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How Powerful is Demography?
The Serendipity Theorem Revisited[*]

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Abstract

Introduced by Samuelson (1975), the Serendipity Theorem states that the competitive economy will converge towards the optimum steady-state provided the optimum population growth rate is imposed. This paper aims at exploring whether the Serendipity Theorem still holds in an economy with risky lifetime. We show that, under general conditions, including a perfect annuity market with actuarially fair return, imposing the optimum fertility rate and the optimum survival rate leads the competitive economy to the optimum steady-state. That Extended Serendipity Theorem is also shown to hold in economies where old adults work some fraction of the old-age, whatever the retirement age is fixed or chosen by the agents.

Keywords: Serendipity Theorem, fertility, mortality, overlapping generations, retirement.
JEL codes: E13, E21, I18, J10.

1 Introduction

Despite significant differences across countries, it is unquestionable that most economies have, during the last decades, converged from a demographic equilibrium characterized by a (relatively) high fertility and a (relatively) low longevity to another equilibrium, with a lower fertility and a higher longevity. Much attention has been paid, within economics, to that evolution. In particular, growth theory has, in the recent years, regarded the demographic equilibrium as *an output* to be explained, and built up several models aimed at explaining the demographic transition.[1]

However, there is also another way to look at the demography of an economy. Actually, one may treat demographic variables as *inputs*, whose levels can affect economic outcomes significantly. Indeed, given that fertility and mortality are major determinants of the functioning of an economy (e.g. savings, labour supply, etc.), one may think about their capacity to allow an economy to reach more or less high standards of living. More precisely, demographic variables can be regarded as powerful instruments to be influenced.

Such an alternative view leads to the following problem. Suppose that demographic variables could be controlled perfectly by a government. [2] Then, two questions arise. First, *to which values* should those demographic variables be fixed? Second, *if* those demographic variables can be fixed optimally, to what extent would these allow a decentralized economy to reach the social optimum? In other words, would a perfect control of demographic variables lead a market economy to the optimum?

The second question was first asked and answered by Samuelson (1975), who highlighted, by means of his Serendipity Theorem, the power of demography. Actually, the Serendipity Theorem states that, if there exists a unique stable steady-state equilibrium in a Diamond-type overlapping generations (OLG) economy, a competitive economy will converge towards the most golden rule steady-state provided the optimum cohort growth rate is imposed. That theoretical result reveals the unexpected capacity of demographic variables - in this case, the cohort growth rate - to drive the economy towards the social optimum. To put it differently, when the Serendipity Theorem holds, governments only need to impose optimal fertility behaviour, and the rest of the economic variables will take automatically their optimal levels.

Note, nevertheless, that the scope of Samuelson's results has been somewhat qualified by subsequent studies, such as the one by Deardorff (1976), Michel and Pestieau (1993) and Jaeger and Kuhle (2009). Whereas those studies cast an important light on the scope of the Serendipity Theorem, these concentrate mainly on the characterization of the economic environment under which Samuelson's result holds, without refining the demographic environment. More precisely, those studies all keep the standard Diamond-type OLG structure, with a given cohort growth rate, and a fixed length of life equal to two periods. However, one may want to know whether the Serendipity Theorem is robust to a finer characterization of

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[1]See Blackburn and Cipriani (2002), Doepke (2004), Galor and Moav (2005), de la Croix and Licandro (2007), and Cervellati and Sunde (2007).

[2]That assumption is clearly strong, but it should be reminded that fertility and mortality are *perfectly observable*, contrary to many economic variables. Children and grand-parents are indeed hard to hide.

the demography within the model, taking into account, in particular, the longevity of agents, in line with the recent work by Chakraborty (2004).

The goal of this paper is to re-examine the Serendipity Theorem in the context of an OLG economy with risky lifetime. In that economy, the demography becomes two-dimensional: the population size and age-structure depend not only on the fertility rate, but, also, on the survival rate. Does the Serendipity Theorem still hold in that more general context, and, if yes, under which conditions?

The present paper proposes to answer that question. For that purpose, we shall first consider an economy that is close to the one proposed in the first part of Chakraborty's (2004) paper, and where agents surviving to the second period are retirees. Then, we shall introduce labour supply during the second period (firstly as an exogenous fraction of the old-age, and then as a fraction chosen by the agents), and examine its consequences for the Serendipity Theorem. Throughout this paper, it is assumed, in the spirit of Samuelson, that fertility and longevity can be controled without cost. Naturally, that simplification is only made for analytical convenience, and is only a starting point.[3]

At this early stage of our investigations, it should be stressed that we are well informed of the somewhat surprising *inversion* operated by Samuelson, and which is also embraced by the present paper. Clearly, a natural way to think about demographic variables consists of treating these as outputs, which cannot be directly controlled, but which can only be influenced indirectly, through some actions affecting the fundamentals of the economy. The Serendipity Theorem starts from the opposite view, and this could be regarded as counterintuitive.

Although we shall not try here to provide a complete discussion on that complex issue, it should be noted that it is not obvious at all that economic variables are more easy to control than demographic variables. One reason why one could argue in favour of Samuelson's approach is that demographic variables can, at least, be easily observed, contrary to most economic variables. Another reason why one may argue in favour of Samuelson's approach is related to the speed of intervention: trying to influence demographic variables through the fundamentals of the economy may take ages, whereas simple reglementations on e.g. fertility can do the job quite quickly, which may be most useful if governments face urgent environmental constraints.

Naturally, none of those arguments is decisive, but at least these suggest that it is not obvious that Samuelson's inversion takes necessarily the problem in the wrong direction. The direction he proposes is also worth being explored, as a natural companion to studies proposing an indirect control of demographic variables. Moreover, in any case, Samuelson's approach allows us to have a concrete idea of the power of demography, i.e. of its influence on the functioning of the economy, and of its capacity (or incapacity) to lead to long-run optimality. These are the reasons why we shall pursue Samuelson's approach here.

This paper is organized as follows. Section 2 presents the model. Section 3 characterizes the optimal fertility rate and survival rate, and re-examines the Serendipity Theorem. Section 4

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[3]On the optimal cohort growth rate under costly, endogenous fertility, see Abio *et al* (2004). Regarding optimal longevity, de la Croix and Ponthiere (2009) study the optimal accumulation of capital in the context of a costly longevity.

introduces (exogenous) second-period labour, and discusses the Serendipity Theorem in that context. Section 5 considers the case of endogenous old-age labour. Concluding remarks are drawn in Section 6.

2   The model

Let us consider a standard, Diamond-type OLG economy with physical capital accumulation. All agents live a first period of life (of length normalized to 1) for sure, during which they supply their labour inelastically, and save some resources for their old days.

Each young adult has also n children during the first period. Hence, the labour force, denoted by L_t, follows the dynamic law:
$$L_{t+1} = L_t n$$
where n can be interpreted as the fertility rate.

However, unlike in Diamond (1965), not all agents survive to the second period: only a fraction π of the young cohort reaches the old age. In other words, life expectancy at birth in that economy equals $1 + \pi$. Hence the population at time t can be written as
$$
\begin{aligned}
N_t &= L_t + \pi L_{t-1} \\
&= L_{t-1}(n + \pi)
\end{aligned}
$$

The production of an output Y_t involves capital K_t and labour L_t, according to the function
$$Y_t = F(K_t, L_t) = \bar{F}(K_t, L_t) + (1 - \delta)K_t$$
where δ is the depreciation rate of capital.[4] The production function $\bar{F}(K_t, L_t)$ is assumed to be homogeneous of degree one. Hence, the total production function $F(K_t, L_t)$ is also homogeneous of degree one, and the production process as a whole can be rewritten in intensive terms as
$$y_t = f(k_t)$$
where k_t denotes the capital per worker, while we have $f'(k) > 0$ and $f''(k) < 0$.[5]

The resource constraint of the economy, stating that what is produced is either consumed or invested, is:
$$F(K_t, L_t) = c_t L_t + d_t \pi L_{t-1} + K_{t+1}$$
At the steady state, and in intensive terms, we have

$$f(k) - nk = c + \pi \frac{d}{n} \tag{1}$$

Individual preferences are assumed to be represented by a function having the expected utility form, with a temporal utility function $u(.)$ increasing and concave in consumption.

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[4]That function is used by de la Croix and Michel (2002, p. 4).

[5]More precisely, k denotes the capital per young agent. In Sections 4 and 5, we will allow old agents to work, so that capital per young agent and capital per worker will then differ.

Hence, provided the utility of death is normalized to zero, individual expected lifetime utility takes the form $u(c) + \pi u(d)$ where c and d denote first- and second-period consumptions. We assume $u'(.) > 0$ and $u''(.) < 0$.

3   Optimum fertility rate and survival rate

In order to consider what the Serendipity Theorem becomes in the economy under study, we shall first consider the social planner's problem, and derive the optimum levels of the fertility rate n and the survival rate π.

3.1   The planner's problem

Consider how the fertility rate n and survival rate π can be chosen in such a way as to reach the best of the optima, that is, the *optimum optimorum*. The problem of the social planner consists of choosing consumptions c, d and capital k, and demographic variables n and π in such a way as to maximize the expected lifetime welfare at the steady-state, which amounts to maximize the average lifetime utility at the steady-state, subject to the feasibility constraint:

$$\max_{c,d,k,n,\pi} u(c) + \pi u(d) \text{ subject to (1)}$$

An interior optimum $(c^\star, d^\star, k^\star, n^\star, \pi^\star)$ should satisfy the following FOCs:[6]

$$\frac{u'(c^\star)}{u'(d^\star)} = n^\star \tag{2}$$

$$f'(k^\star) = n^\star \tag{3}$$

$$f(k^\star) - n^\star k^\star = c^\star + \pi^\star \frac{d^\star}{n^\star} \tag{4}$$

$$\pi^\star \frac{d^\star}{(n^\star)^2} = k^\star \tag{5}$$

$$u(d^\star) - d^\star u'(d^\star) = 0 \tag{6}$$

Condition (2) describes the optimal distribution of resources among generations, while condition (3) describes the optimum capital accumulation pattern. Expression (4) is the feasibility constraint. Taken together, those three conditions characterize usually the optimal levels of c, d and k for given levels of n and π. Condition (5) defines implicitly the optimum fertility rate: as stressed by Jaeger and Kuhle (2009), it explicitates the trade-off between the negative capital widening effect (i.e. k) and the positive intergenerational transfer effect (i.e. $\pi \frac{d}{n^2}$), whose size depends positively on the survival rate π. Given that those two effects of fertility are playing in opposite directions, there is some intuitive support for the existence of an interior optimum fertility rate. Condition (6) characterizes the interior optimum survival rate.

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[6]In the spirit of Samuelson's work, we will focus mainly here on conditions characterizing an *interior* optimum. However, we will briefly discuss below the plausibility of a corner optimum survival rate.

Remark: Equation (6) can be rewritten as

$$\frac{u'(d)}{u(d)} = \frac{1}{d}$$

where the LHS is the fear of ruin, a measure of risk-aversion.

Condition (6) states that the marginal welfare gain from a higher survival prospect, $u(d)$, should be equal to the marginal cost of a higher survival prospect, which is given by $du'(d)$. Note that, provided the optimum steady-state is characterized by sufficiently high levels of second-period consumptions, that condition for an interior optimum survival rate is unlikely to be satisfied, as we have

$$u(d) - du'(d) > 0 \tag{7}$$

in an economy where the value of a statistical life (VSL) is positive.

Remark: The value of a statistical life, defined as the shadow price of a reduction of the risk of death per unit of risk, can be rewritten as

$$\frac{\frac{\partial U}{\partial \pi}}{\frac{\partial U}{\partial d}} = \frac{u(d) - du'(d)}{u'(d)}$$

which is positive only provided $u(d) - du'(d) > 0$.

Thus, if the VSL is positive at the social optimum, the optimum survival rate is not an interior solution, but a corner solution, equal to $\pi^* = 1$. On the contrary, if, at the social optimum, the VSL is negative, we have

$$u(d) - du'(d) < 0 \tag{8}$$

so that the condition (6) is never satisfied, and we have the other corner solution: $\pi^\star = 0$.

It is thus only in the special case of a zero VSL at the optimum that condition (6) holds. But how can we know whether the VSL is positive or not at the social optimum? In general, it is widely acknowledged in the empirical literature on VSL estimates that the VSL is positive and is increasing in the level of wealth. Hence, if, at the laissez-faire, the VSL is positive (as this seems to be the case), and if the social optimum involves a higher old-age consumption than the laissez-faire (which is also plausible), the VSL must also be positive at the social optimum (as the VSL is increasing in d).

Thus, provided the condition $u(d) - du'(d) > 0$ holds, there exists a fundamental asymmetry between births and deaths: although there are some reasons for an interior optimum fertility rate n^*, the same is not true for the survival rate, whose optimal value is, under reasonable assumptions, a corner solution.

Whether condition (6), (7) or (8) prevails depends not only on the level of old-age consumption, but, also, on the shape of individual temporal utility functions. To illustrate the crucial role played by the shape of $u(\cdot)$, the Appendix concentrates on the case of a CIES utility function with an intercept.

Finally, it should be noted that the above first-order conditions are necessary, but not sufficient, for $(c^\star, d^\star, k^\star, n^\star, \pi^\star)$ to be a maximum. Actually, a sufficient condition for a

maximum is that the first-order derivatives are equal to zero, and that the Hessian matrix of this optimization problem is negative definite. The second-order conditions are:[7]

$$\frac{(\pi^\star)^2 u''(c^\star)}{n^\star} + n^\star \pi^\star u''(d^\star) \ < \ 0 \quad (9)$$

$$n^\star \pi^\star u'(d^\star) f''(k^\star) \left[\pi^\star u''(c^\star) + (n^\star)^2 u''(d^\star) \right] \ > \ 0 \quad (10)$$

$$\pi^\star u'(d^\star) \left[(n^\star)^2 \pi^\star \left[u'(d^\star) \right]^2 f''(k^\star) + (n^\star)^2 u'(d^\star) \left[\pi^\star (n^\star + 2k^\star f''(k^\star)) u''(c^\star) \right] \right]$$
$$-\pi^\star u'(d^\star)((n^\star)^3 + 2d^\star \pi^\star f''(k^\star)) u''(d^\star) \ < \ 0 \quad (11)$$

$$-(d^\star)^2 (n^\star)^3 \pi^\star \left[u'(d^\star) \right]^2 \left[u'(d^\star) f''(k^\star) + (n^\star + 2k^\star f''(k^\star)) u''(c^\star) \right] u''(d^\star) \ > \ 0 \quad (12)$$

Conditions (9) and (10) are, by the concavity of the temporal utility $u(\cdot)$ and of the production function $f(\cdot)$, always verified. However, the same is not true for conditions (11) and (12).

3.2 The Serendipity Theorem

Let us now consider a competitive economy and assume that a steady-state equilibrium exists, and is unique and stable. Factors are paid at their marginal productivity:

$$w = f(k) - kf'(k) \quad (13)$$
$$R = f'(k) \quad (14)$$

where w is the wage, while R is the return on capital.

For the sake of space constraints, the existence and uniqueness of a stationary equilibrium are not discussed here formally. However, provided agents are expected utility maximizers and provided there is a perfect annuity market with actuarially fair returns, it can be shown that an equilibrium exists under the assumptions identified by de la Croix and Michel (2002, chapter 1): $u'(c) > 0$, $u''(c) < 0$, and $\lim_{c_t \to 0} u'(c) = +\infty$, as well as, for all $k > 0$, $f(k) > 0$, $f'(k) > 0$ and $f''(k) < 0$. Moreover, the condition guaranteeing the uniqueness of a stationary equilibrium in de la Croix and Michel (2002, p. 34) can also be easily extended to the case of risky lifetime. Note, however, that the risk of death has an ambiguous effect on the uniqueness condition, as it affects both the time horizon and the savings return (see Chakraborty, 2004).

The problem faced by a young agent is to choose his optimal savings subject to his budget constraint. Following the literature, we assume that there exists a perfect annuity market here, which yields an actuarially fair return on savings. Hence, under that assumption, the second period consumption is

$$d = \frac{Rs}{\pi}$$

where s denotes individual savings. Under $w = c + s$, the lifetime budget constraint of the agent can be written as

$$w = c + \pi \frac{d}{R} \quad (15)$$

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[7]See the Appendix for the derivation.

The problem of a young agent can thus be written as

$$\max_{c,d} u(c) + \pi u(d) \text{ subject to } w = c + \pi \frac{d}{R}$$

From the FOCs, we have

$$\frac{u'(c)}{u'(d)} = R \tag{16}$$

Finally, in equilibrium, capital equals savings:

$$nk = s = w - c \tag{17}$$

For given (n, π), a stationary competitive equilibrium is a vector $(\tilde{w}, \tilde{R}, \tilde{c}, \tilde{d}, \tilde{k})$ satisfying (13)-(17).

Assume that n is at its optimum value $n^\star$, i.e. (5) holds. Then, the market conditions (13)-(17) would coincide with the optimal conditions (2)-(3)-(4). If we abstracts from the survival rate, this result coincides with the standard Serendipity Theorem: imposing the optimum fertility rate suffices to bring the economy at the optimum steady-state.

However, the condition (6) for an interior optimum survival rate - or conditions (7) or (8) for a corner optimum survival rate - does not follow automatically from individual behaviour under the optimum fertility rate, and may remain non-satisfied if only the optimum fertility rate is imposed.

Nevertheless, if the social planner can impose *both* the optimum fertility rate *and* the optimum survival rate, then, it is straightforward to see from the above FOCs that all the other variables of the economy take their optimum values. The following proposition summarizes the results.

Proposition 1 *Suppose that there exists a unique and stable steady-state equilibrium with a positive capital $k > 0$.*

Assume that Conditions (2)-(5), (6), and (9)-(12) hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $0 < \pi^\star < 1$.

Assume that Conditions (2)-(5), (7), and (9)-(11) hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $\pi^\star = 1$.

Assume that Conditions (2)-(5), (8), and (9)-(11) hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $\pi^\star = 0$.

Therefore, the introduction of survival rates in the OLG framework does not invalidate the Serendipity Theorem.[8] However, it is true that, in that extended framework, a government

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[8]Note that, if agents could, at the laissez-faire, affect their survival probability (e.g. through health spending), then there may be a difference between the laissez-faire and the social optimum, as agents may ignore the effect of their health investment on the return of their savings, and choose a non-optimal level of health investment (see Becker and Philipson, 1998). This possibility does not arise here, where agents take the demographic parameters n and π as given.

can only drive the economy towards its optimum steady-state provided it imposes *both* the optimum fertility rate and the optimum survival rate. In general (i.e. provided the optimum old-age consumption is sufficiently large), the optimum π is equal to 1, so that the Serendipity Theorem requires here to impose maximal and riskless longevity for all, in such a way as to reach the optimum long-run equilibrium.[9]

At this stage, it is crucial to highlight the fundamental asymmetry between the two demographic variables: although adding new persons and adding life-periods to existing persons seem to be *a priori* quite similar things, the 'message' to be diffused by a social planner controlling agents' fertility and mortality, would have to vary strongly on the two demographic sides, in the sense that the imposed life expectancy would be the maximum one (i.e. $\pi^\star = 1$), whereas the imposed fertility would not be the maximum one.

4   Exogenous old-age labour

Whereas Section 3 showed that the introduction of mortality within an OLG economy does not invalidate, but only leads to a re-qualification, of the Serendipity Theorem, it may be argued that the introduction of mortality was, in the above framework, not capturing the overall effect of ageing on the economy. The reason why one may remain unsatisfied is that the above model treats all survivors to the second period as retirees.

Actually, that assumption is not fully realistic, as one may expect that, as the life expectancy grows, the working time grows also. Hence, this section aims at complementing the basic model developed above by a more realistic one, where agents surviving to the second period can also take part in the production process. Undoubtedly, introducing such a possibility adds additional connections between fertility and mortality, as we shall now see.

Assume now that the surviving old agents work an exogenous fraction λ of the second period, with $0 < \lambda < 1$. Hence the total labour force becomes

$$L_t + \lambda \pi L_{t-1} = L_t \left(1 + \frac{\lambda \pi}{n} \right)$$

Production still involves capital and labour as before. For simplicity, it is assumed that old workers have the same productivity as young ones (i.e. they compensate exactly their old age by their additional experience)

$$Y_t = F \left(K_t, L_t \left(1 + \frac{\lambda \pi}{n} \right) \right)$$

Hence, under CRS, production can be written, in intensive terms, as

$$y_t = F \left(k_t, 1 + \frac{\lambda \pi}{n} \right)$$

where y_t is the output per young adult, and k_t is the capital per young adult.

---

[9]Whereas one might be skeptical in the capacity of governments to impose $\pi^\star$, it should be stressed that it may be easier to control for this than for $n^\star$.

The resource constraint is derived as follows. We have

$$K_{t+1} = F\left(K_t, L_t\left(1 + \frac{\lambda\pi}{n}\right)\right) - L_t c_t - \pi L_{t-1} d_t$$

Hence we have, at the steady-state

$$F\left(k, 1 + \frac{\lambda\pi}{n}\right) - nk = c + \pi\frac{d}{n} \tag{18}$$

4.1 The social planner's problem

Under that alternative framework, the problem of the social planner becomes

$$\max_{c,d,k,n,\pi} u(c) + \pi u(d) \text{ subject to (18)}$$

Under the FOCs, we have, at an interior optimum,

$$\frac{u'(c^\star)}{u'(d^\star)} = n^\star \tag{19}$$

$$F_k\left(k^\star, 1 + \frac{\lambda\pi^\star}{n^\star}\right) = n^\star \tag{20}$$

$$F\left(k^\star, 1 + \frac{\lambda\pi^\star}{n^\star}\right) - n^\star k^\star = c^\star + \pi^\star\frac{d^\star}{n^\star} \tag{21}$$

$$-k^\star + \pi^\star\frac{d^\star}{n^2} - F_L\left(k^\star, 1 + \frac{\lambda\pi^\star}{n^\star}\right)\frac{\lambda\pi^\star}{(n^\star)^2} = 0 \tag{22}$$

$$u(d^\star) - d^\star u'(d^\star) + F_L\left(k^\star, 1 + \frac{\lambda\pi^\star}{n^\star}\right)\lambda u'(d^\star) = 0 \tag{23}$$

In comparison with the basic model, the second condition is different, as the marginal productivity of capital depends on the survival rate, unlike what used to prevail before. Similarly, the condition (21) - the feasibility constraint - is also affected by old-age workers: the survival rate has here a positive effect on the feasible set.

In comparison with the basic model [i.e. condition (5)], condition (22), which characterizes the optimum fertility rate, contains an additional term, the third one, which captures the negative effect of n on the output per young worker y_t. The two other effects are the same as before. Thus, if we compare the optimum interior fertility under old-age labour (i.e. $\lambda > 0$), we see that the optimum n is likely to be smaller than without old-age labour (i.e. $\lambda = 0$).

Condition (23) characterizes the interior optimum survival rate. Here again, there is an additional term in comparison with condition (6), which captures the positive effect of a higher survival rate on the labour force, and, hence, on the output per young worker. That

additional, positive term is likely to reinforce the likelihood of a corner solution for optimum π, i.e. for $\pi^\star = 1$:

$$u(d) - du'(d) + F_L\left(k, 1 + \frac{\lambda\pi}{n}\right)\lambda u'(d) > 0 \tag{24}$$

Hence, the positive influence of the survival rate on the feasibility set makes the condition for the corner solution $\pi^\star = 0$, which is

$$u(d) - du'(d) + F_L\left(k, 1 + \frac{\lambda\pi}{n}\right)\lambda u'(d) < 0 \tag{25}$$

even less plausible than under no old-age labour (i.e. $\lambda = 0$).

Finally, the sufficient conditions for $(c^\star, d^\star, k^\star, n^\star, \pi^\star)$ to be a maximum are now:[10]

$$\frac{(\pi^\star)^2 u''(c^\star)}{n^\star} + n^\star \pi^\star u''(d^\star) \;<\; 0 \tag{26}$$

$$n^\star \pi^\star u'(d^\star) F_{KK}\left[\pi^\star u''(c^\star) + (n^\star)^2 u''(d^\star)\right] \;>\; 0 \tag{27}$$

$$n^\star \pi^\star u'(d^\star)\left[(\pi^\star)^2 F_{KL}^2 u'(d^\star)\varphi - F_{KK}(n^\star F_L^2 u''(c^\star)u''(d^\star))\right]$$
$$-n^\star \pi^\star u'(d^\star) F_{KK}\left((\pi^\star)^2 F_{LL} u'(d^\star)\varphi\right) \;<\; 0 \tag{28}$$

$$\pi^\star \left[u'(d^\star)\right]^2\left[\Gamma + (n^\star)^3\Delta + (\pi^\star)^2 F_{KL}^2\Theta - (\pi^\star)^2 F_{LL}\Lambda\right] \;>\; 0 \tag{29}$$

with

$$
\begin{aligned}
\varphi \;&\equiv\; \pi^\star u''(c^\star) + (n^\star)^2 u''(d^\star)\\
\Gamma \;&\equiv\; 2(n^\star)^2\pi^\star F_{KL}\left(-\lambda F_L^2 u''(c^\star)u''(d^\star) + (n^\star)^2 F_L u'(d^\star)u''(d^\star)\right),\\
\Delta \;&\equiv\; -F_L^2\left((n^\star + 2k^\star F_{KK})u''(c^\star) + F_{KK}u'(d^\star)\right)u''(d^\star)\\
&\quad +\pi^\star\left(\pi^\star(n^\star + 2k^\star F_{KK})u''(c^\star) + (n^\star)^3 u''(d^\star)\right),\\
\Theta \;&\equiv\; (n^\star)^2\pi^\star\left(u'(d^\star)\right)^2 + u''(c^\star)\left(2k^\star(n^\star)^2\pi^\star u'(d^\star) + \lambda^2\left(-F_L^2 u''(d^\star)\right)\right),\\
\Lambda \;&\equiv\; u''(c^\star)\left[(n^\star)^2\pi^\star(n^\star + 2k^\star F_{KK})u'(d^\star) + \lambda^2 F_{KK}(-F_L^2 u''(d^\star))\right],\\
&\quad +n^2\left((n^\star)^3 u'(d^\star)u''(d^\star) + F_{KK}\left(\pi^\star\left(u'(d^\star)\right)^2 + 2(k^\star(n^\star)^2 + \lambda F_L)u'(d^\star)u''(d^\star)\right)\right).
\end{aligned}
$$

Conditions (26) and (27) are identical to conditions (9) and (10) in the model without old-age labour. As in the basic model, it is straightforward to see that those conditions are always satisfied. However, conditions (28) and (29) differ from (11) and (12). Moreover, those two conditions are not necessarily satisfied.

4.2   The Serendipity Theorem

We now look at the competitive steady state assuming that it is unique and stable. As before, factors are paid at their marginal productivities:

$$w = \left(F\left(k, 1 + \frac{\lambda\pi}{n}\right) - kF_k\left(k, 1 + \frac{\lambda\pi}{n}\right)\right)\frac{n}{n + \lambda\pi} \tag{30}$$

$$R = F_k\left(k, 1 + \frac{\lambda\pi}{n}\right) \tag{31}$$

---

[10]See the Appendix for the derivation.

We can now consider the problem faced by a young agent, who chooses his optimal savings subject to his budget constraint. Under a perfect annuity market with an actuarially fair return on savings, the second-period consumption is, under an (exogenous) second-period labour λ, equal to

$$d = \frac{Rs}{\pi} + \lambda w$$

Under $w = c + s$, the budget constraint of the agent can be written as

$$w = \left(c + \pi \frac{d}{R}\right)\left(\frac{R}{R + \lambda \pi}\right) \tag{32}$$

The problem of a young agent can thus be written as

$$\max_{c,d} u(c) + \pi u(d)$$

subject to the above budget constraint. From the FOCs, we have the same equation as before, i.e. Equation (16). Finally, in equilibrium, capital equals savings, i.e. (17) holds.

For given (n, π), a stationary competitive equilibrium is a vector $(\tilde{w}, \tilde{R}, \tilde{c}, \tilde{d}, \tilde{k})$ satisfying (16), (17), and (30)-(32).

Assume that n is at its optimum value $n^\star$, i.e. (22) holds. Then, the market conditions (16), (17), and (30)-(32) would coincide with the optimal conditions (19)-(21). Thus, once old-age labour is introduced ($\lambda > 0$), and if we abstract from the choice of the optimal survival rate, the Serendipity Theorem still holds: imposing the optimum fertility rate suffices to bring the economy at the optimum steady-state.

Once we consider the choice of the optimal survival rate, it is clear, here again, that the condition (23) for an interior optimum survival rate - or the conditions (24) and (25) for a corner optimum survival rate - do not follow automatically from individual behaviour under the optimum fertility rate.

Nevertheless, if the social planner can impose *both* the optimum fertility rate *and* the optimum survival rate, then, here again, all the other variables of the economy take also their optimum values. The only difference with respect to the basic model consists of the levels of those optimum levels. The following proposition summarizes the results.

Proposition 2 *Suppose that there exists a unique and stable steady-state equilibrium with a positive capital $k > 0$.*

Assume that Conditions (19)-(22), (23), and (26)-(29) hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $0 < \pi^\star < 1$.

Assume that Conditions (19)-(22), (24) and (26)-(28), then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $\pi^\star = 1$.

Assume that Conditions (19)-(22), (25) and (26)-(28) hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $\pi^\star = 0$.

Therefore, the introduction of old-age labour does not invalidate the extended Serendipity Theorem. Naturally, it is true that, under the possibility of second-period work, the incentive to save is likely to be reduced, so that the mere existence of a steady-state equilibrium with a strictly positive capital level becomes here a stronger assumption. However, provided the existence, uniqueness and stability of the stationary equilibrium still hold, Proposition 2 tells us that, if the government can impose the optimum levels of n and π - which differ from their levels in the basic model - then it is still guaranteed that the economy will converge towards the optimum steady-state. In sum, the introduction of old-age labour only changes the level of the target for the fertility rate n - and, possibly, the one for π - but not the possibility to reach the social optimum by merely imposing the optimum pair $(n^\star, \pi^\star)$.

5   Endogenous old-age labour

Finally, let us conclude our re-examination of the Serendipity Theorem by considering the case where old-age labour is chosen by agents when being young, and where there exists some disutility from old-age labour. While assuming that agents choose the length of their working time is not fully realistic (strong legislative limitations still prevail in some countries), it may be worth, nonetheless, to develop that alternative case, to see how robust our results are to the exogeneity of old-age labour supply.

Assume now that young adults choose their old-age working time by maximizing their expected lifetime welfare

$$u(c_t) + \pi u(d_{t+1}) - \pi v(\lambda_{t+1})$$

where $v(\cdot)$ denotes the disutility of second-period labour.[11] We assume that the disutility of old-age labour is a strictly increasing, convex function. We also have $\lim_{\lambda_{t+1} \to 0} v'(\lambda_{t+1}) = 0$ and $\lim_{\lambda_{t+1} \to 1} v'(\lambda_{t+1}) = +\infty$.

As above, production still involves capital and labour. For simplicity, it is still assumed that old workers have the same productivity as young ones. Hence total output is

$$Y_t = F\left(K_t, L_t\left(1 + \frac{\lambda_t \pi}{n}\right)\right)$$

where $L_t\left(1 + \frac{\lambda_t \pi}{n}\right)$ is the total labour force. The only difference with respect to the previous section is that the old-age labour time λ_t is now endogenous. Under CRS, production can be written, in intensive terms, as

$$y_t = F\left(k_t, 1 + \frac{\lambda_t \pi}{n}\right)$$

where y_t is the output per young adult, and k_t is the capital per young adult.

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[11]That modeling is close to the one in Hu (1979) and de la Croix *et al* (2004), but for risky longevity.

5.1 The social planner's problem

Under that alternative framework, the problem of the social planner becomes

$$\max_{c,d,k,\lambda,n,\pi} u(c) + \pi u(d) - \pi v(\lambda) \text{ subject to (18)}$$

Under the FOCs, we have, at an interior optimum:

$$\frac{u'(c^\star)}{u'(d^\star)} = n^\star \tag{33}$$

$$F_k\left(k^\star, 1 + \frac{\lambda^\star \pi^\star}{n^\star}\right) = n^\star \tag{34}$$

$$u'(c^\star)F_L\left(k^\star, 1 + \frac{\lambda^\star \pi^\star}{n^\star}\right)\frac{1}{n^\star} = v'(\lambda^\star) \tag{35}$$

$$F\left(k^\star, 1 + \frac{\lambda^\star \pi^\star}{n^\star}\right) - n^\star k^\star = c^\star + \pi^\star \frac{d^\star}{n^\star} \tag{36}$$

$$-k^\star + \pi^\star \frac{d^\star}{(n^\star)^2} - F_L\left(k^\star, 1 + \frac{\lambda^\star \pi^\star}{n^\star}\right)\frac{\lambda^\star \pi^\star}{(n^\star)^2} = 0 \tag{37}$$

$$u(d^\star) - d^\star u'(d^\star) + F_L\left(k^\star, 1 + \frac{\lambda^\star \pi^\star}{n^\star}\right)\lambda^\star u'(d^\star) - v(\lambda^\star) = 0 \tag{38}$$

In comparison with the previous section, there is here an additional FOC (35), concerning the optimal old-age labour $\lambda^\star$. It states that the old-age labour is optimal when the marginal gain in utility terms from working one more year (left-hand side) equals the marginal disutility from not retiring. Simplification yields

$$u'(d)F_L\left(k, 1 + \frac{\lambda\pi}{n}\right) = v'(\lambda) \tag{39}$$

In comparison with the model with exogenous λ [i.e. condition (22)], condition (37), which characterizes the optimum fertility rate, exhibits no explicit difference. However, it is likely to yield another optimum n, because consumptions and old-age labour take other values than in (27), as $F_L\left(k, 1 + \frac{\lambda\pi}{n}\right) = v'(\lambda)/u'(d)$ under the optimal λ.

Condition (38) characterizes the interior optimum survival rate. There is here an additional, negative term in comparison with condition (23). That term captures the negative effect of a higher survival rate on old-age utility given old-age labour. The condition for a corner solution $\pi^\star = 1$ is now:

$$u(d) - du'(d) + F_L\left(k, 1 + \frac{\lambda\pi}{n}\right)\lambda u'(d) - v(\lambda) > 0 \tag{40}$$

The condition for the corner solution $\pi^\star = 0$ becomes

$$u(d) - du'(d) + F_L\left(k, 1 + \frac{\lambda\pi}{n}\right)\lambda u'(d) - v(\lambda) < 0 \tag{41}$$

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Finally, the second-order conditions for a maximum include now an additional condition, relative to the optimal level of old-age labour. Hence we have now five conditions. To save space, we only report here the first three ones.

$$\frac{(\pi^\star)^2 u''(c^\star)}{n^\star} + n^\star \pi^\star u''(d^\star) \;<\; 0 \quad (42)$$

$$F_{KK}\left[\pi^\star u''(c^\star) + (n^\star)^2 u''(d^\star)\right] \;>\; 0 \quad (43)$$

$$-\left[(\pi^\star)^2 F_{KL}^2 u'(d^\star)\left(\pi^\star u''(c^\star) + (n^\star)^2 u''(d^\star)\right) - F_{KK}(n^\star F_L^2 u''(c^\star) u''(d^\star))\right]$$
$$+F_{KK}\left((\pi^\star)^2 F_{LL} u'(d^\star) - n^\star \pi^\star v''(\lambda^\star)\right)\left(\pi^\star u''(c^\star) + (n^\star)^2 u''(d^\star)\right) \;<\; 0 \quad (44)$$

Conditions (42) and (43) are the same as in the previous section, because the first-order conditions for optimal d and k are formally identical whatever λ is exogenous or endogenous. However, condition (44) differs from its counterparts in the previous Section (i.e. expression (28)). Whereas conditions (42) and (43) are necessarily satisfied (thanks to the concavity of $u(\cdot)$ and $F(\cdot, \cdot)$, the same is not true for the other conditions. Only particular assumptions on the functional forms would allow us to say more about their satisfaction.

5.2 The Serendipity Theorem

Consider now the competitive economy. As before, factors are paid at their marginal productivities, i.e. (30) and (31) hold.

The young agent chooses his savings and old-age labour supply subject to his budget constraint. The problem of a young agent can be written as

$$\max_{c,d,\lambda} u(c) + \pi u(d) - \pi v(\lambda)$$

subject to the lifetime budget constraint (32).

From the FOCs, we have the Euler equation (16) and an additional condition related to labour supply:

$$\pi v'(\lambda) = u'(c)\left(c + \pi\frac{d}{R}\right)\left(\frac{\pi}{R + \lambda\pi}\right) \quad (45)$$

Finally, in equilibrium, capital equals savings, i.e. (17) holds.

For given (n, π), a stationary competitive equilibrium is a vector $(\tilde{w}, \tilde{R}, \tilde{c}, \tilde{d}, \tilde{k}, \tilde{\lambda})$ satisfying (16), (17), (30)-(31), (32) and (45).

If n is fixed at its optimum level, so that condition (37) holds, satisfied, then it follows that conditions (16), (17), (30)-(31), (32) imply the optimal rules (33)-(34) and (36).

However, in comparison with the previous Section, we now have an additional condition characterizing the social optimum: condition (35), which characterizes the optimal old-age labour. Can this be obtained from the individual's decision, described by condition (45)? Actually, it can be shown that imposing the optimal values of demographic parameters n

and π suffices to induce the optimal old-age working time. To see this, let us first substitute for $R = n$ and for (36) in expression (45):

$$\pi v'(\lambda) = u'(c) \left(F\left(k, 1 + \frac{\lambda\pi}{n}\right) - nk \right) \left(\frac{\pi}{n + \lambda\pi} \right)$$

Given that $F\left(k, 1 + \frac{\lambda\pi}{n}\right) = Rk + w\left(1 + \frac{\lambda\pi}{n}\right)$, and given (16), we have

$$v'(\lambda) = u'(d) F_L \left(k, 1 + \frac{\lambda\pi}{n}\right) \tag{46}$$

which coincides with condition (35). Thus, imposing $\pi^\star$ and $n^\star$ suffices to decentralize the optimum retirement age. Endogenizing the old-age labour does not break the Extended Serendipity Theorem.

Proposition 3 *Suppose that there exists a unique and stable steady-state equilibrium with a positive capital $k > 0$.*

Assume that the first order Conditions (33)-(37), (38) and the second order conditions for a maximum hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $0 < \pi^\star < 1$.

Assume that the first order Conditions (33)-(37), (40) and the second order conditions for a maximum hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $\pi^\star = 1$.

Assume that the first order Conditions (33)-(37), (41) and the second order conditions for a maximum hold, then, if the government imposes $n^\star$ and $\pi^\star$, the economy will converge towards the optimum steady-state, which involves $-1 < n^\star < +\infty$ and $\pi^\star = 0$.

Undoubtedly, Proposition 3 illustrates the robustness of the Extended Serendipity Theorem studied in the previous sections. Controlling for demographic conditions $(n^\star, \pi^\star)$ leads to the optimum steady-state not only in a world where agents *either* do not work when being old (Proposition 1) *or* do work during some fixed period (Proposition 2), but, also, in a world where agents organize their working lifeplans by themselves (Proposition 3). Hence the capacity to decentralize the optimum steady-state on the mere basis of demographic controls is quite robust to the assumptions made on old-age working time.

6   Conclusion

Despite the large attention that was paid to the economic environment (i.e. utility and production functions) under which Samuelson's Serendipity Theorem holds, little had been said on the conditions of the demographic environment guaranteeing that result. The present paper, by reconsidering the Serendipity Theorem in a Chakraborty-type economy, aimed at re-examining that theorem under a richer demographic structure, involving a risky lifetime.

For that purpose, we developed a two-period OLG model with risky lifetime, and showed that, if there exists only one stable steady-state, then, provided the government can impose the optimum levels of the fertility rate *and* of the survival rate, all other economic variables will take their optimum values, that is, the *optimum optimorum* will be reached. That result was also shown to hold - but with different targets - in a more general framework, where adults surviving to the old age are allowed to work a fraction of the second period, whatever that fraction is exogenously fixed or endogenously chosen by agents.

Hence, the introduction of mortality in a Diamond-type economy does not infirm the Serendipity Theorem, as the imposition of the optimum fertility rate is still highly beneficial here, even though this is no longer sufficient to reach the *optimum optimorum*, which requires also the optimum survival rate to be imposed. This paper tends thus to emphasize, in some sense, a limitation of the Serendipity Theorem, as one cannot, by the use of a single demographic control, reach the best steady-state: longevity must also be controlled for, and its level does affect the optimum level of fertility. The two demographic dimensions must thus be treated together.

Finally, it should be stressed here that a crucial assumption lies behind the possibility to keep the Serendipity Theorem in the context of risky lifetime: the existence of a perfect annuity market. Undoubtedly, without it, the question of whether fixing the optimal pair $(n^\star, \pi^\star)$ suffices to induce the optimum steady-state would become more complex. Given the under-development of annuity markets in real life, a natural direction to look at for future research would consist of reconsidering the Serendipity Theorem under alternative assumptions. Regarding other possible extensions, the introduction of costs for fertility and survival would also be most welcome. Given that such a treatment would depart from the original spirit of Samuelson's approach, it is left for further research.

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7   Appendix

7.1   The CIES example

Let us now see in which particular cases of temporal utility function condition (6) could be satisfied. For instance, under Constant Intertemporal Elasticity of substitution (CIES) utility function,

$$u(d) = \frac{(d)^{1-\sigma}}{1-\sigma} + \alpha$$

we have:

$$u(d) - du'(d) = \frac{(d)^{1-\sigma}}{1-\sigma} + \alpha - (d)^{1-\sigma}$$

The RHS is zero only if

$$\frac{(d)^{1-\sigma}}{1-\sigma} + \alpha = (d)^{1-\sigma}$$

$$\alpha = (d)^{1-\sigma}\left(\frac{-\sigma}{1-\sigma}\right)$$

That condition states that, for a positive or zero level of α, the intercept of the temporal utility function, the optimal survival rate is not an interior solution, but is a corner solution, with $\pi^\star = 1$, as we have condition (7), i.e. $u(d) - du'(d) > 0$, so that condition (6) cannot be satisfied. Thus, it is only under a particular, negative α that condition (6) can be satisfied. Clearly, α cannot be positive, but it cannot be too negative either: if α is smaller than the threshold, we have condition (8), i.e. $u(d) - du'(d) < 0$, so that the optimal π is a corner solution, and equals 0.

7.2   Second-order conditions

The Hessian matrix of the second-order derivatives associated to the planner problem of Section 3 is

$$H \equiv \begin{bmatrix} \frac{\partial^2 U}{\partial d^2} & \frac{\partial U^2}{\partial d \partial k} & \frac{\partial U^2}{\partial d \partial n} & \frac{\partial U^2}{\partial d \partial \pi} \\ \frac{\partial U^2}{\partial k \partial d} & \frac{\partial^2 U}{\partial k^2} & \frac{\partial U^2}{\partial k \partial n} & \frac{\partial U^2}{\partial k \partial \pi} \\ \frac{\partial U^2}{\partial n \partial d} & \frac{\partial U^2}{\partial n \partial k} & \frac{\partial^2 U}{\partial n^2} & \frac{\partial U^2}{\partial n \partial \pi} \\ \frac{\partial U^2}{\partial \pi \partial d} & \frac{\partial U^2}{\partial \pi \partial k} & \frac{\partial U^2}{\partial \pi \partial n} & \frac{\partial^2 U}{\partial \pi^2} \end{bmatrix}$$

Hence,

$$u''(c)\begin{bmatrix} \frac{\pi^2}{n^2} + \pi\frac{u''(d)}{u''(c)} & \frac{\pi(n-f')}{n} & \frac{\pi u'(c)}{u''(c)n^2} - \frac{\pi\left(\frac{\pi d}{n^2}-k\right)}{n} & \frac{u'(d)}{u''(c)} - \frac{u'(c)}{u''(c)n} + \frac{d\pi}{n^2} \\ \frac{\pi(n-f')}{n} & (f'-n)^2 + \frac{u'(c)}{u''(c)}f'' & \left(\frac{\pi d}{n^2}-k\right)(f'-n) - \frac{u'(c)}{u''(c)} & \frac{d(n-f')}{n} \\ \frac{\pi u'(c)}{n^2 u''(c)} - \frac{\pi\left(\frac{\pi d}{n^2}-k\right)}{n} & \left(\frac{\pi d}{n^2}-k\right)(f'-n) - \frac{u'(c)}{u''(c)} & -\frac{2d\pi u'(c)}{n^3 u''(c)} + \left(\frac{\pi d}{n^2}-k\right)^2 & \frac{du'(c)}{n^2 u''(c)} - \frac{d\left(\frac{\pi d}{n^2}-k\right)}{n} \\ \frac{u'(d)}{u''(c)} - \frac{u'(c)}{u''(c)n} + \frac{d\pi}{n^2} & \frac{d(n-f')}{n} & \frac{du'(c)}{n^2 u''(c)} - \frac{d\left(\frac{\pi d}{n^2}-k\right)}{n} & \frac{d^2}{n^2} \end{bmatrix}$$

Substituting for first-order conditions and multiplying by n yields:

$$\begin{bmatrix} \frac{u''(c)\pi^2}{n} + n\pi u''(d) & 0 & \pi u'(d) & \frac{\pi u''(c)d}{n} \\ 0 & n^2 u'(d)f''(k) & -n^2 u'(d) & 0 \\ \pi u'(d) & -n^2 u'(d) & -\frac{2d\pi u'(d)}{n} & du'(d) \\ \frac{\pi u''(c)d}{n} & 0 & du'(d) & \frac{d^2 u''(c)}{n} \end{bmatrix}$$

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A sufficient condition for (d, k, n, π) to be a maximum is that the Hessian matrix is negative definite. Four conditions guarantee that the Hessian matrix is negative definite. Those conditions concern the determinants of the four submatrices, of sizes 1x1, 2x2, 3x3 and 4x4. Those conditions are conditions (9)-(12) in Section 3.

7.3 Second-order conditions in Section 4

Substituting for first-order conditions in the Hessian matrix yields:

$$
u'(d)
\begin{bmatrix}
\frac{u''(c)\pi^2}{u'(d)n}+n\pi\frac{u''(d)}{u'(d)} & 0 & -\frac{\pi F_L u''(c)}{u'(d)n} & \pi \\
0 & n^2 F_{KK} & n\pi F_{KL} & -n^2-\pi\lambda F_{KL} \\
-\frac{\pi u''(c) F_L}{u'(d)n} & n\pi F_{LK} & \frac{F_L^2 u''(c)}{n}+\pi^2 F_{LL} & -\frac{nF_L}{n}-\frac{\pi^2\lambda F_{LL}}{n} \\
\pi & -n^2-\pi\lambda F_{KL} & -\frac{nF_L}{n}-\frac{\pi^2\lambda F_{LL}}{n} & \frac{-2kn^3}{n^2}+\frac{\pi^2\lambda^2 F_{LL}}{n^2}
\end{bmatrix}
$$

Given that the FOCs for optimal d and k are exactly identical to the ones under no old-age labour, this is not surprising that the 2x2 submatrix is the same as before. However, the FOCs for optimal n and π are different from the ones in Section 3, and this has some consequences on the 3x3 and 4x4 submatrices. As above, four conditions guarantee that the Hessian matrix is negative definite. Those conditions concern the determinants of the four submatrices, of sizes 1x1, 2x2, 3x3 and 4x4. Those conditions are conditions (26)-(29) in Section 4.

7.4 Second-order conditions in Section 5

The Hessian matrix is now a 5x5 matrix

$$
\begin{bmatrix}
\frac{\partial^2 U}{\partial d^2} & \frac{\partial U^2}{\partial d\partial k} & \frac{\partial U^2}{\partial d\partial n} & \frac{\partial U^2}{\partial d\partial \pi} & \frac{\partial U^2}{\partial d\partial \lambda} \\
\frac{\partial U^2}{\partial k\partial d} & \frac{\partial^2 U}{\partial k^2} & \frac{\partial U^2}{\partial k\partial n} & \frac{\partial U^2}{\partial k\partial \pi} & \frac{\partial U^2}{\partial k\partial \lambda} \\
\frac{\partial U^2}{\partial n\partial d} & \frac{\partial U^2}{\partial n\partial k} & \frac{\partial^2 U}{\partial n^2} & \frac{\partial U^2}{\partial n\partial \pi} & \frac{\partial U^2}{\partial n\partial \lambda} \\
\frac{\partial U^2}{\partial \pi\partial d} & \frac{\partial U^2}{\partial \pi\partial k} & \frac{\partial U^2}{\partial \pi\partial n} & \frac{\partial^2 U}{\partial \pi^2} & \frac{\partial U^2}{\partial \pi\partial \lambda} \\
\frac{\partial U^2}{\partial \lambda\partial d} & \frac{\partial U^2}{\partial \lambda\partial k} & \frac{\partial U^2}{\partial \lambda\partial n} & \frac{\partial U^2}{\partial \lambda\partial \pi} & \frac{\partial U^2}{\partial \lambda^2}
\end{bmatrix}
$$

Substituting for the first-order conditions in the entries and simplifying yields

$$
\begin{bmatrix}
\frac{u''(c)\pi^2}{n}+n\pi u''(d) & 0 & -\frac{\pi F_L u''(c)}{n} & \pi u'(d) & u''(c)\frac{d\pi}{n}-u''(c)\frac{\lambda F_L}{n} \\[2mm]
0 & n^2 u'(d)F_{KK} & n\pi F_{KL}u'(d) & -u'(d)n^2-u'(d)\pi\lambda F_{KL} & n\lambda F_{KL}u'(d) \\[2mm]
-\frac{\pi u''(c)F_L}{n} & n\pi F_{LK}u'(d) & \frac{F_L^2 u''(c)}{n}-\pi n v''(\lambda)+\pi\left(\pi F_{LL}u'(d)\right) & -u'(d)\frac{nF_L}{n}-u'(d)\frac{\pi^2\lambda F_{LL}}{n} & \frac{\lambda F_L^2 u''(c)+n\pi^2\lambda F_{LL}u'(d)}{n\pi}-\frac{F_L\left[d\pi u''(c)+n^2(\pi-1)u'(d)\right]}{n\pi} \\[2mm]
\pi u'(d) & -u'(d)n^2-u'(d)\pi\lambda F_{KL} & -u'(d)\frac{nF_L}{n}-u'(d)\frac{\pi^2\lambda F_{LL}}{n} & u'(d)\frac{-2kn^3}{n^2}+u'(d)\frac{\pi^2\lambda^2 F_{LL}}{n^2} & u'(d)\frac{dn-\frac{n\lambda F_L}{\pi}}{n}-u'(d)\frac{\pi\lambda^2 F_{LL}}{n} \\[2mm]
u''(c)\frac{d\pi}{n}-u''(c)\frac{\lambda F_L}{n} & n\lambda F_{KL}u'(d) & \frac{\lambda F_L^2 u''(c)+n\pi^2\lambda F_{LL}u'(d)}{n\pi}-\frac{F_L\left[d\pi u''(c)+n^2(\pi-1)u'(d)\right]}{n\pi} & u'(d)\frac{dn-\frac{n\lambda F_L}{\pi}}{n}-u'(d)\frac{\pi\lambda^2 F_{LL}}{n} & \frac{\left(d-\frac{\lambda F_L}{\pi}\right)^2 u''(c)}{n}+\frac{n\lambda^2 F_{LL}u'(d)}{n}
\end{bmatrix}
$$

Five conditions guarantee that the Hessian matrix is negative definite. Those conditions concern the determinants of the five submatrices, of sizes 1x1, 2x2, 3x3, 4x4 and 5x5. The first three of them are conditions (42)-(44) in Section 5.