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Automation, population aging, and growth

Master Thesis

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Master of Science in Economics

LUND UNIVERSITY

Lund

2017

Abstract

In this paper we analyze the effects that automation and population aging exert on economic growth. We do that by means of an Overlapping Generations Model (Diamond, 1965) in which automation capital is taken into account in the production structure of the economy. The framework we use was first created by Gasteiger and Prettner (2017) and we further develop it by adding a new feature: a pay-as-you-go pension system. The model predicts that automation could produce the collapse of the economy if the latter and labour are perfect substitutes. However, after simulating seven different scenarios, we find that restricting the amount of investment in automation and ensuring a stable or growing population, long-run growth can be achieved.

Keywords: automation, robots, population aging, economic growth, PAYGO pension system, Overlapping Generations Model.

Acknowledgements

My deepest gratitude goes to Fundación Ramón Areces for awarding me one of the full postgraduate scholarships to study second cycle university studies abroad. Without any doubt, the foundation and its team made my stay in Sweden possible, and hence, the realization of my first master thesis as a student of the MSc Economics at Lund University.

It is fair to express my thankfulness to Klas Fregert, my supervisor. He has always welcomed me to his office to discuss obstacles I have been facing through the realization of this master thesis. His support and guidance have been key to guarantee the completion and success of this master thesis.

I will always be indebted to my professors at my home university, especially Bernd Theilen, Antonio Quesada, and Miquel Manjón. They all prepared me very well to succeed in Lund and I will always thank them their support and encouragement to come to study in Sweden.

Finally, I want to thank my parents, Alfredo and Mercedes, for their endless support, encouragement, and commitment with my studies. They have always supported me economically but also expressing their affection and motivating me when I have faced tough situations throughout my studies. I must recognize that part of this work and personal achievements belong to them.

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1. Introduction

Over the last sixty years the developed world has witnessed a decrease in fertility and a wave of increased automation in the workplace. Although millions of workers were displaced by machines in the past, the economy has been able to create new jobs, absorb the displaced labour and grow strongly. In fact, Bessen (2016) reports that only one occupation has been completely replaced by automation since 1950: the elevator operator. The rapid population aging process as a consequence of low fertility rates and the acceleration of automation and robotics in developed countries make particularly interesting and necessary the creation of a framework to study how these facts will affect economic growth in the future.

On the one hand, during the twentieth century, automation affected blue-collar workers in agriculture or manufacturing, but it created new jobs in the service industry. On the other hand, automation in the form of artificial intelligence is threatening nowadays many jobs carried out by white-collar workers, such as traders or accountants. Although new jobs related to digital technologies or data analysis are being created in the present, the increased pace at which the automation of tasks performed by labour is evolving triggers the concern that labour will become superfluous (Autor, 2015). In fact, a report from Manyika et al (2017) states that around 50% of all jobs could be automated by 2055. This pessimistic scenario is supported by the fact that labour income shares have steadily declined since 1975 in many developed countries (ILO and OECD, 2015). The latter could be explained by the decline in employment and salaries of middle skilled workers as they have been replaced by machines (Autor, Levy and Murnane, 2003; Acemoglu and Autor, 2011; and Autor and Dorn, 2013).

It has been documented that population aging leads to the creation of excess savings and hence to the standstill of economic growth (Summers, 2013). A thesis that goes in line with the former is reported in Gordon (2016), in which it is argued that an old society reduce the labour force, productivity and thus economic growth. However, Acemoglu and Restrepo (2017) report a significant and positive relationship between population aging and GDP per capita. They argue that those countries facing a rapid process of population aging and low fertility rates are more likely to introduce automation in the economy, leading to an increase in productivity and economic growth. Abeliansky and Prettner (2017), by means of an empirical work, support the latter and find that a 1% decrease in population growth leads to an expansion of 2% in the rate at which robot density grow.

In this work, we will document some results that oppose the view of Acemoglu and Restrepo (2017). We find, by means of an Overlapping Generations Model, that the aging process ongoing in developed countries could hamper economic growth in the future when the stock of automation capital increases. Moreover, a key finding of our research is that restricting the amount of investment in automation capital[1] could lead to experience no losses in welfare.

The thesis will be organized as follows: first, in Section 2 the theoretical framework upon our work is based will be developed and explained; secondly, we will set some different scenarios and perform some simulations in Section 3; it will be followed by a policy discussion in Section 4; and our work will be finished by stating the main conclusions of our research in Section 5.

2. Theoretical Model

The framework employed to build the model lies in the Overlapping Generations Model (Diamond, 1965) with automation capital developed by Gasteiger and Prettner (2017), and improved by featuring a pay-as-you-go pension system, henceforth PAYGO pension system. We consider households that live for three time periods: childhood, adulthood and retirement. During the first part of their lives, individuals do not make any economic decision, i.e. their parents fulfil their needs via their decisions. Adults intelastically supply all their labour and decide the amount invested in traditional capital and automation capital, so their savings in t add to the capital stock in $t+1$. Moreover, a fraction of their salary is taken by the Government to fund a pay-as-you-

[1]The terms automation and traditional capital were first coined by Prettner (2017).

go pension system. Retirees do not work and enjoy a pension and the rewards from investing during adulthood. The evolution of the population size is exogenous and is expected to grow at a rate *n,* so that $L_{t+1} = (1+n) \cdot L_t$.

Following Prettner (2017), the production function of the economy is given by:

$$Y_t = K_t^{\alpha}(L_t + B_t)^{1-\alpha} \tag{1}$$

where Y_t denotes aggregate output (GDP), L_t is the adult population –or total labour– in t, K_t is the total stock of traditional capital (machines for example), B_t denotes the total stock of automation capital (high-frequency trading algorithms or 3D printers for example), and $\alpha \in (0,1)$ is the elasticity of output with respect to traditional capital.

Notice that (1) implies that labour and automation are perfect substitutes with each other. Moreover, perfect competition in the goods and factors markets is assumed so that production factors are rewarded according to their marginal value products:

$$w_t = \theta_{t+1} = \frac{\partial Y}{\partial L} = \frac{\partial Y}{\partial B} = (1-\alpha)\left(\frac{K_t}{L_t + B_t}\right)^{\alpha} \tag{2}$$

$$\sigma_{t+1} = \frac{\partial Y}{\partial K} = \alpha\left(\frac{L_t + B_t}{K_t}\right)^{1-\alpha} \tag{3}$$

where w_t denotes wages at time t, and σ_{t+1} and θ_{t+1} denote the reward in *t+1* from investing at time *t* in traditional capital and automation capital respectively. Notice that the reward from automation and traditional capital have the subscript *t+1,* but they depend on the stock of traditional and automation capital, and total labour at time *t.* The reason lies behind the fact that the rewards from investing today in traditional and automation capital are obtained tomorrow, i.e. individuals make the decision of investing a fraction of their savings on automation and/or traditional capital at *t*, and obtain the reward in the next period, at *t+1*. Moreover, wages at time *t* depend on the stock of capital and labour in *t* because individuals supply their labour in *t* and receive the reward from working in the same time period.

On the one hand, from (2) we can see that wages and the reward from investing in automation capital increase with the amount of traditional capital and decreases as labour and automation capital increases. On the other hand, (3) indicates that the return of traditional capital increases with labour and automation capital but decreases when accumulating more traditional capital.

Both traditional capital and automation capital depreciate at the same rate δ so that they accumulate as follows:

$$K_{t+1} = (1-\delta)K_t + \rho S_t \quad (4)$$

$$B_{t+1} = (1-\delta)B_t + (1-\rho)S_t \quad (5)$$

where S_t accounts for total savings in the economy at time t and ρ is an arbitrary constant denoting the proportion of savings channelled to traditional capital.

The pension p_t received by retirees in *t* is financed by taxing the adult cohort in *t,* i.e. the younger generation pays the pension of the old generation (PAYGO pension system). We assume that the government always keep the budget balanced, i.e. no deficits are allowed, so that its budget constraint is $\tau_t \cdot L_t = p_t \cdot L_{t-1}$. Given that population grows at the constant rate *n*, $\tau_t \cdot (1+n)L_{t-1} = p_t \cdot L_{t-1}$, and hence

$$\tau_t \cdot (1+n) = p_t. \quad (6)$$

The adults' budget constraint is given by

$$c_{1,t} + k_{t+1} + b_{t+1} + \tau_t = w_t \quad (7)$$

where $c_{1,t}$ is individual consumption during adulthood, k_{t+1} and b_{t+1} are individual investment in traditional and automation capital respectively at time *t*, where the subscript *t+1* denotes that this will be the stock of capital invested in *t* from which individuals will receive the rewards in *t+1*, τ_t is the tax associated to the PAYGO pension system, and w_t is the wage income received by individuals in *t*.

The retirees budget constraint is given by

$$c_{2,t+1} = \sigma_{t+1} \cdot k_{t+1} + \theta_{t+1} \cdot b_{t+1} + \tau_t \cdot (1+n) \quad (8)$$

Where $c_{2,t+1}$ is individual consumption during retirement, σ_{t+1} denotes the capital rewards from investing in traditional capital, θ_{t+1} is the capital rewards from investing in automation capital and $\tau_t \cdot (1+n)$ denotes the pension that retirees receive –see equation (6) and its explanation above for a proper understanding of the PAYGO pension system.

Notice the difference between k_t and b_t, and K_t and B_t respectively. The first ones, in small letters, denote the investment in traditional and automation capital respectively that one economic agent decide to allocate from its wage, whereas the second ones, in capital letters, denote the aggregate stock of traditional and automation capital respectively.

From (7), we can work out individual savings and, thus, the investment that each individual does in traditional and automation capital each period:

$$s_t = k_{t+1} + b_{t+1} = w_t - \tau_t - c_{1,t} \tag{9}$$

For the sake of simplicity, the amount of savings allocated to investment in traditional and automation capital are assumed to be exogenously given. Notice in equations (4) and (5) that the fraction invested in traditional capital and automation capital is accounted by ρ and $1-\rho$ respectively.

Using the non-arbitrage condition $\sigma_{t+1} = \theta_{t+1} = 1 + r_{t+1}$, we obtain the following intertemporal budget constraint:

$$c_{1,t} + \tau_t + \frac{c_{2,t+1} - \tau_t \cdot (1+n)}{1+r_{t+1}} = w_t \tag{10}$$

Notice that the non-arbitrage condition is essential to solve the model and obtain the general equilibrium. The term r_{t+1} is exogenously given and denotes the interest rate prevailing in the market. The rewards of traditional and automation capital, and the rewards from investing in any financial product, for example, should be the same so that individuals do not obtain profits from buying and selling different products, i.e. they have to be indifferent between investing in financial products, traditional or automation capital. Furthermore, in order to clarify it, $1 + r_{t+1}$ stands for the total capital that individuals will obtain in *t+1*, i.e. if individuals invest 1 unit of wage in time *t* they will obtain the same 1 unit invested in the previous period plus the rewards from investing, r_{t+1}, in *t+1*. Furthermore, notice that in this model there does not exist any financial product, i.e. the only source of investment is traditional or automation capital. However, we use $1 + r_{t+1}$ for conventional purposes and indicates that the rewards from investing in automation and traditional capital should be the same in equilibrium so that there is not arbitrage possibilities.

Let the following expression be the household's lifetime utility:

$$U_t = c_{1,t} \cdot {c_{2,t+1}}^{\beta} \tag{11}$$

where $c_{1,t}$ denotes consumption in adulthood, $c_{2,t+1}$ is the consumption when they retire, and β is the discount factor. Therefore, the household's utility maximization problem is the maximization of their lifetime utility U_t –equation (11) – with respect to (10), the intertemporal budget constraint. Optimal consumption during adulthood is given by the following expression:

$$c_{1,t} = \frac{c_{2,t+1}}{\beta \cdot (1 + r_{t+1})} \tag{12}$$

Equation (12) stem from the so-called Euler equation. Notice that the Euler equation is not affected by the tax charged to the adult cohort to finance the PAYGO pension that retirees receive. The reason lies behind the fact that these taxes are lump sum, see equation (6).

Plugging (12) into the left-hand side of (10), we can solve for the consumption of the adult cohort as a function of wages, discount factors, tax rate, population growth and interest rates:

$$c_{1,t} = \frac{w_t}{1+\beta} + \frac{\tau_t}{1+\beta} \cdot \left(\frac{1+n}{1+r_{t+1}} - 1\right) \tag{13}$$

Plugging (13) into (9) we obtain the proper expression to work out individual savings:

$$s_t = \frac{\beta}{1+\beta} \cdot w_t - \frac{\tau_t}{1+\beta} \cdot \left(\frac{1+n}{1+r_{t+1}} + \beta\right) \tag{14}$$

Finally, we plug (2) into (14) and obtain individual savings:

$$s_t = \frac{\beta \cdot (1-\alpha)}{1+\beta} \cdot \left(\frac{K_t}{L_t+B_t}\right)^{\alpha} - \frac{\tau_t}{1+\beta} \cdot \left(\frac{1+n}{1+r_{t+1}} + \beta\right) \tag{15}$$

Multiplying total labour, L_t, by (15) we can obtain aggregate savings, S_t, or the so-called (traditional and automation) capital accumulation dynamics:

$$S_t = K_{t+1} + B_{t+1} = \frac{\beta\cdot(1-\alpha)}{1+\beta}\cdot\left(\frac{K_t}{L_t+B_t}\right)^{\alpha}\cdot L_t - \frac{\tau_t}{1+\beta}\cdot\left(\frac{1+n}{1+r_{t+1}}+\beta\right)\cdot L_t \tag{16}$$

Following Gasteiger and Prettner (2017), the following non-arbitrage condition is obtained by setting $\sigma_t = \theta_t$:

$$B_t = \frac{1-\alpha}{\alpha}\cdot K_t - L_t \tag{17}$$

See their article for a better understanding of the non-arbitrage condition and its implications on the production structure.

Definition 1. A *general competitive equilibrium* (with initial $K_0 > 0$, $B_0 > 0$, production function F and perfect foresight) is a sequence $\{c_{1,t}, c_{2,t}, w_t, 1+r_t, \sigma_t, \theta_t, K_t, B_t\}_{t\geq 1}$, such that $\{w_t, 1+r_t, \sigma_t, \theta_t\}_{t\geq 1}$ satisfy (2), (3), and $1+r_t = \sigma_t = \theta_t$, $\{c_{1,t}, c_{2,t}\}_{t\geq 1}$ satisfy (10) and (11), $\{K_t, B_t\}_{t\geq 1}$ satisfy (16), and $\{L_t\}_{t\geq 1}$ satisfies the population growth path described by $L_{t+1} = (1+n)\cdot L_t$.

Finally, the steady state solution is obtained when dividing (16) by L_{t+1} and using (17):

$$k = \alpha + \frac{\alpha^{1+\alpha}\cdot(1+\alpha)^{1-\alpha}\cdot\beta}{(1+n)\cdot(1+\beta)} - \alpha\cdot\frac{\tau_t}{(1+n)\cdot(1+\beta)}\cdot\left(\frac{1+n}{1+r_{t+1}}+\beta\right) \tag{18}$$

where *k* is the capital-labour ratio in the steady state. Notice that the steady state is solved by setting $k_t = k_{t+1} = \ldots = k_{t+n}$. As in the original model without a PAYGO pension system proposed by Gasteiger and Prettner (2017), there is no growth in the capital-labour ratio and, hence, GDP per capita stagnates. The main difference with respect to the paper cited above is the fact that including a PAYGO pension system, the capital-labour ratio of the economy is lower. Namely, the right-hand part of equation (18) does not appear in the original model. Notice further that given the fact that there is no total factor productivity growth, it seems natural that GDP per capita stagnates to a constant level.

The reason for the economy to stagnate is that the main driver of the economy – investment– is fully financed by savings. As investment in automation increases, wages decrease because labour and automation capital are perfect substitutes. Eventually, the reduction of wages will lead economic agents to reduce their savings and, thus, their investment. The reduction of aggregate investment will eventually turn out to decrease automation and capital stock, which in turn will cut down production.

3. A simulation: calibration

The purpose of this section is to simulate the effects of automation and population aging on economic growth in a hypothetical economy described by the model built in section 2 over 250 periods, each period accounting for 25 years. In order to do so, different scenarios will be set. First, and as a starting point, there will be no population growth and, hence, the effects of automation on growth will be analyzed in full. Second, the more realistic scenario will be presented and we will set an economy in which population is aging, i.e. the workforce is reduced. Third, we will simulate different scenarios so as to try to find how to overcome the negative effects of automation and population aging on growth.

The hypothetical economy will present, in the benchmark model –Simulation 1–, the following initial conditions: K_0=3.000.000, B_0=1.000.000, and L_0=2.000.000 in every simulation carried out. For subsequent simulations, the initial conditions will be the steady state values obtained in the benchmark model. This economy will try to replicate the conditions of a developed economy, such as for example the U.S., Sweden, France or Germany. For that reason, α is set according to the well-known standard value of 1/3 in developed economies. The parameter τ is set initially at 0.05 but will be slightly modified in subsequent sections so as to experiment with the model. The depreciation of capital, δ, is assumed to be the same for both traditional and automation capital, and will be set at 0.15 throughout all the exercise. Finally, the proportion of savings invested in traditional capital, ρ, will be fixed at 0.5 –we think this is a plausible assumption as the non-arbitrage condition holds. However, different experiments will be carried out by modifying the latter.

3.1. The effects of automation on economic growth

The simulation carried out in this section will be used as a benchmark for the following ones that will be performed. For the first simulation we assume that population size remains constant for the whole sample, i.e. 250 generations, thus we will be able to study the effects that automation exerts on economic growth in our hypothetical economy.

The calibrated economy relies on the exogenous parameters that are presented in Table 1.

Table 1: Parameters. Simulating automation effects.

Parameter	Values	Parameter	Values
α	0,333	n	0
1- α	0,667	1+n	1
ρ	0.5	r	0,03
β	0,8	1+r	1,03
1+β	1,8	δ	0,15
τ	0,05	1- δ	0,85

The values obtained after simulating this scenario can be summarized in Graphs 1 to 5 in Appendix A.

As stated in Section 2, the economy stagnates and there is no room for potential long-run growth. In period 1, automation capital presents higher returns than traditional capital and, hence, there is more relative investment in that source of capital. The increase in automation capital stock leads to a reduction in wages as they both are perfect substitutes, which in turn decreases individual savings and, hence, total savings. Therefore, the only source of investment in this model –savings– collapses and so do the stock of traditional and automation capital, and the economy until the new stationary state is achieved in period 134, with less production and investment. It may be clearly seen in Graph 2 that the capital-labour ratio and GDP per capita are reduced.

The depression of wages as a consequence of the increased automation in the workplace leads to a reduction in consumption –both during adulthood and retirement– and, thus, in utility. Therefore, it is clear that automation capital turns out to reduce economic growth and welfare in the economy.

In the steady state, GDP and traditional and automation capital stock present the following figures: Y_0=2.150.660, B_0=K_0=1.060.730. This steady state will be employed in subsequent simulations as the initial conditions upon the simulations are based.

3.2. Population aging, automation and growth

In this subsection we present a more realistic scenario. In the last years, as explained in the introduction, we have witnessed a decrease in fertility in developed countries. It is leading the population in these countries to age and experience a reduction in the workforce which will be more evident in the coming years. Therefore, the purpose of this subsection is to replicate in a more reliable way the dynamics of demographics and automation, and their effects on growth.

The aging process of population in our model will be simulated by exogenously assuming that the labour force is reduced every generation –every 25 years– by 0.2%. The rest of the parameters are exactly the same used in the last simulation.

Table 2: Parameters. Simulating a decrease in population.

Parameter	Values	Parameter	Values
α	0,333	**n**	**-0.002**
1- α	0,667	**1+n**	**0.998**
ρ	0.5	r	0,03
β	0,8	1+r	1,03
1+β	1,8	δ	0,15
τ	0,05	1- δ	0,85

The initial conditions of this scenario are set according to the steady state values obtained in the benchmark simulation. Therefore, Y_0=2.150.660, B_0=K_0=1.060.730, and L_0=2.000.000.

The dynamic transitions to the new steady state may be observed in Appendix B, in Graphs 6 to 17.

The reduction in labour leads the economy to collapse. Even though wages increase as a consequence of the scarcity of labour, which boosts individual savings and consumption levels both during adulthood and retirement above the prior steady state level, the engine of the economy –total savings– is reduced in line with population.

The latter leads to less aggregate investment both in traditional and automation capital, and hence, to less production or GDP. The decrease of traditional and automation capital leads to a new steady state in which the capital-labour ratio is lower than the prior steady state, but GDP per capita is higher in the new steady state. The latter is explained by the fact that the rate at which population decrease is higher than the rate at which the economy collapses –in absolute value.

Therefore, even though the decrease in fertility –exogenously assumed by a decrease of 0.2% in labour each generation– leads to negative growth rates, the welfare of individuals seem to experience a slight increase. The increase in wages allows individuals to experience higher consumption possibilities and, hence, utility.

3.3. What can we do to prevent the collapse of the economy?

The simulation results acquired in prior subsections present a very pessimistic scenario in the future of developed economies. For that reason we think it is very important to think about which factors could help to mitigate the effects of automation on economic growth and the welfare of citizens. Therefore, in this section we will explore four different possibilities which could prevent the collapse of the economy.

First, our model includes a built-in PAYGO pension system, so the question is: is there any fiscal policy that could prevent the collapse of the economy? Could a higher or lower taxation during adulthood, and hence a higher or lower consumption during retirement through higher or lower pensions, help the economy grow?

Second, we all are aware that the reduction in the labour force is playing a major role in growth. As discussed in the introduction, some economists argue that the aging process in developed economies is halting economic growth through an increase in savings and a reduction in investment. On the other hand, it has also been argued that the reduction in the workforce is prompting the adoption of robots and automation, and hence the investment in this source of capital is increasing. Although it is still not clear what causes what, we think it is very interesting to know whether an increase in population would lead to higher growth in the age of automation.

Third, in a setting in which automation capital and labour are perfect substitutes, it seems clear that the main responsible for the economy to collapse is automation capital and robots. Therefore, we want to experiment whether a decrease in the fraction that individuals invest in automation capital could improve the outcomes and, hence, put the economy in a path of growth.

Forth, given the results we obtain from the three points stated above, we will combine in the same simulation a restriction on the amount of savings channelled to automation capital and a positive growth rate in population.

These are questions that will be addressed in Subsection 3.3.1. to 3.3.4. We will first explore the role that taxation of individuals during adulthood may play on growth; secondly we will study whether an increase in the workforce could lead to a higher growth rate; we will continue seeing whether controlling for the fraction that is invested in automation growth plays a major role in growth; and finally, we will simulate an economy with positive population growth, featuring a PAYGO pension system and a restriction on the amount of investment in automation capital.

3.3.1. The role of the PAYGO pension system on growth

As stated above, in this subsection we aim for knowing whether changes in the taxation of individuals so as to alter the pension they get once individuals are retired could potentially benefit growth rates in the future.

One could argue that by taxing individuals more during adulthood and allowing them to have a better pension during retirement could prompt them to take more risks during adulthood as they would know that they will have a safe and higher income during their elder phase of life. In fact Carlsson (2014) reports that a higher trust in the pension that economic agents will receive is one of the main drivers of risk-taking by individuals.

Unfortunately, our framework does not allow us to take into account risk-taking by individuals, but we still think it could be a good proxy for the situation we want to create. Therefore we will carry out two simulations. On the one hand, we will simulate an increase of 100% in the tax rate associated to the PAYGO pension system. On the other hand, we will simulate a scenario in which there is not a publicly funded pension system, a scenario that could perfectly resemble the situation of a country such as the U.S.

First, let's simulate an increase in the tax associated to the pension system from 0.05 to 0.1 while the workforce is reduced in every generation by 0.2%. The initial conditions are again the same as in prior simulations in prior sections. The summary of all the settings –parameters– employed in this simulation can be seen in Table 3.

Table 3: Parameters. Changing taxes and decrease of population.

Parameter	Values	Parameter	Values
α	0,333	**n**	**-0.002**
1- α	0,667	**1+n**	**0.998**
ρ	0.5	r	0,03
β	0,8	1+r	1,03
1+β	1,8	δ	0,15
$\boldsymbol{\tau}$	**0,1**	1- δ	0,85

In Appendix C.1, results obtained from setting the parameters stated in Table 3 may be seen summarized in charts.

It can be easily appreciated that after increasing the tax rate related to the PAYGO pension system from 0.05 to 0.1, the economy initiates a transition path to a new steady state in which production decreases as a consequence of the bust in investment of traditional and automation capital. The difference with respect to Simulation 2 is that the increase in taxes speeds up the collapse of the economy.

The reason behind the quicker decrease in GDP is that the increase in taxes prompts a very quick response from individuals, who drastically reduce their savings in the next period –see Graph 25. This in turn affects investment in automation and traditional capital, which is reduced. The reduction in traditional capital investment lower wages, leading to smooth reduction in individual and total savings until the new stationary state is achieved. On the other hand, the relative scarcity of traditional capital boosts capital rewards, and capital rewards in the steady state are now higher than before.

Furthermore, the reduction in wages also leads to a decrease in consumption levels, both during adulthood and retirement. It may be seen in Graphs 27 and 28. The latter turns out into a lower utility in the new steady state.

Both traditional capital and GDP are reduced at a faster pace than population. Therefore, the new steady state solutions for the capital-labour ratio and GDP per capita are now below the steady state achieved in the benchmark simulation – Simulation 1.

Therefore, we can conclude with this simulation that increasing taxes is not a good solution given the fact that the economy collapses at a faster pace and the welfare of individuals decreases.

Secondly, as stated above, we will simulate our model in a scenario in which the pension system is neglected, i.e. τ=0. The rest of parameters employed in the simulation can be seen in Table 4.

Table 4: Parameters. Changing taxes and decrease of population.

Parameter	Values	Parameter	Values
α	0,333	**n**	**-0.002**
1- α	0,667	**1+n**	**0.998**
ρ	0.5	r	0,03
β	0,8	1+r	1,03
1+β	1,8	δ	0,15
$\boldsymbol{\tau}$	**0**	1- δ	0,85

The results can be summarized in Graphs 30 to 41 in Appendix C.2.

Neglecting the PAYGO pension system leads to the reduction in taxes during adulthood from 0.05 to 0. The result is easily observed in Graph 37, where we can see that there is a huge increase in individual savings the next period after the tax is reduced. We also can see that the transition path describes a higher individual savings in the new steady state.

The increase in individual savings turns out to increase total savings, and hence, total investment in automation and traditional capital, which leads to an increase in production.

On the one hand, the boost in traditional capital stock depresses its returns. On the other hand, the decrease in population is higher than the increase in automation capital stock, which leads to an increase in wages, allowing individuals to experience more consumption possibilities and, thus, utility.

It may be seen that both capital-labour ratio and GDP per capita are higher now in the new steady state.

It should be remarked, though, that the increase in GDP is not sustained over time, i.e. there is no long-run growth. As population decreases, total savings do so as well. It leads then to a decrease in total investment and a reduction in production. However, it is important to highlight that neglecting the PAYGO pension system leads to a welfare increase in the new steady state compared to the benchmark simulation.

3.3.2. Population growth and automation

The purpose of this subsection is to investigate whether population growth could offset the negative effects that automation capital stock exerts in the economy. To accomplish our goal, we will make a simulation in which the workforce is increased by 0.2% every generation, i.e. every 25 years.

Table 5: Parameters. Simulating an increase in population.

Parameter	Values	Parameter	Values
α	0,333	**n**	**0.002**
1- α	0,667	**1+n**	**1.002**
ρ	0.5	r	0,03
β	0,8	1+r	1,03
1+β	1,8	δ	0,15
τ	0.05	1- δ	0,85

The parameters employed in this scenario may be viewed in Table 5. The results obtained after simulating this scenario are summarized in charts 42 to 53 in Appendix D.

The first effect that a positive population growth exerts on the economy is through wages and total savings. First, notice that the increase in population leads to boost total savings, hence increasing investment in the stock of automation and capital stock. This increase in automation capital stock turns out to depress wages, which in turn leads to a decrease in individual savings, consumption possibilities for both adults and retirees, and a decrease in utility.

Although individual savings in the new steady state are lower with respect to the benchmark simulation, the increase in population leads to boost total savings, increasing the stock of automation and traditional stock and, hence, production (Y).

Given the fact that GDP growth, the rate at which capital stock accumulates, and population growth are fairly similar, the capital-labour ratio and GDP per capita in the new steady state remain almost the same compared to the benchmark simulation.

Therefore, it seems clear that an increasing population leads to achieving long-run growth, but the welfare of individuals slightly decreases given the assumption made regarding automation capital and labour: they are perfect substitutes. Perfect substitutability implies that automation capital accumulation depresses wages, and hence, consumption possibilities and utility. Notice that, in that case, the problem of automation capital accumulation is exacerbated by the growing labour.

It is important to highlight, though, that the loss in welfare is quite low, almost neglecting. Given this fact, an increasing population seems not to be detrimental for the state of the economy, but the contrary: a slight decrease in welfare may turn out into long-run growth.

3.3.3. Restricting the amount of investment in automation capital

After the analysis carried out throughout the completion of this thesis it seems clear that one of the main factors driving the collapse of the economy is automation capital. Therefore, we think it is worth to give an answer to the question: what if we could restrict the amount of savings channelled to investment in automation capital?

To accomplish our goal, we will simulate an economy with the same characteristics described for the past simulations but we will change the parameter ρ, i.e. the fraction of savings that are invested in traditional physical capital. So we will simulate a scenario in which individuals are “forced” to invest 80% of their savings in traditional capital and the remaining 20% in automation capital. Notice that this scenario includes the PAYGO pension system with a tax rate of 0.05 over income and that population decrease at a 0.2% rate as in previous scenarios. The parameters employed for this simulation may be observed in Table 6 and the results are summarized in Graphs 54 to 65 in Appendix E.

Table 6: Parameters. Restricting automation capital investment and decrease in population.

Parameter	Values	Parameter	Values
α	0,333	**n**	**-0.002**
1- α	0,667	**1+n**	**0.998**
$\boldsymbol{\rho}$	**0.8**	r	0,03
β	0,8	1+r	1,03
1+β	1,8	δ	0,15
τ	0.05	1- δ	0,85

Restricting the amount that individuals can invest in automation capital leads to a reduction in the stock of this type of capital in the new steady state –it may be seen in Graph 56. The main consequence is an increase in wages as both automation capital stock and population decrease, i.e. the scarcity of these factors boost wages. On the other hand, given that the majority of investment goes to traditional capital, the stock of the latter increase and, hence, the rewards of traditional capital are reduced.

Notice that the increase in wages turns out to increase individual savings by about 56%, which leads to a high increase in total investment. The latter boosts production in the economy for a period of about 100 generations as it may be seen in Graph 54. However, the effects of an aging population will eventually kick in the model, reducing total savings and thus total investment, which will start to depress the economy.

However, it may be seen in Graphs 57 and 58 that GDP per capita and the capital-labour ratio in the new steady state are higher than that in the steady state acquired in the benchmark model, where solely automation capital was analyzed.

It is important to highlight that the increase in wages allow individuals to have more consumption possibilities. In fact, consumption levels both during adulthood and retirement increase by about 43% in the new steady state. The latter leads economic agents to experience a higher utility, which increase with respect to the steady state in the benchmark model by 85%.

Therefore, it is clear that restricting the amount individuals invest in automation capital leads to economic growth –though not sustained over time as long as population is aging– and a huge increase in the welfare of individuals in the new steady state.

Notice that from this simulation we can interpret that automation capital directly exerts its effects on the welfare of individuals, as well as on growth, whereas the size of population determines the size of the economy.

3.3.4. Restricting investment in automation and increasing population

Throughout Subsection 3.3 we have been experimenting with exogenous parameters in our model so as to figure out what would lead the economy to a path of long-run growth in a scenario in which automation capital competes with workers. So far we have seen that the effects of automation capital in the economy are generally dependant on population growth. Moreover, we also found that restricting the amount of investment in automation capital lead to increases in the welfare of individuals, even though the workforce size is reduced. Finally, neglecting the PAYGO pension system could lead to an expansion of the economy during some generations, but not to perpetual long-run growth.

In this section we aim for simulating a hypothetical economy in which some of the features independently simulated before, and that seem to enhance the performance of the economy, are combined.

It is well known that the publicly funded pension system known as PAYGO pension system is very valued by the majority of citizens in Europe and most of the developed countries –the U.S., we think, are an exception. As we want to create plausible and realistic scenarios, the next simulation will be carried out with the pension system, even though it seems from past simulations that neglecting it could actually help to correct the problem of stagnation. Therefore, in this section we will simulate a scenario in which the labour force increases by 0.2% every generation and where individuals are imposed a restriction on the amount invested in automation capital, i.e. they will be forced to invest 80% of their savings in traditional capital.

The parameters used in this simulation are stated in Table 7 and the results of the simulations are summarized in Graphs 66 to 77 in Appendix F.

Table 7: Parameters. Restricting automation capital investment and increase in population.

Parameter	Values	Parameter	Values
α	0,333	**n**	**0.002**
1- α	0,667	**1+n**	**1.002**
$\boldsymbol{\rho}$	**0.8**	r	0,03
β	0,8	1+r	1,03
1+β	1,8	δ	0,15
τ	0.05	1- δ	0,85

It may be seen in Graph 66 that GDP in that case steadily increases over time due to the expansion of labour, which ensures a constant growth in total savings, boosting investment in traditional capital above the steady state level acquired in the benchmark simulation –see the dashed lines reflecting the prior steady state. On the other hand, the stock of automation capital is reduced due to the restriction on the investment in that source of capital, though finally starts to pick up as population and total savings increase.

The investment in traditional capital is large enough to ensure that the latter increases faster than population growth, which leads to experience a rise in the capital-labour ratio. Furthermore, GDP also grows above the rate at which population grows and, hence, GDP per capita in the new steady state is also above the prior one.

In a similar fashion described in Simulation 6, the restriction in the investment of automation capital leads to a decrease in the stock of the latter and an increase in the stock of traditional capital, which leads wages to rise whereas capital rewards sink in the new steady state. The reason for wages to increase lies in two pillars: (1) the decrease of the rate at which automation capital stock accumulates is higher than the increase in population growth (in absolute values), and (2) the boost in traditional capital stock pushes salaries up.

The increase in wages has a direct effect on individuals. On the one hand, consumption levels for both adults and retirees are now higher in the new steady state. On the other hand, the increase in consumption levels allows individuals to experience a higher utility in the new steady state.

Therefore, combining a restriction on the amount that individuals invest in automation capital and an increasing population, long-run growth is achieved and the welfare of individuals is larger in the new steady state, compared to the one acquired in the benchmark simulation.

3.4. Steady state solutions analysis

This subsection will be devoted to present the steady state solutions obtained in the seven simulations already explained in prior sections. We think these results are very informative to the readers of this thesis as they allow for a plausible comparison among the different scenarios simulated. Given the fact that each simulation's initial conditions are the steady state acquired in the benchmark simulation –Simulation 1–, we can compare them against the former. Special attention should be devoted to welfare indicators: consumption levels and, especially, utility. Moreover, the results stated here will be key to develop the next section, in which a policy discussion will take place. Figures may be observed in Table 8 below.

Notice that in those simulations in which there is population growth –either positive or negative– GDP, traditional and automation capital stock, and total savings always grow in the steady state. The direction of the arrows in Table 8 indicates whether there is positive (↑) or negative (↓) growth. In the case in which there is positive growth first and then negative growth, this situation will be pointed out as ↑↓.

If we compare Simulations 2 to 7 with the benchmark (Simulation 1), we can see that improvements on the welfare of individuals are achieved in Simulations 4, 6 and 7, though it clearly improves in the last two.

Table 8: Steady state solutions for the simulations carried out in Section 3.

	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5	Simulation 6	Simulation 7
Y	2150659	↓	↓	↑↓	↑	↑↓	↑
K	1060729	↓	↓	↑↓	↑	↑↓	↑
B	1060729	↓	↓	↑↓	↑	↑↓	↑
K+B	2121458	↓	↓	↑↓	↑	↑↓	↓↑
(K+B)/L	1,06	1,08	0,52	1,51	1,04	1,67	1,61
K/L	0,53	0,54	0,26	0,75	0,52	1,34	1,29
Y/L	1,08	1,09	0,75	1,32	1,06	1,34	1,31
w, θ	0,4687	0,4706	0,3946	0,5038	0,4667	0,6676	0,6611
σ	0,6752	0,6695	0,9528	0,5840	0,6808	0,3323	0,3389
s	0,1591	0,1600	0,0771	0,2239	0,1581	0,2476	0,2446
S	318218.8	↓	↓	↑↓	↑	↑↓	↑
c1	0,2596	0,2606	0,2176	0,2799	0,2585	0,3701	0,3665
c2	0,2139	0,2148	0,1793	0,2306	0,2129	0,3049	0,3019
U	0,0756	0,0761	0,0550	0,0866	0,0750	0,1431	0,1406

First, neglecting the PAYGO pension system –Simulation 4– leads to increases in consumption and utility levels in the steady state with respect to the benchmark –in which the effects of automation capital where analyzed in an economy with no population growth. Although this measure does not allow the economy to grow positively, we can achieve a slightly higher utility in the steady state, compared to the benchmark.

Second, it is clear from Simulations 6 and 7 that automation capital is the main driver of the collapse of the economy. We find in the mentioned simulations that restricting the amount of investment in automation capital turns out to increase consumption and utility of individuals. In particular, utility in these scenarios increases by about 100% in the steady state with respect to benchmark –Simulation 1. Moreover, the restriction on investment of automation capital prevents the collapse of the economy.

Third, we find that the sign of the economic growth rate is dependent on the population growth dynamics. It can be observed in Simulations 6 and 7, welfare in the economy is very similar, but whereas in Simulation 6 economic growth increases first and then it is reduced, the latter steadily increases in Simulation 7, where population growth rate is positive.

Forth, GDP per capita in the stationary state is higher for the scenarios stated above –Simulations 4, 6 and 7–, comparing to the benchmark. Although GDP per capita is quite similar, we find that capital-labour ratio differs significantly, being much higher in the scenarios in which restrictions on the amount of investment directed to automation capital are imposed –Simulations 6 and 7.

Finally, it seems clear that automation poses important threats in the stability of the future economy if our assumption on automation capital and labour is true. Therefore, given the simulations carried out in this paper, it seems reasonable to either restrict the amount of investment in automation capital or promote fertility and/or immigration policies combined with the restriction on automation capital. This topic will be further discussed in the following section.

4. Policy discussion

The simulations performed in the last section point out that automation capital could be a serious threat for the stability of the economy if the assumption that automation capital and labour are perfect substitutes is correct. The results acquired, especially the ones obtained from the last two simulations, give room for some policy decisions that could be taken so as to prevent the collapse of the economy and maintain the welfare of citizens.

First, performing a simulation in which the scenario neglects the PAYGO pension system helps the economy to channel more funds into investment –both in traditional and automation capital–, hence leading to a period in which some generations experience economic growth, though not sustained over time, and also welfare levels slightly increase over time with respect to the benchmark. However, the latter, combined with the fact that it is not a plausible solution for long-run growth, lead us to discard this policy. Furthermore, although this policy might be combined with other policies as it seems to enhance the performance of the economy, we think it would be non-sense in countries in which the PAYGO pension system is well established and is very popular among citizens, such as European countries.

Second, from simulations 6 and 7 we can assert that restricting the amount of investment in automation capital lead to experience gains in welfare in the new steady state. We think this is key to ensure a healthy economy in the future. Therefore, we encourage governments and policy makers to start taking the necessary decisions to halt the process of massive automation in the workforce.

The restriction imposed on the amount of capital invested in automation capital could be achieved by law-enforcement, though it may present problems when tracking individual decision-making as it is probably very difficult to really know how much economic agents are investing and whether the capital invested is really directed towards traditional or automation capital. Therefore, we think the quotas for investing in automation capital could probably be easier to achieve through taxes. Although more research on the topic is necessary, taxing robots –automation capital– could prevent investors from channelling savings to this source of capital and incentivize them to place the money into physical or traditional capital, thus mitigating the drawbacks and potential dangers that the later could produce in the economy.

These restrictions could also be achieved by incentivizing investment in traditional capital through tax deductions in corporate taxes –for the case of businesses– or in income taxes –in case of individuals. On the other hand, in order to encourage investment in traditional capital, subsidies could be applied to when investing in this source of capital. For example, for every quantity that is invested in traditional capital, the State could give a subsidy of 10% of the total amount invested.

It seems clear that the collapse of the economy comes from the assumption that automation capital –in the form of robots, for example– and labour are perfect substitutes. The assumption stem from the fact that automation in the last years is replacing humans in the workplace, not coexisting with humans and making their work easier, reliable and safer. Think for example of the trading floors. Although there are still companies employing high-skilled traders for the job, high-frequency trading through the use of algorithms and automated software is taking over all these positions, letting trading floors obsolete. Another example could be exemplified with supply chains in big corporations such as IKEA or Inditex, where warehouses are almost completely automated and barely human interaction is needed. Therefore, it would be interested to incentivize the use of a type of robotics that is complementary to labour, i.e. that human interaction with machines is needed, where robots and workers can coexist in the same workplace, where robots just help humans to perform better and more efficiently, carrying out dangerous procedures, etc. To ensure that these complementary robots are installed in corporations, we think it would be interesting to study the role that subsidies or tax deductions would have on automation capital investment. Another possibility that could be explored, though we think it is not feasible, is forbidding the adoption of robots that are perfect substitutes with human labour. We think though that it is not plausible because it would be very costly and certainly impossible to track every investment and companies adopting robotics in the workplace. So we encourage exploring how subsidies or tax deductions would incentivize the adoption of complementary robotics.

Third, as explained above, automation capital is the main factor affecting growth and the welfare of individuals, though from Simulation 7 we can see that population size plays its role in the size of the economy and economic growth. Population growth is a key explanatory factor of the size of the economy, and from Simulation 7 we know that, combining restrictions in the amount of savings invested in automation capital and a growing population, long-run growth could be achieved.

The developed world is facing one of the most important challenges in a modern economy: a decrease in fertility. Kohler, Billari and Ortega (2006) point out three basic pillars that explain the fall in fertility rates: (1) Socioeconomic reasons such as uncertainty, increased returns to education and labour market conditions; (2) Sociological reasons, i.e. social pressures and changes in mentality of individuals; and (3) Institutional settings, which account for the lack of child-care support or changes in the gender role played in the family.

For example, the youth in advanced economies is choosing to have children at later stages in their lives and to give birth to lesser children than ever before. *Millennials* are independent and career-oriented individuals who postpone commitment in relationships to their thirties, as opposed to what previous generations have done, which has led advanced economies to experience a huge decrease in fertility after the *baby boom* era, posing important threats to the stability of the social security and publicly funded pension systems, and the economy in general.

Therefore, we think that policy makers should introduce fiscal instruments and policies so as to encourage fertility. For example, Lalive and Zweimueller (2005) state that the length of parental leaves could exert positive effects on fertility. Some households might decide not to have children because they think they cannot spend enough time to raise children. Introducing this policy could help couples to take this decision. Moreover, for the case of Germany, it has been proved by Hank et al. (2004) that child care subsidies incentivize fertility as it may help individuals with less resources to afford the costs of rising children.

It is well known that one of the explanations behind the fall in fertility rates is that young women are joining the labour market. As both men and women are working, couples postpone their decision to give birth and have fewer children. Therefore, subsidies or tax deductions should be introduced to incentivise couples (in which both partners work) so that they give birth more often and sooner. In fact, Azmat and Gonzalez (2009) state that blending child discounts for parents and a tax credit for working mothers incentivized fertility and female employment in Spain.

Another socioeconomic reason lies behind the fact that raising children have increasingly become more expensive over the last decades. The importance of education is much higher now than some years ago and the costs of it have been steadily increasing over time. We think that providing free education –university level included– and lowering the costs of having children could probably incentivize fertility. However, we think it would take time until society internalizes these benefits.

Furthermore, the lack of fertility could be offset by choosing right immigration policies. We are aware that some countries have economic and socioeconomic problems and cannot provide a proper level of welfare. However, the developed world has the institutions and infrastructure to provide wellbeing to its inhabitants. So it could be argued that the lack of fertility may be replaced by welcoming immigrants, and especially by opening our borders and incentivizing somehow those immigrants that are young and can be easily trained to carry out tasks in the workplace.

5. Conclusions

During the realization of this master thesis we have developed a theoretical framework to study how automation and population aging could potentially affect economic growth and welfare in a modern economy through the use of an Overlapping Generations Model (Diamond, 1965). Our model stem from the work first done by Gasteiger and Prettner (2017), but we also introduce a new feature not explored in the literature before: a pay-as-you-go pension system.

To build our model, we assume that automation capital and labour are perfect substitutes in the economy, i.e. they compete with each other. The analysis of our theoretical model allows us to conclude that if this assumption holds true, the economy will collapse as a consequence of the increased automation capital stock. This process is explained by the fact that as automation capital stock accumulates in the economy, wages are depressed because labour and automation compete with each other. The reduction in wages leads individuals to lose the ability to save resources out of their wages, which depresses total savings in the economy. In the framework we employ, savings are the engine of the economy as they are the only source of investment. Therefore, total savings are reduced and so do the investment in automation and traditional capital, leading total production –GDP– in the economy to collapse.

Furthermore, the decrease in wages also exerts important effects on the welfare of individuals. The latter implies that individuals experience less consumption possibilities both during adulthood and retirement, hence leading to a decrease in utility, i.e. welfare.

However, we present two key findings so as to prevent the collapse of the economy through our simulations. First, we find that restricting the amount that individuals invest in automation capital lead to increases in welfare as wages increase, allowing individuals to increase their savings, investment, consumption during both periods, and hence, utility. Second, restricting investment on automation and ensuring a constant population growth lead to increase welfare of individuals and allow for long-run growth in the economy.

It is also important to highlight that we find that automation exerts negative effects on both economic growth and welfare of individuals. However, the effect of automation on economic growth is also dependent on population growth, which plays an important role on determining the size of the economy.

Finally, our simulations and policy discussion in Section 4 suggest interesting questions for future research. First, the findings on the effects of automation on economic growth may be purely dependent on the framework employed. Other authors find opposite conclusions. For that reason, we think academia should firmly address this issue and reach the proper framework to study this problem. Second, in this thesis we state that restricting the amount invested in automation and ensuring population growth may save the economy, and thus propose some policy-making solutions. We think it is very important to study how these restrictions on investment should be introduced. Is it better to introduce taxes or subsidies? Should we incentivize the use of complementary robotics? How? These are questions still unsolved and that require a profound study.

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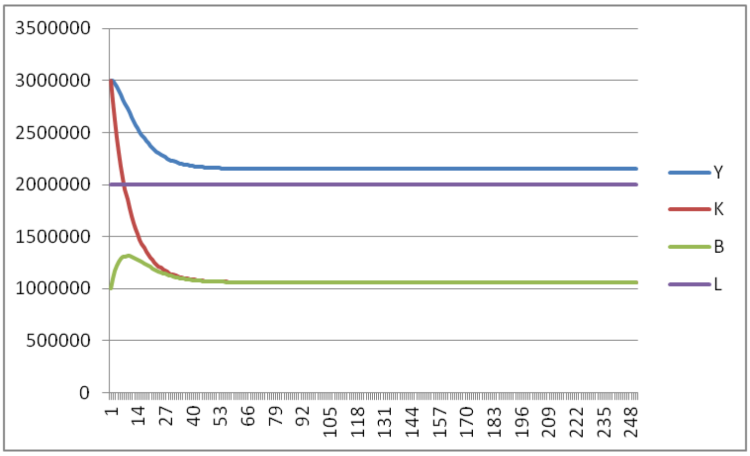
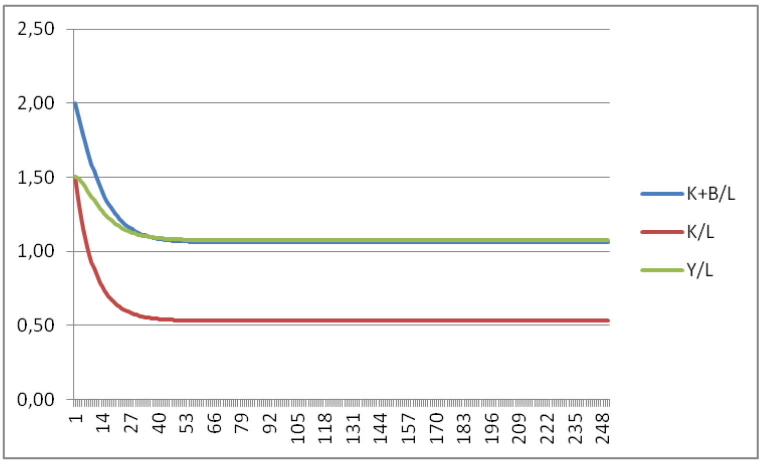
Appendix A: Simulation 1

Graphs in Appendix A are related to the experiment carried out in Simulation 1, where the effects of automation are analyzed in full in an Overlapping Generations Model.

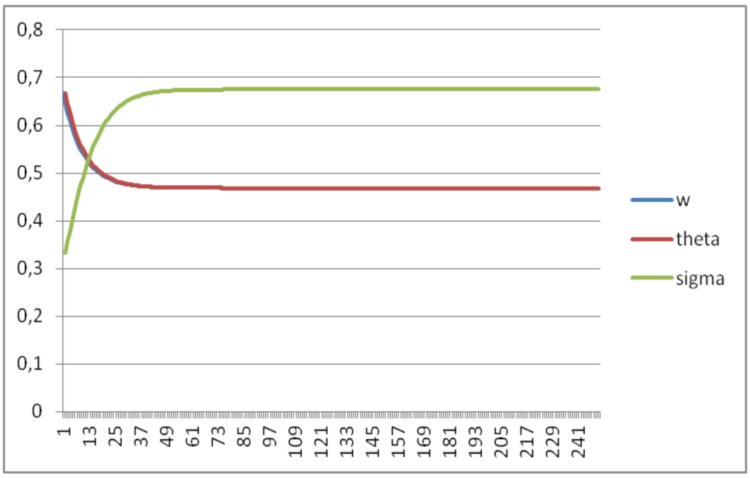
Graph 1: Simulation 1: GDP, traditional and automation capital, labour



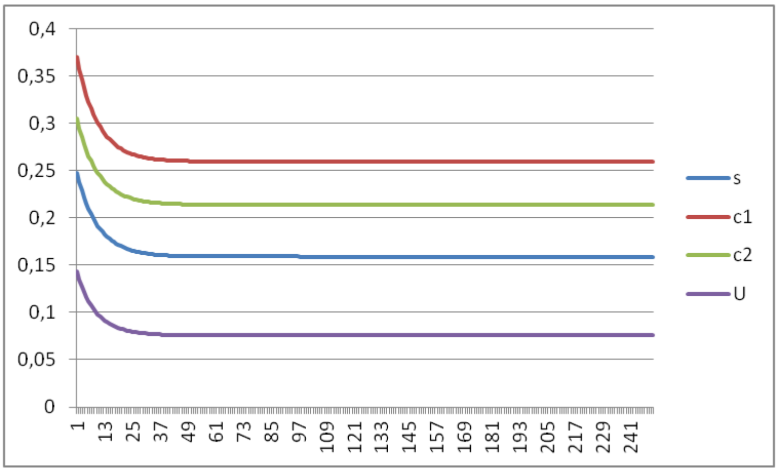
Graph 2: Simulation 1: Total capital and traditional capital shares, and GDP per capita (per unit of labour)



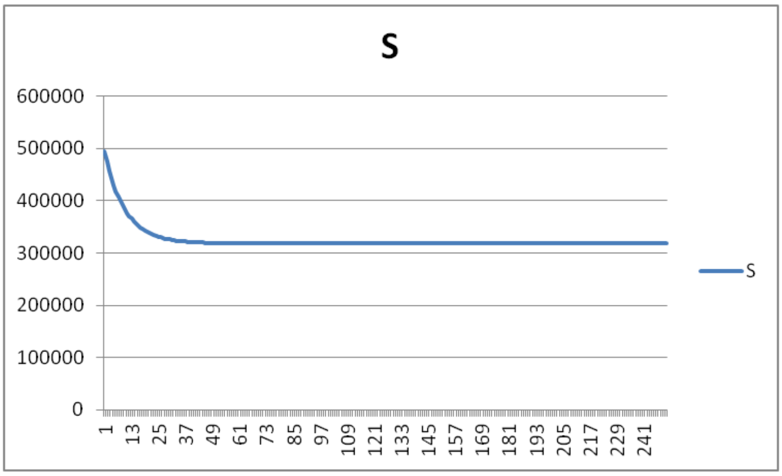
Graph 3: Simulation 1: wages, and traditional and automation capital rewards



Graph 4: Simulation 1: individual savings, consumptions and utility



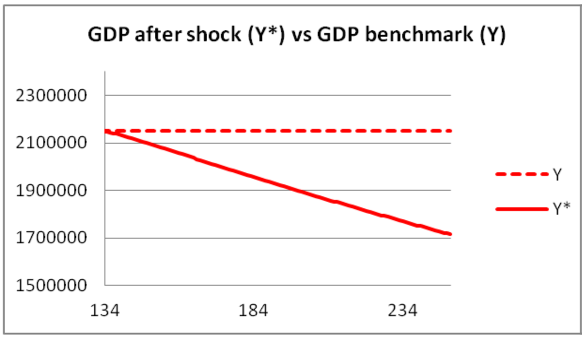
Graph 5: Simulation 1: total savings



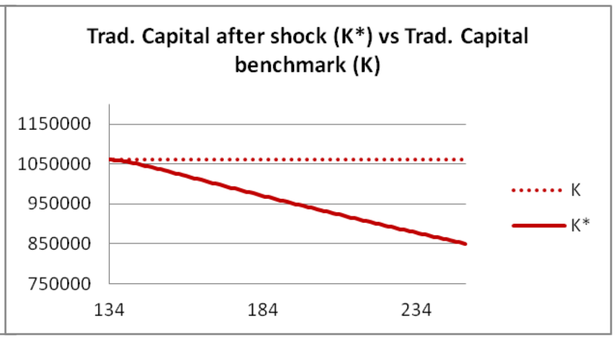
Appendix B: Dynamic Transitions (Simulation 2)

The graphs presented below present the initial constant steady state, i.e. the initial condition, from the benchmark simulation (Simulation 1) –with dashed lines– and the transition path to the new steady state –with straight lines– after reducing the exogenous parameter *n*, i.e. a decrease in population.

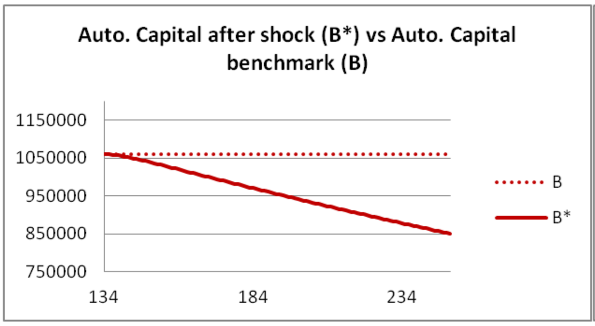
Graph 6: GDP comparison



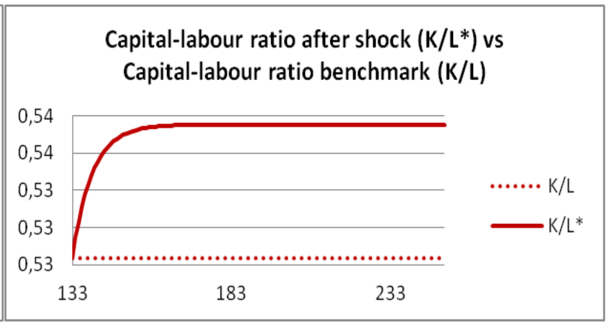
Graph 7: Traditional Capital comparison



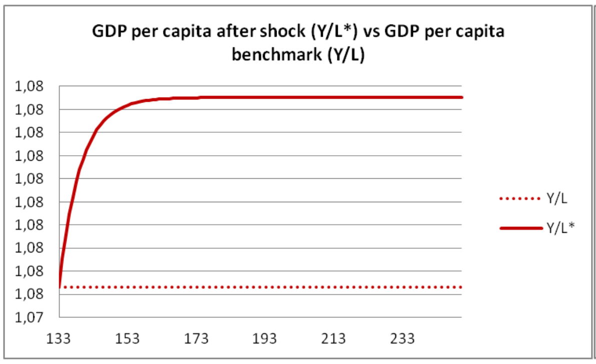
Graph 8: Automation Capital comparison



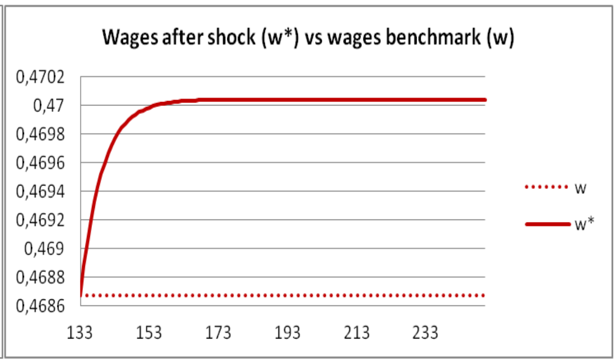
Graph 9: Capital-labour ratio comparison



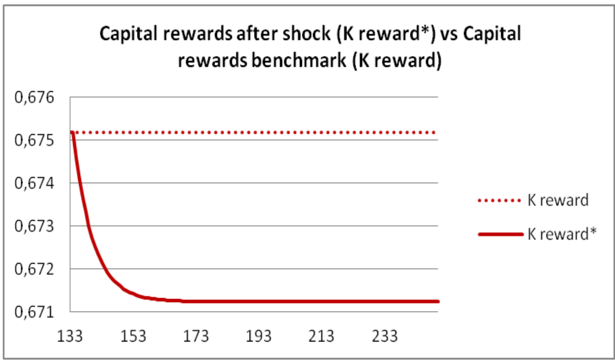
Graph 10: GDP per capita comparison



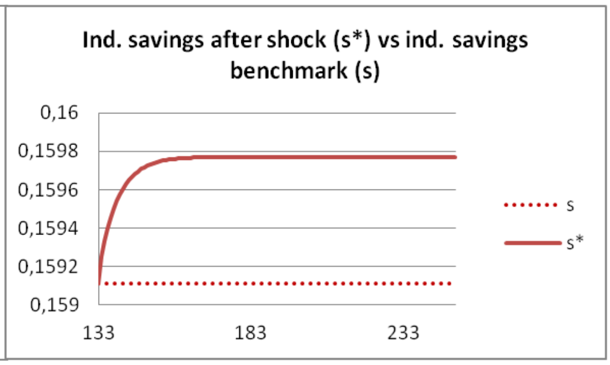
Graph 11: wages comparison



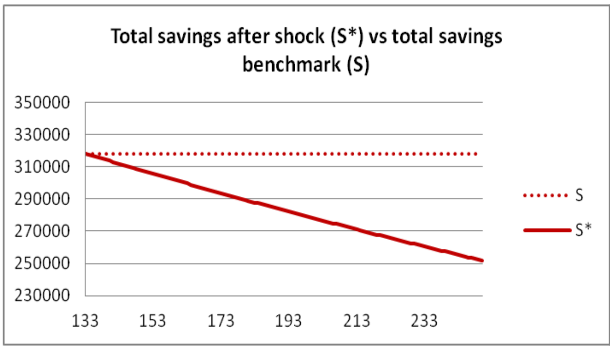
Graph 12: Capital rewards comparison



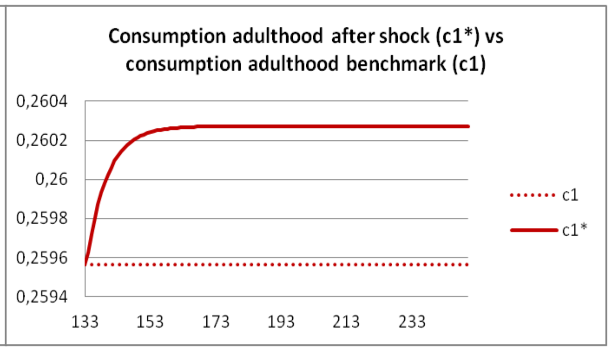
Graph 13: Individual savings comparison



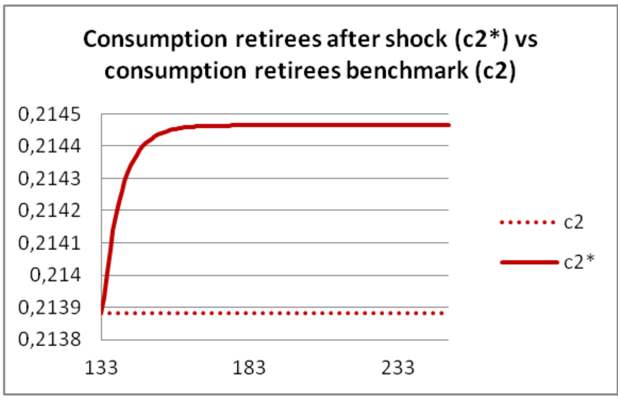
Graph 14: Total savings comparison



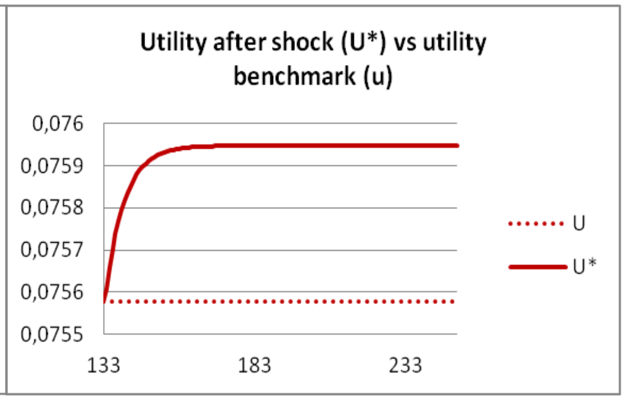
Graph 15: Adult consumption comparison



Graph 16: Retiree consumption comparison



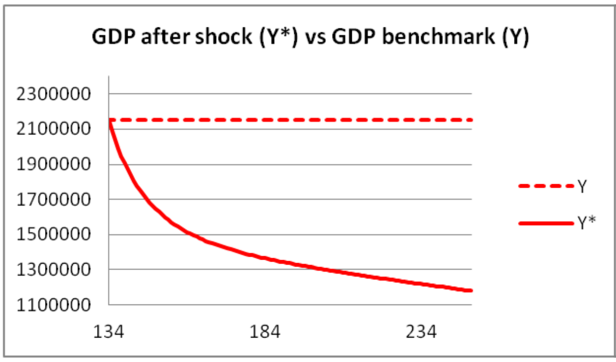
Graph 17: Utility comparison



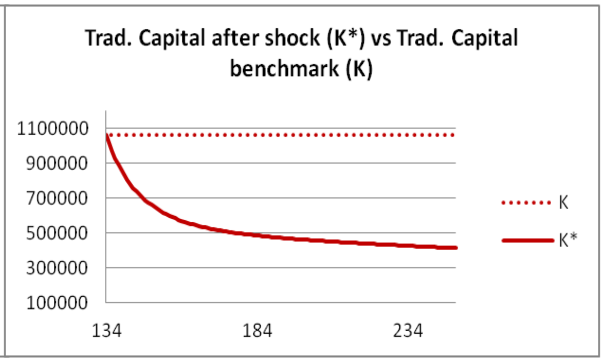
Appendix C.1: Dynamic Transition (Simulation 3)

The graphs presented below present the initial constant steady state, i.e. the initial condition, from the benchmark simulation (Simulation 1) –with dashed lines– and the transition path to the new steady state –with straight lines– after increasing the exogenous parameter τ from 0.05 to 0.1, i.e. we simulate an increase in the tax rate that adults pay to finance the PAYGO pension system.

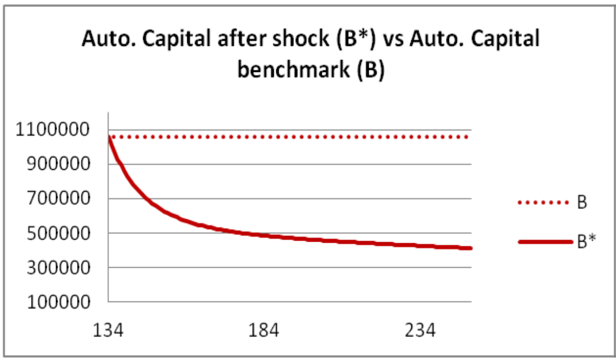
Graph 18: GDP comparison



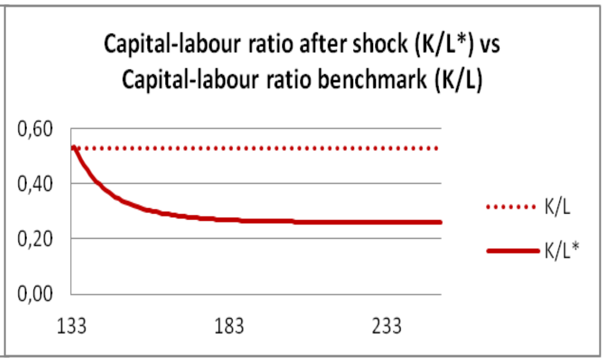
Graph: 19: Traditional capital comparison



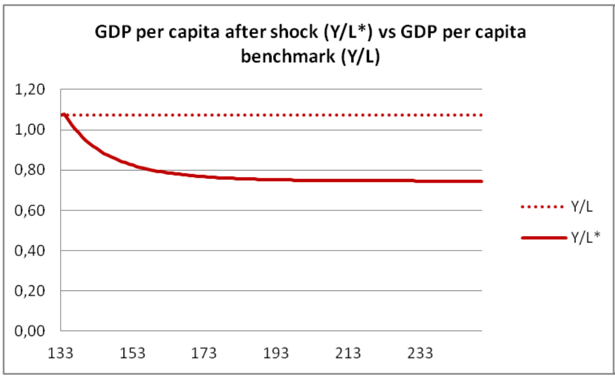
Graph 20: Automation capital comparison



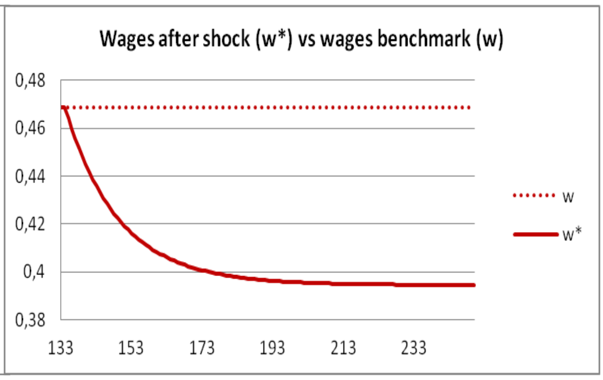
Graph 21: Capital-labour ratio comparison



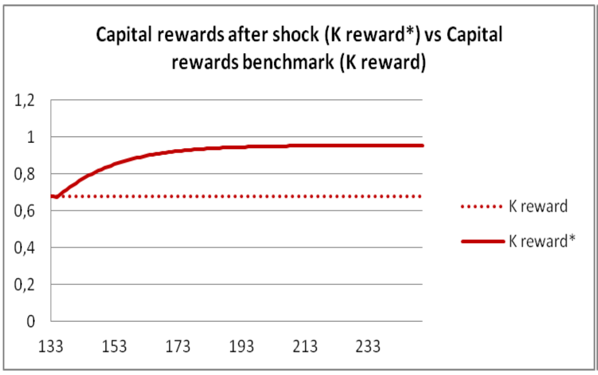
Graph 22: GDP per capita comparison



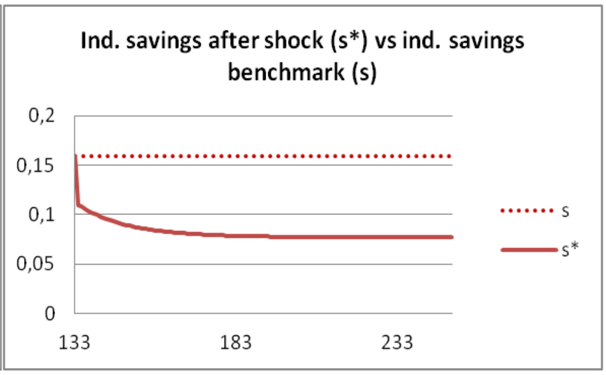
Graph 23: Wages comparison



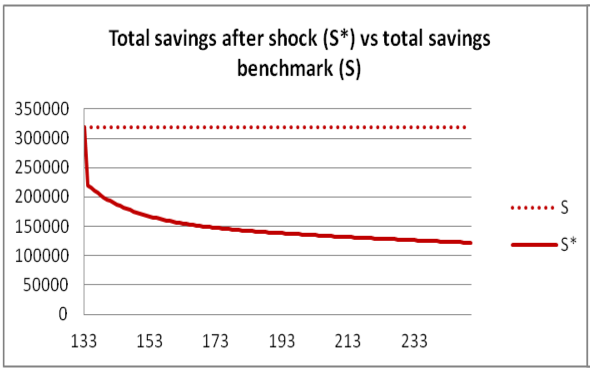
Graph 24: Capital rewards comparison



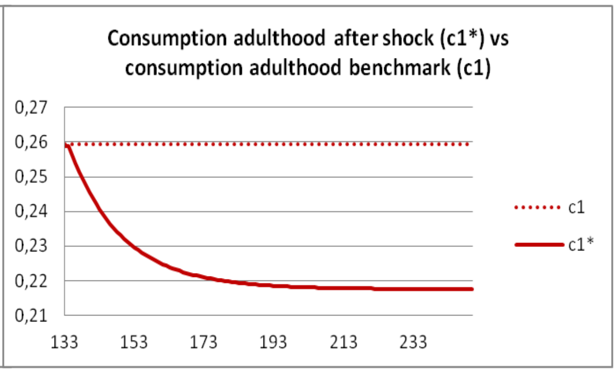
Graph 25: Individual savings comparison



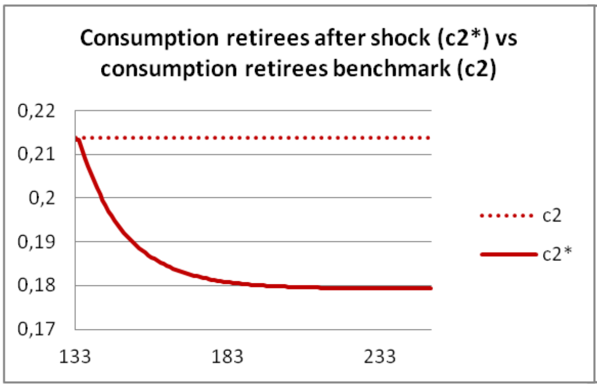
Graph 26: Total savings comparison



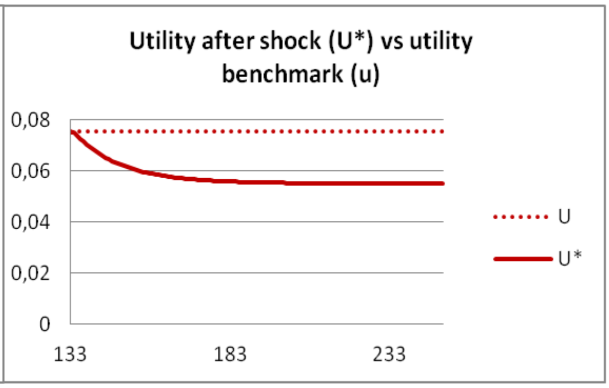
Graph 27: Adult consumption comparison



Graph 28: Retirees consumption comparison



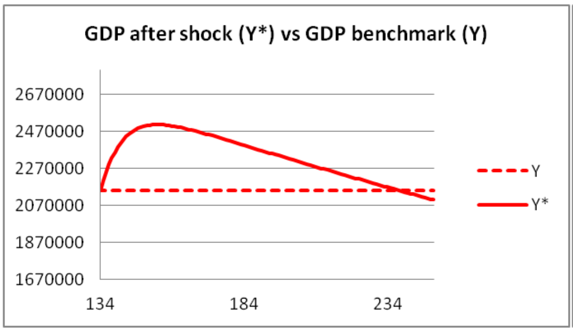
Graph 29: Utility comparison



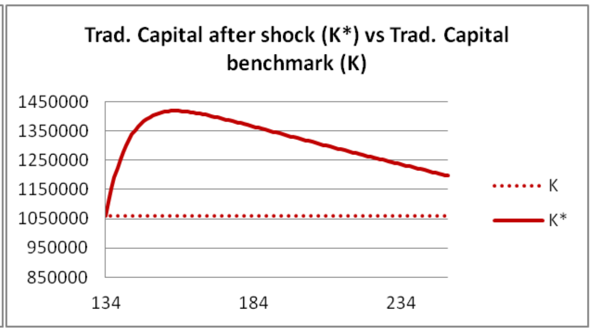
Appendix C.2: Transitional Dynamics (Simulation 4)

The graphs presented below present the initial constant steady state, i.e. the initial condition, from the benchmark simulation (Simulation 1) –with dashed lines– and the transition path to the new steady state –with straight lines– after decreasing the exogenous parameter τ from 0.05 to 0, i.e. we simulate a decrease in the tax rate that adults pay to finance the PAYGO pension system.

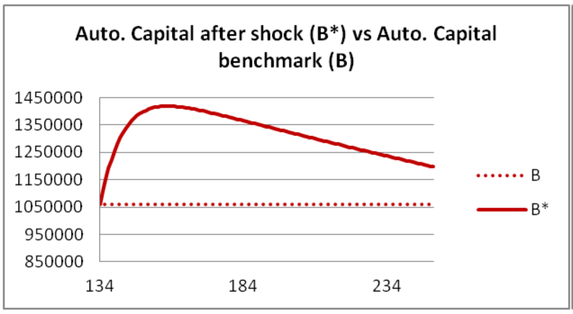
Graph 30: GDP comparison



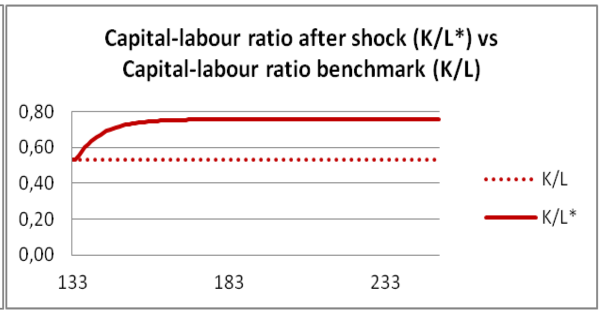
Graph 31: Traditional capital comparison



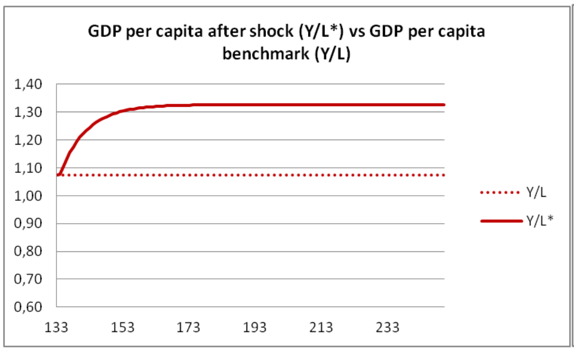
Graph 32: Automation capital comparison



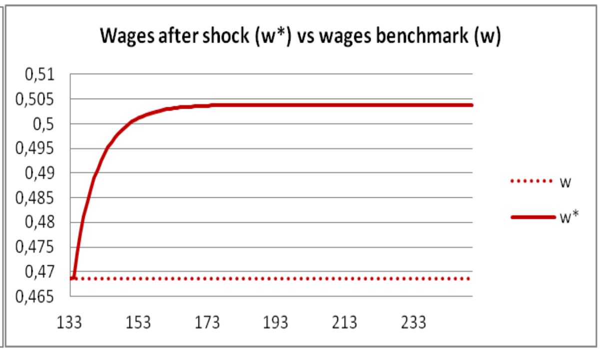
Graph 33: Capital-labour ratio comparison



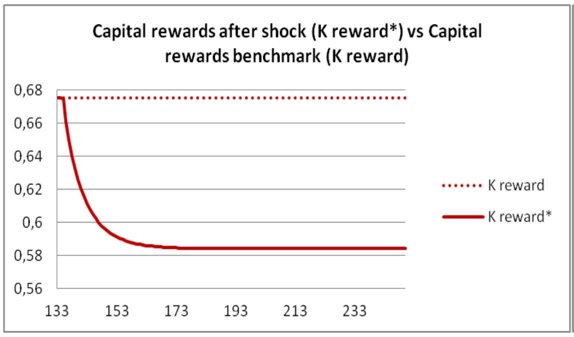
Graph 34: GDP per capita comparison



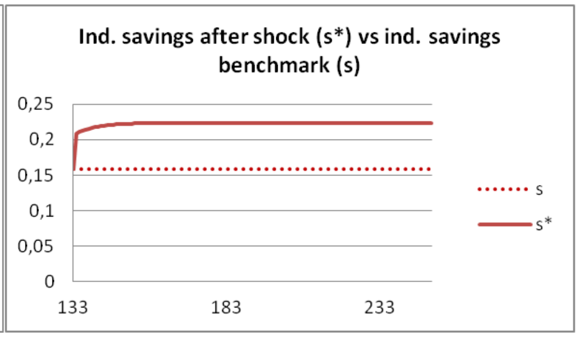
Graph 35: Wages comparison



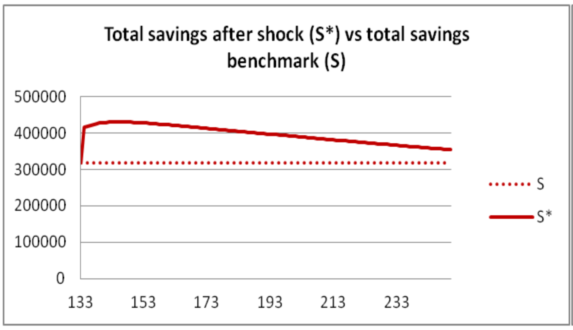
Graph 36: Capital rewards comparison



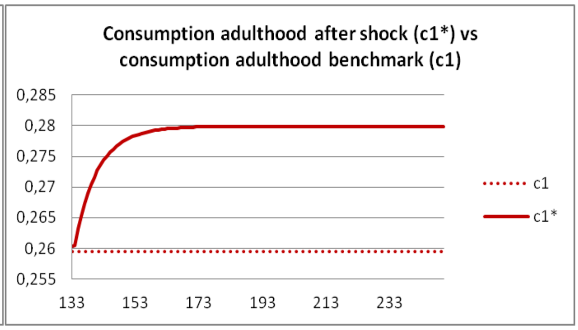
Graph 37: Individual savings comparison



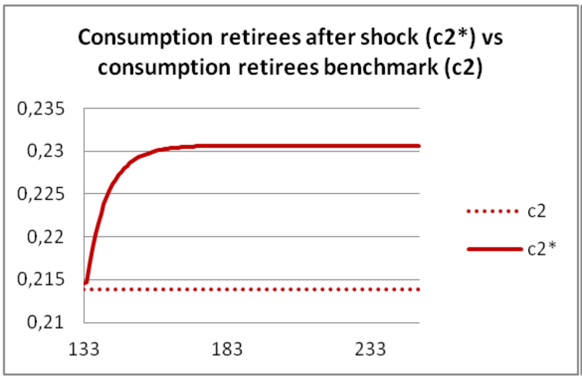
Graph 38: Total savings comparison



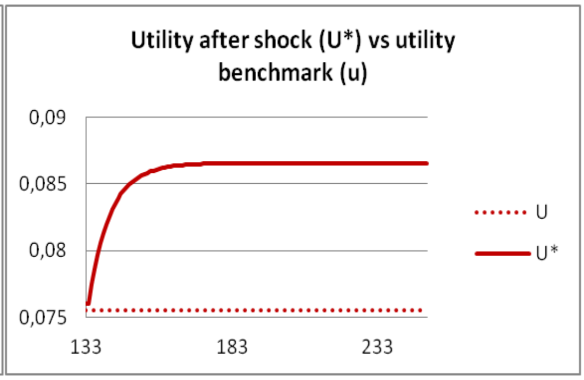
Graph 39: Adult consumption comparison



Graph 40: Retirees consumption comparison



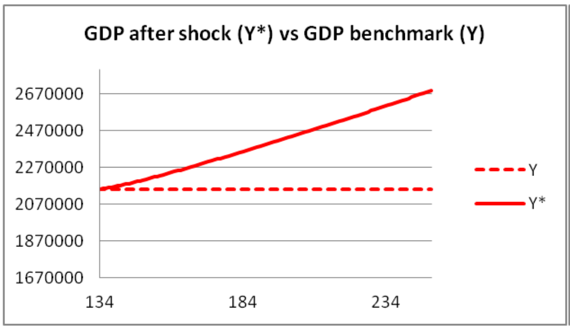
Graph 41: Utility comparison



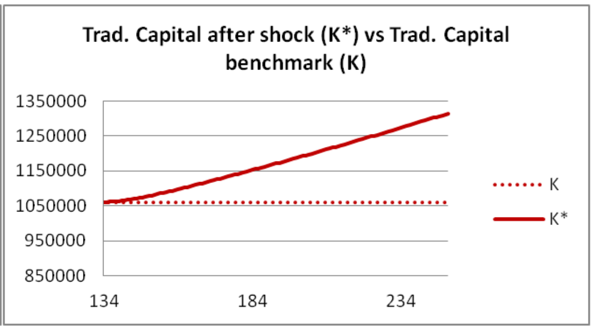
Appendix D: Transitional Dynamics (Simulation 5)

The graphs presented below present the initial constant steady state, i.e. the initial condition, from the benchmark simulation (Simulation 1) –with dashed lines– and the transition path to the new steady state –with straight lines– after an increase in the rate at which population grow, i.e. we simulate how an increase in population could offset the negative effects of automations on growth.

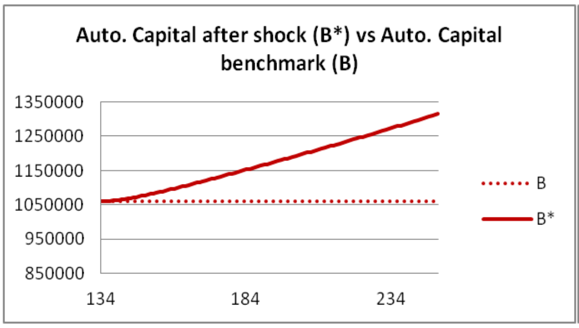
Graph 42: GDP comparison



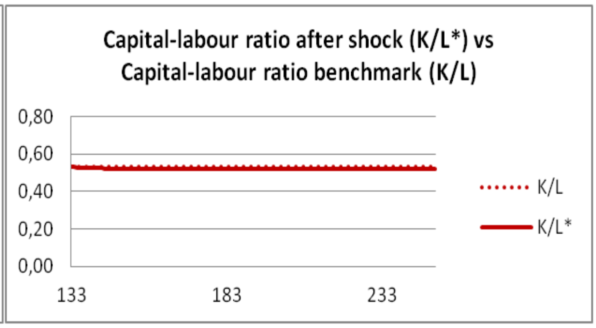
Graph 43: Traditional capital comparison



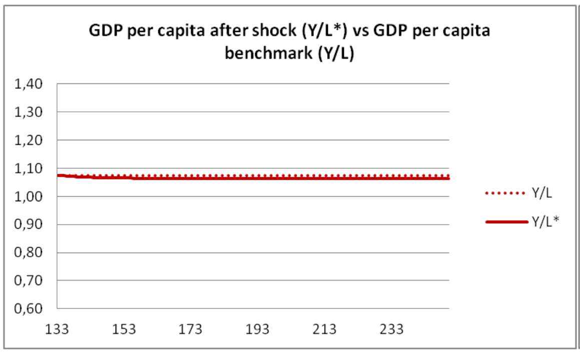
Graph 44: Automation capital comparison



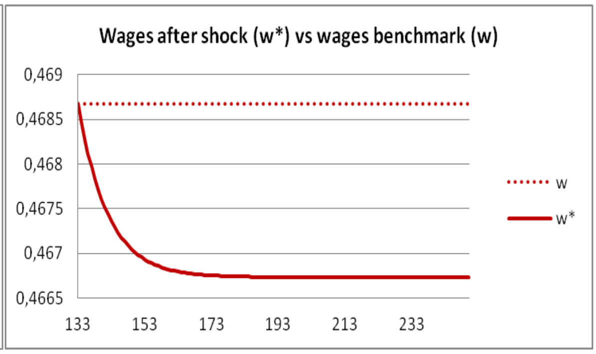
Graph 45: Capital-labour ratio comparison



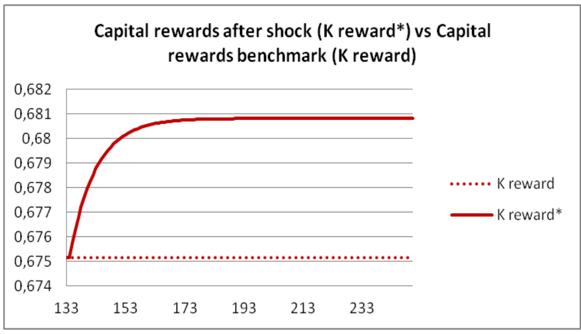
Graph 46: GDP per capita comparison



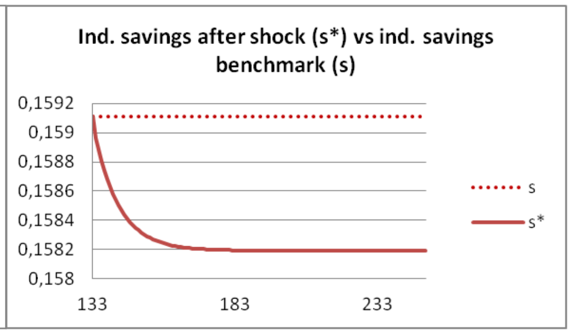
Graph 47: Wages comparison



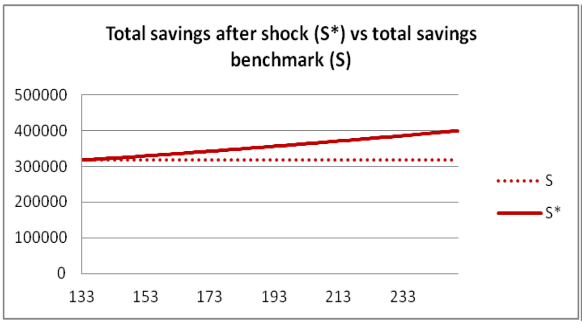
Graph 48: Capital rewards comparison



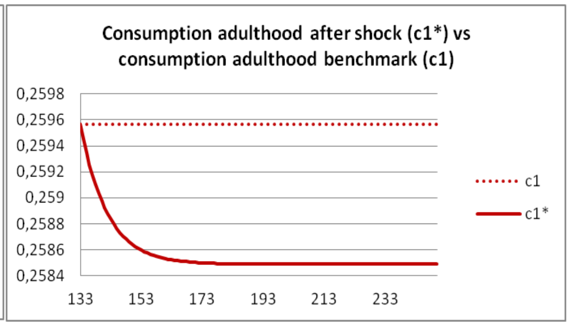
Graph 49: Individual savings comparison



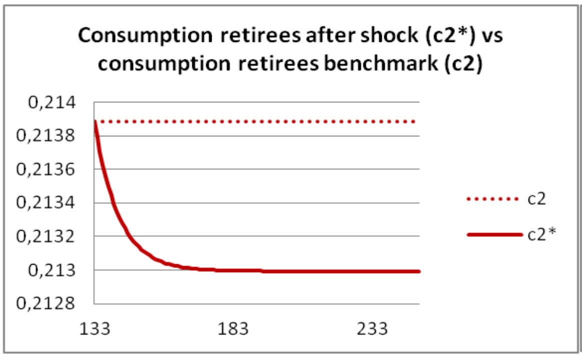
Graph 50: Total savings comparison



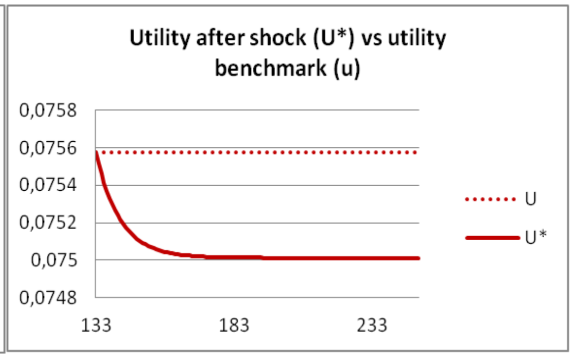
Graph 51: Adult consumption comparison



Graph 52: Retirees consumption comparison



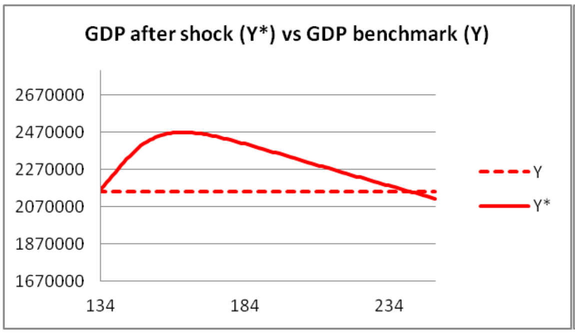
Graph 53: Utility comparison



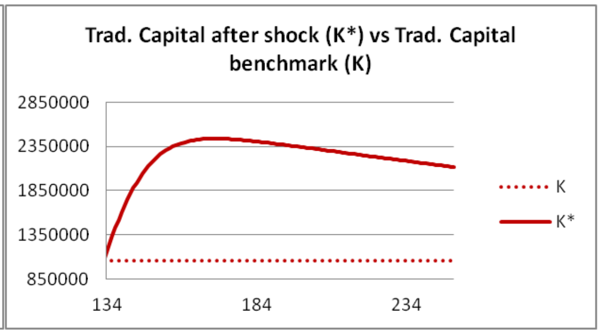
Appendix E: Transitional Dynamics (Simulation 6)

The graphs presented below present the initial constant steady state, i.e. the initial condition, from the benchmark simulation (Simulation 1) –with dashed lines– and the transition path to the new steady state –with straight lines– after restricting the amount of investment on automation capital, i.e. we simulate how a restriction on automation capital investment could lead to mitigate the effects of automation on growth.

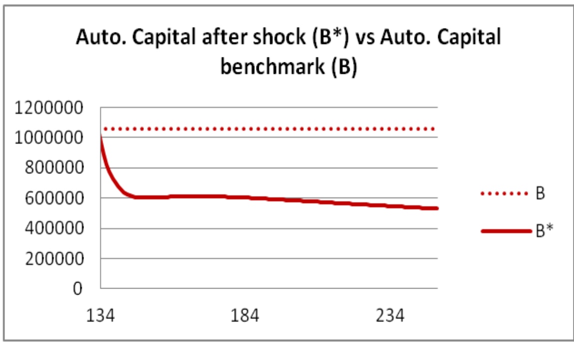
Graph 54: GDP comparison



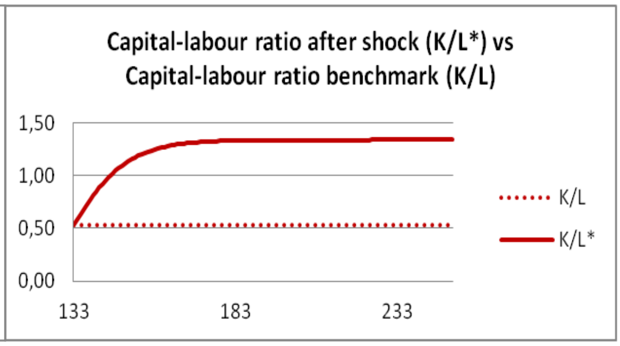
Graph 55: Traditional capital comparison



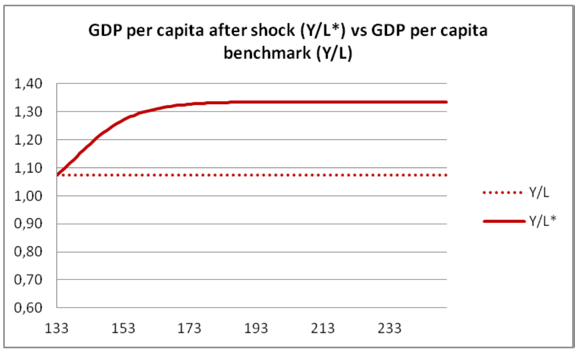
Graph 56: Automation capital comparison



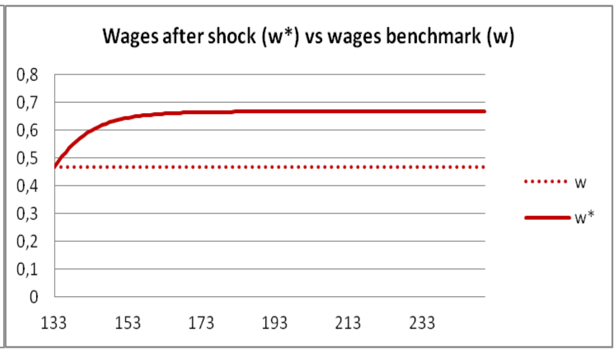
Graph 57: Capital-labour ratio comparison



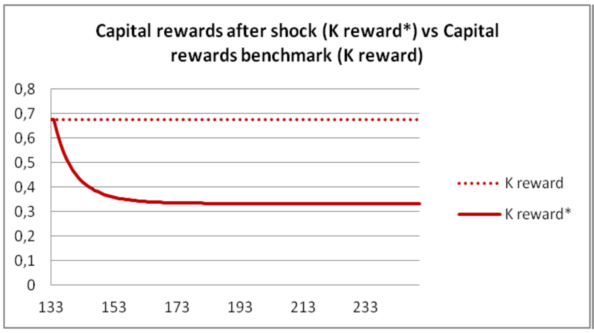
Graph 58: GDP per capita comparison



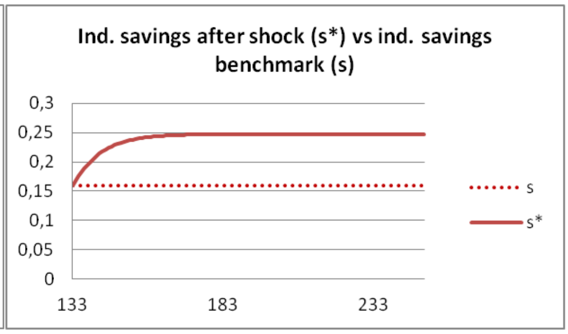
Graph 59: Wages comparison



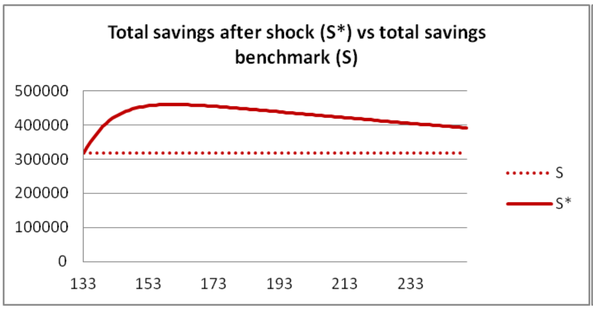
Graph 60: Capital rewards comparison



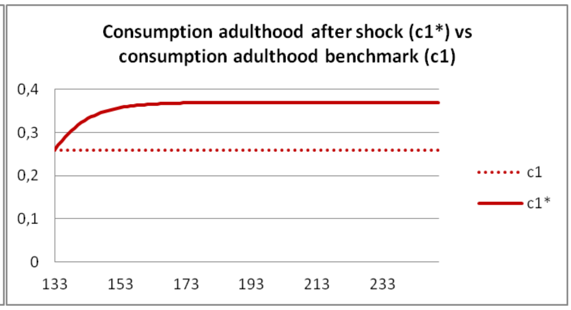
Graph 61: Individual savings comparison



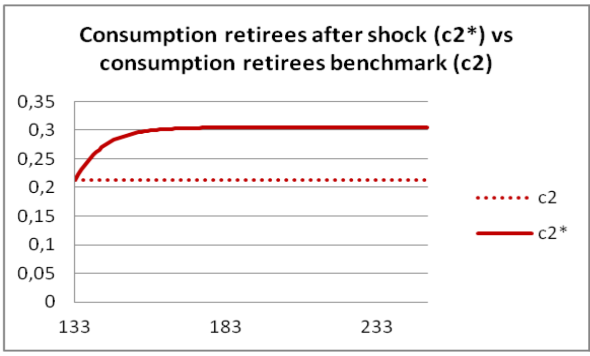
Graph 62: Total savings comparison



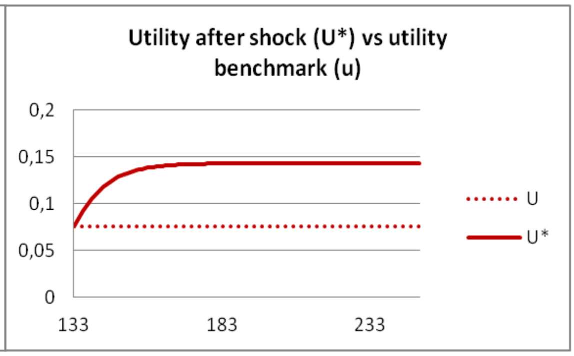
Graph 63: Adult consumption comparison



Graph 64: Retirees consumption comparison



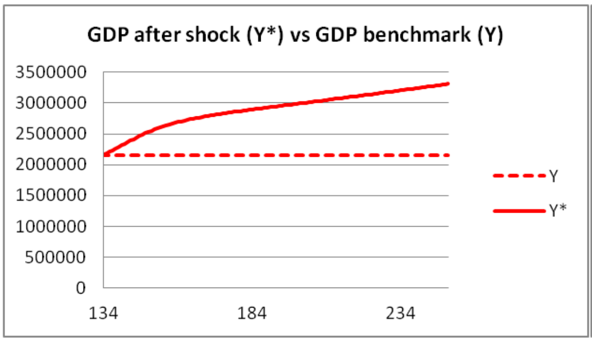
Graph 65: Utility comparison



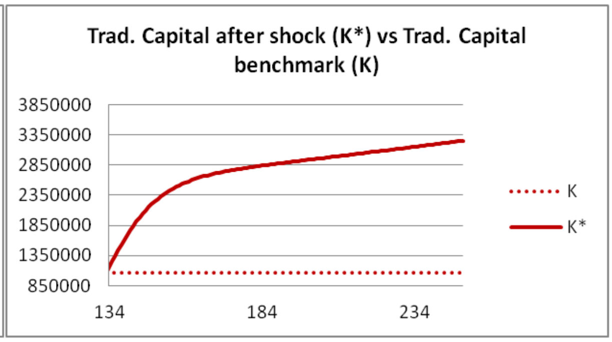
Appendix F: Transitional Dynamics (Simulation 7)

The graphs presented below present the initial constant steady state, i.e. the initial condition, from the benchmark simulation (Simulation 1) –with dashed lines– and the transition path to the new steady state –with straight lines– after restricting the amount of investment on automation capital and the rate at which population grow, which is positive in this experiment.

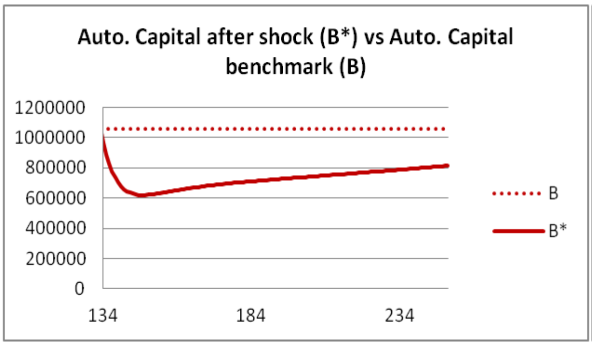
Graph 66: GDP comparison



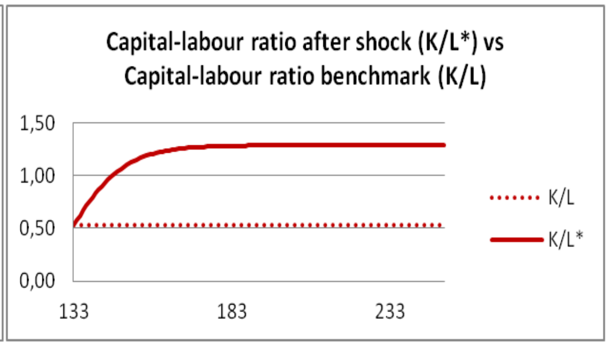
Graph 67: Traditional capital comparison



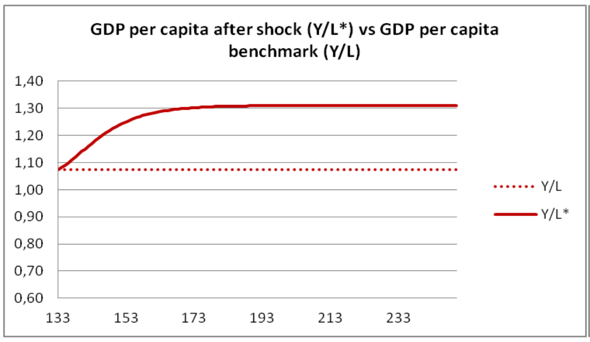
Graph 68: Automation capital comparison



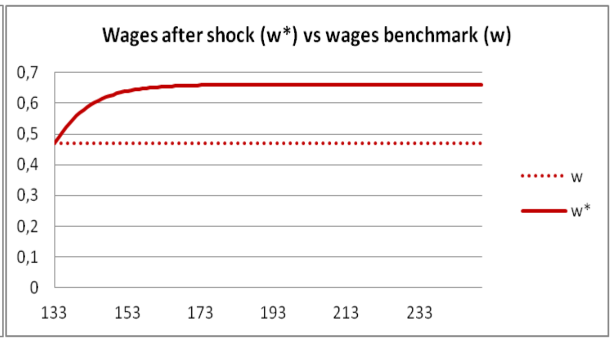
Graph 69: Capital-labour ratio comparison



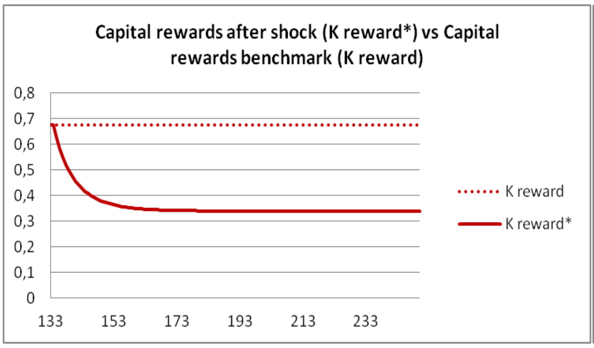
Graph 70: GDP per capita comparison



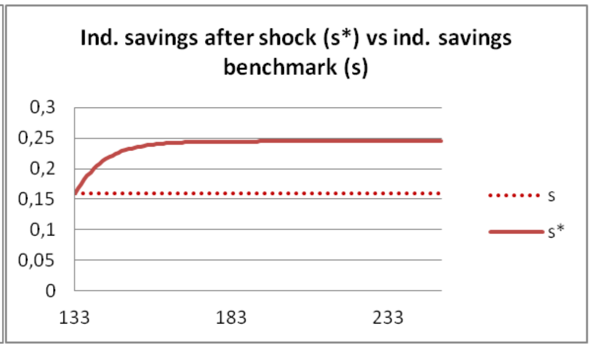
Graph 71: Wages comparison



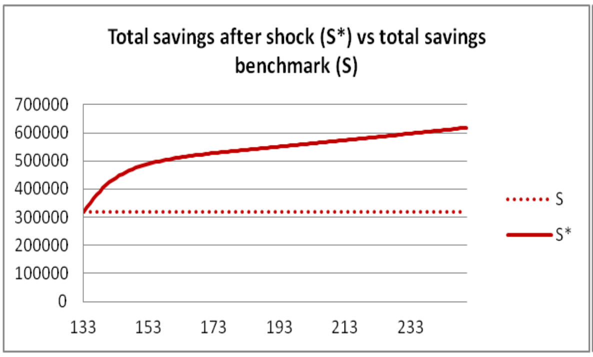
Graph 72: Capital rewards comparison



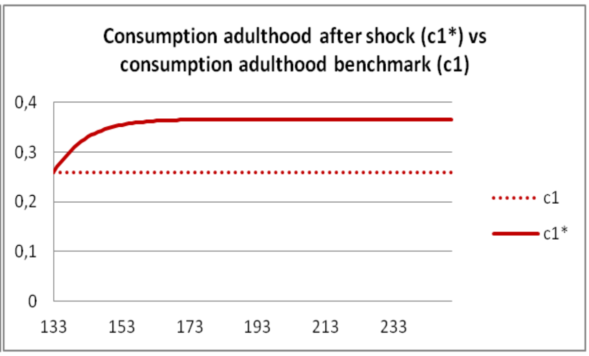
Graph 73: Individual savings comparison



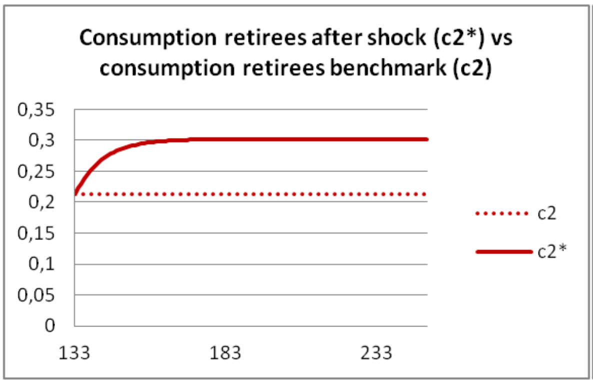
Graph 74: Total savings comparison



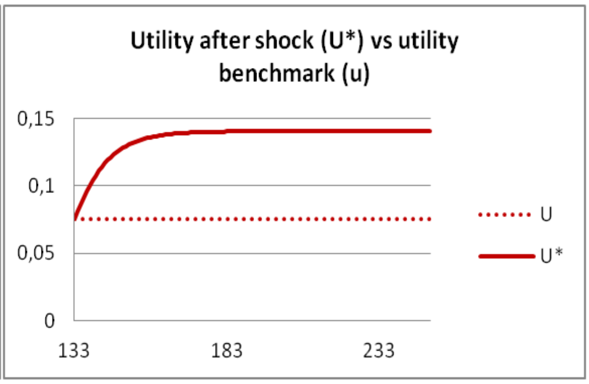
Graph 75: Adult consumption comparison



Graph 76: Retirees consumption comparison



Graph 77: Utility comparison



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