



# Optimal health investment and preferences structure

T Azomahou, Bity Diene, Mbaye Diene, Luc Soete

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T Azomahou, Bity Diene, Mbaye Diene, Luc Soete. Optimal health investment and preferences structure. 2015. halshs-01144802

**HAL Id: halshs-01144802**

**<https://shs.hal.science/halshs-01144802>**

Preprint submitted on 22 Apr 2015

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### **Optimal health investment and preferences structure**

Théophile T. AZOMAHOU

Bity DIENE

Mbaye DIENE

Luc SOETE

*Etudes et Documents* n° 07

Avril 2015

To cite this document:

Azomahou T. T., Diene B., Diene M., Soete L. (2015) "Optimal health investment and preferences structure", *Etudes et Documents*, n° 07, CERDI.

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TEL. + 33 4 73 17 74 00  
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## The authors

Théophile T. Azomahou

Professor

United Nations University (UNU-MERIT) and University of Maastricht, Keizer Karelplein 19,  
6211 TC Maastricht, the Netherlands

Email: [azomahou@merit.unu.edu](mailto:azomahou@merit.unu.edu)

Bity Diene

Associate Professor

Clermont Université, Université d'Auvergne, CNRS, UMR 6587, CERDI, F-63009 Clermont Fd

Email: [bity.diene@udamail.fr](mailto:bity.diene@udamail.fr)

Mbaye Diene

Professor

University Cheikh-Anta-Diop and Consortium pour la Recherche Economique et Sociale  
(CRES), rue 10 Prolongée Cité Iba Ndiaye Diadji no 1-2. Dakar, Sénégal

Email: [mdiene@cres-sn.org](mailto:mdiene@cres-sn.org)

Luc Soete

Professor

United Nations University (UNU-MERIT) and University of Maastricht, Keizer Karelplein 19,  
6211 TC Maastricht, the Netherlands

Email: [l.soete@maastrichtuniversity.nl](mailto:l.soete@maastrichtuniversity.nl)

**Corresponding author:** Théophile T. Azomahou



This work was supported by the LABEX IDGM+ (ANR-10-LABX-14-01) within the program  
“Investissements d’Avenir” operated by the French National Research Agency (ANR)

*Etudes et Documents* are available online at: <http://www.cerdi.org/ed>

Director of Publication: Vianney Dequiedt

Editor: Catherine Araujo Bonjean

Publisher: Chantal Brige-Ukpong

ISSN: 2114 - 7957

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**Abstract**

This paper develops a general equilibrium framework to study the role of preferences structure (additive, multiplicative and convex combination of both) in connecting consumption, health investment, stock of health and capital, and their effects on the wage rate and on productivity. We show that the elasticities of health production, health investment and health cost determine jointly how health influences the wage rate. We examine the steady state and the equilibrium dynamics of the model. In the case of additive preferences, the existence of equilibrium and the stability of the dynamic system require that the ratio of the elasticities of the cost of health and health investment is greater than the elasticity of the production function of health. Health stock can have either positive or negative effects on wage rate. The reverse holds for multiplicative preferences and the effect of health stock on wage rate is always positive. Longevity is a decreasing convex-concave function of the elasticity of inter-temporal substitution of health. We also compare the relative behavior of opportunity costs of health under preferences structure.

**Key words:** Consumption, health investment, preferences structure, wage rates, longevity, opportunity costs

**JEL codes:** C61, C62, I15, E21

**Acknowledgment**

We gratefully acknowledge useful comments and stimulating remarks from Raouf Boucekkine, Noel Bonneuil, Matteo Cervellati, Miguel Perez-Nievas, Hippolyte d'Albis, Frédéric Dufourt, Daniel Opolot and Eleni Yitbarek. This work was supported by the Agence Nationale de la Recherche of the French government through the program 'Investissements d'avenir ANR-10-LABX-14-01'. Théophile Azomahou thanks the support of UNU-MERIT. The usual disclaimer applies.

# 1 Introduction

There is a widely established consensus on the causal relation between health and longevity in the sense that better health conditions extend longevity. Some studies were even interested in the challenges of studying the conditions of a long healthy life, for a long life will often go hand in hand with a decline in health (Kirkwood, 2008). This consensus crumbles when it comes to link or correlate health and productivity, or health and economic growth. This relationship has been the subject of heated debate since the publication of the study by Acemoglu and Johnson (2007) where the authors have casted serious doubts about the fact that better health would lead more growth per capita. Acemoglu and Johnson (2007) have underlined that empirical studies that showed a sizable positive effect of health on individual productivity have not resolved the question of whether health differences are the cause of observed large differences in income since these studies do not incorporate general equilibrium effects. The most important general equilibrium effect comes from diminishing returns of work per effective unit. This is for example the case when physical capital is supplied inelastically. Indeed, in the presence of diminishing returns, estimations based on micro data overestimate the benefits of aggregated productivity due to improved health, especially when improving health comes with increased population. Acemoglu and Johnson (2007) showed that the increase in life expectancy associated with increase in population may have a negative effect on income per capita for the working age population. This result is confirmed in particular for countries that have experienced high life expectancy, leading to a kind of puzzle.

Following the study of Acemoglu and Johnson (2007), other authors such as Ashraf et al. (2008) raised the same question.<sup>1</sup> These authors used a simulation based model that incorporates both micro and macro components, and which takes into account the direct effect of health on worker productivity. Contrary to the popular belief, they found a very moderate effect of improving health on income per capita. Ashraf et al. (2008) concluded that the rationale for health policies should then rely on humanitarian reasons rather than economic ones. The specific econometric questions underlying the debate are very well explained in Strittmater and Sunde (2013).<sup>2</sup>

This paper develops a theoretical framework to contribute to the debate by elaborating in depth on the structure of preferences. How would improving health status affect consumption, wage income and productivity? Depending on the answer, the impact on growth would be sizeable or small. This study aims at providing a theoretical answer to this question by showing that the adopted preferences do matter. To the best of our knowledge, the existing literature has not yet investigated the role of preferences in this regard.

Indeed, from the AIDS empirical literature (e.g., Bloom and Mahal, 1997a, 1997b and Cudington and Hancock, 1994), we know that consumption and health are interconnected but we cannot make conclusions about the net effects of health investment.<sup>3</sup> Indeed, it seems analytically difficult to slice on the net effect of a high health deterioration rate and low health productivity on health investment as not all diseases have the same effects. From a theoretical perspective, in the Grossman's (1972) standard model, health is considered as capital stock that increases with investment. Agents' preferences are separable in health and ordinary consumption. As a result, the returns from these two goods are independent. However, evidences stressed the fact that ordinary consumption is also crucial for health. Moreover, one of the

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<sup>1</sup>See also Weil (2007, 2014).

<sup>2</sup>See Acemoglu and Johnson (2014) and Bloom et al. (2014) to follow up debate.

<sup>3</sup>See also Corrigan et al. (2005) and McDonald and Roberts (2006).

main economic implications of health shock is a probable and significant distortion in savings behavior. Chakraborty (2004) considered the problem of public investment in health within the framework of overlapping generation models. The author showed that in poor countries where life expectancy is weak, individuals are more likely to discount the future and thus less are inclined to save. Cuddington and Hancock (1994) also stated that: health expenditure induces a decrease in savings at the expense of capital accumulation. However, this is questionable due to the fact that health expenditure is harmful to consumption. Therefore, there is an overriding issue as to how to deal with savings in the context of health depreciation.

Our study contributes to the literature in several aspects. Firstly, we adopt a more general set-up by considering both separable and non-separable preferences (additive, multiplicative and a convex combination of both) in consumption and health, meaning in the latter case consumption is also crucial for health. Second, we investigate the effects of health status on the subsequent life cycle, in particular on productivity, wage income and consumption in a general equilibrium setting. In order to have a better picture of the life cycle aspect of the issue, we also include a final good sector where productivity depends on the health stock. Thirdly, we characterize the analytical solutions of the optimization problem to study the equilibrium dynamics. We shall find that the picture is quite sophisticated, depending on the assumed preferences. For simplification, we consider in a first step lifetime of individuals as infinite. However, this facet of our approach is closely related to the framework of Grossman (1972) and Ehrlich and Chuma (1990) that health capital is still a determinant of lifetime utility. Relying on this setting, we connect three factors: health production, health investment and health costs. We have shown that the elasticities of these three variables determine jointly how health affects labor and hence productivity. The framework allows to relate the evolution of wage rate with respect to health status, the transmission channel between wage rate and health being labor productivity. It also enables us to study longevity as well the opportunity cost of health investment.

When the preferences are additively separable, the existence of equilibrium and the stability of the dynamic system require the ratio of the elasticities of the cost of health and health investment is greater than the elasticity of the production function of health. The stock of health can have either positive or negative effects on the wage rate. The latter finding provides a theoretical basis to the empirical debate raised by Acemoglu and Johnson (2007). The economic intuition behind this is that a high stock of health may have a negative effect on the wage rate if economic growth (and hence the distribution of income) declines because of the aging population for example, or because of high opportunity cost in health spending, which harm economic sectors. This is also possible if the improved health leads to a reduction of capital per capita, and thus lower levels of income per capita. When the preferences are multiplicative, the condition reverses in the fact that the ratio of the elasticities of the cost of health and health investment should be lower than the elasticity of the production function of health. Moreover, the effect of health stock on wage rate is always positive. In the case of convex combination of additive and multiplicative preferences, we find that the equilibrium dynamic of the stock of health and investment in health is obtained as a function of time for which we observe an exponential decay. However, the solution of the dynamic system is not analytically tractable. We also obtained that the structure of preferences determines the shape and existence of longevity with respect to the elasticity of substitution of health. Lastly, we establish the conditions for comparing the opportunity cost of health under preference structures.

In this paper, we abstract away from the pure literature on infectious diseases and their modes of transmission (see e.g, Boucekkine and Laffargue, 2010, Goenka and Liu, 2012, Goenka

et al., 2014). It would have been interesting to incorporate this issue in our dynamic setting to assess the impact of health on variables such as capital accumulation, consumption, wages, etc. Here, we do not make any specific assumptions on the nature of diseases (infectious or not) as well as on their transmission process. Incorporating these mechanisms in our model will pose additional extra difficulties that we leave for future research while focusing on the equally difficult issue of preferences structure.

The remainder of the paper proceeds as follows. Section 2 describes the general framework including optimality conditions. In Section 3, we study the model with separable additive preferences meaning that health and consumption enter additively into the utility function. Section 4 is devoted to the model with a multiplicative non-separable preferences which allows for an interaction between health and consumption. Section 5 considers a framework with a convex combination of the additive and the multiplicative preferences. The penultimate section 6 studies the opportunity costs of investment in health and derives some policy implications. The last section concludes the study. Proofs of propositions and further supplement materials are relegated to the Appendix.

## 2 Motivational framework

This section introduces a set of generalities of the framework that will be used subsequently. This includes functional hypotheses and optimality conditions that are required for equilibrium solutions as well separability issues regarding the preferences. The model is based on infinitely-lived consumers where agent's welfare is composed of utility derived from consumption goods and health.

### 2.1 Setting up and assumptions

We assume that the followings:

**Assumption 1** *The instantaneous utility function at time  $z$ ,  $U(C(z)) : \mathbb{R}_+ \rightarrow \mathbb{R}_+$  is  $C^\infty$  with  $U_C > 0$ ,  $U'_C < 0$  and  $\lim_{C(z) \rightarrow 0} U_C = \infty$ , where  $C(z)$  denotes consumption at time  $z$  and subscript means derivative with respect to concern argument and hereafter.*

**Assumption 2** *The healthy time function (or amount of healthy time)  $\varphi(M(z)) : \mathbb{R}_+ \rightarrow \mathbb{R}_+$  is  $C^\infty$  with  $\varphi_M > 0$ ,  $\varphi'_M < 0$ ,  $\lim_{M(z) \rightarrow 0} \varphi_M < \infty$  and  $\lim_{M(z) \rightarrow \infty} \varphi_M = 0$ ; where  $M(z)$  denotes the stock of health capital.*

**Assumption 3** *The health production function  $\psi(m(z)) : \mathbb{R}_+ \rightarrow \mathbb{R}_+$  is  $C^\infty$  with  $\psi_m > 0$ ,  $\psi'_m < 0$ ,  $\lim_{m(z) \rightarrow 0} \psi_m < \infty$  and  $\lim_{m(z) \rightarrow \infty} \psi_m = 0$ ; where  $m(z)$  denotes the health investment.*

**Assumption 4** *The production function  $F(K(z), L(z)) : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$  is  $C^\infty$ . Moreover,*

- i)  $F_1 > 0$ ,  $F_{11} < 0$ ,  $F_2 > 0$ ,  $F_{22} < 0$ ,  $F_{12} = F_{21} > 0$  and  $F_{11}F_{22} - F_{12}F_{21} > 0$  where the place of the subscripts  $\{1, 2\}$  refer to the derivatives of the function with respect to the first and second arguments, namely  $K$  and  $L$ .
- ii)  $\lim_{K(z) \rightarrow 0} F_1 = \infty$  and  $\lim_{K(z) \rightarrow \infty} F_1 = 0$
- iii)  $F(0, L(z)) = F(K(z), 0) = 0$ .

Assumptions 1-4 are optimality conditions. They guarantee convexities of the optimization problem. The specific functional forms that will be used subsequently fulfill these hypothesis. Consistent with Ehrlich and Chuma (1990), we consider that the stock of health capital can be maintained or increased through purposive investments  $m(z)$ . However, health is submitted to a natural biological deterioration at the rate  $\delta_M$ . Thus, in contrary to Ehrlich and Chuma (1990), we assume a constant rate of health depreciation. However, the greater the health that one intends to maintain in later years, the earlier one must initiate significant investments in counteracting the depreciation of health. Let denote  $\rho$  the time preference or discount rate. Individuals maximize lifetime utility, subject to the state variables. The general framework is stated as:

$$\max \int_0^\infty \mathcal{V}\{S[U(C(z)), \varphi(M(z))], N[U(C(z)), \varphi(M(z))]\} e^{-\rho z} dz \quad (1)$$

subject to the law of motion of non-human assets and health:

$$\dot{A}(z) = r(z)A(z) + w(z)\varphi(M(z)) - C(z) - h(m(z)) \quad (2)$$

$$\dot{M}(z) = \psi(m(z)) - \delta_M M(z) \quad (3)$$

where  $r(z)$  and  $w(z)$  are the interest and wage rate rate respectively,  $h(m(z))$  denotes the cost of investment in health. The functions  $S[U(C(z)), \varphi(M(z))]$  and  $N[U(C(z)), \varphi(M(z))]$  denotes the additive and non additive components of the felicity  $\mathcal{V}(S, N)$  respectively. Subsequently, three different versions of  $\mathcal{V}(S, N)$ : namely separable, multiplicative and a convex combination of both be will be studied in which the utility function  $U(C(z))$  and health function  $\varphi(M(z))$  will be taken as the constant relative risk aversion (CRRA) representation. We will also consider in Appendix (C) examples of alternative preferences for  $U(C(z))$  and  $\varphi(M(z))$ : namely the logarithmic and the quadratic.

From the production side, we consider a representative firm with Cobb-Douglas technology for the function  $F$  with the refinement that productivity depends on health deep parameters. Moreover, we assume productivity in this sector as a function of the health stock.<sup>4</sup> This leads to  $Y(z) = B(M(z))F(K, L)$  where,  $Y(z)$ ,  $K(z)$  and  $L(z)$  are respectively the output, capital and labor, while  $B(M(z))$  is the productivity as a function of the health stock  $M$ . Let the effective labor supply be  $\mathcal{N}(z) = \gamma(M)L(z)$ . The fraction  $\gamma(M)$  shall depend on the level of health,  $L(z)$  being the total labor input and  $\gamma(M)$  is an increasing function. As productivity depends on the stock of health,  $B(M(z)) = a(z)\gamma(M)^{1-\epsilon}$  with  $0 < \epsilon < 1$  and  $a(z)$  represents the technical progress which corresponds also to the global productivity. For the limit conditions of  $B(M)$ , the minimum level of health is assumed  $M = M_{\min} \geq 0$ . Furthermore,  $B(M_{\min}) = a(z)$  if one assumes that  $\gamma(M_{\min}) = 1$ . We also assume that  $B(\infty) = M_{\max}$  (which implies that the productivity cannot increase indefinitely) and  $B_{MM} \leq 0$ . Let us denote  $\hat{k} = \frac{K}{L}$  the capital-labor ratio. Then the output per labor is given by  $f(\hat{k}) = \frac{Y(z)}{L(z)} = B(M(z))\hat{k}(z)^\epsilon$ .

## 2.2 Optimality

Individuals maximize lifetime utility as stated in Eq. (1), subject to the state variables  $\dot{A}(z)$  and  $\dot{M}(z)$  in Eqs. (2) and (3) respectively. The Hamiltonian of this optimal control problem is

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<sup>4</sup>We thank two anonymous referees of the Journal for suggesting to make the productivity in the final sector as a function of the health stock and their suggestion to study the effect health not only on felicity but also on labor supply and wage income.



given by:

$$\begin{aligned} H(C, m, M, A, \lambda_A, \lambda_M) &= \mathcal{V} \{ S [U(C(z)), \varphi(M(z))] , N [U(C(z)), \varphi(M(z))] \} e^{-\rho z} \\ &+ \lambda_A [r(z)A(z) + w(z)\varphi(M(z)) - C(z) - h(m(z))] e^{-\rho z} \\ &+ \lambda_M [\psi(m(z)) - \delta_M M(z)] e^{-\rho z} \end{aligned} \quad (4)$$

The optimality conditions (where, to ease notations, the argument  $z$  is removed when it's not necessary) associated to this problem are given as:

$$\frac{\partial H}{\partial C(z)} = e^{-\rho z} (-\lambda_A + U_C V_N N_U + U_C S_U V_S) = 0 \quad (5a)$$

$$\frac{\partial H}{\partial m(z)} = -e^{-\rho z} \lambda_A h_m + e^{-\rho z} \lambda_M \psi_m = 0 \quad (5b)$$

$$\frac{\partial H}{\partial M(z)} = e^{-\rho z} (-\delta_M \lambda_M + \varphi_M (w \lambda_M + N_\varphi V_N + S_\varphi V_S)) = e^{-\rho z} (\rho \lambda_M - \dot{\lambda}_M) \quad (5c)$$

$$\frac{\partial H}{\partial A(z)} = e^{-\rho z} (r \lambda_A) = e^{-\rho z} (\rho \lambda_A - \dot{\lambda}_A) \quad (5d)$$

with the associated transversality conditions:

$$\lim_{z \rightarrow \infty} \lambda_A(z) e^{-\rho z} A(z) = 0 \quad (6a)$$

$$\lim_{z \rightarrow \infty} \lambda_M(z) e^{-\rho z} M(z) = 0 \quad (6b)$$

The functions  $\lambda_A(z)$  and  $\lambda_M(z)$  are the *costates* and subscripts indicate the first derivative of functions w.r.t mentioned arguments. The general dynamic system is given by:

$$\frac{\dot{C}(z)}{C(z)} = - \frac{(r - \rho)(V_N N_U + S_U V_S) - \Psi_1 \dot{M}(z) \varphi_M}{\Psi_2} \frac{U_C}{C(z)} \quad (7a)$$

$$\frac{\dot{m}(z)}{m(z)} = - \frac{\Phi}{U_C (V_N N_\varphi + S_U V_S) (\psi_m h'_m - h_m \psi'_m)} \frac{\psi_m}{m(z)} \quad (7b)$$

$$\frac{\dot{M}(z)}{M(z)} = \frac{\psi(m(z))}{M} - \delta_M \quad (7c)$$

$$\frac{\dot{k}}{k} = B(M) \hat{k}^{\epsilon-1} - \frac{\hat{C}}{k} - \frac{\hat{m}}{k} - \delta \quad (7d)$$

where  $\delta \geq 0$  is the capital depreciation rate and  $w$  is the wage rate and:

$$\begin{aligned} \Psi_1 &= V_S S_U \varphi + V_N N_U \varphi + N_\varphi (V_{\varphi\varphi} N_U + S_U V_{SN}) + S_\varphi (N_\varphi V_{SN} + S_U V_{SS}) \\ \Psi_2 &= U'_C (V_N N_U + S_U V_S) + U_C^2 (V_{\varphi\varphi} N_U^2 + 2 S_U N_U V_{SN} + V_S S_{UU} + V_N N_{UU} + S_U^2 V_{SS}) \\ \Phi &= U_C (V_N N_\varphi + S_U V_S) [w \varphi_M \psi_m - (\delta_M + r) h_m] + \varphi_M \psi_m (N_\varphi V_N + S_\varphi V_S) \end{aligned}$$

Our objective consists in finding the optimal trajectories of the model key variables: consumption, investment in health, health stock and capital. Given the assumptions 1-4, our optimization program allows to get these optimal variables. It is worth noticing that it would have been interesting to incorporate infectious diseases and their modes of transmission in our dynamic setting to assess the impact of health on variables such as capital accumulation, consumption, wages, etc. Indeed, it is interesting to know how health deterioration may affect the existence of solutions to the maximization of welfare. As well documented in Goenka and Liu (2012) and Goenka et al. (2014), if this damage was done by infectious diseases, then a problem of non-convexity arises and one needs to check existence conditions for optimal solutions.<sup>5</sup>

<sup>5</sup>We are very much grateful to a referee who pointed out to clarify the potential non-convexity issues in the study. Indeed, Goenka and Liu (2012) and Goenka et al. (2014) showed that given the internal propagation mechanism of infectious diseases, there are non-convexities in the transmission process which make the optimization problem subtle.

In fact, Goenka and Liu (2012) and Goenka et al. (2014) discussed the optimal investment in health, in the light of the interaction between the transmission of diseases and the economy. If diseases affect the labor market, health investments choices also affect the transmission of diseases. Health expenditures lead to the accumulation of health capital and thus reduce the spread of diseases and improve convalescence and recovery from illness. However, the non-convexity of the dynamics of infection implies that one should be careful in implementing the optimal control techniques. Indeed, to characterize optimal solutions, the first order conditions (and the transversality conditions) of the Hamiltonian may be necessary but not sufficient. Then there may be jumps issues of state and co-state variables within the feasible set whereas the existence of optimal solutions relies on compactness of the set and absolute continuity of the state variables. In this study we do not make specific assumptions on the nature of diseases (infectious or not) as well as their transmission mechanism. Incorporating these mechanisms in our model will pose additional extra difficulties that we leave for future research while focussing on the equally difficult separability issue of preferences structure.

Some general remarks can be made before addressing the calculation of optimal trajectories. Firstly, Eq.(5a) gives the expected evolution of optimal consumption which can be disentangle into  $\dot{C}(z) = C_1(z) + C_2(z)$ , with  $C_1(z) = \frac{-(r-\rho)(V_N N_U + S_U V_S) U_C}{\Psi_2}$  and  $C_2(z) = \frac{\Psi_1 U_C \dot{M}(z) \varphi_M}{\Psi_2}$ . The term  $C_1(z)$  denotes the Fisher conditions binding the slope of consumption trajectory to the difference between the time preference and interest rates. The term  $C_2(z)$  reflects the interaction between the stock of health and consumption. When time increases, the stock of health shall move towards its minimum level, and the marginal loss of time health  $\varphi_M(M(z))$  will reach its maximum, thereby reducing consumption.

Secondly, the *opportunity cost* of health stock (or unit cost), can be retrieved from the Eq.(5b) as  $\frac{\lambda_M}{\lambda_A} = g(z)$ . At equilibrium, the instantaneous *user cost* of health stock is equal to the instantaneous marginal benefit from one-unit increase in the stock of health. The optimal health investment is determined by the intersection between the curves representing these two elements. We have not chosen an explicit specification for the cost function, but we can still derive some information from the expression of the opportunity cost of health, based on co-state variables. Thus, it can be shown from Eq.(5c) that :

$$g(M(z)) \left( \delta_M + r - \frac{\dot{g}(z)}{g(z)} \right) = \varphi_M \left[ w + \frac{1}{\lambda_A(0)} (N_\varphi V_N + S_\varphi V_S) e^{(\rho-r)z} \right] \quad (8)$$

The first part of this equality stands for the *user cost* of health capital, the form of which as can be seen is comparable to that of physical capital in the theory of investment. It is also termed ‘marginal efficiency of capita’ (Grossman, 1972). The second member is the effect on the utility of an increase in the stock of health. Thus, the *user cost* of health capital should be equal to the instantaneous marginal benefit of an increase in the stock of health. The relations (Eq.8) can be transformed into a differential equation  $g(t)$  which shows after solving that the *opportunity cost* is therefore proportional to:

$$g(M(z)) = \int_z^\infty \left[ \varphi_M(M(x)) \left( w + \frac{1}{\lambda_A(0)} (N_\varphi V_N + S_\varphi V_S) e^{(\rho-r)x} \right) \right] e^{-(\delta_M+r)(x-z)} dx \quad (9)$$

This expression gives the present value of the benefits of health stock available on the remaining life. We will use the cost opportunity term later on in the penultimate section for policy purposes. In the next section, we address the case where the expression of  $\mathcal{V}$  is specified to have a separable term. We shall study the steady state and equilibrium dynamics of the model.

### 3 Additively separable preferences

The interaction between health and the ways it affects felicity has been so far investigated within additive structure preferences (Hall and Jones, 2007). As a result health status and consumption are additively separable functions implying that the marginal utility of consumption is independent from health status. While adopting this approach in this section, let's remember that we add a final good sector to better understand the life cycle aspect agent's behavior. In that case, the welfare function  $\mathcal{V}$  turns to take the form:

$$\mathcal{V}\{S[U(C(z)), \varphi(M(z))], N[U(C(z)), \varphi(M(z))]\} = S[U(C(z)), \varphi(M(z))] = U(C(z)) + \varphi(M(z)) \quad (10)$$

We shall also resort to the constant relative risk aversion (CRRA) felicity function, which has the below functional forms for  $U(C(z))$  and  $\varphi(M(z))$ , and a decreasing return in health investment for function  $\psi(m(z))$ :

$$U(C(z)) = \frac{C(z)^{1-\sigma_1}}{1-\sigma_1} \quad \text{and} \quad \varphi(M(z)) = \frac{M(z)^{1-\sigma_2}}{1-\sigma_2} \quad (11)$$

$$h(m(z)) = \pi m(z)^\alpha \quad \text{and} \quad \psi(m(z)) = b m^\beta \quad (12)$$

with  $\sigma_1 < 1$ ,  $\sigma_2 < 1$ ,  $b > 0$ ,  $\beta > 0$ ,  $\pi > 0$  and  $0 < \alpha < 1$ . Here  $\sigma_1$  is the inverse of elasticity of substitution between consumption at any two points in time, and  $\sigma_2$  denotes the same for health capital.  $U(C(z))$  and  $\varphi(M(z))$  are strictly increasing and concave respectively in  $C(z)$  and  $M(z)$ .  $\psi(m(z))$  represents the health investments function, which is concave in  $m(z)$ , reflecting the assumed diminishing returns in health investment.  $\pi$  is the productivity or efficiency of health investment. Increased health care productivity not only shifts the health production function upward, but causes each unit of health care to have a larger contribution to health as well. Ehrlich and Chuma (1990) also assumed that consumers choose death when the stock of capital  $M(z)$  is under a certain minimal level  $M_{\min}$ . All these functions fulfilled the assumptions 1-3.

#### 3.1 Steady state

The first order conditions with respect to  $C(z)$  and  $A(z)$  from the Hamiltonian (4) yield the traditional Euler equations. One can see that equations (7a) and (7b) turn to be respectively:

$$\frac{\dot{C}(z)}{C(z)} = 0 \iff (r - \rho)S_U V_S - [V_S S_{U\varphi} + S_\varphi S_U V_{SS}] \dot{M}(z) \varphi_M = 0 \quad (13)$$

and

$$\frac{\dot{m}(z)}{m(z)} = 0 \iff U_C S_U [w \varphi_M \psi_m - (\delta_M + r) h_m] + \varphi_M \psi_m S_\varphi = 0 \quad (14)$$

Thus, Eq.(13) defines a differential equation in  $M(t)$  which allows to find the value  $M^*(t)$  at equilibrium. The latter can then be introduced into (14) to find consumption equilibrium  $C^*(t)$  given that the stock of health and investment are linked by the relation (7c). More specifically, using Eqs.(11) and (12) we obtain the demand side system:

$$\frac{\dot{C}}{C} = \frac{r - \rho}{\sigma_1} \quad (15a)$$

$$\frac{\dot{m}}{m} = \frac{(-\varphi_M \psi_m^2 + U_C((r - \rho)h_m \psi_m + ((\delta_M + \rho)h_m - w\varphi_M \psi_m)\psi_m))}{U_C m(\psi_m h'_m - h_m)\psi'_m} \quad (15b)$$

$$\frac{\dot{M}}{M} = \frac{bm^\beta}{M} - \delta_M \quad (15c)$$

Proceeding with the final sector, remember that  $f(\hat{k}) = \frac{Y(z)}{L(z)} = B(M(z))\hat{k}(z)^\epsilon$ . Then, the maximization of the profit function under perfect competition allows to equalize the marginal cost of each factor with its marginal benefit. Therefore,

$$r(z) = \epsilon B(M(z))\hat{k}(z)^{\epsilon-1} - \delta \quad (16)$$

$$w(z) = f(\hat{k}(z)) - \hat{k}(z)f'(\hat{k}(z)) = (1 - \epsilon)B(M(z))\hat{k}(z)^\epsilon \quad (17)$$

Combining the demand and the supply sides, we can now characterize the equilibrium of the economy. We can write

$$\dot{\hat{k}}(z) = B(M(z))\hat{k}(z)^\epsilon - \hat{C}(z) - \hat{m}(z) - (\delta + n)\hat{k}(z) \quad (18)$$

where  $\hat{C}(z)$  and  $\hat{m}(z)$  are respectively the consumption and health expenditure per labor, and  $n$  is the population growth rate. Therefore, the dynamics of the economy can be summarized by the following non-trivial four dimensional system:

$$\frac{\dot{\hat{C}}(z)}{\hat{C}(z)} = \frac{r(z) - \rho}{\sigma_1} \quad (19a)$$

$$\frac{\dot{\hat{m}}(z)}{\hat{m}(z)} = \frac{\delta_M + r}{\alpha - \beta} - \frac{b\beta(w + C^{\sigma_1})M^{-\sigma_2}m^{\beta-\alpha}}{\pi\alpha(\alpha - \beta)} \quad (19b)$$

$$\frac{\dot{\hat{M}}(z)}{\hat{M}(z)} = bm^\beta - \delta_M \quad (19c)$$

$$\dot{\hat{k}}(z) = B(M(z))\hat{k}(z)^\epsilon - \hat{C}(z) - \hat{m}(z) - \delta\hat{k}(z) \quad (19d)$$

including  $\hat{k}(0)$  and  $\hat{M}(0)$  as given and in addition the transversality conditions. The steady-state values of  $\hat{C}$ ,  $\hat{m}$ ,  $\hat{M}$ , and  $\hat{k}$  are obtained by equalizing  $\dot{\hat{C}}$ ,  $\dot{\hat{m}}$ ,  $\dot{\hat{M}}$ ,  $\dot{\hat{k}}$  to zero. We obtain:

$$\hat{C} = \frac{w}{1 - \epsilon} \left( 1 - \frac{\epsilon}{r + \delta} \right) - \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} \widehat{M}^{\frac{1}{\beta}} \quad (20a)$$

$$\hat{m} = \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} \widehat{M}^{\frac{1}{\beta}} \quad (20b)$$

$$\widehat{M}^{\sigma_2 - 1 + \frac{\alpha}{\beta}} = \frac{b \left( \frac{b}{\delta_M} \right)^{-\sigma_2} \beta}{\pi(\delta_M + r)\alpha} \left[ w + \left( \frac{w}{1 - \epsilon} \left( 1 - \frac{\epsilon}{r + \delta} \right) - \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} \widehat{M}^{\frac{1}{\beta}} \right)^{\sigma_1} \right] \quad (20c)$$

$$\hat{k} = B(M)^{\frac{1}{1-\epsilon}} \left( \frac{\delta + \rho}{\epsilon} \right)^{\frac{1}{\epsilon-1}} \quad (20d)$$

The following proposition characterizes the solution of the system.

**Proposition 1** *There is a unique solution to Eq.(20c).*

*Proof.* See Appendix A.

The next proposition states the comparative statics of the model as regard the effect of health stock on the wage rate. It also states the conditions of existence for the equilibrium and the stability of the dynamic system.

**Proposition 2** *The effect of health stock on the wage rate is positive provided that  $\alpha \geq \beta(1 - \sigma_2)$  and  $\alpha > \beta$ . Moreover, there exists a minimum wage rate  $w_0$  from which the stock of health impacts positively on the wage rate.*

*Proof.* See Appendix A.

The condition in the proposition means that the ratio of the elasticities of the cost of health and health investment is greater than the elasticity of the production function of health. In addition, for the stock of health to have a positive effect on the wage rate, it is necessary that the wage rate remains higher than a minimum level  $w_0$ . We seek for conditions under which the minimum level  $w_0$  can be determined. Relying on Eq.(A-1; see Appendix A), setting  $\mathcal{W}_{\mathcal{N}} \geq 0$  and  $\mathcal{W}_{\mathcal{Q}} > 0$  is equivalent to writing respectively  $w \geq f_1(M)$  and  $w > f_2(M)$  where

$$\begin{aligned} f_1(M) &= \frac{(r + \delta)(1 - \epsilon)}{r + \delta - \epsilon} \left[ \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} M^{\frac{1}{\beta}} + \left( \frac{\left( \frac{b}{\delta_M} \right)^{\sigma_2} \left( \frac{\delta_M}{b} \right)^{-\frac{1}{\beta}} M^{\frac{-1 + \alpha - \beta + \beta \sigma_2}{\beta}} \pi(\delta_M + r) \alpha(\beta - \alpha - \beta \sigma_2)}{b \beta \sigma_1} \right)^{\frac{1}{-1 + \sigma_1}} \right] \\ f_2(M) &= \frac{(r + \delta)(1 - \epsilon)}{r + \delta - \epsilon} \left[ \left( \sigma_1 \frac{\epsilon - r - \delta}{(\epsilon - 1)(r + \delta)} \right)^{\frac{1}{1 - \sigma_1}} + \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} M^{\frac{1}{\beta}} \right] \end{aligned}$$

### Insert Figure 1

Figure 1 shows the curves  $f_1(M)$  and  $f_2(M)$ . The dash line curve from the origin becomes solid line from  $M_0$ , while the solid curve from  $w_0$  becomes dash line from  $M_0$ . We have:

$$M_0 = \left[ \frac{\frac{r + \delta - \epsilon}{(1 - \epsilon)(r + \delta)} \left( \frac{b}{\delta_M} \right)^{\frac{1}{\beta} + \sigma_2} \pi(\delta_M + r) \alpha(\alpha - \beta + \beta \sigma_2)}{b \beta} \right]^{\frac{\beta}{1 - \alpha + \beta - \beta \sigma_2}} \quad (21)$$

$$w_0 = \frac{(r + \delta)(1 - \epsilon)}{r + \delta - \epsilon} \left[ \sigma_1 \frac{r + \delta - \epsilon}{(1 - \epsilon)(r + \delta)} \right]^{\frac{1}{1 - \sigma_1}} \quad (22)$$

In fact, the influence of the stock of health on the wage rate is positive in the area bounded by the  $y$ -axis and the solid curve, knowing that the minimum ordinate is  $w_0$ . This domain is  $\sup(f_1, f_2)(M)$ . It is therefore possible that the stock of health has a *negative effect* on the wage rate and it is more related to the specification of the welfare function. Indeed, in the case of additive preferences we find that  $S_{U\varphi}$  and  $V_{SS}$  from Eq.(13) vanish. As a result, the solution  $M^*(z)$  is derived from Eq.(14). Relying on Eq.(7b), the expression of the wage rate is obtained as:

$$w(M^*(z)) = \frac{(\delta_M + r)h_m[m^*(z)]}{\varphi_M[M^*(z)]\psi_m[m^*(z)]} - \frac{S_{\varphi}[M^*(z)]}{U_C[C^*(z)]S_U[C^*(z)]} \quad (23)$$

where the variables  $m^*(z)$  and  $C^*(z)$  are expressed in function of  $M^*(z)$ .

This result calls for some comments. There is a consensus on the positive effects of health on growth and development. Particularly in developing areas such as in Africa where improving the quality of health is crucial. Gallup and Sachs (2001) estimated that elimination of malaria in sub-Saharan Africa would allow the continent to achieve an annual average growth of 2.6%. However, it is not empirically proven convincingly that health has a positive impact on growth and development. Indeed, most studies that have examined this impact do not have a general equilibrium perspective, which prevents them grasping the global dimension of the issue, including possible adverse effects of health (Acemoglu and Johnson, 2007). Our work helps to fill two important theoretical gaps in the literature. The first vacuum is the absence of a comprehensive approach, which shows the role of health in a flexible theoretical framework, without introducing morbidity constraints or constraints related to demographic pressures of the population. Hence our general equilibrium approach can show that the economic effects of health, measured through the wage rate (and therefore productivity) may be positive, but only under certain conditions, especially related to quality of health and costs of health investments.

The second theoretical gap is evidence of negative effects of health on the economic sphere. Acemoglu and Johnson (2007) showed empirically that the effects of health (measured by longevity) on growth of GDP per capita can be negative. Relying on a neoclassical growth model, our study provides a theoretical basis to this finding. Intuitively, a high stock of health may well have a negative effect on the wage rate if economic growth (and hence the distribution of income) is reduced due to the aging population for example, or because of high opportunity cost in health spending, which harm economic sectors. This is also possible, if improved health leads to a reduction of capital per capita, and thus lower levels of income per capita.

### 3.2 Phase diagrams

Let us now study the equilibrium dynamics of the system with phase diagrams. To this end, we express the variable in units of physical capital by setting:  $c = \frac{C}{k}$ ,  $\bar{m} = \frac{m}{k}$  and  $\bar{M} = \frac{M}{k}$ . It follows that the variables follows the system:

$$\frac{\dot{c}}{c} = \frac{r - \rho}{\sigma_1} - \frac{r + \delta(1 - \epsilon)}{\epsilon} + c + \bar{m} \quad (24a)$$

$$\frac{\dot{\bar{m}}}{\bar{m}} = \frac{\delta_M + r}{\alpha - \beta} - \frac{b\beta(w + k^{\sigma_1} c^{\sigma_1}) \bar{M}^{-\sigma_2} \bar{m}^{\beta - \alpha} k^{\beta - \alpha - \sigma_2}}{\pi \alpha (\alpha - \beta)} - \frac{r + \delta(1 - \epsilon)}{\epsilon} + c + \bar{m} \quad (24b)$$

$$\frac{\dot{\bar{M}}}{\bar{M}} = \frac{b \bar{m}^{\beta} k^{\beta - 1}}{\bar{M}} - \delta_M - \frac{r + \delta(1 - \epsilon)}{\epsilon} + c + \bar{m} \quad (24c)$$

The condition in the proposition ensures also the existence and uniqueness of the steady state and guarantees the stability. Relying on the implicit behavior of  $\bar{m}$  and parameters conditions, we prove below that this leads to the the existence and uniqueness of the solution. We are now interested in the changes in the equilibrium, when some health parameters are modified. We propose a geometrical representation by drawing the phase diagrams associated to the system (24a)-(24c). The diagrams are plotted on different planes while fixing each of the variables. Lemma 1 elaborates on the phase diagrams in Figures 2, 3 and 4.

**Lemma 1** *We have:*

- i) *For  $\bar{m}$  fixed, the curve  $\dot{c} = 0$  is a horizontal line and the locus  $\dot{\bar{M}} = 0$  is an increasing and concave function. Moreover we have  $\lim_{\bar{M} \rightarrow \infty} c = b_2$  for  $b_2$  given.*
- ii) *For  $c$  fixed, the curve  $\dot{\bar{M}} = 0$  monotonically increases and the locus  $\dot{\bar{m}} = 0$  is a decreasing and convex function with  $\lim_{\bar{m} \rightarrow 0} \bar{M} = 0$  and  $\lim_{\bar{m} \rightarrow b^-} \bar{M} = \infty$ .*

- iii) For  $\bar{M}$  fixed, the curve  $\dot{c} = 0$  is a decreasing straight line and the locus  $\dot{m} = 0$  is an increasing function over a real support and it decreases monotonically from  $\bar{m}_0$ .

### Insert Figures 2, 3, 4

Fixing  $\bar{m} = \bar{m}_0$  leads to the phase diagram onto the plane  $(c, \bar{M})$  (see Figure 2). We have two curves. The first one ( $\dot{c} = 0$ ) is independent of the stock of health. An increase of the rate of health depreciation ( $\delta_M$ ) implies a shift of the second curve ( $\dot{\bar{M}}$ ) towards the left. This curve is increasing with both consumption and health. The shift induces a decrease of health from the steady state  $E_0$  to a new one  $E_1$ , where consumption remains constant.

The second phase diagram in Figure 3 is plotted onto the plane  $(\bar{m}, \bar{M})$  by fixing  $c$ . The two curves are increasing with the variables  $\bar{m}$  and  $\bar{M}$ , but the stock of health grows faster than the flow of investment. An increasing rate of health depreciation leads to a high reduction of the stock of health which is not fully compensated by the investment. So the two curves shift down to the steady state  $E_1$ .

Fixing  $\bar{M}$  gives the third diagram in Figure 4 on the plane  $(c, \bar{m})$ . Relying on the equation ( $\dot{c} = 0$ ) there is a linear relation between the flow of investment and consumption. The stable manifold is in the zones on the left hand side of  $E_0$  above the curve and the right hand side of  $E_0$  below the curve. Within these two zones, the trajectories converge to the steady state values. An increase of  $\delta_M$  generates a higher level of investment flows. Moreover, a crowding effect appears and consumption jumps backward from the first steady state  $E_0$  to the second one  $E_1$ .

## 4 Multiplicative preferences

In the previous section, consumption and health enter into the utility function in an additive way. As a result, the marginal utility of consumption can be independent from health, which reflects a strong limitation as consumption is also crucial for health. The alternative model in this section seeks to account for this important aspect. The welfare function  $\mathcal{V}$  takes now the form:

$$\mathcal{V}\{S[U(C(z)), \varphi(M(z))], N[U(C(z)), \varphi(M(z))]\} = N[U(C(z)), \varphi(M(z))] = U(C(z))\varphi(M(z)) \quad (25)$$

In order to be able to compare consistently the results, we use the same CRRA felicity functional forms for  $U(C(z))$  and  $\varphi(M(z))$  as in Eq.(11), as well as the same health functions  $h(m(z))$  and  $\psi(m(z))$  in Eq.(12). Also the final sector description is the same. Given this new set-up, we can study the steady state and equilibrium dynamics of the non-separable multiplicative preferences model.

### 4.1 Steady state

Here, Eqs.(7a)-(7b) turn to be respectively

$$\frac{\dot{C}(z)}{C(z)} = 0 \iff (r - \rho)V_N N_U - [V_N N_U \varphi + N_\varphi N_U V_{\varphi\varphi}] \dot{M}(z) \varphi_M = 0 \quad (26)$$

and

$$\frac{\dot{m}(z)}{m(z)} = 0 \iff U_C[w\varphi_M \psi_m - (\delta_M + r)h_m] + \varphi_M \psi_m = 0 \quad (27)$$

As previously, Eq.(26) defines a differential equation in  $M(t)$  which allows to find the value  $M^*(t)$  at equilibrium. The latter can then be plugged into (27) to retrieve consumption equilibrium  $C^*(t)$  thank to relation (7c). The dynamics of the economy is driven at equilibrium by the following system:

$$\begin{aligned}\frac{\dot{\hat{C}}(z)}{\hat{C}(z)} &= \frac{(r - \rho)M(z) + (\delta_M M(z) - bm(z)^\beta)(\sigma_2 - 1)}{M(z)\sigma_1} \\ \frac{\dot{\hat{m}}(z)}{\hat{m}(z)} &= \frac{1}{\pi\alpha(\alpha - \beta)(1 + \sigma_1)M(z)^{1+\sigma_2}} \left[ \pi(\delta_M + r)\alpha M(z)^{1+\sigma_2}(1 + \sigma_1) \right. \\ &\quad \left. - b\beta m(z)^{\beta-\alpha}(wM(z)(1 + \sigma_1) + C(z)M(z)^{\sigma_2})(1 + \sigma_2) \right] \\ \dot{\hat{M}}(z) &= -\delta_M + \frac{bm^\beta}{m(z)} \\ \dot{\hat{k}}_z &= B(M(z))\hat{k}(z)^\epsilon - \hat{C}(z) - \hat{m}(z) - \delta\hat{k}(z)\end{aligned}\tag{28}$$

with  $\hat{k}(0)$  and  $\hat{M}(0)$  given, plus the transversality conditions. The steady-state values of  $\hat{C}$ ,  $\hat{m}$ ,  $\hat{M}$ , and  $\hat{k}$  are obtained by equalizing  $\dot{\hat{C}}$ ,  $\dot{\hat{m}}$ ,  $\dot{\hat{M}}$ ,  $\dot{\hat{k}}$  to zero. We have:

$$\hat{C} = \frac{w}{1 - \epsilon} \left( 1 - \frac{\epsilon}{r + \delta} \right) - \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} \hat{M}^{\frac{1}{\beta}}\tag{29a}$$

$$\hat{m} = \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} \hat{M}^{\frac{1}{\beta}}\tag{29b}$$

$$\hat{M}^{\sigma_2 + \frac{\alpha}{\beta} - 1} = \frac{b\beta}{\pi(\delta_M + r)\alpha} \left( \frac{\delta_M}{b} \right)^{\frac{\beta - \alpha}{\beta}} \left[ w + \left( \frac{w(2(r + \delta) - \delta\epsilon)}{(r + \delta)(1 - \epsilon)} - \left( \frac{\delta_M M}{b} \right)^{\frac{1}{\beta}} \right) \hat{M}^{\sigma_2 - 1} \frac{\sigma_2 - 1}{\sigma_1 - 1} \right]\tag{29c}$$

$$\hat{k} = B(M)^{\frac{1}{1 - \epsilon}} \left( \frac{\delta + \rho}{\epsilon} \right)^{\frac{1}{\epsilon - 1}}\tag{29d}$$

The following results hold:

### Proposition 3

- i) The dynamic system (29a)-(29d) admits a stable solution.
- ii) The effect of health stock on wage rate is positive provided that  $\beta(1 - \sigma_2) \leq \alpha < \beta$ .

*Proof.* See Appendix A.

To study how the wage rate behaves in this case, on can rely on Eq.(29c). Solving the latter with respect to wage leads to:

$$w(M) = \frac{\left( \frac{\delta_M}{b} \right)^{\frac{\alpha}{\beta}} M^{-1+\sigma_2} \pi(\delta_M + r)\alpha \left( M^{\frac{\alpha}{\beta}} + \frac{\delta_M \left( \frac{\delta_M}{b} \right)^{-\frac{\alpha}{\beta}} \left( \frac{\delta_M M}{b} \right)^{\frac{1}{\beta}} \beta(-1+\sigma_2)}{\pi(\delta_M + r)\alpha(-1+\sigma_1)} \right)}{\delta_M \beta \left( 1 + \frac{M^{-1+\sigma_2}(2r+2\delta-\delta\epsilon)(-1+\sigma_2)}{(r+\delta)(1-\epsilon)(-1+\sigma_1)} \right)}\tag{30}$$

which is fully expressed in terms of  $M$ . On can check (see Appendix A, Proof of Proposition 3) that  $w(M)$  here is an increasing function of  $M$ .

As we can see from Propositions 2 and 3, the conditions for the wage rate be related to health stock are different. Both cases share a common condition which is  $\alpha \geq \beta(1 - \sigma_2)$ . However,



whereas in the additive case one needs in addition  $\alpha > \beta$ , the multiplicative preference requires  $\alpha < \beta$  leading to the inequality condition in Proposition 3. The latter states that the ratio of the elasticities of the cost of health and health investment must be lower than the elasticity of the production function of health. The stock of health has throughout a positive effect on the wage rate. Compared to the additive preference, we no longer have the domain of negative effect of stock of health on the wage rate which was displayed in Figure 1. Formally, this result clearly follows from the structure of preferences. However, from an economic and empirical perspective, how could one explain this change in wage rate with respect to preferences.

In the case of additive preferences, health status and consumption are additively separable in the utility function implying that the marginal utility of consumption is independent from health status. This does not fit in for instance with the notion that good nutrition is also important for health. Indeed, healthy eating might lead to a reduction in mortality from chronic illness, and appropriate dietary advice can prevent physical and mental deterioration and improve the quality of life. Evidence from Friis and Michaelsen (1998) supports this rationale. Therefore, consumption is also crucial for health. The multiplicative non-separable preferences highlights the interaction between consumption and health although it is very difficult to slice on the net effect of a high health deterioration rate and low health productivity on health investment.

Another way to interpret the common relationship  $\alpha \geq \beta(1 - \sigma_2)$  between the Propositions 2 and 3 is to consider the changes in inter-temporal substitution of health with respect to health investment and the cost of that investment. Indeed it appears that the higher the health investment (i.e.  $\beta$ ), the lower the elasticity of substitution. Inter-temporal substitutability of health can become zero if the cost of investment in health become increasingly high. In order to improve substitutability of health stock over time, justifying a reduction in inertia of household health behavior, there must be a combination of two phenomena: a gradual decrease in elasticity of health production and a simultaneous increase of the costs of health investment. This may seem against intuition. However, it should be noted that if households determine the level of current health stock taking into account its level in the previous period, this may affect the future marginal utility of health stock. Indeed, any increase in the level of health of the current period increases the future marginal utility of health. The effect of inter-temporal substitution between present and future stocks becomes weak if health habits are persistent. In this case, the representative household has to spend much more wealth between the current period and the future period to improve the stock of future health. And even with a low rate of health depreciation, the costs of health investments become increasingly high.

## 4.2 Phase diagrams

We now elaborate on how the health parameters affect the steady-state values, notably the health investment variable and the consequences on consumption, capital stock and savings. To this end, we study the equilibrium dynamics of this economy. Using the same variable definition above, the dynamical system is computed as:

$$\begin{aligned}
\frac{\dot{c}}{c} &= \frac{-(r-\rho)M + (-1+\sigma_2)(-\delta_M M + bm^\beta k^{-\beta+1})}{-\sigma_1 M} - \frac{r+\delta(1-\epsilon)}{\epsilon} + c + \bar{m} \\
\frac{\dot{\bar{m}}}{\bar{m}} &= c^{\sigma_1} m^{1-\alpha} M^{\sigma_2} k^{-\sigma_2+\alpha-1} \left( \left( bm^{-1+\beta} M^{-\sigma_2} k^{\sigma_2-\beta+1} \left( \frac{c^{1-\sigma_1}}{-1+\sigma_1} + wc^{-\sigma_1} \left( \frac{M^{1-\sigma_2} k^{\sigma_2-1}}{-1+\sigma_2} \right) \right) \right. \right. \\
&\quad \left. \left. + \pi(-\delta_M - r)\alpha c^{-\sigma_1} m^{-1+\alpha} k^{1-\alpha} \left( \frac{M^{1-\sigma_2} k^{\sigma_2-1}}{-1+\sigma_2} \right) \right) (-1+\sigma_2) \right) / (\pi\alpha(\alpha-\beta)((-Mk^{-1}))) \\
&\quad - \frac{r+\delta(1-\epsilon)}{\epsilon} + c + \bar{m} \\
\frac{\dot{\bar{M}}}{\bar{M}} &= \frac{b\bar{m}^\beta k^{\beta+1}}{\bar{M}} - \delta_M - \frac{r+\delta(1-\epsilon)}{\epsilon} + c + \bar{m}
\end{aligned} \tag{31}$$

Here again, we turn to analysis of the changes in the equilibrium when some health parameters are modified. Lemma 2 documents on the phase diagrams in Figures 5, 6 and 7 which are associated to the system Eq.(31).

**Lemma 2** *We have:*

- i) *For  $\bar{m}$  fixed, the curve  $\dot{c} = 0$  is a horizontal line and the locus  $\dot{\bar{M}} = 0$  is an increasing and concave function, with  $\lim_{\bar{M} \rightarrow \infty} c = a'$  for  $a'$  given.*
- ii) *For  $c$  fixed, the curves  $\dot{\bar{m}} = 0$  and  $\dot{\bar{M}} = 0$  are convex and monotonically increasing with  $\lim_{\bar{m} \rightarrow a} \bar{M} = \infty$  and  $\lim_{\bar{m} \rightarrow a'} \bar{M} = \infty$  for  $a$  and  $a'$  given.*
- iii) *For  $\bar{M}$  fixed, the curve  $\dot{c} = 0$  is decreasing and the locus  $\dot{\bar{m}} = 0$  is an increasing function and it decreases monotonically from  $\bar{m}_1$ .*

### Insert Figures 5, 6, 7

We fix  $\bar{m}$  and get the first diagram in Figure 5 onto the plane  $(c, \bar{M})$ . As for the additive case, the curve  $\dot{c} = 0$  doesn't depend on the stock of health  $\bar{M}$ . The consumption depends though only on the flow of investment and on the rate of health depreciation. The curve  $\dot{\bar{M}} = 0$  is concave and increases with both variables. Starting from the steady state  $E_0$ , an increase of  $\delta_M$  shifts upward the level of consumption, leading to the final equilibrium point  $E_1$ . The depreciation of health reduces the stock of health, but this reduction is compensated by the shift of consumption. The result is a net increase of health.

The second phase diagram in Figure 6 is plotted onto the plane  $(\bar{m}, \bar{M})$  by fixing  $c$ . The two curves are increasing with the variables  $\bar{m}$  and  $\bar{M}$ , but the stock of health grows faster than the flow of investment. An increasing rate of health depreciation leads to a high reduction of the stock of health which is not fully compensated by the investment. So the two curves shift down to the steady state  $E_1$ .

The third diagram in Figure 7 is obtained onto the plane  $(c, \bar{m})$  by fixing  $\bar{M}$ . There is a linear relation between  $c$  and  $\bar{m}$  that gives the monotonically decreasing curve. An increase of the depreciation rate shifts upward the consumption and the flow of investment in health on the curve  $\dot{c} = 0$ . We have the same with the curve  $\dot{\bar{m}} = 0$ . The final steady state is reached at  $E_1$  where both variables increase.

Let us discuss insights from the equilibrium dynamic considering the effects of parameters in the different models and taking into account the dynamics of transition. We assume the economy is on balanced growth path when a parameter varies, and we analyze the adjustments to the new

equilibrium path. Let's take the example of the phase diagram where we consider a variation of the rate of depreciation of health  $\delta_M$ . Fixing  $\bar{m}$ , the phase diagrams are obtained on the plane  $(\dot{c}, \dot{M})$  of Figures 2 and 5 wherein there are two curves for the additive and multiplicative cases. The first ones ( $\dot{c} = 0$ ) are independent of the stock of health. The curves  $\dot{M} = 0$  are concave and grow with both variables. In the case of the separable utility, an increase in the rate of impairment of health implies a movement of the second curve ( $\dot{M} = 0$ ) to the left. This induces a reduction of the health by the move from the stable equilibrium  $E_0$  to a new equilibrium  $E_1$  where consumption remains constant. Conversely, in the multiplicative case, starting from the steady state  $E_0$ , an increase in  $\delta_M$  shifts up the level of consumption, leading to the end point of equilibrium  $E_1$ . Impairment of health reduces the stock of health, but this decrease is offset by the increase in consumption. The result is a net increase in the stock of health.

Fixing  $\bar{c}$  gives both Figures 3 and 6 on the plane  $(\dot{m}, \dot{M})$  that relate the stock of health to health investment. For the additive as well as for the multiplicative case, the curve ( $\dot{M} = 0$ ) increases, but the health stock increases faster than investment flows. When impairment of health increases, this implies a lower level of health stock. The curve  $\dot{m} = 0$  moves to the left. But the flow of investment increases, which means that the final steady state is reached when the curve  $\dot{M} = 0$  shifts to the right. The final state of equilibrium point is  $E_1$  where the stock of health is lower than the first equilibrium point  $E_0$ .

Fixing  $\bar{M}$  produces Figures 4 and 7 in the plane  $(\dot{c}, \dot{m})$ . For the additive case, starting from the equation ( $\dot{c} = 0$ ) we see that there always exists a linear relationship between the flow of health investments and consumption. The trajectories converge to equilibrium from the areas of stability on the left values of  $E_0$ . An increase in  $\delta_M$  generates a high level of investment flows. In addition, a crowding effect appears and consumption reduced from  $E_0$  to  $E_1$ . For the multiplicative case, the equilibrium is reached at point  $E_1$  where both variables increase simultaneously.

## 5 Convex combination of preferences

In this section, we combine both cases in a general framework. Indeed, it is likely that between purely additive and multiplicative preferences, there might a range of choice in between depending parameter link that may drive agents' behavior. The welfare function  $\mathcal{V}$  takes now the form:

$$\mathcal{V}(\cdot) = sU(C(z))\varphi(M(z)) + (1-s)[U(C(z)) + \varphi(M(z))] \quad (32)$$

and  $s$  is a parameter link such that  $0 \leq s \leq 1$ . If  $s = 1$  then the individual preference becomes additive and for  $s = 0$  it is multiplicative.

The dynamic system then is obtained by the Eqs.(7a)-(7d). The optimization equations (5a)-(5d) provide sufficient conditions for maximizing welfare because of the concavity of the utility function, the production of health and health investment. The Hamiltonian is a concave function of the state variables and control variables. The following result holds:

**Proposition 4** *The equilibrium values of health stock are located on a trajectory which is time dependent and given by the relation:*

$$\widehat{M}(z, s) = \left[ \theta_0(s) + \theta_1 e^{-z(r-\rho)} \right]^{\frac{1}{1-\sigma_2}} \quad (33)$$

with  $\theta_0(s) = -s \frac{1-\sigma_2}{1-s}$  and  $\theta_1 = \bar{\lambda}(1-\sigma_2)$  where  $\bar{\lambda}$  is an integration constant.

*Proof.* See Appendix A.

Proposition 4 is interesting as it shows that the balance health variables  $\widehat{M}$  and  $\widehat{m}$  can be expressed as a function of time, regardless of other real variables such as consumption and capital per capita. However, as Eqs.(7a)-(7d) of the general system establish the links between the variables in the model, the equilibrium expression of these variables can be recovered. But this approach is analytically complicated if not impossible. Moreover, as we have documented in the Appendix B, studying analytically the equilibrium dynamics of the model in the case of convex combination of preferences is unbearable.

The expression of health investment at equilibrium  $\widehat{m}(z)$  is then obtained as:

$$\widehat{m}(z) = \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} \left[ \theta_0(s) + \theta_1 e^{-z(r-\rho)} \right]^{\frac{1}{\beta(1-\sigma_2)}} \quad (34)$$

Relying on Eq.(7b) and using  $S_\varphi[M^*(z)] = (1-s)\varphi_M[M^*(z)]$  and  $S_U[C^*(z)] = (1-s)U_C[C^*(z)]$  the expression of wage rate is obtained as:

$$w(M^*(z)) = \frac{(\delta_M + r)h_m[m^*(z)]}{\varphi_M[M^*(z)]\psi_m[m^*(z)]} - \frac{\varphi_M[M^*(z)]}{U_C^2[C^*(z)]} \quad (35)$$

where  $M^*(z)$  and  $m^*(z)$  are replaced by their expressions.

Figure 8 shows the evolution of the stock of health and health investment. The curves depart from an initial value at time  $z = 0$  given by the expressions  $\widehat{M}(0, s)$  and  $\widehat{m}(0, s)$  as described below. As in the model of Ehrlich and Chuma (1990),  $\widehat{M}$  and  $\widehat{m}$  are decreasing and tend to a minimum.

### Insert Figure 8

Furthermore, Proposition 4 allows us to study the limits behavior of stock and investment in health. We can distinguish two cases: i) infinite horizon ( $z \rightarrow \infty$ ) and ii) finite horizon ( $z \rightarrow T$ ). In the first case, taking the limit of Eqs.(33) and (34), we obtain respectively:  $\lim_{z \rightarrow \infty} \widehat{M}(z, s) = \widehat{M}(\infty, s) = [\theta_0(s)]^{\frac{1}{1-\sigma_2}}$  and  $\lim_{z \rightarrow \infty} \widehat{m}(z, s) = \widehat{m}(\infty, s) = \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} [\theta_0(s)]^{\frac{1}{\beta(1-\sigma_2)}}$ . For  $z = 0$ , we have  $\widehat{M}(0, s) = [\theta_0(s) + \bar{\lambda}(1 - \sigma_2)]^{\frac{1}{1-\sigma_2}}$  and  $\widehat{m}(0, s) = \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} [\theta_0(s) + \bar{\lambda}(1 - \sigma_2)]^{\frac{1}{\beta(1-\sigma_2)}}$ . Infinite horizon also implies high health deterioration meaning that health will tend to its minimum. It follows that  $\widehat{M}_{\min}(\infty, s) = [\theta_0(s)]^{\frac{1}{1-\sigma_2}}$  and  $\widehat{m}_{\min}(\infty, s) = \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} [\theta_0(s)]^{\frac{1}{\beta(1-\sigma_2)}}$ .

The case of finite horizon is of particular interest because it provides the expression of the time limit for the stock of health to be low, and that life ends at some  $T(\cdot, s)$ . We have:

$$\lim_{z \rightarrow T} \widehat{M}(z, s) = \widehat{M}(T, s) = \left[ \theta_0(s) + \bar{\lambda}(1 - \sigma_2) e^{-T(r-\rho)} \right]^{\frac{1}{1-\sigma_2}} \quad (36)$$

When  $T$  is reached, health reaches its minimum given by Eq.(36). Figure 9 displays the graph for that case.  $\widehat{M}(T, s)$  decreases and reaches its minimum at horizon  $T(s)$ .

### Insert Figure 9

An interesting theoretical issue is what would be the value of time horizon  $T$ , if the minimum level of health is known. Let's recall our approach to better understand the theoretical

importance of the finite time horizon. In the model, we looked for the optimal paths of consumption, capital and health variables for infinite horizon. The framework of convex combination of preferences leads to purely temporal expression of health stock and health investment. These variables depend on what we call the *structure parameter* or *convexity* of the model,  $s$ . The latter allows to balance the model between the two polar cases: additive and multiplicative welfare function. The benefit of having optimal variables that are expressed in terms of time is that one can identify the limits which in turn depend on the model parameters. Therefore, setting  $s$ , and making assumptions about the minimum value of the stock of health, we can infer a temporal horizon that represents longevity, i.e. life duration over which health keeps economic activities of work, consumption and investment. Suppose the minimum stock is not zero, then  $T$  can be obtained from Eq.(36) for  $\widehat{M}(T, s) = \widehat{M}_{\min}(s)$ , and be expressed in terms of other model parameters as:

$$T = \frac{1}{r - \rho} \ln \left( \frac{\bar{\lambda}(1 - \sigma_2)}{\widehat{M}_{\min}(s) - \theta_0(s)} \right) = T_0 + \frac{1}{r - \rho} \ln \left( \frac{1 - \sigma_2}{\widehat{M}_{\min}(s) + s \frac{1 - \sigma_2}{1 - s}} \right) \quad (37)$$

with  $T_0 = \frac{1}{r - \rho} \ln \bar{\lambda}$ . The study of function  $T$  with respect to parameters is interesting from two points of view. First, this horizon should ideally be farthest from zero as possible. Therefore, it is crucial to understand the role of each parameter to achieve this goal. Secondly, we have not explicitly sought optimal longevity as in Ehrlich and Chuma (1990). However, our approach leads to a model of optimal lifetime which generalizes Ehrlich and Chuma (1990). Indeed, as the authors, we find the same parameters that determine lifespan. In addition, here, lifespan also depends on the way welfare is chosen, i.e. parameter  $s$ . If we elaborate only on the effect of  $\sigma_2$  parameter, we have the following representation of  $T$ :

### Insert Figure 10

In Figure 10,  $\bar{\sigma}_2 = 1 - \frac{(1-s)}{2s} \widehat{M}_{\min}(s)$  and  $\bar{\bar{\sigma}}_2 = 1 - \frac{(1-s)}{\bar{\lambda}(1-s)-s} \widehat{M}_{\min}(s)$  and  $T(\bar{\sigma}_2, s)$  is given by Eq.(37) evaluated at  $\bar{\sigma}_2$ . Figure 10 also shows interesting aspects of the modeling. First of all, observe the vertical dotted line that stresses the constraint  $\sigma_2 < 1$ . The longevity  $T$  curve shows a convex-concave shape. Indeed, the first portion of the curve which departs from  $T(s, 0)$  decreases convexly to reach the inflection point  $(T(\bar{\sigma}_2, s), \bar{\sigma}_2)$  where the curve becomes concave till the point  $\bar{\bar{\sigma}}_2$ . Therefore, longevity is a decreasing function of the elasticity of inter-temporal substitution of health  $\sigma_2$ . We also see that as long as  $\sigma_2 < \bar{\bar{\sigma}}_2$ , lifespan is strictly positive. This indicates that there is a maximal bound for  $\sigma_2$  beyond which the stock of health is minimal. Thus, the choice of  $\sigma_2$  will impact the longevity modeling. Indeed, if  $\sigma_2 \in ]\bar{\bar{\sigma}}_2, 1[$ , longevity is zero, this means that the stock of health has no effect on real variables. As a result, there is no longer life:  $\widehat{M}(z, s) = \widehat{M}_{\min}(s) = 0$  for all  $z$ . However, if one chooses  $\sigma_2 \in ]0, \bar{\bar{\sigma}}_2[$ , it is still possible to give a positive value to  $T$  provided to identify the structural parameter  $s$  which gives more weight to either the additive preference ( $s \rightarrow 0$ ) or the multiplicative one ( $s \rightarrow 1$ ). For  $s = 1$  (multiplicative), we have  $\bar{\sigma}_2 = \bar{\bar{\sigma}}_2 = 1$ . So one can choose  $\sigma_2$  in the range  $[0, 1[$  and therefore  $T > 0$ . In other words, opting for multiplicative preferences rules out the problem of existence of  $T$ . However, if an additive preference ( $s = 0$ ) is chosen, one should care about the issue of existence of  $T$ .

Some comments related to Propositions 2, 3 and 4 are in order. In economic theory, the effect of health quality care is often approached indirectly. Indeed, it is straightforward to measure health inputs and the indirect effects of health on the economy (through indicators

that are positively correlated with good health conditions, such as increased life expectancy, low morbidity rates, etc.). Although the quality of health is not directly measurable, our model allows to specify conditions for good health, by connecting three quantitative factors, namely health production, health investment and health costs. We have shown that the elasticities ( $\alpha$ ,  $\beta$  and  $\sigma_2$ ) of these three variables work together to define how health status influences labor. The model enables us to link the evolution of wage rates with respect to health. The transmission belt between the wage rate and health is labor productivity. As better health conditions enhances human capacities, the values created in the production process are improve in turn.

Two problems arise: those of causality and indeterminacy. There is a causality problem because when wage rates become too high, the most productive agents, that is to say, those with higher wages, consume more and more goods that improve health. Thus, causality can pass from greater labor productivity to better health, not from health to productivity. This is typically a reverse causality issue. The indeterminacy arises with the model specification. Indeed, there are values of the elasticities ( $\alpha = \beta$ ) for which the model may not have equilibrium and the influence of health on the wage rate becomes indeterminate. This also coincides with the fact that the opportunity cost of health stock becomes time independent. Figure 11 shows the combinations of parameters  $\alpha$  and  $\beta$  that allows our models to have solutions.

### Insert Figure 11

The axis  $OO'$  makes an angle of  $45^\circ$  with the axis  $O\beta$  and the combination solutions which have the properties of additive and multiplicative case is delimited by the bold lines of the trapezium ( $OO'O''O'''$ ), once the parameters  $\alpha$  and  $\beta$  are set. On one hand, this is actually a combination of points belonging to the surfaces of triangles  $OO'O''$  (additive preferences) and  $OO''O'''$  on the other hand (multiplicative preferences). These points are on the segment  $O'E'$ . However, the intersection points  $E$  with the segment  $OO''$  are excluded from the model because they check the equality condition  $\alpha = \beta$ .

It is worth to notice a recurring problem in the field of health investment. Indeed, usually the aim is to look for the second best optimum in order to conciliate efficiency and social equity by proposing an optimal tax system and subsidies. Indeed, according to neoclassical theory, efficiency is reached when all agents behave competitively, and optimal allocations are then first best. Equity can be achieved through redistribution of income between healthy workers, workers whose health stock is low, and investors. This would have allowed us to disconnect the ‘final distribution of health stock’ of that resulting from the ex-post prices and elasticities structure of production and investment. But at this stage of our model, the issue is not that of equity. Our intuition is that we could have come up with explanations for the difference in results between the additive and the multiplicative preferences. We leave this for future research.

## 6 Opportunity costs of health

In this section, we compare the opportunity costs of health investment under the three alternative preferences. Such comparison is useful for policy analysis. Indeed, for a decision maker, it is interesting to know what investment alternative is the most effective in face of limited resources. Actually, for public policy reasons, the health sector is in competition with others economic sectors. As a result, the less costly alternative might be privileged. However, cost is only one input of the decision, as the latter should also consider the expected benefit from the investment in order to have a full picture of the decision options. This usually leads to an empirical cost

benefit analysis. Our objective here is to shed a theoretical light on the cost aspect of that mechanism.

In section 2, we established in Eq.(9) the expression of the opportunity cost in a very general way. The latter provides the present value of the benefits of health stock available on the remaining life. We can derive the analogue of Eq.(9) for each type of preference. In the additive case, we have:

$$g_1(M(z)) = \int_z^\infty \left[ \varphi_M(M(x)) \left( w(M) + \frac{1}{\lambda_A(0)} (S_\varphi V_S) e^{(\rho-r)x} \right) \right] e^{-(\delta_M+r)(x-z)} dx \quad (38)$$

where the wage rate  $w$  is given by Eq.(20c). For multiplicative preference, we have:

$$g_2(M(z)) = \int_z^\infty \left[ \varphi_M(M(x)) \left( w(M) + \frac{1}{\lambda_A(0)} (N_\varphi V_N) e^{(\rho-r)x} \right) \right] e^{-(\delta_M+r)(x-z)} dx \quad (39)$$

where the wage rate  $w$  is given by Eq.(30). For the convex combination of preferences, we have:

$$g_3(M(z)) = \int_z^\infty \left[ \varphi_M(M(x)) \left( w(M) + \frac{1}{\lambda_A(0)} (sU + (1-s)) e^{(\rho-r)x} \right) \right] e^{-(\delta_M+r)(x-z)} dx \quad (40)$$

where the wage rate  $w$  is given by Eq.(35). The functions or distributions  $g_1(M(z))$ ,  $g_2(M(z))$  and  $g_3(M(z))$  for  $0 \leq z \leq \infty$  can be compared using the notion of *stochastic dominance*. Define the distributions  $g_i(M(x))$  for preferences structure  $i = 1, 2, 3$  (additive, multiplicative and convex combination respectively) as

$$g_i(M(x)) = \varphi_M(M(x)) \left( w_i(M(x)) + \frac{1}{\lambda_A(0)} \Phi_i e^{(\rho-r)x} \right) e^{-(\delta_M+r)(x-z)} \quad (41)$$

where  $\Phi_1 = S_\varphi V_S$ ,  $\Phi_2 = N_\varphi V_N$  and  $\Phi_3 = sN_\varphi V_N + (1-s)S_\varphi V_S$ . We can then write

$$g_i(M(z)) = \int_z^\infty g_i(M(x)) dx$$

implying that  $g_i(M(z))$  is the *complementary cumulative distribution* of  $M(x)$ . That is  $g_i(M(z)) = 1 - \mathcal{F}(M(z))$  where  $\mathcal{F}(M(z)) = \int_{-\infty}^z g_i(M(x)) dx$  is the cumulative distribution of  $M(x)$ .

**Definition 1** A complementary cumulative distribution (CCD)  $\mathcal{F}$  is said to first-order stochastically dominate (FOSD) another distribution  $\mathcal{G}$  if and only if  $\mathcal{F}(x) \geq \mathcal{G}(x)$  for all values of  $x$ . A CCD  $\mathcal{F}$  is said to second-order stochastically dominate (SOSD) another distribution  $\mathcal{G}$  if and only if  $\int_z^\infty \mathcal{F}(x) dx \geq \int_z^\infty \mathcal{G}(x) dx$  for all  $z$ , with a strict inequality for at least some values of  $z$ .

Note that if  $\mathcal{F}$  and  $\mathcal{G}$  in the Definition 1 were cumulative distributions rather than CCDs then the inequalities would be reversed. In relation to the expressions of opportunity costs,  $g_i(M(z))$  FOSD  $g_j(M(z))$  for  $i \neq j$  implies that the opportunity cost under preference structure  $i$  is greater than the opportunity cost under preference structure  $j$  for all values of  $M(z)$ . The following result holds:

**Proposition 5** Let the structure of opportunity costs be as in Eqs.(38-40) and let  $\langle M(x) \rangle_{w_i}$  denote the expected value of  $M(x)$  under wage rate distribution  $w_i(M(x))$ . If  $C(x) \geq (1-\sigma_1)^{\frac{1}{1-\sigma_1}}$  for all  $x$ , then:

- (i)  $g_2(M(z))$  FOSD  $g_1(M(z))$  whenever  $w_1(M(x)) = w_2(M(x))$  for all  $M(x)$  or  $\langle M(x) \rangle_{w_2} \geq \langle M(x) \rangle_{w_1}$ ,

- (ii)  $g_2(M(z))$  FOSD  $g_3(M(z))$  whenever  $w_2(M(x)) = w_3(M(x))$  for all  $M(x)$  or  $\langle M(x) \rangle_{w_2} \geq \langle M(x) \rangle_{w_3}$ ,
- (iii)  $g_3(M(z))$  FOSD  $g_1(M(z))$  whenever  $w_1(M(x)) = w_3(M(x))$  for all  $M(x)$  or  $\langle M(x) \rangle_{w_3} \geq \langle M(x) \rangle_{w_1}$ .

*Proof.* See Appendix A.

**Remark 1** *There are two possible ways to determine whether  $\langle M(x) \rangle_{w_i} \geq \langle M(x) \rangle_{w_j}$  or establishing conditions on the model parameters for the inequality to be true. The first is to directly solve for the average values  $\langle M(x) \rangle_{w_i}$  for all  $i = 1, 2, 3$  and compare the resulting functions. That is for each  $i$   $\langle M(x) \rangle_{w_i} = \int_{-\infty}^{\infty} M(x)w_i(M(x))dx$ . The difficulty with this approach is that computing the respective integrals is not necessarily feasible, specially when the relationship between  $w_i(M(x))$  and  $M(x)$  is implicit as it is the case for the additive preferences (see Eq.20c). Moreover, even when the integration is feasible, the resulting expressions are too complex for direct comparison. The second technique would be to solve for the value of  $M(x)$  (denoted by  $M^*(x)$ ) for which  $w_i(M(x)) = w_j(M(x))$ . For example, in the case of  $w_1(M(x))$  and  $w_2(M(x))$ ,  $M^*(x)$  can be obtained by solving the steady state simultaneous equations. Once  $M^*(x)$  is obtained, one could then obtain the derivative (tangent) of  $w_i(M(x))$  at  $M^*(x)$  for each  $i$ . The idea would then be to compare the resulting values, such that if the derivative of  $w_i(M(x))$  at  $M^*(x)$  is greater than the derivative of  $w_j(M(x))$  at  $M^*(x)$  then  $\langle M(x) \rangle_{w_i} \geq \langle M(x) \rangle_{w_j}$ . This approach is equally infeasible due to complexity of the each  $w_i(M(x))$ .*

Proposition 5 allows to study the relative behavior of the opportunity costs for different types of modeling. Are these costs minimized or exaggerated, if an additive, multiplicative or a convex combination of both is assumed? To answer this question, we have made assumptions about the wage rates to simplify calculations. We find that: i) the opportunity cost is higher in the multiplicative model than in the additive model, ii) it is higher in the multiplicative model than in the convex combination model, iii) it is higher in the convex combination model than in the additive model. The relationships described above are also based on the condition that consumption has a lower limit set defined by the terms of stochastic dominance.

To understand the intuition behind these results, it is worth noticing that in this general equilibrium setting in which labor productivity depends on health, any increase in health investment has an opportunity cost, at least in terms of consumption. Presumably if the inter-temporal substitution of health becomes stronger, it would contradict the gradual depreciation of the stock of health over time. Thus, substitutability cannot grow indefinitely, unless it is accompanied by higher investment costs, which explains the upper limit imposed on the elasticity of inter-temporal substitution.

In terms of policy implication, two contrasting visions appear. First, it is plausible to assume that opportunity costs (in terms of consumption) of investments in health are greater in developing countries than in developed countries, although the constraints on the impact of health on the wage rate appear to be identical for both. The multiplicative preferences are therefore more appropriate for developing countries where the inertia in health behaviors is much higher. Similarly additive preferences which consider consumption and health spending as separable in the welfare function seem more appropriate for developed countries. The dilemma is that in order for health to have a strong influence on the wage rate and therefore on wage



income, it must bear higher and higher costs of health investment. This calls for a tradeoff which is not always easy for developing countries. A solution for these countries would be first to implement public policies aimed at facilitating access to low-cost of health care. This implies increased cooperation with developed countries which have advanced social and health protection systems, while developing social security schemes. Fight against epidemics is a good illustration.

## 7 Conclusion

In this paper, we develop a general equilibrium framework to study the role of preferences structure. We connect the stock of health consumption, capital, wage rate, interest rate and parameters such as time preference and elasticities of inter-temporal substitution. We have shown that there is a unique value of the stock of health, which ensures the equilibrium dynamic of the economy, regardless of the form of the welfare function. We find that there are three parameters that play a crucial role not only for the existence of the equilibrium values, but also for the effect of health on the wage rate: the elasticity of substitution of health between two periods, the elasticity of investment in health and that of the dual cost of this investment relative to investment flows itself.

One question is how the stock of health affects the wage rate. The answer is not straightforward as it might look at first glance. Indeed, if the preferences are additive, the effect of the stock of health on the wage rate is positive only under some parameter constraints defined by the optimization problem. Moreover, the impact is positive only from a minimum wage rate. Therefore it is possible that the stock of health has a negative effect on the wage rate. When the preferences are multiplicative, the effect of health on wages is positive everywhere.

Several challenges remain to be addressed. Some of them include investigating: i) the role for preventive health care along with having the consumer's wage and working time dependent on health, ii) the heterogeneity and population uncertainty (e.g. young/old, insured/uninsured), iii) infectious diseases and their modes of transmission in our dynamic setting to study as to how health deterioration may affect the existence of solutions to the optimization problem as well to assess the impact of health on variables such as capital accumulation, consumption, wage rates and productivity.

## Acknowledgments

We gratefully acknowledge useful comments and stimulating remarks from Raouf Boucekkine, Noel Bonneuil, Matteo Cervellati, Miguel Perez-Nievas, Hippolyte d'Albis, Frédéric Dufourt, Daniel Opolot and Eleni Yitbarek. This work was supported by the Agence Nationale de la Recherche of the French government through the program 'Investissements d'avenir ANR-10-LABX-14-01'. Théophile Azomahou thanks the support of UNU-MERIT. The usual disclaimer applies.

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## Appendix

### A Proofs

#### A.1 Proof of Proposition 1

The proof is quite intuitive. Indeed, let us denote  $w^*$  the equilibrium wage rate. The left hand side of the Eq.(20c) is strictly increasing in  $\widehat{M}$ , while the right hand side is strictly decreasing, and the latter is equal to zero when

$$\widehat{M} = \frac{b}{\delta_M} \left[ \frac{w^*}{1-\epsilon} - (-w^*)^{\frac{1}{\sigma_1}} - \frac{w^*\epsilon}{(r+\delta)(1-\epsilon)} \right]^\beta$$

and equals to  $\frac{b\left(\frac{b}{\delta_M}\right)^{-\sigma_2}\beta}{\pi(\delta_M+r)\alpha} \left[ w^* + \left( \frac{w^*}{1-\epsilon} \left( 1 - \frac{\epsilon}{r+\delta} \right) \right)^{\sigma_1} \right]$  if  $\widehat{M} = 0$ , which implies that there is a unique solution  $\widehat{M}$  to Eq.(20c).  $\square$

#### A.2 Proof of Proposition 2

The proof of the first inequality  $\alpha \geq \beta(1-\sigma_2)$  results in studying the variation of  $w$  with respect to health stock  $M$ . Eq.(20c) can be rewritten in terms of output as:

$$f(M) = \widehat{M}^{\sigma_2-1+\frac{\alpha}{\beta}} - \frac{b\left(\frac{b}{\delta_M}\right)^{-\sigma_2}\beta}{\pi(\delta_M+r)\alpha} \left[ w + \left( \frac{w}{1-\epsilon} \left( 1 - \frac{\epsilon}{r+\delta} \right) - \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} \widehat{M}^{\frac{1}{\beta}} \right)^{\sigma_1} \right]$$

Relying on the implicity function theorem, after rearranging the terms of the derivative below, one gets:

$$\frac{\partial w(M)}{\partial M} = -\frac{\partial f(M)/\partial M}{\partial f(M)/\partial w(M)} = \frac{\mathcal{W}_{\mathcal{N}}}{\mathcal{W}_{\mathcal{D}}} \quad (\text{A-1})$$

where

$$\mathcal{W}_{\mathcal{N}} = \left( \frac{b}{\delta_M} \right)^{\sigma_2} \pi(\delta_M+r)\alpha \left[ \frac{b\left(\frac{b}{\delta_M}\right)^{-\sigma_2} \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} M^{-1+\frac{1}{\beta}} \left( - \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} M^{\frac{1}{\beta}} + \frac{w(1-\frac{\epsilon}{r+\delta})}{1-\epsilon} \right)^{-1+\sigma_1}}{\pi(\delta_M+r)\alpha} \sigma_1 \right. \\ \left. + M^{-2+\frac{\alpha}{\beta}+\sigma_2} \left( -1 + \frac{\alpha}{\beta} + \sigma_2 \right) \right]$$

and

$$\mathcal{W}_{\mathcal{D}} = b\beta \left[ 1 + \frac{\left( 1 - \frac{\epsilon}{r+\delta} \right) \left( - \left( \frac{\delta_M}{b} \right)^{\frac{1}{\beta}} M^{\frac{1}{\beta}} + \frac{w(1-\frac{\epsilon}{r+\delta})}{1-\epsilon} \right)^{-1+\sigma_1}}{1-\epsilon} \sigma_1 \right]$$

It follows from  $\mathcal{W}_{\mathcal{N}}$  and  $\mathcal{W}_{\mathcal{D}}$  that the effect of the health stock on the wage rate is positive if  $\alpha \geq \beta(1-\sigma_2)$ . The proof of the second inequality  $\alpha > \beta$  follows from the stability of equilibria. We introduce this in the following lemma.

**Lemma 3** *The dynamical system is stable iff  $\alpha > \beta$  and  $\alpha \geq \beta(1-\sigma_2)$ .*

*Proof.* The proof of this lemma requires studying the determinant of the Jacobian matrix of the system (24a)-(24c). After deriving and rearranging terms of calculations, the Jacobian is given by

$$\mathcal{J} = \begin{pmatrix} \mathcal{J}_{11} & \mathcal{J}_{12} & \mathcal{J}_{13} \\ \mathcal{J}_{21} & \mathcal{J}_{22} & \mathcal{J}_{23} \\ \mathcal{J}_{31} & \mathcal{J}_{32} & \mathcal{J}_{33} \end{pmatrix}$$

where  $\mathcal{J}_{11} = \mathcal{J}_{12} = \mathcal{J}_{31} = 1$ ,  $\mathcal{J}_{13} = 0$  and

$$\begin{aligned} \mathcal{J}_{21} &= 1 - \frac{bc^{-1+\sigma_1}k^{\sigma_1-\sigma_2-\alpha+\beta}\bar{m}^{-\alpha+\beta}\bar{M}^{-\sigma_2}\sigma_1\beta}{\pi\alpha(\alpha-\beta)} \\ \mathcal{J}_{22} &= 1 - \frac{bk^{-\sigma_2-\alpha+\beta}\bar{m}^{-1-\alpha+\beta}\bar{M}^{-\sigma_2}(c^{\sigma_1}k^{\sigma_1}+w)\beta(-\alpha+\beta)}{\pi\alpha(\alpha-\beta)} \\ \mathcal{J}_{23} &= 1 - \frac{bk^{-\sigma_2-\alpha+\beta}\bar{m}^{-\alpha+\beta}\bar{M}^{-1-\sigma_2}\sigma_2(c^{\sigma_1}k^{\sigma_1}+w)\beta}{\pi\alpha(\alpha-\beta)} \\ \mathcal{J}_{32} &= 1 + \frac{bk^{-1+\beta}\bar{m}^{-1+\beta}\beta}{\bar{M}} \\ \mathcal{J}_{33} &= -\frac{bk^{-1+\beta}\bar{m}^\beta}{\bar{M}^2} \end{aligned}$$

The determinant of  $\mathcal{J}$  is computed as:

$$\begin{aligned} \det(\mathcal{J}) &= -\frac{1}{c\pi\alpha(\alpha-\beta)} \left[ b^2k^{-1-\sigma_2-\alpha+2\beta}\bar{m}^{-1-\alpha+2\beta}\bar{M}^{-2-\sigma_2}\beta(c^{\sigma_1}k^{\sigma_1}\bar{m}\sigma_1 \right. \\ &\quad \left. + c^{1+\sigma_1}k^{\sigma_1}(\alpha + (-1+\sigma_2)\beta) + cw(\alpha + (-1+\sigma_2)\beta)) \right] \end{aligned} \quad (\text{A-2})$$

which is negative if  $\alpha > \beta$  to ensure the positivity of the denominator. This also implies the existence of a saddle point. The stability also depends on the sign of the trace of the matrix. The trace is computed as

$$\text{Tr}(\mathcal{J}) = 2 - \frac{bk^{-1+\beta}\bar{m}^\beta}{\bar{M}^2} + \frac{bk^{-\sigma_2-\alpha+\beta}\bar{m}^{-1-\alpha+\beta}\bar{M}^{-\sigma_2}(c^{\sigma_1}k^{\sigma_1}+w)\beta}{\pi\alpha} \quad (\text{A-3})$$

which is positive.  $\square$

### A.3 Proof of Proposition 3

To prove (i), it is straightforward to check that the left hand side of Eq.(29c) is increasing whereas the right hand side is decreasing. The inequality in ii) can be split into two parts:  $\alpha \geq \beta(1-\sigma_2)$  and  $\alpha < \beta$ . The proof of the first part relies on the study of Eq.(29c). Solving this relation with respect to wage leads to:

$$w(M) = \frac{\left(\frac{\delta_M}{b}\right)^{\frac{\alpha}{\beta}} M^{-1+\sigma_2} \pi(\delta_M + r) \alpha \left( M^{\frac{\alpha}{\beta}} + \frac{\delta_M \left(\frac{\delta_M}{b}\right)^{-\frac{\alpha}{\beta}} \left(\frac{\delta_M M}{b}\right)^{\frac{1}{\beta}} \beta(-1+\sigma_2)}{\pi(\delta_M + r) \alpha(-1+\sigma_1)} \right)}{\delta_M \beta \left( 1 + \frac{M^{-1+\sigma_2} (2r+2\delta-\delta\epsilon)(-1+\sigma_2)}{(r+\delta)(1-\epsilon)(-1+\sigma_1)} \right)} \quad (\text{A-4})$$

The derivative of (A-4) is given by

$$\frac{\partial w(M)}{\partial M} = \frac{\mathcal{W}_{\mathcal{N}}}{\mathcal{W}_{\mathcal{D}}} \quad (\text{A-5})$$

where

$$\begin{aligned}
\mathcal{W}_{\mathcal{N}} = & M^{1+\alpha} \alpha \left( 1 + \frac{M^{-1+\sigma_2}(2r+2\delta-\delta\epsilon)(-1+\sigma_2)}{(r+\delta)(1-\epsilon)(-1+\sigma_1)} \right) \\
& + \left( \frac{M^{\sigma_2}(2r+2\delta-\delta\epsilon) \left( M^{\alpha} + \frac{\delta_M \left( \frac{\delta_M}{b} \right)^{-\alpha} \beta (-1+\sigma_2)^2}{\pi(\delta_M+r)\alpha(-1+\sigma_1)} \right)}{(r+\delta)(1-\epsilon)(-1+\sigma_1)} \right) \\
& + M \left( M^{\alpha} + \frac{\delta_M \left( \frac{\delta_M}{b} \right)^{-\alpha} \beta (-1+\sigma_2)}{\pi(\delta_M+r)\alpha(-1+\sigma_1)} \right) \left( 1 + \frac{M^{-1+\sigma_2}(2r+2\delta-\delta\epsilon)(-1+\sigma_2)}{(r+\delta)(1-\epsilon)(-1+\sigma_1)} \right) \\
& \left( -1 + \frac{1}{\beta} + \sigma_2 \right)
\end{aligned} \tag{A-6}$$

and

$$\mathcal{W}_{\mathcal{D}} = \delta_M \beta \left( 1 + \frac{M^{-1+\sigma_2}(2r+2\delta-\delta\epsilon)(-1+\sigma_2)}{(r+\delta)(1-\epsilon)(-1+\sigma_1)} \right)^2 \tag{A-7}$$

which proves the first inequality in ii). The proof of the second inequality  $\alpha < \beta$  follows from the stability of equilibria. We introduce the following lemma.

**Lemma 4** *The dynamical system is stable iff  $\alpha < \beta$  and  $\alpha \geq \beta(1 - \sigma_2)$ .*

*Proof.* The proof of this lemma requires studying the determinant of the Jacobian matrix of the system (31). After deriving and rearranging terms of calculations, the Jacobian is given by

$$\mathcal{J} = \begin{pmatrix} \mathcal{J}_{11} & \mathcal{J}_{12} & \mathcal{J}_{13} \\ \mathcal{J}_{21} & \mathcal{J}_{22} & \mathcal{J}_{23} \\ \mathcal{J}_{31} & \mathcal{J}_{32} & \mathcal{J}_{33} \end{pmatrix}$$

where  $\mathcal{J}_{11} = \mathcal{J}_{31} = 1$  and

$$\begin{aligned}
\mathcal{J}_{12} &= 1 - \frac{bk^{1-\beta}\bar{m}^{-1+\beta}\beta(-1+\sigma_2)}{\bar{M}\sigma_1} \\
\mathcal{J}_{13} &= -\frac{k^{-\beta}(\delta_M\bar{M}k^{\beta} - bk\bar{m}^{\beta})(-1+\sigma_2)}{M^2\sigma_1} \\
\mathcal{J}_{21} &= -\frac{\bar{M}\pi\alpha^2 - bk^{1+\alpha-\beta}\bar{m}^{-\alpha+\beta}\beta - \bar{M}\pi\alpha\beta + \bar{M}\pi\alpha(-\alpha+\beta)\sigma_1 + bk^{1+\alpha-\beta}\bar{m}^{-\alpha+\beta}\beta\sigma_2}{\bar{M}\pi\alpha(\alpha-\beta)(-1+\sigma_1)} \\
\mathcal{J}_{22} &= \frac{1}{\pi\alpha(-1+\sigma_1)} k^{-\beta}\bar{m}^{-1-\alpha} M^{-1-\sigma_2} \left( -k^{\beta}\bar{m}^{1+\alpha} M^{1+\sigma_2} \pi\alpha - bck^{1+\alpha}\bar{m}^{\beta} M^{\sigma_2} \beta \right. \\
&\quad \left. - bk^{\alpha+\sigma_2}\bar{m}^{\beta} Mw\beta + \bar{M}(-k^{\beta}\bar{m}^{1+\alpha} M^{\sigma_2} \pi\alpha - bk^{\alpha+\sigma_2}\bar{m}^{\beta})\sigma_1 + bck^{1+\alpha}\bar{m}^{\beta} M^{\sigma_2} \beta\sigma_2 \right) \\
\mathcal{J}_{23} &= \frac{bk^{\alpha-\beta}\bar{m}^{-\alpha+\beta}\bar{M}^{-2-\sigma_2}\beta(-ck\bar{M}^2 + (ck\bar{M}^2 - k^{\sigma_2}Mw + k^{\sigma_2}Mw\sigma_1)\sigma_2)}{\pi\alpha(\alpha-\beta)(-1+\sigma_1)} \\
\mathcal{J}_{32} &= 1 + \frac{bk^{1+\beta}\bar{m}^{-1+\beta}\beta}{\bar{M}} \\
\mathcal{J}_{33} &= -\frac{bk^{1+\beta}\bar{m}^{\beta}}{\bar{M}^2}
\end{aligned}$$

The determinant of  $\mathcal{J}$  is computed as:

$$\begin{aligned} \det(\mathcal{J}) = & \frac{(\alpha - \beta)}{\pi\alpha(1 - \sigma_1)\sigma_1} b k^{-2\beta} \bar{m}^{-1-\alpha+\beta} \bar{M}^{-4-\sigma_2} \beta (b k^{1+\alpha+2\beta+\sigma_2} \bar{m}^\beta \bar{M}^2 w \sigma_1^2 (\alpha - \beta + \beta \sigma_2) \\ & \left[ (1 - \sigma_2) (b k^{1+\alpha} \bar{m}^\beta \bar{M} (k \bar{M}^{\sigma_2} (\bar{m} + c\alpha) + k^{\sigma_2} \bar{M} w) - \delta_M \bar{M} k^\beta (k^{\alpha+\sigma_2} \bar{M}^2 w + b k^{2+\alpha+\beta} \bar{m}^\beta \bar{M}^{\sigma_2} \beta \right. \\ & + k^{1+2\beta} \bar{m}^\alpha \bar{M}^{1+\sigma_2} \pi\alpha + k^{1+\alpha} \bar{M}^{1+\sigma_2} (\bar{m} + c)) + k^{1+\alpha} (\delta_M \bar{M} k^\beta \bar{M}^{\sigma_2} (\bar{m} \bar{M} + c \bar{M} + b k^{1+\beta} \bar{m}^\beta \beta) \\ & + b \bar{m}^\beta \bar{M} (-k \bar{M}^{\sigma_2} (\bar{m} + c\alpha) + k^{\sigma_2} \bar{M} w \beta)) \sigma_2) + \bar{M} \sigma_1 (\delta_M \bar{M} k^\beta (-k^{\alpha+\sigma_2} \bar{M} w + k^{1+2\beta} \bar{m}^\alpha \bar{M}^{\sigma_2} \pi\alpha) \\ & b k^{1+\beta} \bar{m}^\beta (k^{1+2\beta} \bar{M}^{\sigma_2} (\bar{m} + c\alpha) + k^{\sigma_2} \bar{M} w k^{2\beta+\sigma_2} \bar{M} w) + (\delta_M \bar{M} k^\beta (-k^{\alpha+\sigma_2} \bar{M} w + k^{1+2\beta} \bar{m}^\alpha \bar{M}^{\sigma_2} \pi\alpha) \\ & \left. \left. + b k^{1+\beta} \bar{m}^\beta (k^{1+2\beta} \bar{M}^{\sigma_2} (\bar{m} + c\alpha) + k^{\sigma_2} \bar{M} w (\alpha - 2\beta) - k^{2\beta+\sigma_2} \bar{M} w)) \sigma_2 + b k^{1+\alpha+\sigma_2} \bar{m}^\beta \bar{M} w \beta \sigma_2^2) \right) \right] \end{aligned} \quad (\text{A-8})$$

which is negative if  $\alpha < \beta$  to guarantee the positivity of the denominator. This also implies the existence of a saddle point. The stability depends on the sign of the trace of the matrix. It is computed as:

$$\begin{aligned} Tr(\mathcal{J}) = & \frac{1}{\pi\alpha(1 - \sigma_1)} \left( 2\pi\alpha - \frac{b k^{1+\beta} \bar{m}^\beta \pi\alpha}{\bar{M}^2} + \frac{b c k^{1+\alpha-\beta} \bar{m}^{-1-\alpha+\beta} \beta}{\bar{M}} + b k^{\alpha-\beta+\sigma_2} \bar{m}^{-1-\alpha+\beta} \bar{M}^{-\sigma_2} w \beta \right. \\ & \left. + \left( \left( -2 + \frac{b k^{1+\beta} \bar{m}^\beta}{\bar{M}^2} \right) \pi\alpha - b k^{\alpha-\beta+\sigma_2} \bar{m}^{-1-\alpha+\beta} \bar{M}^{-\sigma_2} w \beta \right) \sigma_1 - \frac{b c k^{1+\alpha-\beta} \bar{m}^{-1-\alpha+\beta} \beta \sigma_2}{\bar{M}} \right) \end{aligned} \quad (\text{A-9})$$

which is positive.  $\square$

#### A.4 Proof of Proposition 4

The proof follows from the general system. Indeed, Eq.(7a) in the system becomes a differential equation of the form:

$$s(r - \rho) + \frac{(1 - s)(r - \rho)M(z)^{1-\sigma_2}}{1 - \sigma_2} + (1 - s)M(z)^{-\sigma_2} \dot{M}(z) = 0 \quad (\text{A-10})$$

This differential equation is linear in  $\dot{M}(z)$  and it's straightforward to check that the analytical solution is given by the expression of  $\widehat{M}(z, s)$  (Eq. 33) in the Proposition.  $\square$

#### A.5 Proof of Proposition 5

The proof follows by pairwise comparison of  $g_i(M(z))$ 's. Generally,

$$g_i(M(z)) - g_j(M(z)) = \int_z^\infty \varphi_M(M(x)) \left( w_i(M(x)) - w_j(M(x)) + \frac{1}{\lambda_A(0)} (\Phi_i - \Phi_j) e^{(\rho-r)x} \right) e^{-(\delta_M+r)(x-z)} dx \quad (\text{A-11})$$

implying that the crucial components when performing pairwise comparisons are  $w_{ij}(M(x)) = w_i(M(x)) - w_j(M(x))$  and  $\Phi_{ij}(z) = \Phi_i - \Phi_j$ . Since  $\varphi_M(M(x)) \geq 0$  for all  $M(x)$ , it follows that  $g_i(M(z)) - g_j(M(z)) \geq 0$  (that is  $g_i(M(z))$  FOSD  $g_j(M(z))$ ) if either; (a)  $w_{ij}(M(x)) > 0$  and  $\Phi_{ij}(x) \geq 0$  for all  $x$  hence all  $M(x)$ , (b) or  $w_{ij}(M(x)) = 0$  and  $\Phi_{ij}(x) \geq 0$  for all  $x$  hence all  $M(x)$ , (c) or  $\Phi_{ij}(x) \geq 0$  for all  $x$  and there exists an  $x^*$  hence  $M(x^*)$  such that  $w_{ij}(M(x)) > 0$  for all  $M(x) \geq M(x^*)$ .

If  $\langle M(x) \rangle_{w_i}$  is the expected value of  $M(x)$  under wage rate distribution  $w_i(M(x))$ , the conditions that  $w_{ij}(M(x)) > 0$  for all  $M(x)$  and that there exists an  $M(x^*)$  such that  $w_{ij}(M(x)) > 0$  for all  $M(x) \geq M(x^*)$ , are equivalent to saying that  $\langle M(x) \rangle_{w_i} \geq \langle M(x) \rangle_{w_j}$ . The first condition for  $g_i(M(z))$  to FOSD  $g_j(M(z))$  is then that  $\langle M(x) \rangle_{w_i} \geq \langle M(x) \rangle_{w_j}$ . What remains is to show condition under which  $\Phi_{ij}(x) \geq 0$  for each pair of  $i$  and  $j$ .

(i) For the case of additively separable and multiplicative preferences, we have that

$$\Phi_{21}(x) = N_\varphi V_N - S_\varphi V_S$$

From the expression of  $V$ ,  $N$  and  $S$ , we have that  $V_N = V_S = S_\varphi = 1$  and  $N_\varphi = U(C(x))$ . Such that  $N_\varphi V_N = U(C(x))$  and  $S_\varphi V_S = 1$ .  $\Phi_{21}(x)$  then becomes

$$\Phi_{21}(x) = U(C(x)) - 1 = \frac{1}{1 - \sigma_2} C(x)^{1 - \sigma_2} - 1$$

Implying that  $\Phi_{21}(x) \geq 0$  if  $C(x) \geq (1 - \sigma_1)^{\frac{1}{1 - \sigma_1}}$  for all  $x$ .

(ii) Similarly, for the multiplicative and convex combination preferences,

$$\Phi_{23}(x) = N_\varphi V_N - (s N_\varphi V_N + (1 - s) S_\varphi V_S) = (1 - s) U(C(x)) - (1 - s) = (1 - s)(U(C(x)) - 1)$$

Since  $0 < s < 1$ , it follows that  $\Phi_{23}(x) \geq 0$  if  $U(C(x)) - 1 \geq 0$  for all  $x \Rightarrow C(x) \geq (1 - \sigma_1)^{\frac{1}{1 - \sigma_1}}$  for all  $x$ .

(iii) Finally, for the convex combination and additive preferences,

$$\Phi_{31}(x) = s N_\varphi V_N + (1 - s) S_\varphi V_S - S_\varphi V_S = s(U(C(x)) - 1)$$

Hence  $\Phi_{31}(x) \geq 0$  if  $C(x) \geq (1 - \sigma_1)^{\frac{1}{1 - \sigma_1}}$  for all  $x$ .  $\square$

## B Note on the convex combination of preferences

For the convex combination of preferences, the steady state of the model is governed by the system:

$$\begin{aligned} \frac{\dot{C}(z)}{\hat{C}(z)} &= \frac{(-1 + s)(r - \rho)M(z) + s(r - \rho)M(z)^{\sigma_2}(-1 + \sigma_2) - (-1 + s)(-1 + \sigma_2)(-\delta_M M(z) + b m(z)^\beta)}{\sigma_1((-1 + s)M(z) + sM(z)^{\sigma_2}(-1 + \sigma_2))} \\ \frac{\dot{m}(z)}{\hat{m}(z)} &= C(z)^{\sigma_1} m(z)^{1 - \alpha} M(z)^{\sigma_2} \left( b \beta m(z)^{-1 + \beta} M(z)^{-\sigma_2} \left( -s - \frac{(-1 + s)C(z)^{1 - \sigma_1}}{-1 + \sigma_1} \right. \right. \\ &\quad \left. \left. + w C(z)^{-\sigma_1} \left( -s - \frac{(-1 + s)M(z)^{1 - \sigma_2}}{-1 + \sigma_2} \right) \right) + \pi(-\delta_M - r)\alpha C(z)^{-\sigma_1} m(z)^{-1 + \alpha} \left( -s \right. \right. \\ &\quad \left. \left. - \frac{(-1 + s)M(z)^{1 - \sigma_2}}{-1 + \sigma_2} \right) \right) (-1 + \sigma_2) \Bigg/ (\pi \alpha (\alpha - \beta) ((-1 + s)M(z) + sM(z)^{\sigma_2}(-1 + \sigma_2))) \\ \dot{M}(z) &= -\delta_M + \frac{b m(z)^\beta}{m(z)} \\ \dot{k}_z &= B(M(z)) \hat{k}(z)^\epsilon - \hat{C}(z) - \hat{m}(z) - \delta \hat{k}(z) \end{aligned} \tag{A-12}$$

with  $\hat{k}(0)$  and  $\hat{M}(0)$  given, plus the transversality conditions. The steady-state values  $\hat{C}$ ,  $\hat{m}$ ,  $\hat{M}$ , and  $\hat{k}$  can be obtained by equalizing  $\dot{C}$ ,  $\dot{m}$ ,  $\dot{M}$ ,  $\dot{k}$  to zero. The dynamics of the economy is



driven at the equilibrium by the following system:

$$\begin{aligned}
\frac{\dot{c}}{c} &= \frac{(-1+s)(r-\rho)\overline{M}k^{-1} + s(r-\rho)\overline{M}^{\sigma_2}k^{-\sigma_2}(-1+\sigma_2) - (-1+s)(-1+\sigma_2)(-\delta_M\overline{M}k^{-1} + b\overline{m}^\beta k^{-\beta})}{\sigma_1((-1+s)\overline{M}k^{-1} + s\overline{M}^{\sigma_2}k^{-\sigma_2}(-1+\sigma_2))} \\
&\quad - \frac{r + \delta(1-\epsilon)}{\epsilon} + c + \overline{m} \\
\frac{\dot{\overline{m}}}{\overline{m}} &= C^{\sigma_1}\overline{m}^{1-\alpha}\overline{M}^{\sigma_2}k^{-\sigma_2+\alpha-1} \left( \left( b\beta\overline{m}^{-1+\beta}\overline{M}^{-\sigma_2}k^{\sigma_2-\beta+1} \left( -s - \frac{(-1+s)C^{1-\sigma_1}}{-1+\sigma_1} \right. \right. \right. \\
&\quad \left. \left. + wC^{-\sigma_1} \left( -s - \frac{(-1+s)\overline{M}^{1-\sigma_2}k^{\sigma_2-1}}{-1+\sigma_2} \right) \right) \right) + \pi(-\delta_M - r)\alpha C^{-\sigma_1}\overline{m}^{-1+\alpha}k^{1-\alpha} \left( -s \right. \\
&\quad \left. \left. - \frac{(-1+s)\overline{M}^{1-\sigma_2}k^{\sigma_2-1}}{-1+\sigma_2} \right) \right) (-1+\sigma_2) \Bigg/ (\pi\alpha(\alpha-\beta)((-1+s)\overline{M}k^{-1} + s\overline{M}^{\sigma_2}k^{-\sigma_2}(-1+\sigma_2))) \\
&\quad - \frac{r + \delta(1-\epsilon)}{\epsilon} + c + \overline{m} \\
\frac{\dot{\overline{M}}}{\overline{M}} &= -\delta_M + \frac{b\overline{m}^\beta k^{\beta+1}}{\overline{M}} - \frac{r + \delta(1-\epsilon)}{\epsilon} + c + \overline{m}
\end{aligned} \tag{A-13}$$

The Jacobian of this system is given by

$$\mathcal{J} = \begin{pmatrix} \mathcal{J}_{11} & \mathcal{J}_{12} & \mathcal{J}_{13} \\ \mathcal{J}_{21} & \mathcal{J}_{22} & \mathcal{J}_{23} \\ \mathcal{J}_{31} & \mathcal{J}_{32} & \mathcal{J}_{33} \end{pmatrix}$$

where  $\mathcal{J}_{11} = \mathcal{J}_{13} = \mathcal{J}_{21} = \mathcal{J}_{31} = 1$  and

$$\begin{aligned}
\mathcal{J}_{12} &= 1 - \frac{bk^{1-\beta}\overline{m}^{-1+\beta}(-1+s)\beta(-1+\sigma_2)}{\sigma_1 \left( \frac{\overline{M}(-1+s)}{k} + k^{-\sigma_2}\overline{M}^{\sigma_2}s(-1+s) \right)} \\
\mathcal{J}_{13} &= -\frac{k^{-\beta}(\delta_M\overline{M}k^\beta - bk\overline{m}^\beta)(-1+\sigma_2)}{M^2\sigma_1} \\
\mathcal{J}_{22} &= (k^{-\beta}\overline{m}^{-1-\alpha}\overline{M}^{-\sigma_2}(bk^{1+\alpha+\sigma_2}\overline{m}^\beta\overline{M}^{\sigma_2}(-1+s)\beta C(-1+\sigma_2) \\
&\quad + bk^{1+\alpha+\sigma_2}\overline{m}^\beta\overline{M}^{\sigma_2}s\beta C^{\sigma_1}(-1+\sigma_1)(-1+\sigma_2) + (k^\beta\overline{m}^{1+\alpha}\overline{M}^{\sigma_2}\pi\alpha \\
&\quad + bk^{\alpha+\sigma_2}\overline{m}^\beta w\beta)(-1+\sigma_1)(k^{\sigma_2}M(-1+s) - k\overline{M}^{\sigma_2}s + k\overline{M}^{\sigma_2}s\sigma_2)))/(\pi\alpha(-1+\sigma_1)(k^{\sigma_2}\overline{M}(-1+s) \\
&\quad - kM^{\sigma_2}s + k\overline{M}^{\sigma_2}s\sigma_2)) \\
\mathcal{J}_{23} &= (bk^{\alpha-\beta+\sigma_2}\overline{m}^{-\alpha+\beta}\overline{M}^{-1-\sigma_2}\beta(w(-1+\sigma_1)\sigma_2(k^{\sigma_2}\overline{M}(-1+s) - k\overline{M}^{\sigma_2}s + k\overline{M}^{\sigma_2}s\sigma_2))^2 \\
&\quad + k\overline{M}^{\sigma_2}(-1+s)C(-1+\sigma_2)(k^{\sigma_2}\overline{M}(-1+s) - k\overline{M}^{\sigma_2}s\sigma_2 + k\overline{M}^{\sigma_2}s\sigma_2^2) \\
&\quad + k\overline{M}^{\sigma_2}sC^{\sigma_1}(-1+\sigma_1)(-1+\sigma_2)(k^{\sigma_2}M(-1+s) \\
&\quad - k\overline{M}^{\sigma_2}s\sigma_2 + kM^{\sigma_2}s\sigma_2^2)))/(\pi\alpha(\alpha-\beta)(-1+\sigma_1)(k^{\sigma_2}\overline{M}(-1+s) - k\overline{M}^{\sigma_2}s + k\overline{M}^{\sigma_2}s\sigma_2)^2) \\
\mathcal{J}_{32} &= 1 + \frac{bk^{1+\beta}\overline{m}^{-1+\beta}\beta}{\overline{M}} \\
\mathcal{J}_{33} &= -\frac{bk^{1+\beta}\overline{m}^\beta}{\overline{M}^2}
\end{aligned}$$

The determinant of  $\mathcal{J}$  is computed as:

$$\begin{aligned} \det(\mathcal{J}) = & \frac{1}{M^2} k^{-2\beta} ((k^{\sigma_2} m^{-1-\alpha} (\delta_M M k^\beta - b k m^\beta) M^{1-\sigma_2} (-1+s)(-1+\sigma_2) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s \sigma_2 \\ & + k M^{\sigma_2} s \sigma_2^2) (b k^{1+\alpha+\sigma_2} m^\beta M^{\sigma_2} (-1+s) \beta C(z) (-1+\sigma_2) + b k^{1+\alpha+\sigma_2} m^\beta M^{\sigma_2} s \beta C(z)^{\sigma_1} (-1 \\ & + \sigma_1) (-1+\sigma_2) + (k^\beta m^{1+\alpha} M^{\sigma_2} \pi \alpha + b k^{\alpha+\sigma_2} m^\beta w \beta) (-1+\sigma_1) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s \\ & + k M^{\sigma_2} s \sigma_2))) / (\pi \alpha (-1+\sigma_1) \sigma_1 (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s + k M^{\sigma_2} s \sigma_2)^3) \\ & + (b k^{\alpha+\beta+\sigma_2} m^{-\alpha+\beta} M^{1-\sigma_2} \beta \left( 1 - \frac{b k^{-\beta} m^{-1+\beta} (-1+s) \beta (-1+\sigma_2)}{\sigma_1 \left( \frac{M(-1+s)}{k} + k^{-\sigma_2} M^{\sigma_2} s (-1+\sigma_2) \right)} \right) (w(-1+\sigma_1) \\ & \sigma_2 ((k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s + k M^{\sigma_2} s \sigma_2)^2 + k M^{\sigma_2} (-1+s) C(z) (-1+\sigma_2) (k^{\sigma_2} M(-1+s) \\ & - k M^{\sigma_2} s \sigma_2 + k M^{\sigma_2} s \sigma_2^2) + k M^{\sigma_2} s C(z)^{\sigma_1} (-1+\sigma_1) (-1+\sigma_2) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s \sigma_2 \\ & + k M^{\sigma_2} s \sigma_2^2))) / (\pi \alpha (\alpha - \beta) (-1+\sigma_1) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s + k M^{\sigma_2} s \sigma_2)^2) - b k^{1+3\beta} m^\beta \\ & \left( 1 - \frac{b k^{-\beta} m^{-1+\beta} (-1+s) \beta (-1+\sigma_2)}{\sigma_1 \left( \frac{M(-1+s)}{k} + k^{-\sigma_2} M^{\sigma_2} s (-1+\sigma_2) \right)} + (k^{-\beta} m^{-1-\alpha} M^{\sigma_2} (b k^{1+\alpha+\sigma_2} m^\beta M^{\sigma_2} (-1+s) \beta C(z) \right. \\ & (-1+\sigma_2) + b k^{1+\alpha+\sigma_2} m^\beta M^{\sigma_2} s \beta C(z)^{\sigma_1} (-1+\sigma_1) (-1+\sigma_2) + (k^\beta m^{1+\alpha} M^{\sigma_2} \pi \alpha + b k^{\alpha+\sigma_2} m^\beta w \beta) \\ & (-1+\sigma_1) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s + k M^{\sigma_2} s \sigma_2))) / (\pi \alpha (-1+\sigma_1) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s + k M^{\sigma_2} s \sigma_2))) \\ & - (k^{\beta+\sigma_2} M (1 + \frac{b k^{1+\beta} m^{-1+\beta} \beta)}{M}) \left( \frac{(\delta_M M k^\beta - b k m^\beta) (-1+s) (-1+\sigma_2) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s \sigma_2 + k M^{\sigma_2} s \sigma_2^2)}{\sigma_1} \right. \\ & + 1 / (\pi \alpha (\alpha - \beta) (-1+\sigma_1)) b k^\alpha m^{-\alpha+\beta} M^{-\sigma_2} \beta (w(-1+\sigma_1) \sigma_2 (k^{\sigma_2} M(-1+s) \\ & - k M^{\sigma_2} s + k M^{\sigma_2} s \sigma_2) 2 + k M^{\sigma_2} (-1+s) C(z) (-1+\sigma_2) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s \sigma_2 + k M^{\sigma_2} s \sigma_2^2) \\ & + k M^{\sigma_2} s C(z)^{\sigma_1} (-1+\sigma_1) (-1+\sigma_2) (k^{\sigma_2} M(-1+s) - k M^{\sigma_2} s \sigma_2 + k M^{\sigma_2} s \sigma_2^2))) / (k^{\sigma_2} M(-1+s) \\ & - k M^{\sigma_2} s + k M^{\sigma_2} s \sigma_2)^2) \end{aligned}$$

and the trace is

$$\begin{aligned} Tr(\mathcal{J}) = & 1 - \frac{b k^{1+\beta} \bar{m}^\beta}{\bar{M}^2} + (k^{-\beta} \bar{m}^{-1-\alpha} \bar{M}^{-\sigma_2} (b k^{1+\alpha+\sigma_2} \bar{m}^\beta \bar{M}^{\sigma_2} (-1+s) \beta C(-1+\sigma_2) \\ & + b k^{1+\alpha+\sigma_2} \bar{m}^\beta \bar{M}^{\sigma_2} s \beta C^{\sigma_1} (-1+\sigma_1) (-1+\sigma_2) + (k^\beta \bar{m}^{1+\alpha} \bar{M}^{\sigma_2} \pi \alpha \\ & + b k^{\alpha+\sigma_2} \bar{m}^\beta w \beta) (-1+\sigma_1) (k^{\sigma_2} \bar{M}(-1+s) - k \bar{M}^{\sigma_2} s + k \bar{M}^{\sigma_2} s \sigma_2))) / (\pi \alpha (-1+\sigma_1) (k^{\sigma_2} \bar{M}(-1+s) \\ & - k \bar{M}^{\sigma_2} s + k \bar{M}^{\sigma_2} s \sigma_2)) \end{aligned} \tag{A-14}$$

One can see that studying analytically the stability properties this case (convex combination of preferences) is simply unbearable given the expression of the determinant.

## C Examples of alternative preferences

In order to illustrate various aspects of the general results, we provide two examples of alternatives utility functions: the logarithm and the quadratic. The former is well-known to be a special case of the CRRA utility function.

### C.1 The logarithm utility

We use a simple logarithm form for the utility functions of consumption and health. The other functions remain the same:  $U(C) = \ln(C)$ ,  $\varphi(M) = \ln(M)$ ,  $\psi(m) = b m^\beta$  and  $h(m) = \pi m^\alpha$ . We assume the preferences are additive. The dynamic system of the economy becomes:

$$\frac{\dot{C}(z)}{\hat{C}(z)} = r(z) - \rho \quad (\text{B-1})$$

$$\frac{\dot{m}(z)}{\hat{m}(z)} = \frac{-b\beta(w + C(z))m(z)^{\beta-\alpha}}{\pi\alpha(\alpha - \beta)M(z)} + \frac{\delta_M + r(z)}{\alpha - \beta} \quad (\text{B-2})$$

$$\dot{M}(z) = -\delta_M + \frac{bm^\beta}{M(z)} \quad (\text{B-3})$$

$$\dot{k}(z) = B(M(z))\hat{k}(z)^\epsilon - \hat{C}(z) - \hat{m}(z) - \delta\hat{k}(z) \quad (\text{B-4})$$

As we can see, there is a unique root, say  $f(M)$  for the system (B-1)-(B-4). To obtain  $f(M)$ , we set (B-2)-(B-4) to zero for  $k = \frac{\epsilon}{(1-\epsilon)(r+\delta)}w$ . Then, replacing  $m$  by its expression from (B-3) leads to:

$$f(M) = M^{\frac{\alpha}{\beta}} - \frac{\delta_M\beta\left(\frac{\delta_M}{b}\right)^{-\frac{\alpha}{\beta}}}{\pi(\delta_M + r)\alpha} \left[ \frac{2(r + \delta_M) - \delta\epsilon}{(1 - \epsilon)(r + \delta)}w - \left(\frac{\delta_M}{b}\right)^{\frac{1}{\beta}} \right] M^{\frac{1}{\beta}} \quad (\text{B-5})$$

The unique follows from that when we set  $f(M) = 0$ , then the first component increases with  $M$  and the second decreases. We now show how the wage rate depends on health. For that, we express  $w$  as function of  $M$  by solving  $f(M) = 0$ :

$$w(M) = \frac{(r + \delta)(1 - \epsilon)}{\delta_M\beta(2r + 2\delta - \delta\epsilon)} \left(\frac{\delta_M}{b}\right)^{\frac{1}{\beta}} \left[ \left(\frac{\delta_M}{b}\right)^\alpha (\delta_M + r)\pi\alpha M^{\frac{\alpha}{\beta}} + \delta_M\beta M^{\frac{1}{\beta}} \right] \quad (\text{B-6})$$

The wage rate is an increasing function of the stock of health. Its evolution depends on the relative values of the degrees of homogeneity of the health production and the cost of investment function, (then on  $\alpha$  and  $\beta$ ). This is shown in a simulation exercise as plotted in Figure 12. The left hand side figure display the relation for parameters values  $\{\alpha, \beta, \delta_M, r, b, \epsilon, \delta, \pi\} = \{0.2, 5, 0.01, 0.02, 1, 0.4, 0.05, 2\}$  and the right hand side is for  $\{4, 0.2, 0.01, 0.02, 1, 0.4, 0.05, 2\}$ . Albeit in both cases, the wage rate is an increasing function of the stock of health, the pattern of increase differs.

### Insert Figure 12

Indeed, when the growth rate of investment in health is lower than the one of its cost, meaning when  $\beta > \alpha$ , the stock of health increases faster than the wage rate, up to a certain level, say  $M_0$ , which an inflexion point after which, the relative evolution of the two variables changes ( $w$  growing faster than  $M$ ). To obtain this inflexion point, we observe that  $w(M)$  is of the form  $aM^{\frac{\alpha}{\beta}} + bM^{\frac{1}{\beta}}$ . Setting to zero the second derivative of that expression yields

$$M_0 = \left[ \frac{\beta - 1}{\pi\alpha(\alpha - \beta)(\delta_M + r)} \left(\frac{\delta_M}{b}\right)^{-\alpha} \right]^{\frac{\beta}{\alpha-1}} \quad (\text{B-7})$$

In the case where  $\beta < \alpha$ , there is no inflexion in the curve which becomes concave. To complete the example, let us briefly study the equilibrium dynamics. In that case, the Jacobian matrix turns to be

$$\mathcal{J} = \begin{pmatrix} 1 & 1 & 0 \\ 1 - \frac{bk^{\alpha-\beta}m^{-\alpha+\beta}\beta}{M\pi\alpha} & 1 - \frac{bk^{1+\alpha-\beta}m^{-1-\alpha+\beta}\left(\frac{c}{k}+w\right)\beta(-\alpha+\beta)}{1 + \frac{M\pi\alpha}{bk^{1-\beta}m^{-1+\beta}\beta}} & \frac{bk^{1+\alpha-\beta}m^{-\alpha+\beta}\left(\frac{c}{k}+w\right)\beta}{-\frac{M^2\pi\alpha}{bk^{1-\beta}m^\beta}} \\ 1 & 1 + \frac{M\pi\alpha}{bk^{1-\beta}m^{-1+\beta}\beta} & -\frac{M^2\pi\alpha}{M^2} \end{pmatrix}$$

The determinant of  $\mathcal{J}$  is computed as:

$$\begin{aligned}\det(\mathcal{J}) &= -\frac{\beta b^2 k^{1+\alpha-2\beta} m^{-1-\alpha+2\beta} (m + (c + k + w)\alpha)}{M^3 \pi \alpha (\alpha - \beta)} \\ \text{Tr}(\mathcal{J}) &= 2 - \frac{b k^{1-\beta} m^\beta}{M^2} + \frac{b k^{\alpha-\beta} m^{-1-\alpha+\beta} (c + kw)\beta}{M \pi \alpha}\end{aligned}$$

One can easily check that  $\det(\mathcal{J}) < 0$  if  $\alpha > \beta$ . This leads to the conclusion that the system admits a saddle point if  $\alpha > \beta$ . One of the conclusion that we can draw from the specific logarithm utility is that, although this specification is free of the elasticity of substitution parameter used in CRRA utility framework, the core findings hold.

## C.2 The quadratic utility

Unlike the preceding example in which the logarithm specification is a particular case of the CRRA, the quadratic function departs sufficiently from it. Here, we will illustrate the three cases of preferences: additive, multiplicative and the convex combination. We assume functions of the forms:

$$\begin{aligned}U(C(z)) &= C(z) - \eta_1 (C(z))^2 \\ \varphi(M(z)) &= M(z) - \eta_2 (M(z))^2\end{aligned}$$

with  $\eta_1 \neq 0$  and  $\eta_2 \neq 0$ . As before, the health functions  $\psi$  and  $h$  maintain the same functional form:  $\psi(m(z)) = bm^\beta$  and  $h(m(z)) = \pi m^\alpha$ , and we also assume the same production function.

### C.2.1 Separable additive case

In this setting, the equilibrium values are given by  $\bar{c}^* = \frac{1}{2\eta_1}$ ,  $\bar{M}^* = \frac{1}{2\eta_2}$ ,  $\bar{m}^* = \left(\frac{\delta_M}{b}\right)^{\frac{1}{\beta}} \frac{1}{(2\eta_1)^{\frac{1}{\beta}}}$ ,  $\bar{k}^* = \frac{\epsilon}{2(r+\delta-\delta\epsilon)\eta_1} \left[1 + \eta_1 (2\eta_2 \frac{b}{\delta_M})^{-\frac{1}{\beta}}\right]$  and  $w^*(M) = \frac{(r+\delta)(1-\epsilon)}{2(r+\delta-\delta\epsilon)\eta_1} \left[1 + \eta_1 (2\eta_2 \frac{b}{\delta_M})^{-\frac{1}{\beta}} M^{\frac{1}{\beta}}\right]$ . We see that the equilibrium value of wage rate  $w^*$  is determined by the stock health under the conditions of Proposition 2.

### Insert Figure 13

Figure 13 shows the relationship between the wage rate the stock of health. The vertical line represents the stock of health equilibrium  $M^*$  and  $w^*$  the wage rate at equilibrium;  $\bar{w} = \frac{(r+\delta)(1-\epsilon)}{2(r+\delta-\delta\epsilon)\eta_1}$  denotes the intercept or the minimum wage. The wage rate in this example is an increasing function of the stock of health.

### C.2.2 Multiplicative case

The equilibrium value of the stock of health is obtained as:

$$\bar{M}^*(z) = \frac{1 - \sqrt{1 - 4\eta_2 e^{-(r-\rho)z}}}{2\eta_2} \quad (\text{B-8})$$

Consumption at equilibrium is given by:

$$\bar{c}^* = \frac{1}{2\eta_1} + \frac{a_0}{a_1} + a_2 w + \sqrt{\frac{1}{4\eta_1^2} + \left(\frac{a_0}{a_1} + a_2 w\right)^2} \quad (\text{B-9})$$

where  $a_0 = \pi(r + \delta_M)\eta_1\left(\frac{\delta_M}{b}\right)^{\frac{\alpha}{\beta}}(\bar{M}^*)^{\frac{\alpha}{\beta}}(\bar{M}^* - \eta_2\bar{M}^{*2})$ ,  $a_1 = b\beta\frac{\delta_M}{b}\bar{M}^*(1 - 2\eta_2\bar{M}^*)$  and  $a_2 = -\bar{M}^* + \eta_2\bar{M}^{*2}$ . The balance wage rate  $w^*(M)$  can be retrieved from Eq.(B-9). However, its expression is rather complex. From Eq.(B-8), one observes that  $\bar{M}^*(z)$  depends on time  $z$  and can be represented as in Figure 14.

### Insert Figure 14

The graph shows an initial time  $z_0 = \frac{\ln(4\eta_2)}{r-\rho}$  under which there is no balance of stock health. Moreover, the balance path of the initial stock of health ( $\frac{1}{2\eta_2}$ ) in the multiplicative model corresponds to the balance path of the stock of health in the additive model, the latter being represented by the horizontal line. In other words, there exists a maximum level ( $\frac{1}{2\eta_2}$ ) the stock of health can not exceed. The stock of health in the multiplicative model decreases over time to a zero minimum value. One conclusion we can draw from this example is that the multiplicative model is more general as it provides information on the steady state of the additive model.

### C.2.3 Convex combination

The equilibrium value of the stock of health is given by:

$$\bar{M}^*(z) = \frac{1}{2\eta_2} - \frac{\sqrt{(1-s)(r-\rho) + 4s(r-\rho)\eta_2\kappa(s)e^{-(r-\rho)z}}}{2\eta_2\sqrt{(1-s)(r-\rho)}} \quad (\text{B-10})$$

where  $\kappa(s) \propto -4e^{(1-s)(r-\rho)\eta_2}$ . The equilibrium value is closely linked to parameter  $s$  and it can be shown that  $\bar{M}^*(z)$  increases with  $s$ . The longevity  $T$  is computed as:

$$T = T_0 - \frac{1}{r-\rho} \ln \left( s + M_{\min}(1-s) - \eta_2 M_{\min}^2(1-s) \right) \quad (\text{B-11})$$

where  $T_0 = \frac{1}{r-\rho} \ln \left( \frac{\kappa(s)}{4(r-\rho)} \right)$ .

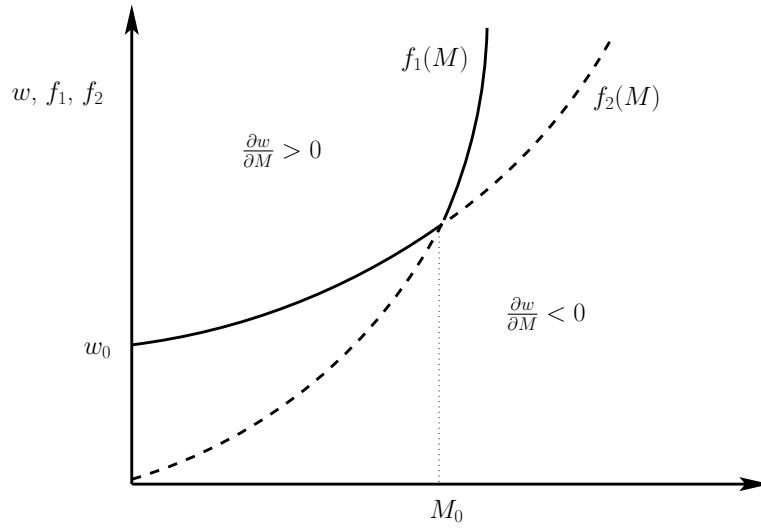
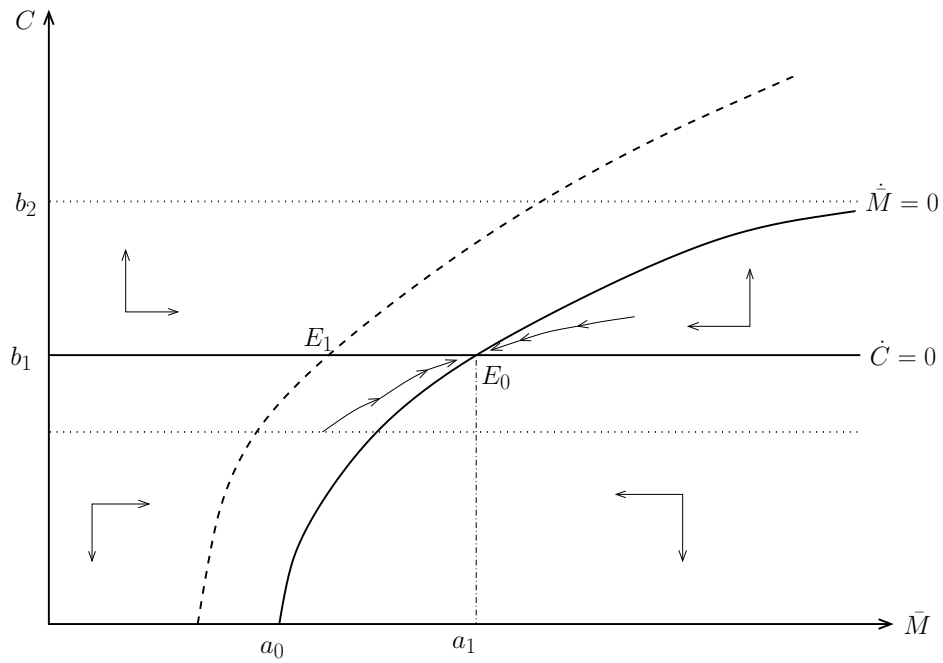


Figure 1: Domains of wage rate


 Figure 2: Phase diagram for additive separable preferences, plane  $(C, \bar{M})$

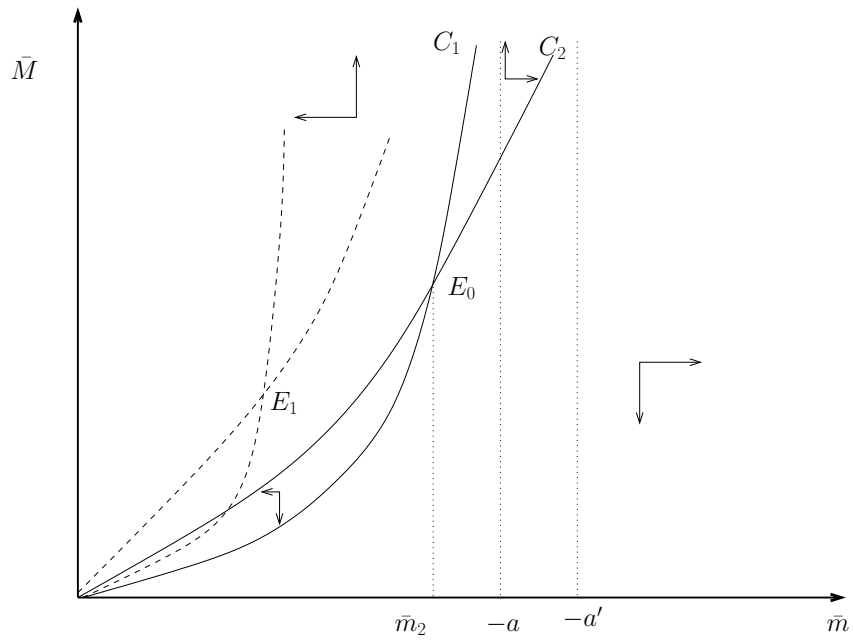


Figure 3: Phase diagram for additive separable preferences, plane  $(\bar{M}, \bar{m})$

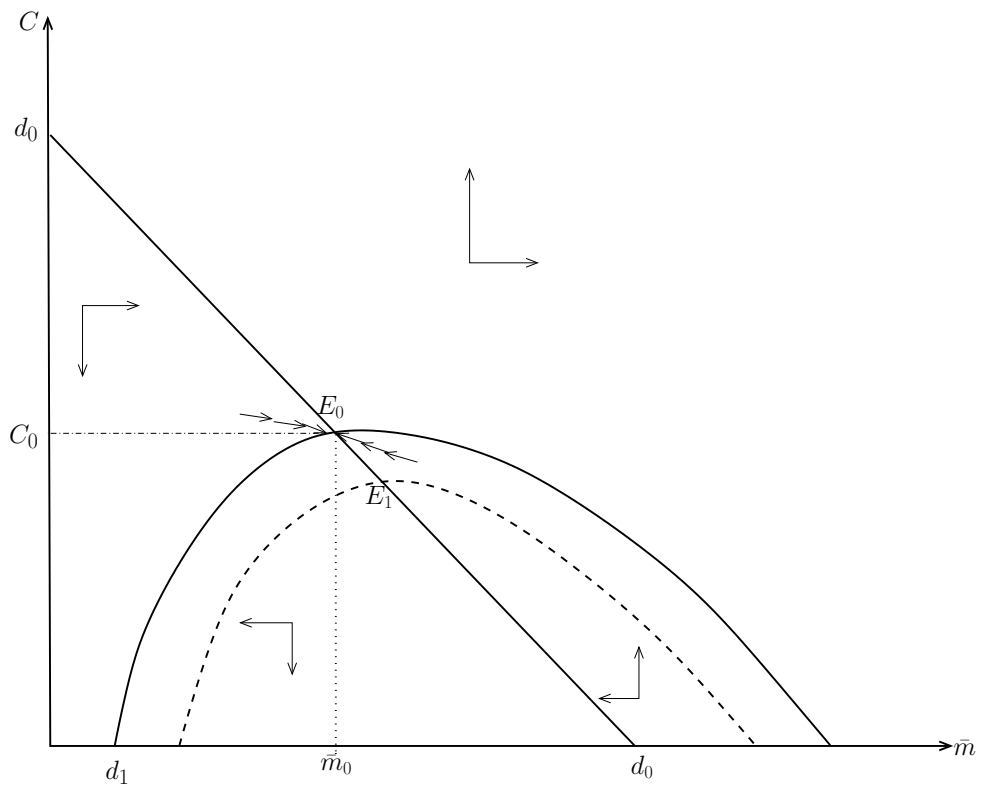


Figure 4: Phase diagram for additive separable preferences, plane  $(C, \bar{m})$

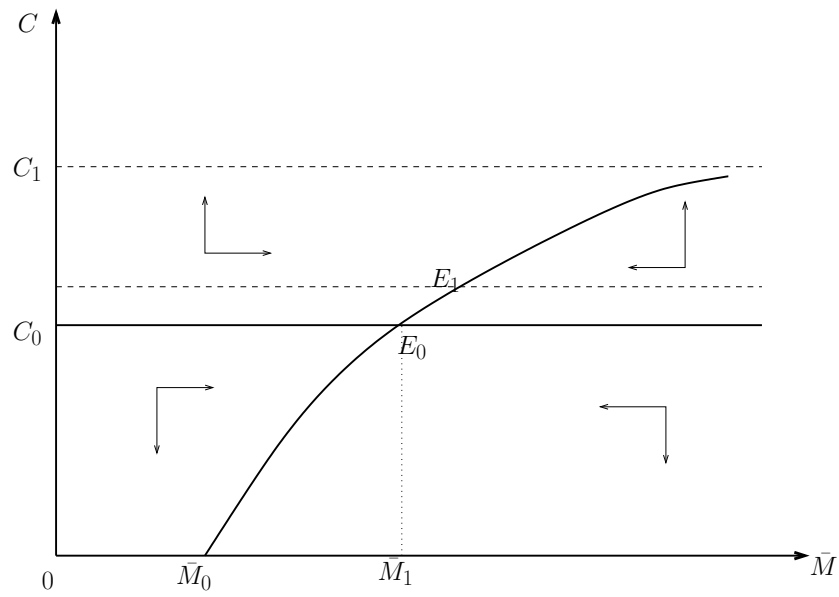


Figure 5: Phase diagram for multiplicative non-separable preferences, plane  $(C, \bar{M})$

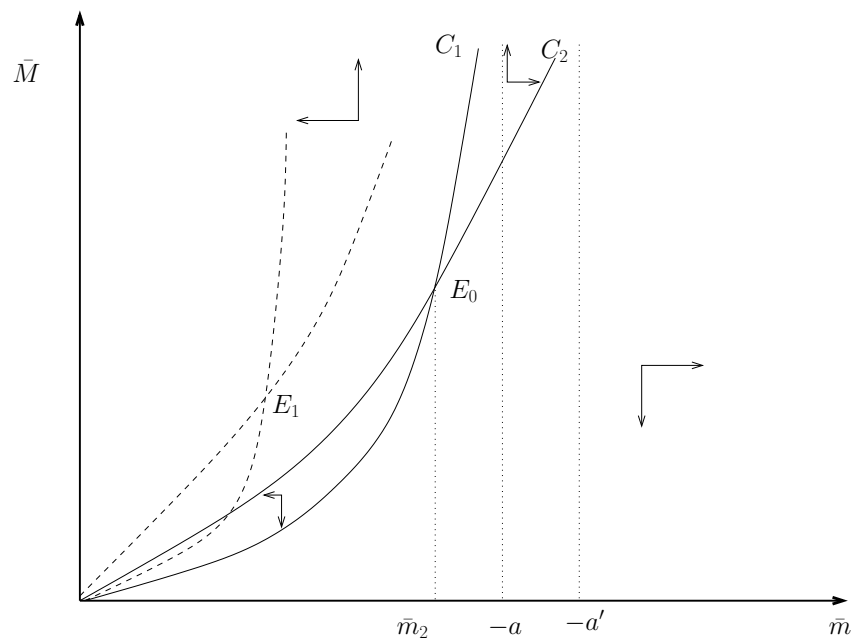


Figure 6: Phase diagram for multiplicative non-separable preferences, plane  $(\bar{M}, \bar{m})$



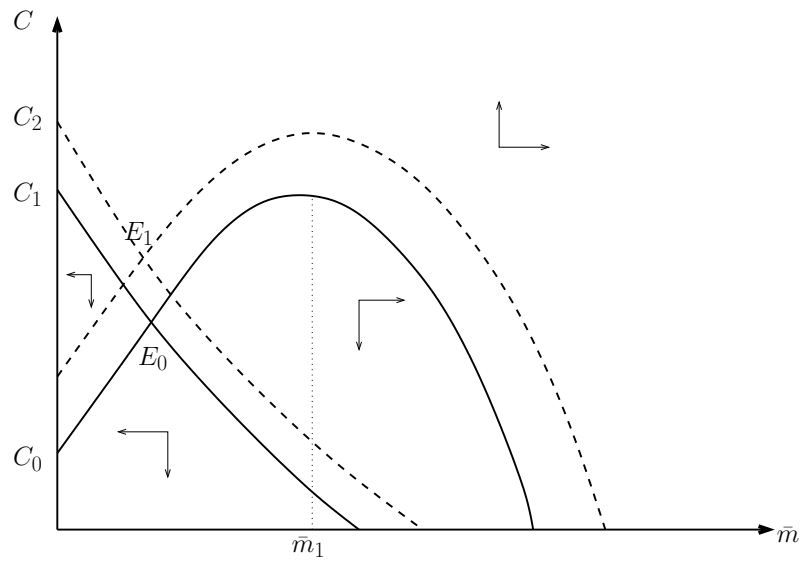


Figure 7: Phase diagram for multiplicative non-separable preferences, plane  $(C, \bar{m})$

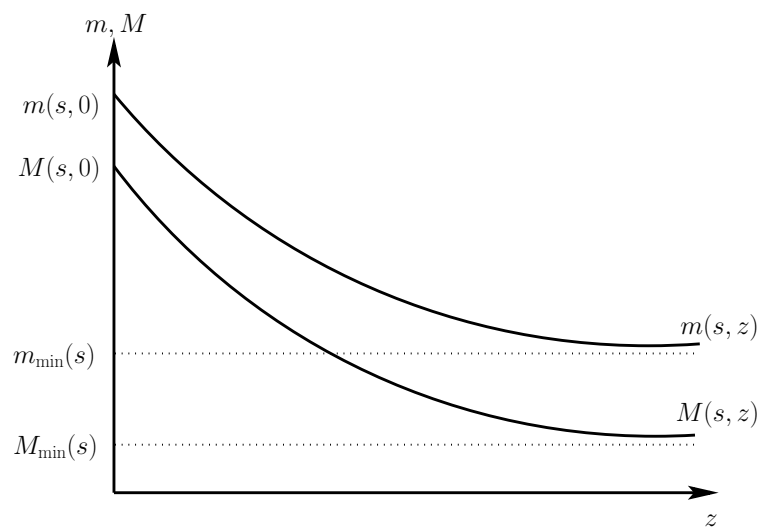


Figure 8: Evolution of stock of health and health investment

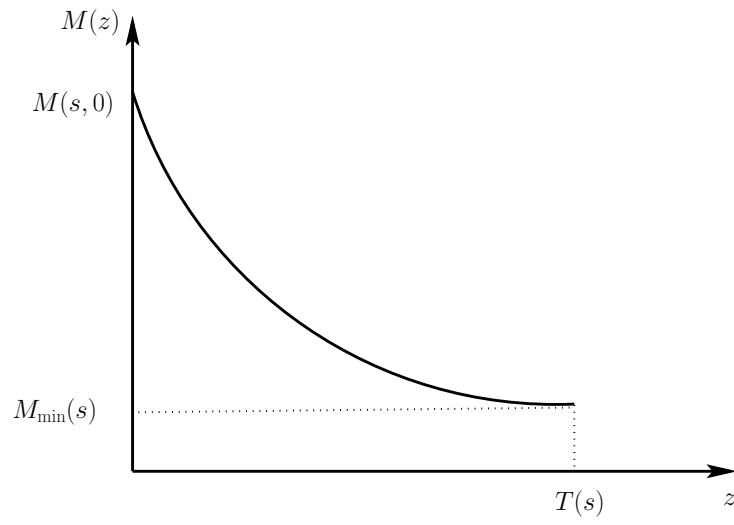


Figure 9: Evolution of stock of health in finite horizon

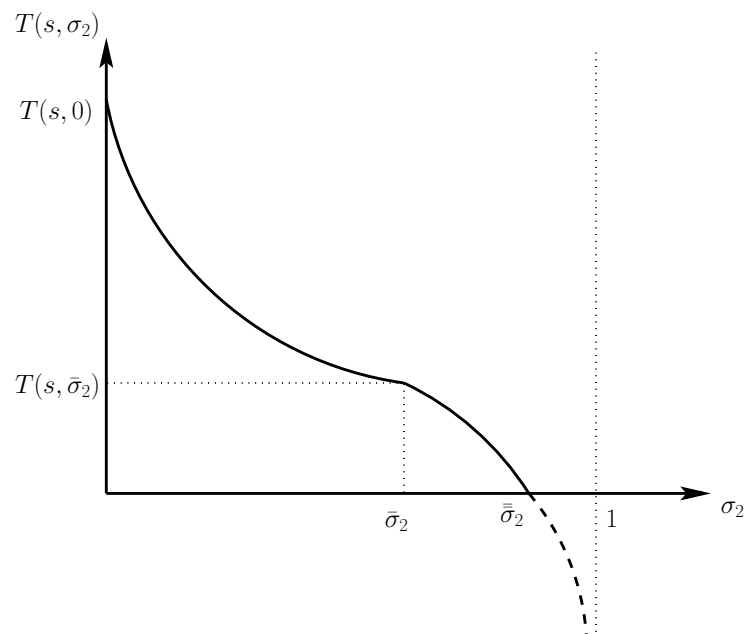


Figure 10: Evolution of longevity

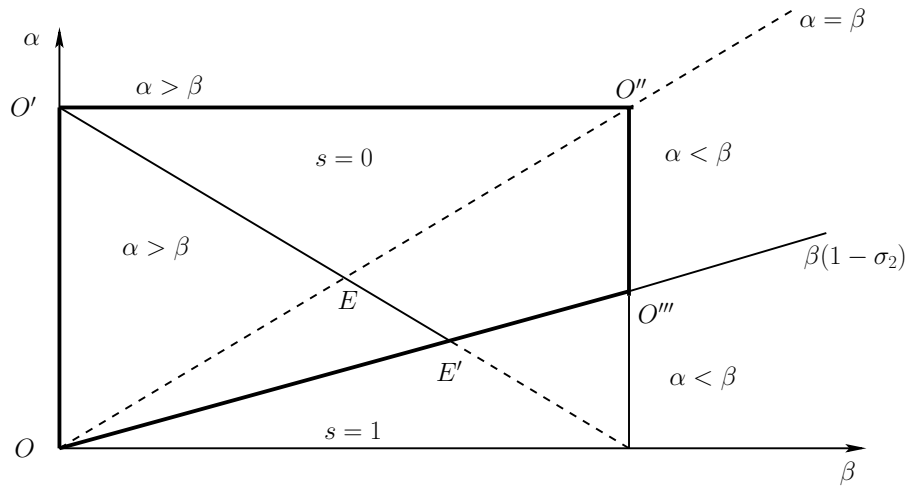


Figure 11: Combination of elasticities

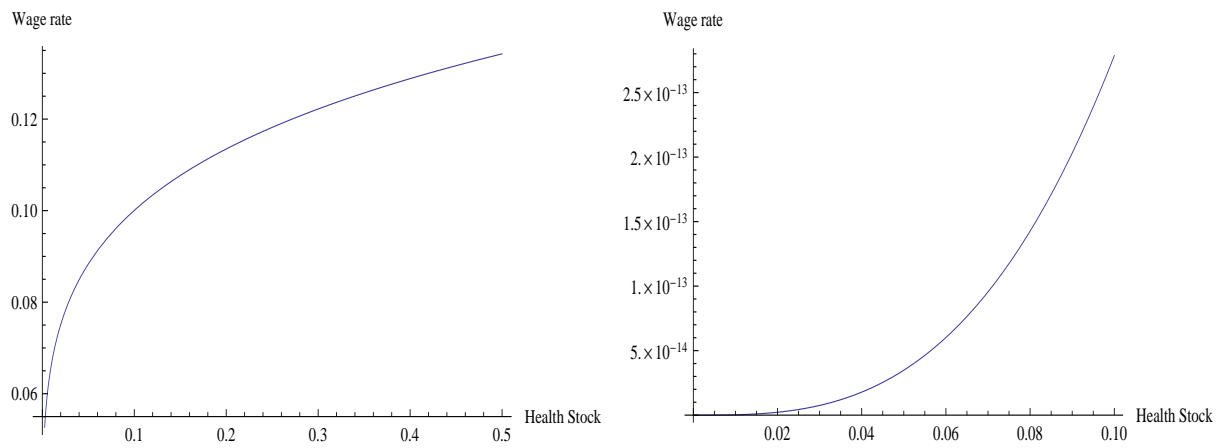


Figure 12: The logarithmic utility: relation between wage rate and health stock for parameter values

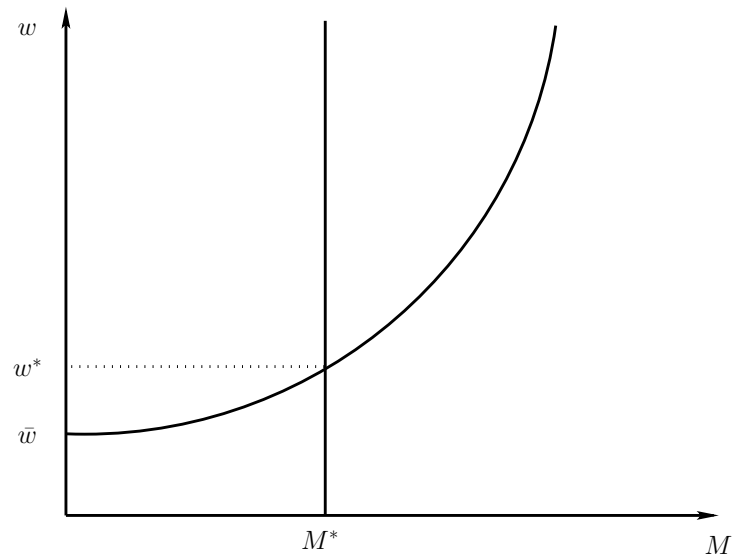


Figure 13: The quadratic utility: evolution of equilibrium stock of health for additive preferences

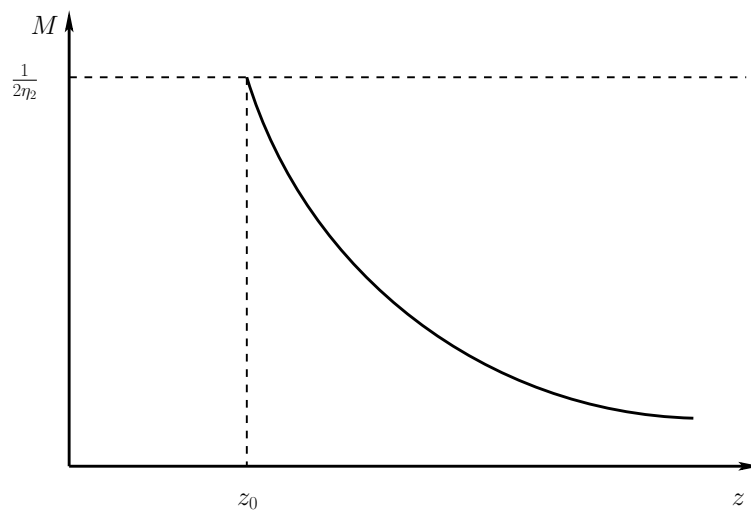


Figure 14: The quadratic utility: evolution of equilibrium stock of health