2.20, 2.01)$	$(2.19, 2.01)$	$(2.18, 2.01)$	$(2.17, 2.02)$	$(2.16, 2.02)$	$(2.16, 2.02)$
$\Delta U_{(i)\to(ii)}$ [%]	3.34	3.84	4.35	4.86	5.38	5.90	6.43
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(1.57, 1.90)$	$(1.48, 1.80)$	$(1.38, 1.69)$	$(1.29, 1.58)$	$(1.19, 1.47)$	$(1.09, 1.36)$	$(0.98, 1.24)$
ΔU_{direct} [%]	$(0.011, 0.013)$	$(0.011, 0.013)$	$(0.011, 0.013)$	$(0.011, 0.013)$	$(0.011, 0.013)$	$(0.011, 0.014)$	$(0.011, 0.014)$
ΔU_{equil} [%]	$(-0.154, -0.193)$	$(-0.176, -0.219)$	$(-0.199, -0.245)$	$(-0.221, -0.273)$	$(-0.245, -0.301)$	$(-0.269, -0.330)$	$(-0.293, -0.359)$
ΔU_{growth} [%]	$(1.72, 2.08)$	$(1.64, 2.00)$	$(1.57, 1.92)$	$(1.50, 1.84)$	$(1.42, 1.76)$	$(1.34, 1.67)$	$(1.26, 1.58)$

Table 3: Sensitivity analysis with respect to the spillover parameter η.

β	0.5	0.6	0.7	0.75	0.8	0.9	1
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4790, 1.4196)$	$(1.4605, 1.3929)$	$(1.4473, 1.3738)$	$(1.4420, 1.3662)$	$(1.4374, 1.3595)$	$(1.4296, 1.3484)$	$(1.4235, 1.3395)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.4493, 0.5429)$	$(0.4953, 0.5775)$	$(0.5615, 0.6319)$	$(0.6028, 0.6664)$	$(0.6499, 0.7059)$	$(0.7641, 0.8010)$	$(0.9097, 0.9203)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$
$\Delta U_{(i)\to(ii)}$ [%]	4.55	4.55	4.55	4.55	4.55	4.55	4.55
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(5.77, 8.29)$	$(5.71, 8.22)$	$(5.61, 8.12)$	$(5.54, 8.04)$	$(5.45, 7.95)$	$(5.14, 7.65)$	$(4.11, 6.91)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.94, 79.16)$	$(72.91, 79.12)$	$(72.86, 79.06)$	$(72.83, 79.02)$	$(72.78, 78.96)$	$(72.63, 78.79)$	$(72.15, 78.37)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.63, 3.50)$	$(3.63, 3.50)$	$(3.64, 3.51)$	$(3.64, 3.51)$	$(3.64, 3.52)$	$(3.66, 3.53)$	$(3.71, 3.57)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.16, 1.99)$	$(2.17, 2.00)$	$(2.18, 2.01)$	$(2.18, 2.01)$	$(2.19, 2.02)$	$(2.21, 2.04)$	$(2.29, 2.10)$
$\Delta U_{(i)\to(ii)}$ [%]	4.78	4.81	4.84	4.86	4.88	4.87	4.26
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(0.76, 0.98)$	$(0.91, 1.15)$	$(1.13, 1.41)$	$(1.29, 1.58)$	$(1.50, 1.81)$	$(2.23, 2.54)$	$(4.68, 4.39)$
ΔU_{direct} [%]	$(0.006, 0.008)$	$(0.008, 0.009)$	$(0.010, 0.012)$	$(0.011, 0.013)$	$(0.014, 0.016)$	$(0.022, 0.024)$	$(0.054, 0.047)$
ΔU_{equil} [%]	$(-0.133, -0.172)$	$(-0.158, -0.202)$	$(-0.195, -0.244)$	$(-0.221, -0.273)$	$(-0.256, -0.309)$	$(-0.371, -0.423)$	$(-0.713, -0.684)$
ΔU_{growth} [%]	$(0.89, 1.14)$	$(1.06, 1.35)$	$(1.31, 1.64)$	$(1.50, 1.84)$	$(1.74, 2.10)$	$(2.58, 2.94)$	$(5.34, 5.03)$

Table 4: Sensitivity analysis with respect to the curvature β of the healthcare technology.

δ [%]	5	6	7	7.5	8	9	10
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p_{max}^{(i)}, p_{max}^{(ii)})$ [%]	$(1.4416, 1.3650)$	$(1.4418, 1.3655)$	$(1.4419, 1.3660)$	$(1.4420, 1.3662)$	$(1.4420, 1.3664)$	$(1.4421, 1.3668)$	$(1.4422, 1.3671)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.5997, 0.6591)$	$(0.6012, 0.6623)$	$(0.6023, 0.6651)$	$(0.6028, 0.6664)$	$(0.6032, 0.6676)$	$(0.6038, 0.6700)$	$(0.6043, 0.6721)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.64, 3.53)$	$(3.62, 3.51)$	$(3.61, 3.49)$	$(3.61, 3.48)$	$(3.61, 3.47)$	$(3.60, 3.45)$	$(3.60, 3.43)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.11, 1.99)$	$(2.12, 1.98)$	$(2.13, 1.97)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.15, 1.95)$	$(2.16, 1.94)$
$\Delta U_{(i)\to(ii)}$ [%]	6.61	5.77	4.96	4.55	4.16	3.38	2.61
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(5.41, 7.87)$	$(5.47, 7.95)$	$(5.52, 8.01)$	$(5.54, 8.04)$	$(5.57, 8.07)$	$(5.61, 8.12)$	$(5.64, 8.17)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.76, 78.92)$	$(72.79, 78.96)$	$(72.82, 79.00)$	$(72.83, 79.02)$	$(72.84, 79.03)$	$(72.86, 79.06)$	$(72.88, 79.09)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.66, 3.57)$	$(3.65, 3.54)$	$(3.64, 3.52)$	$(3.64, 3.51)$	$(3.64, 3.50)$	$(3.63, 3.48)$	$(3.63, 3.47)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.15, 2.04)$	$(2.16, 2.03)$	$(2.17, 2.02)$	$(2.18, 2.01)$	$(2.19, 2.01)$	$(2.20, 2.00)$	$(2.21, 1.99)$
$\Delta U_{(i)\to(ii)}$ [%]	6.92	6.09	5.27	4.86	4.46	3.67	2.89
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(1.14, 1.44)$	$(1.21, 1.51)$	$(1.26, 1.56)$	$(1.29, 1.58)$	$(1.31, 1.60)$	$(1.34, 1.63)$	$(1.37, 1.65)$
ΔU_{direct} [%]	$(0.017, 0.020)$	$(0.014, 0.017)$	$(0.012, 0.014)$	$(0.011, 0.013)$	$(0.011, 0.012)$	$(0.009, 0.011)$	$(0.008, 0.010)$
ΔU_{equil} [%]	$(-0.286, -0.356)$	$(-0.257, -0.318)$	$(-0.232, -0.287)$	$(-0.221, -0.273)$	$(-0.211, -0.260)$	$(-0.193, -0.237)$	$(-0.177, -0.217)$
ΔU_{growth} [%]	$(1.41, 1.78)$	$(1.45, 1.81)$	$(1.48, 1.84)$	$(1.50, 1.84)$	$(1.51, 1.85)$	$(1.52, 1.85)$	$(1.54, 1.85)$

Table 5: Sensitivity analysis with respect to the capital depreciation rate δ.

α	0.35	0.4	0.45	0.5	0.55	0.6	0.65
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(4.69, 6.69)$	$(5.08, 7.25)$	$(5.55, 7.91)$	$(6.10, 8.70)$	$(6.78, 9.67)$	$(7.62, 10.87)$	$(8.71, 12.43)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4249, 1.3409)$	$(1.4296, 1.3479)$	$(1.4352, 1.3562)$	$(1.4420, 1.3662)$	$(1.4503, 1.3786)$	$(1.4607, 1.3944)$	$(1.4743, 1.4151)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.5644, 0.6194)$	$(0.5757, 0.6331)$	$(0.5884, 0.6486)$	$(0.6028, 0.6664)$	$(0.6194, 0.6873)$	$(0.6391, 0.7125)$	$(0.6630, 0.7437)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.54, 3.41)$	$(3.56, 3.43)$	$(3.58, 3.45)$	$(3.61, 3.48)$	$(3.64, 3.51)$	$(3.68, 3.54)$	$(3.72, 3.58)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$
$\Delta U_{(i)\to(ii)}$ [%]	4.42	4.47	4.51	4.55	4.59	4.62	4.62
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(4.43, 6.37)$	$(4.74, 6.84)$	$(5.11, 7.39)$	$(5.54, 8.04)$	$(6.07, 8.84)$	$(6.72, 9.82)$	$(7.56, 11.08)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.97, 79.22)$	$(72.93, 79.16)$	$(72.89, 79.10)$	$(72.83, 79.02)$	$(72.75, 78.91)$	$(72.66, 78.78)$	$(72.53, 78.60)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.55, 3.43)$	$(3.58, 3.45)$	$(3.61, 3.48)$	$(3.64, 3.51)$	$(3.68, 3.55)$	$(3.72, 3.59)$	$(3.77, 3.63)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.17, 1.99)$	$(2.17, 2.00)$	$(2.18, 2.01)$	$(2.18, 2.01)$	$(2.19, 2.02)$	$(2.19, 2.03)$	$(2.20, 2.04)$
$\Delta U_{(i)\to(ii)}$ [%]	4.62	4.70	4.78	4.86	4.93	4.98	5.00
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(0.87, 1.06)$	$(1.01, 1.24)$	$(1.15, 1.41)$	$(1.29, 1.58)$	$(1.41, 1.74)$	$(1.50, 1.85)$	$(1.54, 1.90)$
ΔU_{direct} [%]	$(0.003, 0.004)$	$(0.005, 0.006)$	$(0.008, 0.009)$	$(0.011, 0.013)$	$(0.017, 0.020)$	$(0.025, 0.030)$	$(0.038, 0.044)$
ΔU_{equil} [%]	$(-0.082, -0.101)$	$(-0.115, -0.142)$	$(-0.160, -0.197)$	$(-0.221, -0.273)$	$(-0.307, -0.377)$	$(-0.427, -0.525)$	$(-0.601, -0.737)$
ΔU_{growth} [%]	$(0.94, 1.16)$	$(1.12, 1.38)$	$(1.30, 1.60)$	$(1.50, 1.84)$	$(1.70, 2.09)$	$(1.90, 2.35)$	$(2.10, 2.60)$

Table 6: Sensitivity analysis with respect to the income share of capital α.

	Scenario (i) $T = 73.1\,[a]$ $h = 6.1\,[\%]$	Scenario (ii) $T = 79.4\,[a]$ $h = 8.7\,[\%]$
Regime (a)		
$p_{max}\,[\%]$	1.4228	1.3387
$\psi\,[\%]$	0.4462	0.4949
$r\,[\%]$	4.31	4.17
$g\,[\%]$	2.10	2.00
$\Delta U_{(i)\to(ii)}\,[\%]$	6.61	
Regime (b)		
$h\,[\%]$	4.15	6.32
$T\,[a]$	72.37	78.35
$r\,[\%]$	4.42	4.30
$g\,[\%]$	2.24	2.18
$\Delta U_{(i)\to(ii)}\,[\%]$	8.10	
Comparison regime (a) $\to$ (b)		
$\Delta U_{(a)\to(b)}\,[\%]$	5.22	6.69
$\Delta U_{direct}\,[\%]$	0.434	0.534
$\Delta U_{equil}\,[\%]$	0.731	0.887
$\Delta U_{growth}\,[\%]$	4.05	5.27

Table 7: Utility gains for a hypothetical average OECD country for improvements in the healthcare technology and switching from unconditioned to a contingent annuity claims regime in case of internalized learning-by-investing externality and spillovers from healthcare to consumption-good production.

on healthcare investments we run an additional numerical simulation in which we internalize the Romer (1986) learning-by-investing externality and the spillover effect from healthcare investments on consumption-good production. This hypothetical scenario illustrates the quantitative effect of the moral-hazard effect of unconditioned annuities without any interactions with the two other externalities. Table 7 shows the results for the reference parameter values, i.e., $\alpha = 0.5$, $\delta = 7.5\%$, $\beta = 0.75$ and $\eta = 0.15$. We find that the welfare loss due to the moral-hazard effect of unconditioned annuities is substantially larger compared to the results in Table 2 where we did not internalize the other two externalities: 5.22% in scenario (i) and 6.69% in scenario (ii). The reason is that the return on capital is more sensitive to changes in healthcare investments if the learning-by-investing externality is internalized. As a consequence, the opportunity costs of healthcare investments in terms of reducing the return on capital are higher than without internaliziation of the learning-by-investing externality. We also find that now the direct effect ΔU_{direct} is higher and of comparable size to the equilibrium effect ΔU_{equil}, which itself is now negative. Again, we find that the results are very robust over the whole parameter range of our sensitivity analyses.

Running a sensitivity analysis over the same range of parameter values as in the reference specification, we find that – again – results are qualitatively and quantitatively robust, as shown in Tables 8–11.

η	0	0.05	0.1	0.15	0.2	0.25	0.3
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p_{max}^{(i)}, p_{max}^{(ii)})$ [%]	$(1.4317, 1.3517)$	$(1.4287, 1.3474)$	$(1.4258, 1.3431)$	$(1.4228, 1.3387)$	$(1.4197, 1.3343)$	$(1.4167, 1.3299)$	$(1.4136, 1.3254)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.5188, 0.5762)$	$(0.4948, 0.5493)$	$(0.4706, 0.5222)$	$(0.4462, 0.4949)$	$(0.4216, 0.4674)$	$(0.3969, 0.4398)$	$(0.3719, 0.4119)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.32, 4.16)$	$(4.32, 4.16)$	$(4.32, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.18)$	$(4.31, 4.18)$	$(4.30, 4.18)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.12, 1.98)$	$(2.11, 1.99)$	$(2.11, 1.99)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.09, 2.01)$	$(2.08, 2.02)$
$\Delta U_{(i)\to(ii)}$ [%]	4.94	5.49	6.05	6.61	7.18	7.77	8.35
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(4.13, 6.28)$	$(4.13, 6.30)$	$(4.14, 6.31)$	$(4.15, 6.32)$	$(4.16, 6.34)$	$(4.17, 6.35)$	$(4.18, 6.37)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.25, 78.16)$	$(72.29, 78.22)$	$(72.33, 78.29)$	$(72.37, 78.35)$	$(72.42, 78.41)$	$(72.46, 78.48)$	$(72.50, 78.54)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.45, 4.31)$	$(4.44, 4.31)$	$(4.43, 4.31)$	$(4.42, 4.30)$	$(4.41, 4.30)$	$(4.40, 4.29)$	$(4.39, 4.29)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.29, 2.19)$	$(2.27, 2.19)$	$(2.26, 2.18)$	$(2.24, 2.18)$	$(2.23, 2.17)$	$(2.22, 2.17)$	$(2.20, 2.16)$
$\Delta U_{(i)\to(ii)}$ [%]	6.63	7.12	7.61	8.10	8.60	9.11	9.62
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(6.24, 7.95)$	$(5.89, 7.53)$	$(5.55, 7.11)$	$(5.22, 6.69)$	$(4.88, 6.27)$	$(4.55, 5.86)$	$(4.22, 5.44)$
ΔU_{direct} [%]	$(0.166, 0.207)$	$(0.256, 0.316)$	$(0.345, 0.426)$	$(0.434, 0.534)$	$(0.523, 0.643)$	$(0.612, 0.751)$	$(0.700, 0.858)$
ΔU_{equil} [%]	$(1.252, 1.506)$	$(1.077, 1.297)$	$(0.903, 1.091)$	$(0.731, 0.887)$	$(0.561, 0.684)$	$(0.394, 0.484)$	$(0.228, 0.286)$
ΔU_{growth} [%]	$(4.82, 6.24)$	$(4.56, 5.91)$	$(4.30, 5.59)$	$(4.05, 5.27)$	$(3.80, 4.94)$	$(3.54, 4.62)$	$(3.29, 4.30)$

Table 8: Sensitivity analysis with respect to the spillover parameter η in case of internalized externalities.

β	0.5	0.6	0.7	0.75	0.8	0.9	1
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4501, 1.3784)$	$(1.4365, 1.3585)$	$(1.4267, 1.3444)$	$(1.4228, 1.3387)$	$(1.4193, 1.3338)$	$(1.4136, 1.3255)$	$(1.4091, 1.3189)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.3326, 0.4032)$	$(0.3667, 0.4289)$	$(0.4157, 0.4693)$	$(0.4462, 0.4949)$	$(0.4811, 0.5242)$	$(0.5657, 0.5949)$	$(0.6734, 0.6835)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$
$\Delta U_{(i)\to(ii)}$ [%]	6.61	6.61	6.61	6.61	6.61	6.61	6.61
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(4.89, 7.17)$	$(4.68, 6.92)$	$(4.36, 6.56)$	$(4.15, 6.32)$	$(3.87, 6.02)$	$(2.94, 5.05)$	$(0.00, 2.30)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.64, 78.72)$	$(72.56, 78.61)$	$(72.45, 78.45)$	$(72.37, 78.35)$	$(72.27, 78.22)$	$(71.95, 77.82)$	$(70.97, 76.74)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.38, 4.26)$	$(4.39, 4.27)$	$(4.41, 4.29)$	$(4.42, 4.30)$	$(4.43, 4.32)$	$(4.48, 4.37)$	$(4.64, 4.52)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.19, 2.11)$	$(2.21, 2.13)$	$(2.23, 2.16)$	$(2.24, 2.18)$	$(2.27, 2.20)$	$(2.33, 2.27)$	$(2.54, 2.47)$
$\Delta U_{(i)\to(ii)}$ [%]	7.69	7.83	8.00	8.10	8.22	8.45	8.21
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(3.20, 4.25)$	$(3.78, 4.96)$	$(4.63, 5.99)$	$(5.22, 6.69)$	$(5.98, 7.58)$	$(8.61, 10.48)$	$(17.41, 19.17)$
ΔU_{direct} [%]	$(0.265, 0.337)$	$(0.313, 0.395)$	$(0.384, 0.478)$	$(0.434, 0.534)$	$(0.499, 0.607)$	$(0.722, 0.842)$	$(1.483, 1.535)$
ΔU_{equil} [%]	$(0.431, 0.534)$	$(0.515, 0.635)$	$(0.641, 0.783)$	$(0.731, 0.887)$	$(0.851, 1.023)$	$(1.282, 1.493)$	$(2.935, 3.108)$
ΔU_{growth} [%]	$(2.51, 3.37)$	$(2.95, 3.94)$	$(3.60, 4.73)$	$(4.05, 5.27)$	$(4.63, 5.95)$	$(6.60, 8.14)$	$(12.99, 14.53)$

Table 9: Sensitivity analysis with respect to the curvature β of the healthcare technology in case of internalized externalities.

δ [%]	5	6	7	7.5	8	9	10
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p_{max}^{(i)}, p_{max}^{(ii)})$ [%]	$(1.4229, 1.3385)$	$(1.4229, 1.3386)$	$(1.4228, 1.3387)$	$(1.4228, 1.3387)$	$(1.4227, 1.3388)$	$(1.4226, 1.3389)$	$(1.4226, 1.3390)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.4477, 0.4932)$	$(0.4471, 0.4939)$	$(0.4465, 0.4946)$	$(0.4462, 0.4949)$	$(0.4459, 0.4953)$	$(0.4453, 0.4960)$	$(0.4447, 0.4966)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.30, 4.19)$	$(4.30, 4.18)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.32, 4.17)$	$(4.32, 4.16)$	$(4.33, 4.16)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.08, 2.02)$	$(2.09, 2.01)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.11, 1.99)$	$(2.12, 1.98)$	$(2.12, 1.98)$
$\Delta U_{(i)\to(ii)}$ [%]	8.56	7.77	7.00	6.61	6.23	5.46	4.70
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(4.09, 6.22)$	$(4.12, 6.26)$	$(4.14, 6.30)$	$(4.15, 6.32)$	$(4.16, 6.34)$	$(4.18, 6.38)$	$(4.21, 6.42)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.35, 78.31)$	$(72.36, 78.32)$	$(72.37, 78.34)$	$(72.37, 78.35)$	$(72.38, 78.36)$	$(72.39, 78.38)$	$(72.40, 78.39)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.38, 4.29)$	$(4.40, 4.30)$	$(4.41, 4.30)$	$(4.42, 4.30)$	$(4.42, 4.30)$	$(4.44, 4.31)$	$(4.45, 4.31)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.19, 2.16)$	$(2.21, 2.17)$	$(2.23, 2.17)$	$(2.24, 2.18)$	$(2.26, 2.18)$	$(2.28, 2.18)$	$(2.30, 2.19)$
$\Delta U_{(i)\to(ii)}$ [%]	9.83	9.14	8.45	8.10	7.75	7.04	6.33
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(3.91, 5.13)$	$(4.44, 5.77)$	$(4.96, 6.39)$	$(5.22, 6.69)$	$(5.47, 6.98)$	$(5.97, 7.56)$	$(6.47, 8.13)$
ΔU_{direct} [%]	$(0.443, 0.554)$	$(0.439, 0.546)$	$(0.436, 0.538)$	$(0.434, 0.534)$	$(0.432, 0.530)$	$(0.429, 0.523)$	$(0.425, 0.516)$
ΔU_{equil} [%]	$(0.310, 0.388)$	$(0.479, 0.592)$	$(0.648, 0.790)$	$(0.731, 0.887)$	$(0.814, 0.982)$	$(0.979, 1.168)$	$(1.142, 1.349)$
ΔU_{growth} [%]	$(3.16, 4.19)$	$(3.52, 4.63)$	$(3.88, 5.06)$	$(4.05, 5.27)$	$(4.22, 5.47)$	$(4.57, 5.87)$	$(4.90, 6.26)$

Table 10: Sensitivity analysis with respect to the capital depreciation rate δ in case of internalized externalities.

α	0.35	0.4	0.45	0.5	0.55	0.6	0.65
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(4.69, 6.69)$	$(5.08, 7.25)$	$(5.55, 7.91)$	$(6.10, 8.70)$	$(6.78, 9.67)$	$(7.62, 10.87)$	$(8.71, 12.43)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4094, 1.3189)$	$(1.4131, 1.3243)$	$(1.4175, 1.3308)$	$(1.4228, 1.3387)$	$(1.4293, 1.3486)$	$(1.4377, 1.3613)$	$(1.4487, 1.3783)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.4110, 0.4520)$	$(0.4212, 0.4643)$	$(0.4328, 0.4785)$	$(0.4462, 0.4949)$	$(0.4619, 0.5144)$	$(0.4805, 0.5381)$	$(0.5035, 0.5677)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.31, 4.17)$	$(4.32, 4.17)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.10, 2.00)$	$(2.11, 1.99)$
$\Delta U_{(i)\to(ii)}$ [%]	6.83	6.77	6.70	6.61	6.51	6.37	6.19
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(3.15, 4.78)$	$(3.42, 5.21)$	$(3.75, 5.71)$	$(4.15, 6.32)$	$(4.64, 7.08)$	$(5.27, 8.05)$	$(6.08, 9.31)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.53, 78.57)$	$(72.49, 78.51)$	$(72.43, 78.44)$	$(72.37, 78.35)$	$(72.30, 78.25)$	$(72.21, 78.12)$	$(72.09, 77.96)$
$(r^{(i)}, r^{(ii)})$ [%]	$(4.42, 4.31)$	$(4.42, 4.30)$	$(4.42, 4.30)$	$(4.42, 4.30)$	$(4.42, 4.30)$	$(4.42, 4.30)$	$(4.42, 4.29)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.25, 2.19)$	$(2.25, 2.18)$	$(2.25, 2.18)$	$(2.24, 2.18)$	$(2.24, 2.17)$	$(2.24, 2.16)$	$(2.24, 2.16)$
$\Delta U_{(i)\to(ii)}$ [%]	8.54	8.42	8.28	8.10	7.89	7.64	7.31
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(5.80, 7.51)$	$(5.64, 7.27)$	$(5.44, 7.00)$	$(5.22, 6.69)$	$(4.94, 6.31)$	$(4.60, 5.84)$	$(4.18, 5.27)$
ΔU_{direct} [%]	$(0.342, 0.426)$	$(0.368, 0.457)$	$(0.398, 0.493)$	$(0.434, 0.534)$	$(0.477, 0.583)$	$(0.528, 0.642)$	$(0.592, 0.713)$
ΔU_{equil} [%]	$(1.226, 1.521)$	$(1.087, 1.341)$	$(0.924, 1.132)$	$(0.731, 0.887)$	$(0.499, 0.594)$	$(0.216, 0.239)$	$(-0.138, -0.201)$
ΔU_{growth} [%]	$(4.23, 5.56)$	$(4.18, 5.48)$	$(4.12, 5.38)$	$(4.05, 5.27)$	$(3.96, 5.13)$	$(3.86, 4.96)$	$(3.72, 4.76)$

Table 11: Sensitivity analysis with respect to the income share of capital α in case of internalized externalities.

A.10 Internalizing the Spillover Effect of Healthcare Investments on Consumption Good Production

The over-investment result of Proposition 5 rests on the assumption that either the spillover-effect of healthcare on manufacturing is not present, i.e. $\eta = 0$, or it is not internalized by subsidizing healthcare investments. Yet, when this market distortion is internalized by a corresponding subsidy, financed, for example, via a lump-sum or labor tax,[39] the equilibrium condition (20) originating from the households' first-order condition changes to[40]

$$\frac{\sigma}{1-\sigma}\frac{H'(\bar{h})}{x(\bar{h},\bar{p})} - \frac{1}{(1-\bar{h})}\frac{1-\eta}{1-\eta\bar{h}} = -H'(\bar{h})\left(\frac{1}{x(\bar{h},\bar{p})} - \frac{1}{y(\bar{h},\bar{p})}\frac{1}{1-\eta\bar{h}}\right) \tag{A.31}$$

As the subsidy lowers the costs of healthcare, we observe that the second term in (A.31) reflecting the household's healthcare costs becomes smaller, while the last term on the right-hand side reflecting the extra wealth obtained over the additional expected lifetime becomes larger (as a smaller part of labor income wealth needs to be spent on health). The latter results from $\frac{1}{1-\eta\bar{h}} > 1$ for $\eta > 0$ and $h > 0$, which implies that the right-hand side of (A.31) may now become negative and as a consequence under-investment in healthcare in the decentralized equilibrium without annuity rates conditioned on individual healthcare investments will be possible. We also directly observe that under-investment is more likely if the spillover effect is strong implying a stronger increase in labor income wealth by investing in healthcare.

To quantify the strength of the spillover externality, we run an additional simulation in which we internalize the positive spillover effect of healthcare investments on consumption-good production (but leave the learning-by-investing externality untouched). As this implies an additional incentive for households to invest in healthcare – beyond increases in longevity –, as better healthcare increases the households' wage, one expects that that households would not overspend in healthcare to the same extent as we had found without internalizing the spillover effect (see Table 2). The results shown in Table 12 confirm this conjecture. In fact, we observe less overspending in regime (a) compared to regime (b). Accordingly, the welfare loss due to the moral-hazard effect of unconditioned annuity claims is lower. However, the effects are rather small. Compared to the standard case without internalizing the spillovers of healthcare investments to consumption-good production, the welfare losses decrease from 1.29% to 1.23% in scenario (i) and from 1.58% to 1.42% in scenario (ii).

To investigate the qualitative and quantitative robustness of the numerical calibration exer-

[39] Note that in our model a tax on labor income is not distortionary, as labor supply is inelastic.

[40] This condition is derived by inserting the social cost of healthcare $w^H(t)$, as defined in Section 5 and specifically spelled out in footnote 16, into the household's optimisation problem, as described in Appendix A.1 (possibly also including a tax that does not depend on the individual household's choices to finance the subsidy). Solving the household's utility maximization problem yields the first-order condition regarding healthcare investments as in the social planner's problem (17). Yet, for any given $h(s)$, the household's consumption path is still characterized by the standard Euler equation (A.4). Appreciating that when all households invest the same amount h in healthcare in steady state the interest rate $r(t)$, the wage rate $w(t)$ and the annuity return $a(t,s)$ must be the same as in Proposition 4 and $L^H(t) = hN(t)$, we obtain $w^H(t) = w(t)\frac{1-\eta}{1-\eta h}$ and the first-order condition (A.31). Existence of a steady-state equilibrium can be shown by following the same line of argument, as in the proof of Proposition 4. However, for a unique steady-state equilibrium a stronger condition than the corresponding one given in Proposition 4 is necessary.

	Scenario (i) $T = 73.1\,[a]$ $h = 6.1\,[\%]$	Scenario (ii) $T = 79.4\,[a]$ $h = 8.7\,[\%]$
Regime (a)		
$p_{max}\,[\%]$	1.4315	1.3514
$\psi\,[\%]$	0.5171	0.5739
$r\,[\%]$	3.61	3.48
$g\,[\%]$	2.14	1.96
$\Delta U_{(i)\to(ii)}\,[\%]$	4.55	
Regime (b)		
$h\,[\%]$	5.60	8.15
$T\,[a]$	72.89	79.12
$r\,[\%]$	3.64	3.51
$g\,[\%]$	2.18	2.01
$\Delta U_{(i)\to(ii)}\,[\%]$	4.75	
Comparison regime (a) $\to$ (b)		
$\Delta U_{(a)\to(b)}\,[\%]$	1.23	1.42
$\Delta U_{direct}\,[\%]$	0.084	0.094
$\Delta U_{equil}\,[\%]$	-0.199	-0.231
$\Delta U_{growth}\,[\%]$	1.35	1.56

Table 12: Utility gains for a hypothetical average OECD country for improvements in the healthcare technology and switching from unconditioned to a conditioned annuity claims regime in case of internalizes spillovers from healthcare to consumption-good production.

cise, we also run an extensive sensitivity analysis over the whole range of parameter values for η, β, δ and α. The results are shown in Tables 13–16. Again, we find that the results are very robust over the whole parameter range of our sensitivity analyses.

η	0	0.05	0.1	0.15	0.2	0.25	0.3
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4418, 1.3664)$	$(1.4384, 1.3615)$	$(1.4349, 1.3564)$	$(1.4315, 1.3514)$	$(1.4280, 1.3463)$	$(1.4244, 1.3412)$	$(1.4209, 1.3360)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.6015, 0.6678)$	$(0.5736, 0.6368)$	$(0.5454, 0.6055)$	$(0.5171, 0.5739)$	$(0.4885, 0.5422)$	$(0.4597, 0.5102)$	$(0.4307, 0.4779)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.62, 3.47)$	$(3.62, 3.47)$	$(3.61, 3.47)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.60, 3.48)$	$(3.60, 3.49)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.15, 1.95)$	$(2.15, 1.95)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.13, 1.97)$	$(2.13, 1.97)$	$(2.12, 1.98)$
$\Delta U_{(i)\to(ii)}$ [%]	3.01	3.52	4.03	4.55	5.08	5.62	6.16
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(5.56, 8.06)$	$(5.57, 8.09)$	$(5.59, 8.12)$	$(5.60, 8.15)$	$(5.62, 8.18)$	$(5.63, 8.20)$	$(5.65, 8.23)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.84, 79.03)$	$(72.85, 79.06)$	$(72.87, 79.09)$	$(72.89, 79.12)$	$(72.91, 79.15)$	$(72.93, 79.18)$	$(72.94, 79.20)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.65, 3.50)$	$(3.65, 3.51)$	$(3.64, 3.51)$	$(3.64, 3.51)$	$(3.63, 3.51)$	$(3.62, 3.51)$	$(3.62, 3.51)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.20, 2.00)$	$(2.19, 2.00)$	$(2.18, 2.00)$	$(2.18, 2.01)$	$(2.17, 2.01)$	$(2.16, 2.01)$	$(2.15, 2.01)$
$\Delta U_{(i)\to(ii)}$ [%]	3.34	3.80	4.27	4.75	5.24	5.74	6.25
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(1.57, 1.90)$	$(1.46, 1.73)$	$(1.34, 1.58)$	$(1.23, 1.42)$	$(1.13, 1.28)$	$(1.02, 1.14)$	$(0.92, 1.01)$
ΔU_{direct} [%]	$(0.011, 0.013)$	$(0.037, 0.043)$	$(0.061, 0.070)$	$(0.084, 0.094)$	$(0.106, 0.116)$	$(0.126, 0.136)$	$(0.145, 0.152)$
ΔU_{equil} [%]	$(-0.154, -0.193)$	$(-0.170, -0.208)$	$(-0.185, -0.221)$	$(-0.199, -0.231)$	$(-0.211, -0.240)$	$(-0.222, -0.246)$	$(-0.232, -0.250)$
ΔU_{growth} [%]	$(1.72, 2.08)$	$(1.59, 1.90)$	$(1.47, 1.73)$	$(1.35, 1.56)$	$(1.23, 1.40)$	$(1.12, 1.25)$	$(1.01, 1.11)$

Table 13: Sensitivity analysis with respect to the spillover parameter η.

β	0.5	0.6	0.7	0.75	0.8	0.9	1
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$	$(6.10, 8.70)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4632, 1.3974)$	$(1.4473, 1.3744)$	$(1.4360, 1.3580)$	$(1.4315, 1.3514)$	$(1.4275, 1.3456)$	$(1.4209, 1.3361)$	$(1.4156, 1.3284)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.3855, 0.4676)$	$(0.4249, 0.4974)$	$(0.4817, 0.5443)$	$(0.5171, 0.5739)$	$(0.5575, 0.6079)$	$(0.6555, 0.6898)$	$(0.7804, 0.7926)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$	$(3.61, 3.48)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$
$\Delta U_{(i)\to(ii)}$ [%]	4.55	4.55	4.55	4.55	4.55	4.55	4.55
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(5.80, 8.35)$	$(5.75, 8.29)$	$(5.66, 8.21)$	$(5.60, 8.15)$	$(5.52, 8.07)$	$(5.26, 7.83)$	$(4.44, 7.28)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.98, 79.23)$	$(72.95, 79.20)$	$(72.92, 79.15)$	$(72.89, 79.12)$	$(72.86, 79.08)$	$(72.75, 78.97)$	$(72.42, 78.70)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.63, 3.50)$	$(3.63, 3.50)$	$(3.63, 3.50)$	$(3.64, 3.51)$	$(3.64, 3.51)$	$(3.65, 3.52)$	$(3.69, 3.55)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.16, 1.99)$	$(2.16, 1.99)$	$(2.17, 2.00)$	$(2.18, 2.01)$	$(2.18, 2.01)$	$(2.20, 2.03)$	$(2.26, 2.07)$
$\Delta U_{(i)\to(ii)}$ [%]	4.72	4.73	4.75	4.75	4.75	4.70	4.09
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(0.73, 0.89)$	$(0.87, 1.05)$	$(1.08, 1.27)$	$(1.23, 1.42)$	$(1.43, 1.62)$	$(2.10, 2.24)$	$(4.17, 3.71)$
ΔU_{direct} [%]	$(0.050, 0.059)$	$(0.060, 0.069)$	$(0.074, 0.084)$	$(0.084, 0.094)$	$(0.098, 0.108)$	$(0.144, 0.149)$	$(0.289, 0.248)$
ΔU_{equil} [%]	$(-0.120, -0.147)$	$(-0.143, -0.172)$	$(-0.176, -0.208)$	$(-0.199, -0.231)$	$(-0.229, -0.261)$	$(-0.329, -0.354)$	$(-0.609, -0.558)$
ΔU_{growth} [%]	$(0.80, 0.98)$	$(0.96, 1.15)$	$(1.19, 1.39)$	$(1.35, 1.56)$	$(1.56, 1.77)$	$(2.29, 2.45)$	$(4.49, 4.02)$

Table 14: Sensitivity analysis with respect to the curvature β of the healthcare technology.

δ [%]	5	6	7	7.5	8	9	10
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(4.69, 6.69)$	$(5.08, 7.25)$	$(5.55, 7.91)$	$(6.10, 8.70)$	$(6.78, 9.67)$	$(7.62, 10.87)$	$(8.71, 12.43)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p^{(i)}_{max}, p^{(ii)}_{max})$ [%]	$(1.4167, 1.3294)$	$(1.4208, 1.3355)$	$(1.4256, 1.3427)$	$(1.4315, 1.3514)$	$(1.4386, 1.3622)$	$(1.4477, 1.3760)$	$(1.4596, 1.3943)$
$\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.4831, 0.5318)$	$(0.4931, 0.5440)$	$(0.5043, 0.5579)$	$(0.5171, 0.5739)$	$(0.5319, 0.5928)$	$(0.5495, 0.6156)$	$(0.5710, 0.6442)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.54, 3.41)$	$(3.56, 3.43)$	$(3.58, 3.45)$	$(3.61, 3.48)$	$(3.64, 3.51)$	$(3.68, 3.54)$	$(3.72, 3.58)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$
$\Delta U_{(i)\to(ii)}$ [%]	4.42	4.47	4.51	4.55	4.59	4.62	4.62
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(4.46, 6.44)$	$(4.78, 6.91)$	$(5.16, 7.48)$	$(5.60, 8.15)$	$(6.14, 8.96)$	$(6.82, 9.98)$	$(7.68, 11.29)$
$(T^{(i)}, T^{(ii)})$ [a]	$(73.00, 79.27)$	$(72.97, 79.23)$	$(72.94, 79.18)$	$(72.89, 79.12)$	$(72.83, 79.04)$	$(72.76, 78.94)$	$(72.66, 78.81)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.55, 3.42)$	$(3.58, 3.45)$	$(3.60, 3.47)$	$(3.64, 3.51)$	$(3.67, 3.54)$	$(3.71, 3.58)$	$(3.76, 3.63)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.16, 1.99)$	$(2.17, 1.99)$	$(2.17, 2.00)$	$(2.18, 2.01)$	$(2.18, 2.01)$	$(2.19, 2.02)$	$(2.19, 2.03)$
$\Delta U_{(i)\to(ii)}$ [%]	4.53	4.61	4.68	4.75	4.82	4.87	4.89
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(0.79, 0.90)$	$(0.94, 1.07)$	$(1.08, 1.25)$	$(1.23, 1.42)$	$(1.37, 1.59)$	$(1.49, 1.73)$	$(1.56, 1.81)$
ΔU_{direct} [%]	$(0.038, 0.042)$	$(0.050, 0.055)$	$(0.065, 0.073)$	$(0.084, 0.094)$	$(0.110, 0.123)$	$(0.143, 0.160)$	$(0.188, 0.209)$
ΔU_{equil} [%]	$(-0.072, -0.082)$	$(-0.102, -0.118)$	$(-0.143, -0.166)$	$(-0.199, -0.231)$	$(-0.276, -0.322)$	$(-0.385, -0.449)$	$(-0.541, -0.630)$
ΔU_{growth} [%]	$(0.82, 0.94)$	$(0.99, 1.13)$	$(1.16, 1.34)$	$(1.35, 1.56)$	$(1.54, 1.79)$	$(1.73, 2.02)$	$(1.91, 2.24)$

Table 15: Sensitivity analysis with respect to the capital depreciation rate δ.

α	0.35	0.4	0.45	0.5	0.55	0.6	0.65
Regime (a)							
$(h^{(i)}, h^{(ii)})$	$(4.69, 6.69)$	$(5.08, 7.25)$	$(5.55, 7.91)$	$(6.10, 8.70)$	$(6.78, 9.67)$	$(7.62, 10.87)$	$(8.71, 12.43)$
$(T^{(i)}, T^{(ii)})$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$	$(73.10, 79.40)$
$(p_{max}^{(i)}, p_{max}^{(ii)})$ [%]	$(1.4249, 1.3409)$	$(1.4296, 1.3479)$	$(1.4352, 1.3562)$	$(1.4420, 1.3662)$	$(1.4503, 1.3786)$	$(1.4607, 1.3944)$	$(1.4743, 1.4151)$
$(\psi^{(i)}, \psi^{(ii)})$ [%]	$(0.5644, 0.6194)$	$(0.5757, 0.6331)$	$(0.5884, 0.6486)$	$(0.6028, 0.6664)$	$(0.6194, 0.6873)$	$(0.6391, 0.7125)$	$(0.6630, 0.7437)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.54, 3.41)$	$(3.56, 3.43)$	$(3.58, 3.45)$	$(3.61, 3.48)$	$(3.64, 3.51)$	$(3.68, 3.54)$	$(3.72, 3.58)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$	$(2.14, 1.96)$
$\Delta U_{(i)\to(ii)}$ [%]	4.42	4.47	4.51	4.55	4.59	4.62	4.62
Regime (b)							
$(h^{(i)}, h^{(ii)})$ [%]	$(4.43, 6.37)$	$(4.74, 6.84)$	$(5.11, 7.39)$	$(5.54, 8.04)$	$(6.07, 8.84)$	$(6.72, 9.82)$	$(7.56, 11.08)$
$(T^{(i)}, T^{(ii)})$ [a]	$(72.97, 79.22)$	$(72.93, 79.16)$	$(72.89, 79.10)$	$(72.83, 79.02)$	$(72.75, 78.91)$	$(72.66, 78.78)$	$(72.53, 78.60)$
$(r^{(i)}, r^{(ii)})$ [%]	$(3.55, 3.43)$	$(3.58, 3.45)$	$(3.61, 3.48)$	$(3.64, 3.51)$	$(3.68, 3.55)$	$(3.72, 3.59)$	$(3.77, 3.63)$
$(g^{(i)}, g^{(ii)})$ [%]	$(2.17, 1.99)$	$(2.17, 2.00)$	$(2.18, 2.01)$	$(2.18, 2.01)$	$(2.19, 2.02)$	$(2.19, 2.03)$	$(2.20, 2.04)$
$\Delta U_{(i)\to(ii)}$ [%]	4.62	4.70	4.78	4.86	4.93	4.98	5.00
Comparison regime (a) $\to$ (b)							
$\Delta U_{(a)\to(b)}$ [%]	$(0.87, 1.06)$	$(1.01, 1.24)$	$(1.15, 1.41)$	$(1.29, 1.58)$	$(1.41, 1.74)$	$(1.50, 1.85)$	$(1.54, 1.90)$
ΔU_{direct} [%]	$(0.003, 0.004)$	$(0.005, 0.006)$	$(0.008, 0.009)$	$(0.011, 0.013)$	$(0.017, 0.020)$	$(0.025, 0.030)$	$(0.038, 0.044)$
ΔU_{equil} [%]	$(-0.082, -0.101)$	$(-0.115, -0.142)$	$(-0.160, -0.197)$	$(-0.221, -0.273)$	$(-0.307, -0.377)$	$(-0.427, -0.525)$	$(-0.601, -0.737)$
ΔU_{growth} [%]	$(0.94, 1.16)$	$(1.12, 1.38)$	$(1.30, 1.60)$	$(1.50, 1.84)$	$(1.70, 2.09)$	$(1.90, 2.35)$	$(2.10, 2.60)$

Table 16: Sensitivity analysis with respect to the income share of capital α.

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