MERIT-Infonomics Research Memorandum series

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2001-029

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September 2001
Keyword: Endogenous growth, skills, product life cycle, product R&D, process R&D, economic policy
JEL: E13,E17,E6, J44, O31,O33, O41

Abstract

In this paper we present the outlines of an endogenous growth model that focuses on the labour market- and skill-aspects of economic policy measures that may have an impact on technological change, and hence on the long term effectiveness of the policy measures concerned. The link between skills and technology is two-fold. On the one hand, new technology is high-skilled intensive, while on the other hand, process R&D may actively change the skill-mix of existing production technologies in the direction of a more intensive use of least-cost production factors/skills. Hence, we endogenise both product R&D and process R&D decisions. The product R&D generates new varieties of goods with a higher quality than older varieties. New and older varieties are assumed to be imperfect substitutes, so that new varieties only gradually replace older varieties. Process R&D in turn is geared towards downscaling the skill-requirements of the jobs associated with producing the different varieties of output. Because high-skilled labour has different uses (it is an input to final output production, but also into product and process R&D activities), whereas low-skilled labour is used only in final output generation, we can show how various alternative policy measures may affect R&D decisions, hence growth performance, but also the distribution of income between skills. We also show that the promotion of process R&D in particular has beneficial effects both for the employment perspectives of low-skilled workers and for growth in general. In simulation experiments with the model we show that the model, even in its present state, is able to mimic the stylised facts reported by Acemoglu (1997), who observed for the US that an increase in the supply of high-skilled labour does not necessarily imply a fall in the relative wage rate of high-skilled workers in the long run. We show that the ensuing increase in R&D activity creates its own demand for high-skilled workers when new products arrive on the market that are high-skilled intensive during the first phase of their life-cycle, as we assume it to be the case. This in turn invokes endogenous process R&D reactions that change the long term composition of the demand for labour by skill and by sector. In various experiments we found that the model generates an interesting interplay between both types of R&D that may have important consequences for the distribution of income between skills, for growth and more generally for the design of economic policy.

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1 Introduction

This paper presents the outlines of an endogenous growth model that focuses on the uneven consequences of growth for employment by skill, and on the potential role of economic policymaking, including science and technology policy, in this respect.

It is now generally accepted that technology does not fall as manna from heaven, but is instead the result of positive action by man. These insights are far removed from the notion of technological change taking place as an autonomous process that can be relied upon to continue ad infinitum and at no costs at that. In endogenous growth theory (see Romer (1990) and Aghion and Howitt (1992, 1998), for instance), but also in industrial organisation (see Tirole (1988), for example), this idea has been forcefully and successfully replaced by the notion of profit seeking entrepreneurs generating technological change through research and development. More specifically, in this body of literature R&D activities are generally considered to be driven by profit expectations, as much as by cost-considerations, but also by more strategic motivations. At the same time, policy measures geared at curing specific problems or aimed at changing general economic circumstances, may affect expectations as such, the investment climate, or profit flows specifically, the skill-composition of the supply of labour, and so on. By doing so, they may directly affect the rate and direction of technological change, and as such may interfere with the goals of technology policy. For example, a rise in the domestic interest rate meant to support the foreign exchange rate of a currency reduces the present value of profit streams, and may therefore have direct effects on the incentive to engage in R&D.

Our specific focus on the skill aspects of growth comes from the observation that unemployment is unevenly distributed over skills, where low-skilled workers are generally more often and longer unemployed than high-skilled people (cf. van Zon et al. (1998,2000)). One of the reasons why this might be the case is that labour market institutions in Europe are such that low-skilled workers may be over-priced, thus leading to a combination of high wages for the low-skilled but also high levels of unemployment. Another explanation is that growth itself, especially in the form of new products and services, may be high skilled biased. Because of these asymmetries in employment perspectives between skills, and because of the endogenous technology perspective we take, our model combines notions from endogenous growth theory, industrial organisation, but also from Vernon’s product life cycle theory. (cf. Vernon (1966)). The reason to borrow the main elements of Vernon’s life cycle approach is that we believe that skill-biases in technical change can be controlled to some extent, by providing the ‘right’ incentives. The link with Vernon’s life-cycle theory is evident: in the first phase of a products life-cycle, the product is ‘new’ and requires the input of skilled labour, or at least not commonly available resources. When the product matures, it becomes standardised and its production can be transferred to countries where production costs are lower. The change in the geographical location of production follows economic incentives, while at the same time it is temporally bounded by the availability of ‘appropriate’ technologies. In the context of our model, it is appropriate jobs, rather than technologies in general that we want to focus on.

In the first phase of Vernon’s product life cycle, there may be skill-supply constraints regarding high-skilled labour, that limit the production of new goods and services to just a few geographical locations. There are two principally different reactions to such supply-constraints: one could try to increase the supply of the skills that are in high demand, but that takes time, if it’s possible at all. Alternatively, one could try to change the nature of the production process such that low-skilled people can be used instead of only high-skilled people. The latter enables the transfer of technology to the South in a North-South setting, as in Krugman’s representation of Vernon’s product life cycle theory (Krugman (1979)). In our model, though, technology transfer is not the issue per se. Instead, we focus on the employment effects of the creation of new production processes in which high-skilled jobs are replaced by low-skilled ones within a country, rather than between countries as in the Krugman model.

The present model builds on the one presented in van Zon, Sanders and Muysken (1998), but especially on van Zon and Sanders (2000), and it is further called the VZS-model for short. In the VZS-model the demand for labour was divided over high- and low-skilled workers, in accordance with the nature of the products produced. An ‘established product’ is produced using low-skilled labour only, while ‘new’ products were produced using just high-skilled labour. The present model differs from the VZS-model in two principal ways. First, we link the demand for labour explicitly to the job composition of employment. The VZS-model uses a (fixed!) one-to-one correspondence between products and skills-required, so the job-structure of labour demand is implied by the product-structure of the supply of output. In the present model this correspondence between product-nature and job-structure changes dynamically over time, depending on economic incentives. A second difference is that the distinction between ‘established’ and ‘new’ products is not as sharp as in van Zon and Sanders (2000). There are two reasons for this. First, new products are different from older products in that their direct contribution to consumer utility is assumed to exceed that of older products. New products are therefore superior to older products, ceteris paribus, but do not necessarily drive out older ones completely. In that sense we combine love of variety as a source of growth (the varieties are the different 'versions' of a product (-range)) with asymmetric contributions to consumer utility, comparable to the approach taken in van Zon, Meijers and Yetkiner (1999).[1] Secondly, we allow for ex post 'in-house' process R&D that allows producers to change the nature of jobs in such a way that a job that could at first be performed by high-skilled workers only, can now also be performed by low-skilled workers. The benefits from doing process R&D then consist of the cost-savings that can be realised by being able to substitute low-skilled labour for high-skilled labour on those 'down-scaled' jobs. This process R&D also improves the long-term employment opportunities for the low-skilled. Whether these opportunities are realised in the short run still depends very much on relative wages, at least in the absence of serious switching costs.[2] For ease of exposition, however, we have left the ex-post substitutability of low- and high-skilled workers on 'down-scaled' jobs out of consideration in the present version of the model.

The organisation of the rest of the paper is as follows. In section 2 we provide a very brief overview of some alternative approaches to modelling the demand for skills and skill-biases in technical change and define our own position in that respect. In section 3 we provide a more detailed account of the main features of the current model, while section 4 is devoted to a discussion of the way in which various policy variables may influence technological change itself, but also the skill-composition of employment. Moreover, we discuss how various economic policies may change the environment relevant for R&D decisions, and hence growth and the skill-composition of employment. Section 5 provides some illustrative simulation results using the model, while section 6 contains some concluding remarks.

2 Alternative Approaches Regarding the Determination of Employment by Skill

The standard approach towards explaining the skill-composition of employment is to assume a production function that contains various skills as substitutable arguments, next to other production factors. Technical change affecting the skill-composition of employment, ceteris paribus, can then be represented as 'factor-augmenting' technical change. More in

[1] In that paper, we study the role of asymmetries in the contribution of intermediates to effective capital in an endogenous growth model based on Romer (1990). The context differs, therefore, but the principles are the same.

[2] Cf. van Zon et al. (2000) for an application of these ideas regarding asymmetries in substitution possibilities between low- and high-skilled labour.

particular, if a technology is biased such that it would require a more intensive use of a specific skill, this can be represented as ‘negative’ factor augmenting technical change, i.e. ‘factor-using’ technical change in fact. There are a number of problems with this approach. First, it is not clear what exactly the mechanism is behind a change in the ‘quality’ of a skill (i.e. the ‘level of factor augmentation’) due to technical change. Is it job-requirements that are reduced, thus enabling the use of lower-skilled workers instead of high-skilled ones? Or are low-skilled workers combined with (IT-) gadgets that enable them to perform tasks that would require the input of higher skills if those gadgets would not have been available? Second, production processes are series of specific tasks that need to be performed in order to get from raw inputs to final outputs. The execution of these tasks as such is essential to the production of output, and not necessarily the skills that are actually used to perform those tasks. It makes sense then to define a production function in terms of combinations of tasks. Moreover, the employment associated with performing a certain task should then be defined as a combination of (imperfectly) substitutable skills of a level that is at least sufficient to perform the task in question in a technically satisfactory way. Actually, if we define the demand for skills in this way, the notion of process R&D can be defined in a quite natural way: it is the type of R&D that changes the nature of the tasks making up the production process in such a way that it allows entrepreneurs to change the average skill-composition of employment, and hence enjoy the associated reduction in unit production costs. In the context of Vernon’s product life cycle theory, this is what happens during the second stage, i.e. the standardisation phase, of a products lifecycle.

Another, more recent approach, which borrows elements from the Romer (1990) model, and integrates them with the notion of factor augmentation mentioned above, is Acemoglu (1997), who assumes that the (marginal) productivity (that is a measure of implicit quality) of a skill depends on the composition of the capital stock in terms of intermediates. In a love-of-variety setting, increasing the number of varieties of intermediates then implies an increase in the marginal productivity of the associated skill. In that way, the implicit quality of a skill depends on R&D activities, albeit indirectly. Although this approach has its merits (it essentially sticks fairly closely to a widely accepted nested production function approach as taken in Romer (1990)), it also misses the point we made above that technical changes affects first and foremost the job-structure of employment. However, as suggested above, technical change also enables the actual substitution of factors of production through a kind of ‘material augmentation’. This material augmentation (for instance, the combination of low-skilled workers with smart capital that has a user friendly interface) allows the ‘augmented’ factor to perform the same tasks as the non-augmented factor that it replaces (i.e. the augmented factor becomes a substitute for another factor, whereas it wasn't such a substitute before).[3] In defining our own model, we take the first approach, i.e. R&D directly changing the job-composition of employment, rather than the second one, although it is possible in principle to combine the augmentation approach with the 'changing-job-composition' approach. We do this to keep the model as simple as possible at this stage.

The 'changing-job-composition' approach differs markedly from a more naïve approach suggested by the potential combination of the idea of factor augmentation as such, and the endogenisation of Kennedy's induced innovation approach (Kennedy (1966)) through linking the rate of factor augmenting technical change to specific R&D inputs. The reason why we don't follow that naïve approach is that we feel that jobs and implied skill requirements are the essential features of employment rather than implicit notions of the (economic context dependent?) quality of skills or production factors in general.

3 The Model

3.1 General features

The model is developed using neo-classical concepts from consumption and production theory, that are integrated with non-perfect foresight adaptive expectations principles. The reason to choose a non-perfect foresight approach is first that it allows much more flexibility regarding the actual specification of the model. Secondly, it provides one of the excuses for government intervention, which is after all what policy making is about. The imperfect nature of expectations can be accounted for, in a 'rule of thumb' kind of way, by allowing explicitly for risk-premiums in the rates of discount with respect to expected future streams of benefits and costs of particular activities.

In order to keep things as simple as possible, we distinguish only two skills, i.e. high- and low-skilled workers. Wages are skill-specific, and the high-skilled wage premium is then

[3] For example, one could envisage the use of computerised equipment that allows people to perform tasks that could previously be performed in an efficient way only after a sufficient amount of training. Specific examples include scanning equipment used with cash registers in super markets, but also numerically controlled machinery and equipment that act as digitised 'expert systems' and that can be handled by low-skilled people through user-friendly interfaces. Note that the term 'low-skilled' should be understood in a relative sense here, implying that lower skills are required than before.

simply the difference between high-skilled wages over low-skilled wages as a percentage of low-skilled wages. Depending on whether this premium is positive or negative, there is an incentive to try to replace jobs that need to be performed by high-skilled workers by jobs that can also be performed by low-skilled workers. We assume that this can be done by engaging in process R&D.

We also assume that each year new products will enter the market. Those products are imperfect substitutes for older, existing products. Because of that, new products only gradually push older products out of the market, while, in addition, we have monopolistic price setting. By assuming that the direct contribution to consumer utility of a certain volume of new products is larger than that of the same volume of older products, we combine a love of variety approach with a quality ladder approach. In order to keep things as simple as possible, we assume that new products enter the market in combination with a production process that uses a range of high-level jobs requiring high-skilled workers. Through process R&D, the job contents of this range of jobs is reduced, so that low-level jobs arise that can be filled by low-skilled workers.

As stated above, the only factors of production distinguished are high-skilled and low-skilled workers. Low-skilled workers can be used in final output production, but only after the production processes corresponding with the varieties that are produced have been adjusted through process R&D. High-skilled labour, on the other hand, has three competing uses, i.e. final output production, product R&D and process R&D. Labour market arbitrage ensures that wages are the same for all uses. Since we don't have capital as a separate production factor at this stage, profits and wage-income are wholly turned into consumer expenditures.

We now turn to a more detailed description of the various parts of the model.

3.2 The demand for goods and services

The demand for goods and services is derived from a utility maximisation problem under a budget constraint. Let *B*, *U* and C_i be the consumer budget, total utility and the level of consumption of variety i, while Q_i is an implicit measure of the 'quality' of variety i. In that case we have for the present moment in time:

$$U_t = \left(\sum_{i=0}^{t} Q_i C_{i,t}^{\gamma} \right)^{1/\gamma} \tag{1}$$

where utility is described using a linear homogeneous CES function, and t refers to the present. Note that equation (1) implies that at each moment of time just one new variety is introduced with a quality that doesn't change ex post (i.e. after it has been introduced on the market). Given equation (1), utility maximisation gives rise to the following demand equations:

$$C_{i,t} = B_t \left(P_{i,t} / Q_i\right)^{-\varepsilon} \mu^{1-\varepsilon} \tag{2}$$

where μ is the Lagrange multiplier of the utility maximisation problem, and therefore represents the amount of utility per unit of the budget spent, i.e. $\mu = U / B$. $\varepsilon = -\frac{d\ln(C_{i,t})}{d\ln(P_{i,t})} = 1/(1-\gamma)$ is the price elasticity of demand. Furthermore, it can easily be verified that:

$$\mu = \left(\sum_{i=0}^{t} P_{i,t}^{1-\varepsilon} \cdot Q_i^{\varepsilon} \right)^{1/(\varepsilon-1)} \tag{3}$$

i.e. total utility rises in the quality of the varieties, and falls with the prices of the varieties for $\varepsilon > 1$, which is what we assume from now on. Assuming furthermore that the entrepreneurs producing each variety are of measure zero, it follows that they regard μ as essentially out of their control and hence given. This implies that the profit maximising price of each variety can be obtained by maximising profits, conditional on (2), for a given value of μ.

3.3 The supply of goods and services

The production of each variety is described using a neoclassical production function. Moreover, profits per variety, i.e. $\Pi_{i,t}$, depend on consumption levels and consumer prices through $\Pi_{i,t} = (P_{i,t} - \psi_{i,t}) \cdot C_{i,t}$, where $\psi_{i,t}$ are marginal costs (=average costs in case of a linear homogeneous production function, and perfect competition on the markets for production factors). Given (2), the profit maximising price is given by:

$$P_{i,t} = \frac{\varepsilon \cdot \psi_{i,t}}{\varepsilon - 1} \tag{4}$$

which is the well-known Amoroso-Robinson condition. Since we have assumed that $\varepsilon > 1$, it follows that prices exceed marginal costs, and hence that there are positive profits.

3.4 Product R&D and Ex Ante Initial Profits

Using (2) and (4), it follows immediately that profits for variety *i* at time *t* are given by:

$$\Pi_{i,t} = B \cdot \psi_{i,t}^{1-\varepsilon} \cdot Q_i^{\varepsilon} (\varepsilon - 1)^{\varepsilon - 1} \cdot \varepsilon^{-\varepsilon} \cdot \mu^{1-\varepsilon} \tag{5}$$

Equation (5) says that profits from producing a variety i depend positively on the quality level of that variety, and negatively on marginal costs. This suggests two things: **initial** profits are maximised by increasing the marginal quality of the new variety up to the point where the additional profits exactly match the marginal costs of performing product R&D. Moreover**, ex post** profit streams can be increased, ceteris paribus, by lowering marginal costs (through the introduction of low-level jobs instead of high-level ones through process R&D).

Assuming the following 'near-standard' product R&D production function, we get:

$$Q_i = Q_{i-1} \cdot (1 + \delta_Q R_Q{}^{\beta_Q}) \tag{6}$$

where $\delta_Q > 0$ and $0 < \beta_Q < 1$ are fixed parameters. R_Q is the number of R&D workers engaged in product R&D. Note that we do not assume constant returns with respect to R&D efforts, since $0 < \beta_Q < 1$. This is what makes (6) different from a more standard approach, as will become more clear in a moment.[4] Again, we make this assumption to simplify the model.

We assume now that the product R&D sector can not capture the ex post increases in profits due to in-house process R&D, whereas it does capture the expected future profits

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[4] Jones (1995) uses a similar specification of the R&D production function in order to be in line with the observation that observed ('steady state') growth has a tendency to become more intensive in R&D efforts over time. This points to both limited positive spillover effects of previous levels of R&D to current R&D productivity and a decreasing marginal productivity of R&D efforts. We adopt the latter but not the first, again

associated with a new product and its initial (high-skilled intensive) technology by setting the relevant price for its blueprint. More specifically, the product R&D sector maximises its own profits by changing the expected present value of the profit streams associated with the new variety through changing the quality of the variety, for given expectations regarding the growth rates of *B*, μ and ψ_i and given marginal product R&D costs. In that case, the expected present value of a product innovation is given by:

$$PV\Pi_{i,i} = \Pi_{i,i} /(\rho - \hat{\pi}) = \Pi_{i,i} /(\rho - (\hat{B} + (1-\varepsilon)(\hat{\psi}_i + \hat{\mu})) \quad (7)$$

where a hat over a variable denotes its expected rate of growth and ρ is the rate of discount. Substituting (5) into (7) and then differentiating the result with respect to R_Q, we obtain the extra profits that can be generated due to the addition of a marginal R&D worker. Assuming that the marginal costs of an R&D worker are equal to w_R, the optimum input of product R&D workers is implicitly described by equation (8):

$$\delta_Q^{1/(\varepsilon-1)}(1+\delta_Q R_Q{}^{\beta_Q}) = \frac{B^{1/(1-\varepsilon)} Q_{i-1}^{\varepsilon/(1-\varepsilon)} \psi_i w_R^{1/(\varepsilon-1)} \beta_Q{}^{1/(1-\varepsilon)} \varepsilon\mu((\hat{\psi}_i + \hat{\mu})(\varepsilon-1)+\rho)^{1/(\varepsilon-1)}}{\varepsilon-1} \cdot R_Q^{(1-\beta_Q)/(\varepsilon-1)} \quad (8)$$

Equation (8) is derived from the equilibrium condition $\partial PV\Pi_{i,i} / \partial R_Q = w_R$. Both the left hand side of (8), further called *LHS*, and the right hand side of (8), further called *RHS*, are rising functions of R_Q. Since the graph of *RHS* starts from the origin at $R_Q=0$, while that of *LHS* starts above the origin, we must have *RHS* rising faster in R_Q than *LHS* in order to have the graphs of *LHS* and *RHS* intersect in the positive quadrant. Hence, we must have that $(1-\beta_Q)/(\varepsilon-1) > \beta_Q \;\Rightarrow\; \beta_Q < 1/\varepsilon$.

It is now easy to see how (policy induced) changes in the various system parameters would influence the demand for product R&D workers, since any parameter change that shifts up LHS, will result in a rise in R_Q , ceteris paribus. Likewise, any parameter change that shifts up RHS, will result in a fall of R_Q, ceteris paribus. We conclude therefore, that a rise in the productivity of product *R&D* workers shifts up *LHS* and therefore raises R_Q. Likewise, a rise in the rate of discount lowers R_Q because the present value of the expected profit stream falls.

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for reasons of simplicity. However, the results we will be showing would not be fundamentally different if we

A rise in the wage rate for R&D workers lowers R_Q, as expected. Moreover, the higher the quality level that carries over from the previous period, the higher will be R_Q. Finally, increases in the expected growth rate of marginal costs decreases the present value of expected profit streams and hence the incentive to engage in product R&D. Hence in that case R_Q falls. All these results are intuitively plausible.

Although equation (8) does not have a closed form solution for $R_{Q,}$, it can nonetheless be solved in a numerical way, for given values of the various parameters. [5]

3.5 The Demand for Labour by Skill

As stated above, we assume that each variety is produced using a multi-stage neo-classical production function. Various different nestings of the production factors can be envisaged. In order to simplify matters at this stage, however, we assume that there is just one production factor, namely effective labour services, further called $N_{i,t}$, and where the index i refers to a variety. $N_{i,t}$ therefore represents the amount of effective labour services used in the production of $C_{i,t}$. These effective labour services are an aggregate of the high- and low-level tasks that are performed by high-skilled and low-skilled workers, respectively. The mix of low- and high-level tasks that defines an effective unit of labour services is described using a **symmetric** Cobb-Douglas production function, again for ease of exposition.[6]

The number of jobs associated with a variety is equal to *ji*. To simplify matters, we assume that there are infinitely many jobs indexed by a continuous index on the range *0-ji*. The jobs in sub-range *0-li* are low-level jobs, while those in the sub-range *li-ji* are high-level jobs. Moreover, $ls_{i,k,t}$ is the number of low-skilled people on low-level job k associated with variety i, while $hs_{i,k,t}$ is the number of high-skilled people on high-level job k associated with variety I, both at time *t*.

Given the above, we have:

$$N_{i,t} = ji^{\alpha} \cdot Exp(\int_{0}^{li} (1/\,ji) Ln(ls_{i,k,t}) dk + \int_{li}^{ji} (1/\,ji) Ln(hs_{i,k,t}) dk) \qquad (9.A)$$

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would allow for limited positive spillovers at the same time.

[5] This has also been one of the reasons to focus on numerical simulations, rather than purely theoretical ones.

[6] However, without loss of generality, other aggregator functions, like a CES function, could also be used at the cost of an increase in complexity. This holds a fortiori for a multi-stage approach, of course.

where *Exp(x)* represents the anti-log of x. Note that this combination of an anti-log and an integral over natural logarithms mimics the continuous version of a discrete repeated product operator. It can easily be shown that both representations generate the same results.[7] Hence, from now on, we will stick to the repeated product representation of equation (9.A) that is given by:

$$N_{i,t} = ji^{\alpha} \cdot \prod_{k=0}^{li} (ls_{i,k,t})^{1/ji} \cdot \prod_{k=li}^{ji} (hs_{i,k,t})^{1/ji} \tag{9.B}$$

where it should be stressed that *k* is actually a continuous index, rather than a discrete one. Note also that we have included a term ji^{α}. The reason to do so is that the argument of Smithsonian labour division as a source of growth (as it is used in Romer (1990) in the context of a division of activities between intermediate goods, for example), should hold here a fortiori.

Associated with the symmetric CD-function given by (9.B), we have a unit minimum cost function given by :

$$\Lambda_{i,t} = ji^{-\alpha} \cdot \prod_{k=0}^{li} \left(\frac{w_{L,t}}{1/ji} \right)^{1/ji} \cdot \prod_{k=li}^{ji} \left(\frac{w_{H,t}}{1/ji} \right)^{1/ji} = ji^{1-\alpha} \cdot \left(w_{L,t}\right)^{li/ji} \cdot \left(w_{H,t}\right)^{1-li/ji} \tag{10}$$

where $w_{L,t}$ and $w_{H,t}$ are the wage rates at time t of low-skilled and high-skilled workers, respectively. It should be noted that if the latter wage rates would be equal, then total unit labour costs would be equal to that common wage rate only if $\alpha = 1$. If $\alpha > 1$, then total unit labour costs would be lower than the common wage rate, due to the influence of labour division. For the moment, however, we assume that $\alpha = 1$. Since we have assumed that effective labour is the only production factor, while moreover the production function is assumed to be given by $C_{i,t}=N_{i,t}$, it readily follows that marginal costs equals average unit costs, i.e. $\psi_{i,t} = \Lambda_{i,t}$.

Because of the symmetry of the partial effective labour elasticities of the various jobs, all low-level jobs will be filled with an equal number of low-skilled people and all high-level jobs with an equal number of high-skilled people.[8] In that case, and using Shephard's lemma,

[7] That is, if we would act as if the repeated product is also defined over a continuous index.
[8] This distribution of labour maximises the total effective labour services that can be obtained using a given volume of labour of a certain skill-level.

the total demand for low- and high-skilled people by the producer of variety *i*, i.e. $L_{i,t}$ and $H_{i,t}$ respectively, are simply equal to: [9]

$$L_{i,t} = li \cdot \frac{\partial \Lambda_{i,t}}{w_{L,t}} \cdot N_{i,t} = (li / ji) \cdot \left(\frac{w_{H,t}}{w_{L,t}} \right)^{1-li/ji} \cdot N_{i,t} \qquad (11.A)$$

$$H_{i,t} = (ji - li) \cdot \frac{\partial \Lambda_{i,t}}{w_{H,t}} \cdot N_{i,t} = (1 - li / ji) \cdot \left(\frac{w_{H,t}}{w_{L,t}} \right)^{-li/ji} \cdot N_{i,t} \qquad (11.B)$$

It should be noted from (11.A) and (11.B) that the share of low-level jobs in the total number of jobs per variety, i.e. *li/ji*, is a crucial variable in the determination of the demand for low- and high-skilled workers, next to the wage premium of high-skilled workers. Moreover, for a given wage premium ($w_H/w_L>1$), total unit labour costs also depend negatively on the share of low-level jobs in the total number of jobs. Consequently, it may be profitable to try to increase the share of low-level jobs in the total number of jobs, certainly if the wage premium is expected to rise over time. This is what process R&D is about, which we assume to be an in-house activity.

3.6 Process R&D and Ex Post Profits

Defining $si=li/ji$, the corresponding process R&D production function is given by:

$$\Delta s_{i,t} = s_{i,t} - s_{i,t-1} = \delta_P \cdot R_{i,t}^{\ \beta_P} \cdot (1 - s_{i,t-1}) \qquad (12)$$

Equation (12) states that the share of low-level jobs in total jobs will increase through employing process R&D workers. The effectiveness of process R&D decreases while the share of low-level jobs increases, though. It becomes harder and harder to get rid of the last of the high-skilled….

The question now is how much a producer of a variety should spend on process-R&D. The answer follows from an approach similar to the one we have taken regarding the

[9] This follows readily from the fact that the ‘demand’ for a particular low-level job k would be given by: $ls_{i,k,t} / N_{i,t} = (1/ji).\Lambda_{i,t} / w_{L,t}$. Since, moreover, $L_{i,t} = li \cdot ls_{i,k,t}$, equation (11.A) can readily be obtained.

determination of the level of product R&D. For, the producer of variety i who hires an additional process R&D worker at time t, will experience two positive effects from doing so. First, marginal costs will be reduced instantaneously if the wage premium is positive. At the same time, a rise in the share of low-level jobs in total jobs will reduce the expected rate of profit erosion due to the expected growth in the wage premium. The present value of the extra profits due to process R&D is then simply the ratio of the initial jump of profits as a function of the number of process R&D workers, divided by the difference between the discount rate and the expected growth rate of profits, also as a function of the number of process R&D workers. Defining $w_t = w_{H,t}/w_{L,t}$ we find by substitution of (12) into (5) that the expected present value of the permanent increase in profits for the producer of variety i due to the employment of R_i process *R&D* workers is given by:

$$PV\Delta\Pi_{i,t} = \frac{\partial \Pi_{i,t}}{\partial s_{i,t}} \Delta s_{i,t} / (\rho - \hat{\pi}) = \frac{\partial \Pi_{i,t}}{\partial s_{i,t}} \delta_P \cdot R_{i,t}^{\ \beta_P} \cdot (1 - s_{i,t-1}) / (\rho - \hat{\pi}) \qquad (13)$$

where $\hat{\pi}$ now also depends on $R_{i,t}$ through the dependence of unit total labour costs on the share of low-level jobs in the total number of jobs per variety, and the equality of marginal production costs and unit total labour costs mentioned above. The ex post growth in profits is given by equation (14) below, that can readily be obtained by calculating total profits in function of marginal costs and the parameters of the utility function by substituting (4) into (2) and then taking the instantaneous growth rate:

$$\hat{\pi} = (1-\varepsilon)(\hat{\psi} + \hat{\mu}) + \hat{B} = (1-\varepsilon)(s_{i,t}\hat{w}_L + (1 - s_{i,t})\hat{w}_H + \hat{\mu}) + \hat{B} \qquad (14)$$

It follows immediately from equation (14) that ex post profits can be made to grow if the budget grows (this increases the scale of demand, hence absolute profits too), but more importantly, if high-skilled wages grow faster than low-skilled wages, then the ex post growth rate of profits can be increased by raising the share of low-level jobs in total jobs, i.e. s_i. But this should be done by performing process R&D. The latter has therefore two kinds of effects: *a level effect* that changes the job composition of employment and hence average wage costs per unit of effective labour and therefore the level of profits, as well as *a growth effect*

Equation (11.B) can be obtained in an analogous fashion.

through changing the weights by which the growth rates of low- and high-skilled wages contribute to the growth in effective wage costs and hence ex post profit growth.

The net increase in profits due to hiring $R_{i,t}$ R&D workers can now be maximised by equating the partial derivative of (13) (after substituting (12) and (14)) with respect to $R_{i,t}$ and the marginal cost of hiring process R&D workers, i.e. *wR*, in which case we can solve $R_{i,t}$ numerically from:

$$LHS = \begin{array}{c}\{B \cdot Q_i^{\varepsilon} R_i^{\beta_P - 1}(1 - s_{i,t-1}) w^{(s_{i,t-1}-1)(\varepsilon-1)} \beta_P \delta_P ((\varepsilon - 1)/\varepsilon)^{\varepsilon} \mu^{1-\varepsilon} \ln(w_H / w_L)\} \cdot \\ [-\hat{B} + (\varepsilon - 1)(\hat{w}_H (1 - s_{i,t-1}) + \hat{w}_L s_{i,t-1} + \hat{\mu}) + \rho]\end{array} \tag{15.A}$$

$$RHS = w_R (-\hat{B} + (\varepsilon - 1)(\hat{w}_H (1 - s_{i,t-1}) + \hat{w}_L s_{i,t-1} + \hat{\mu} - \delta_P \cdot R_i^{\beta_P} (1 - s_{i,t-1})(\hat{w}_H - \hat{w}_L)) + \rho)^2 \tag{15.B}$$

$$LHS = RHS \tag{15.C}$$

where we have dropped time subscripts in as far as they would refer to the present. Note that *LHS* falls if $R_{i,t}$ increases, while *RHS* increases for increasing $R_{i,t}$. at least if $-\hat{B} + (\varepsilon - 1)(\hat{w}_H (1 - s_{i,t-1}) + \hat{w}_L s_{i,t-1} + \hat{\mu}) + \rho > 0$. The latter is simply the effective rate of discount of expected profits, i.e. the denominator of (14). If this effective rate of discount is negative, then the present value of expected profits is infinitely high, and the process R&D selection problem does not have a solution. We therefore assume that the effective discount rate is positive. Again, it is easy to show[10] that an increase in the discount rate ρ or in w_R will lower $R_{i,t}$ since it shifts *RHS* in an upward direction more than it will shift *LHS*. An increase in the wage-premium lowers $R_{i,t}$, while an increase in the growth rate of the wage premium will raise *LHS* and therefore increase $R_{i,t}$. Again, these results are all plausible a priori.

3.6 Labour market arbitrage

We assume that arbitrage possibilities for high-skilled workers are exhausted completely and instantaneously. Hence, we get:

$$w_R = w_H \tag{16}$$

[10] However, see Appendix A for some interesting implications of equation (15).

3.7 Labour supply and wage formation

Low- and high-skilled labour are inelastically supplied, and it is assumed that the two sub-markets for low- and high-skilled labour are continuously in equilibrium. Hence wages are equilibrium wages. Obviously, the latter assumption can be relaxed, and wage formation could be described using a Phillips-type of approach thus creating an ‘entry-point’ for wage-policy too.

4 Principle Policy Reactions

4.1 Overall Working Principles

The model outlined in the previous paragraph should be able to produce the stylised facts brought forward in Acemoglu (1997) in a relatively straightforward way. Acemoglu observes for the US that an increase in the supply of high-skilled workers does not necessarily mean that the wage premium falls in the long run. This is because of endogenous technology reactions that redirect the bias in technical change towards the exploitation of the drop in the wage premium in the short run. Something similar would also happen in our model. Suppose, for instance, that the supply of high-skilled workers experiences a one-time increase. This would depress the wage premium in the short run. However, this reduction in the wage premium would in turn invoke two different R&D reactions : first, product R&D would increase, because high-skilled intensive new products would become more profitable to produce and sell (thus raising the demand for high-skilled workers), while secondly the marginal costs of doing product R&D (as a high-skilled intensive activity) would decrease as well. The latter obviously also holds for process R&D, but the incentives for doing process R&D would diminish as opposed to those for product R&D, since there is now less to be gained from changing high-level jobs into low-level ones. The net effect on unemployment of the high skilled depends therefore very much on the system parameters, i.e. the price elasticity of demand in particular, especially in combination with the productivity of product R&D workers. In the case of a fairly high price elasticity of demand and high product R&D productivity, one can easily envisage a situation where a spurt in product R&D raises quality by so much that demand is increasingly redirected towards newer products (and hence high-skilled workers) also on that account. This redirection in turn has longer-term effects on R&D

activity of its own, since increases in quality (in the form of knowledge spill-overs from the past) also raise current R&D productivity, hence current R&D efforts.

4.2 Economic Policy Making and Technology Reactions

The model as it is contains some obvious entry points for policy making. Moreover, since it is a simulation model, it can easily be extended to include more policy entry points. Fiscal policy, for instance, affects domestic interest rates as well as the level and composition of expenditures. Obviously, since the demand for products depends on the consumer budget, fiscal policy may directly influence the profitability of doing research in as far as it influences demand directly. If inflationary expectations, or risk-premiums, are influenced too, this also directly affects R&D decision making, hence longer-term growth. The way in which taxes are levied is also of direct importance for growth perspectives. Profit taxes, for instance, would reduce the incentive to engage in product and process R&D, thus reducing growth perspectives, while taxes on wages have an impact on process R&D. This holds a fortiori for differential wage taxes (or social protection costs).

Monetary policy, and its linkage to external balance, influences inflation (and inflationary expectations) as well as domestic interest rates. By introducing capital as a separate production factor in our model, monetary policy (but also fiscal policy) would affect (expected) unit production costs, and depending on the nesting of the production function, redirect the demand for skills in directions that are favourable for doing product and process R&D or not. If, for instance, capital would be largely complementary to high-skilled jobs, then an increase in the interest rate would depress the wage premium and hence invoke additional product R&D, and possibly process R&D through a reduction in the costs of performing R&D.[11] If high-skills and capital would primarily be substitutes, then the opposite would happen, and monetary and fiscal policy measures might have to be supported by additional policy measures that would stimulate R&D activity.

Wage policy too may have a direct effect on growth performance. For instance, if institutional arrangements in Europe would be changed such that the labour market for the low-skilled would be more flexible, this would probably lead to a fall in low-skilled wages and hence to an increase in the wage premium. Apart from the question whether this should be regarded as a reason for concern on its own (because of the redistribution of income this

[11] On the other hand, this also reduces the cost-savings resulting from process R&D, so the net result is ambiguous.

entails between various groups within the population), this also has the effect of redirecting R&D efforts towards process R&D activities, which may have non-negligible effects on current welfare, but also the growth of welfare.

A policy that will have positive effects on all accounts in the long run is one that will raise the supply of high-skilled workers permanently through better education and schooling. However, this would probably require a higher input of high-skills in the short run and hence generate growth bottlenecks on that account. It would further have the effect of increasing the relative scarcity of the low skilled and so reduce income inequality, while long term income per head would rise. The reduction in income inequality may be regarded as another (side-) benefit.

Structural policy, i.e. the promotion of the one sector relative to another, may also have direct growth effects. First of all, directly through the changing sectoral composition of output, but secondly because sectoral shifts may have consequences for the wage premium and hence R&D activities if the skill-intensities of the shrinking and expanding sectors differ. The promotion of a final output sector that is relatively high-skilled intensive, will drive up the wage premium, and hence reduce growth through new products, but will also lead to a deterioration of the competitive position of an economy in the short run, especially with respect to new products. If international learning effects (through spillovers) are important, then this may hamper longer-term growth perspectives.

5 Some Illustrative Model Simulations

5.1 Introduction

In this section we describe a number of simulation experiments we performed using the model. These simulations are based on ‘fake’ data and parameter-values. They only serve the purpose of illustrating how the model works, and what kind of results could be expected from a model built along similar lines but with ‘real’ parameter-estimates instead. The parameter values we have used are listed in the table below.

Parameter	Value	Description
ε	1.5	Price elasticity of demand
β_Q	0.25	Partial R&D output elasticity of product R&D workers

β_P	0.25	Partial R&D output elasticity of process R&D workers
δ_Q	0.1	Productivity parameter product R&D
δ_P	0.1	Productivity parameter process R&D
ρ	0.05	Discount rate (includes capital costs and risk-premium)
$\bar{H}$	0.5	Inelastic supply of high-skilled labour
$\bar{L}$	1	Inelastic supply of low-skilled labour

Table 5.1 Parameter Values

Using these parameter values, we have run the model from period 1 to 200 and so obtained the base-run. As we will show, the model does generate a steady state growth situation, once enough varieties have been generated (and entrepreneurs have become of 'measure nearly zero'), and once expectations have 'settled down'. This is the case after 100 periods or so, depending on the specific parameter values chosen. During the experiments, the first 150 periods are used to obtain a steady state growth situation, and then in period 150 a shock is introduced that is maintained for 25 periods. In period 175, the shock is removed, and the simulation is continued until period 200. During the simulations, expectations are endogenously adjusted, and so are the lagged variables that appear in the model (for instance in the R&D equations). Finally, we have chosen the consumer budget as the numeraire.

Apart from the base run, we have performed 5 experiments labelled 'X1'-'X5'. Experiment 'X1' pertains to a 5 percent rise in the supply of high-skilled labour, while 'X2' refers to a 5 percent rise in the supply of low-skilled labour. These experiment serve the purpose of illustrating our surmise that the model should be able to reproduce the stylised facts (at least for the US with relatively flexible labour markets) that an increase in high-skilled labour supply does not necessarily depress the wage premium in the long term, although it should do so in the short term. Experiment 'X3' is based on a rise of the rate of discount, either through an increase in the risk premium, or in the cost of capital. This experiment illustrates the effects that could be expected from policies aimed at changing either of the components of the discount rate. Experiment 'X4' and 'X5' are concerned with the effects of raising the productivity of the product and process R&D process, for instance through policies aimed at furthering the natural sciences as well as engineering skills.

Although the model generates a lot of data, we only present a few aggregated time-series. The names of these time-series are prefixed by the strings 'Xi_GR_', where the sub-string ‘Xi’ refers to experiment i of those described above. The sub-string ‘GR_’ refers to the fact that we have calculated percentage growth rates of the time-series concerned. The string ‘UTILITY’ refers to consumer utility as given by equation (1), while ‘Q’ refers to the ‘quality’ of a new variety. ‘RPT’ in turn refers to total R&D workers engaged in process R&D, while ‘RQ’ refers to R&D workers engaged in product R&D and ‘HT’ refers to high-skilled workers employed in the final output sector. Finally, ‘W_H’ refers to high-skilled wages, ‘W_L’ pertains to low-skilled wages and ‘W’ signals the ratio of high-skilled and low-killed wages. Since the growth of low-skilled employment is zero (except for the supply-shock concerning low-skilled labour), we leave it out.

5.2 The Base Run

In order to illustrate that the model generates (almost-) steady state growth, we present the outcomes of the percentage growth rates of the variables listed in the previous sub-section for period 150 and 200 in the table below.

Variable	Period 150	Period 200
X0_GR_UTILITY	+7.9086	+7.8716
X0_GR_HT	+0.0009	+0.0002
X0_GR_Q	+2.5561	+2.5558
X0_GR_RPT	-0.0158	-0.0023
X0_GR_RQ	-0.0016	-0.0004
X0_GR_W_H	-0.0068	-0.0009
X0_GR_W_L	+0.0120	+0.0016
X0_GR_W	-0.0188	-0.0026

Table 5.2 Base Run Growth Rates

From the table above, it is clear that the growth rates of high-skilled employment are of the order of 0.01 percent, indicating a stable allocation of high-skilled workers of their three uses. The growth rate of relative wages is of a similar magnitude, while those of total utility and marginal quality are non-zero but (nearly-) constant, as they should be. Note that the ‘error’ in the steady state growth rate is largest for total utility, loosing 0.03 percent in 50 years. Finally note that ‘love of variety’ as a source of growth is readily apparent from the fact that the growth rate of total utility exceeds that of marginal quality Q.

5.2 Experiments X1-X5

X1: an increase of the supply of high-skilled labour by 5 percent

The results of this experiment are depicted in Figures 5.2.1-5.2.3. In Figure 5.2.1 we have depicted the growth rates of total utility and of the quality of the newest variety, i.e. ‘marginal’ quality. When the supply shock is applied, this results in a rise both of the growth rate of marginal quality and in total utility. The bulk of the rise in the growth rate in total utility does not come from the increase in marginal quality, though, but from the rise in employment in the final output sector, and hence a greater volume of consumption. More importantly, however, the larger volume of consumption is also accompanied by a shift in consumption towards high-skilled intensive varieties, since these have become relatively less expensive after the fall in relative wages of the high-skilled.

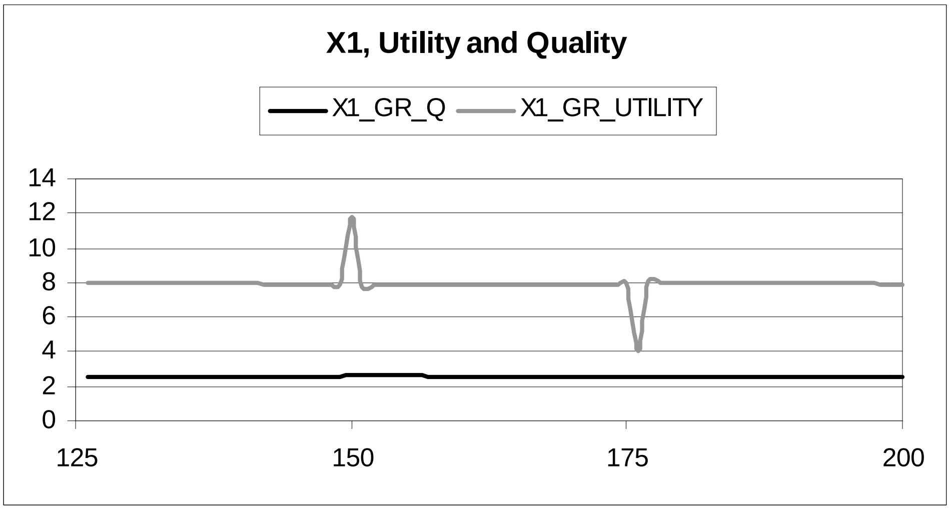

Figure 5.2.1

From Figure 5.2.2 that shows the changes in the employment of high-skilled labour, it is clear that the fall in high-skilled wages resulting from the positive supply-shock (see Figure 5.2.3) makes process R&D less profitable, as we had already explained in section 4. However, the increase in marginal quality, though slight, changes the composition of demand in terms of varieties towards the newer varieties that are relatively high-skilled intensive (being at the beginning of their life-cycle). Therefore, the initial fall in relative wages of the high skilled vanishes in the medium and longer run, resulting in a **level** of relative wages at the end of the experimental period that is even slightly higher than before the shock (not shown here). The growth rate of high-skilled wages just after the downward shock in the beginning of the experimental period rises at first by roughly 0.4 percentage points per year levelling off to slightly more than zero at the end of the experimental period. This is due to the fact that process R&D picks up again during the experimental period (induced by the recovery of relative wages of the high-skilled), thus improving the labour market position of the low skilled in the process. Note that the time-pattern of the relative wage rate follows the stylised pattern reported by Acemoglu (1997). Note, moreover, that when we remove the shock in period 175 the reactions of the model are completely symmetric.

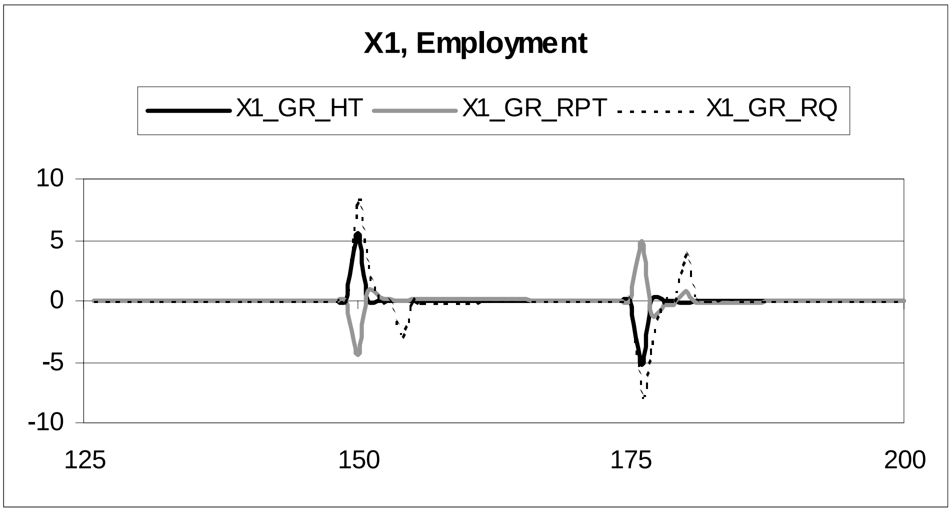

Figure 5.2.2

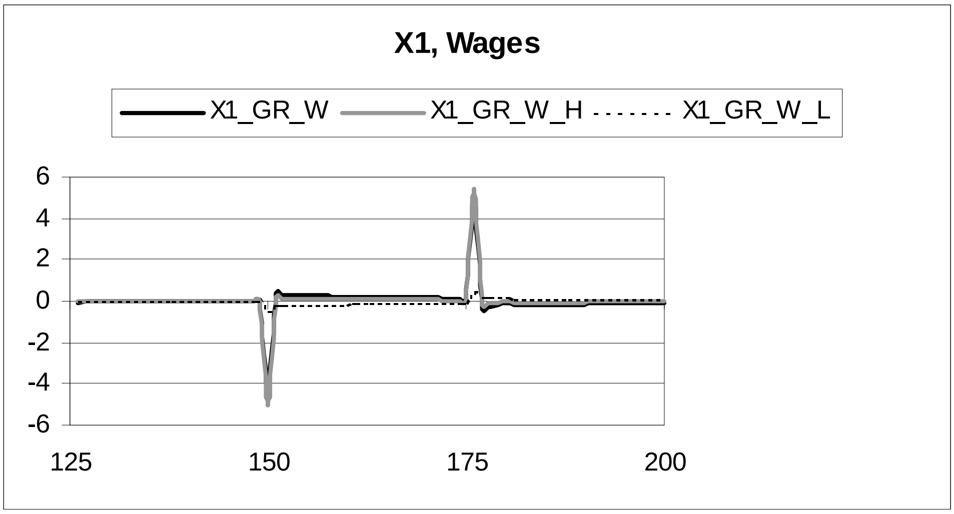

Figure 5.2.3

X2: an increase of the supply of low-skilled labour by 5 percent

The reactions to a supply shock of the low skilled are similar, but smaller in magnitude (utility growth rises by roughly 1.5 percentage points instead of 4 percentage points) due to the fall in RQ in the short term that coincides with an increase in process R&D activity. The latter is reminiscent of the 'Kleinknecht-effect' (Kleinknecht (1998)) who stresses the long-term detrimental effects of a continued policy of wage-moderation that makes for 'lazy' entrepreneurs from an innovation point of view. The increase in process R&D activity enables the release of high-skilled workers from final output production and hence the drop in product R&D activity can be mitigated by alleviating the high-skilled labour supply bottleneck. Note the interesting echo-effect/interplay between process R&D activity and product R&D activity, suggesting the importance of taking into account the intertemporal effects of policy measures that change R&D incentives, directly or indirectly.

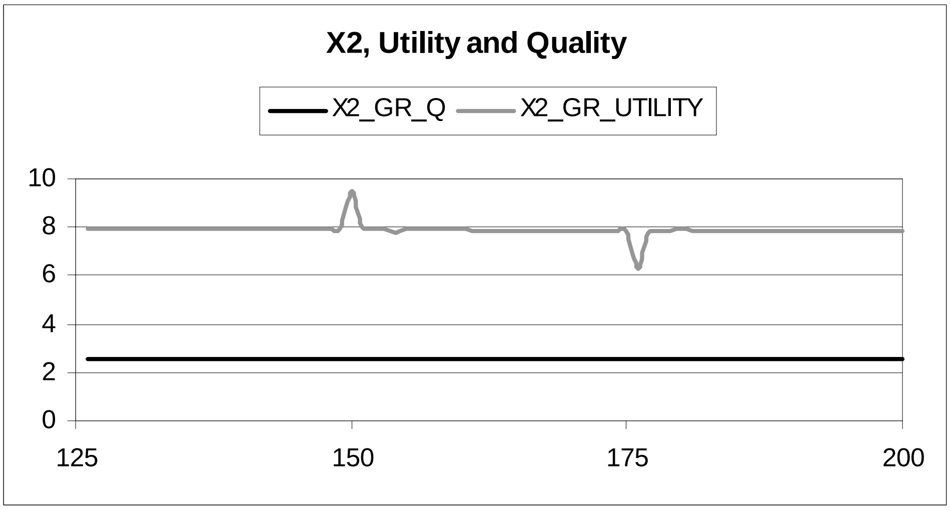

Figure 5.2.4

Figure 5.2.5

A notable difference between this experiment and the previous one is the permanency of the fall in relative wages caused by the increase in the supply of low-skilled workers. This is because the additional employment of the low skilled does not by itself create additional demand for low-skilled labour, as an increase in employment of high-skilled workers in the product R&D sector does for high-skilled labour. In that sense 'Say's law'[12] works only for the high-skilled, thus linking the employment fate of the low-skilled to what happens at the high-skilled end of the labour market.[13] Because 'Say's law' doesn't work for the low skilled, the additional supply of low-skilled labour induces extra demand only after low-skilled wages have fallen relatively to high-skilled wages. At best, this induces additional demand for the low skilled such that relative wages are restored to pre-shock levels, whereas in the previous experiment relative wages for the high-skilled could even rise above pre-shock levels due to the working of 'Say's law'.

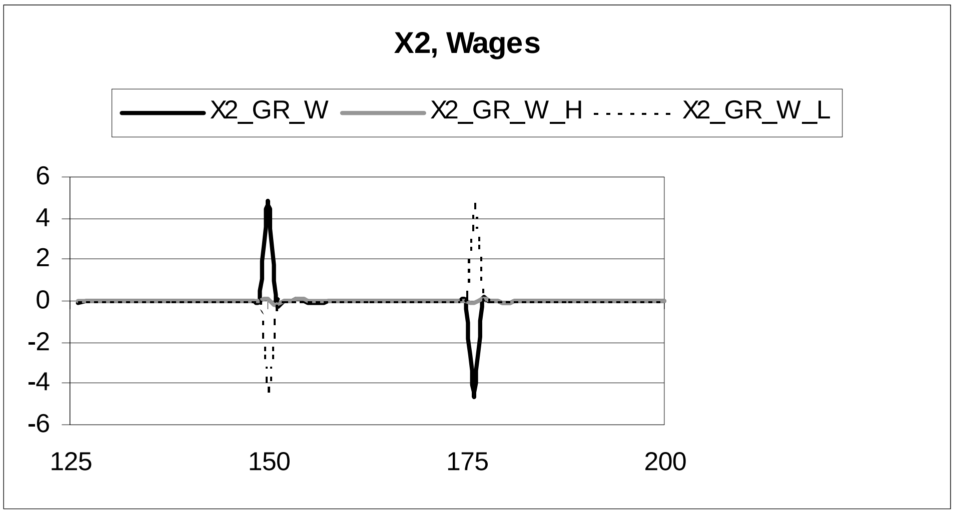

Figure 5.2.6

X3: an increase in the rate of discount

In this experiment, we have increased the rate of discount from 5 percent to 5.5 percent. Note that the same discount rate has been assumed to apply to both process and product R&D activities. It can easily be envisaged, though, that the risk premium on product R&D activities differs from that on process R&D activities. In times of a policy induced fall in capital costs, for instance, this could lead to the occurrence of a wedge between the rates of discount for both activities, and perhaps therefore to unwanted side-effects of such policies.

[12] The 'quotes' refer here to the fact that an increase in the supply of labour (rather than goods) creates its own demand (for labour).

However, in the present version of the model we did not take this into account, again for reasons of simplicity.

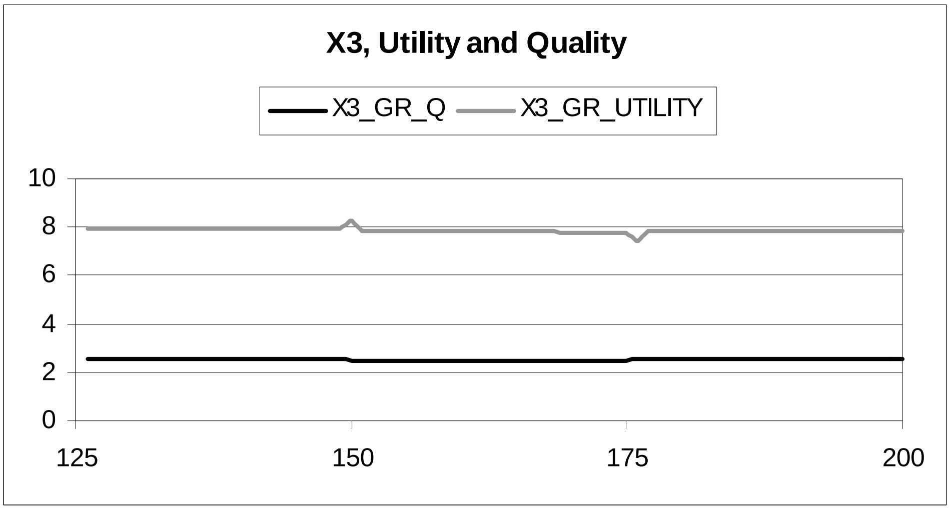

Figure 5.2.7

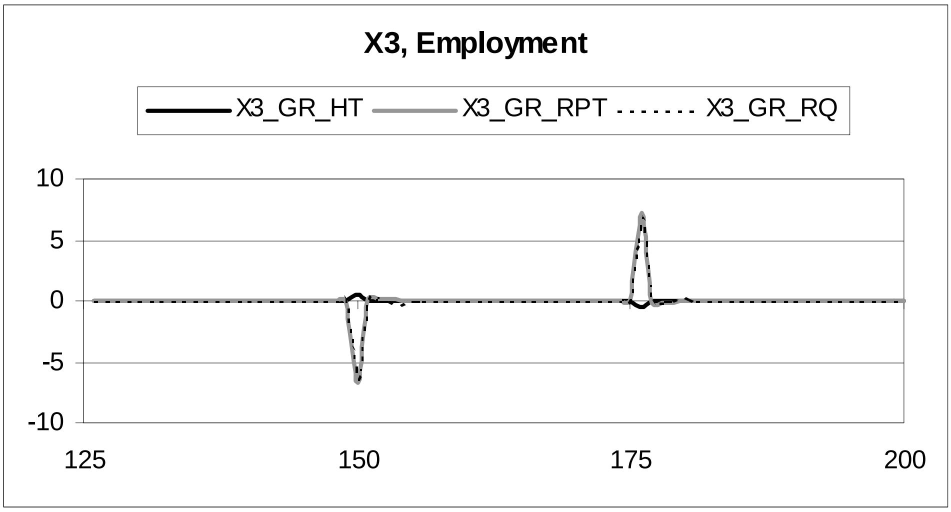

Figure 5.2.8

The first thing to notice is that the reactions to a shock in the discount rate are fairly moderate. Moreover, the welfare effects may seem to be somewhat counterintuitive, since the ultimate source of welfare 'should' be R&D. However, in this experiment we notice an increase in the growth rate of utility, even though there is a decrease in the level of R&D activity. This increase is solely due to the fact that the increase in the discount rate makes R&D activities less profitable, and hence leads to an outflow of high-skilled labour that is absorbed by the final output sector. This leads to an increase in the supply of final output, and

[13] See van Zon et al. (1998) for a similar conclusion in a static model of skill-substitution between high- and low-skilled workers. The conclusions are therefore robust in that they are linked first and foremost to the asymmetries in employment opportunities for low- and high-skilled workers.

hence to an immediate increase of utility, ceteris paribus. However, the growth rate of marginal quality is negatively affected, and after just a few periods, the level of utility falls below that in the base run (not shown here).

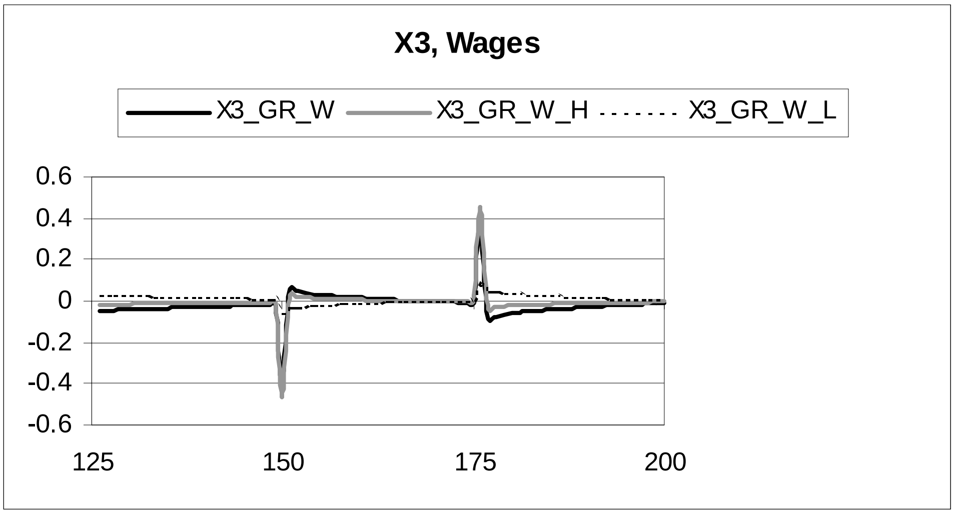

Figure 5.2.9

With respect to relative wages, the decreased employment opportunities for the high-skilled lead to an immediate fall, followed by a gradual return of relative wages to pre-shock levels when high-skilled labour flows back again into R&D activities.

X4: an increase in δ_Q

In this experiment, we have increased the productivity of product R&D workers by 10 percent (i.e. from a value of 0.1 to a value of 0.11). This raises the growth rate of marginal quality by roughly 5 percentage points. Utility rises only gradually, as the varieties with higher qualities are phased into current total consumption. There is no reallocation of high-skilled labour to speak off, since the employment shares of R&D workers are of the order of 1-3 percent of total high-skilled employment. Nonetheless, we can observe some interesting patterns regarding the development of relative wages. The latter rise sharply at first when the demand for high-skilled labour is increased. Then wage growth levels off again, but then the share of new products in total consumption increases (through induced quality improvements). Since these products are high skilled intensive, relative wages start growing again, stabilising only at the end of the experimental period. The opposite holds for wages of the low skilled, except for the sudden change at the beginning of the experimental period. Again, this is caused by the fact that the demand for low-skilled labour is linked solely to what happens with the product composition of the demand for final output.

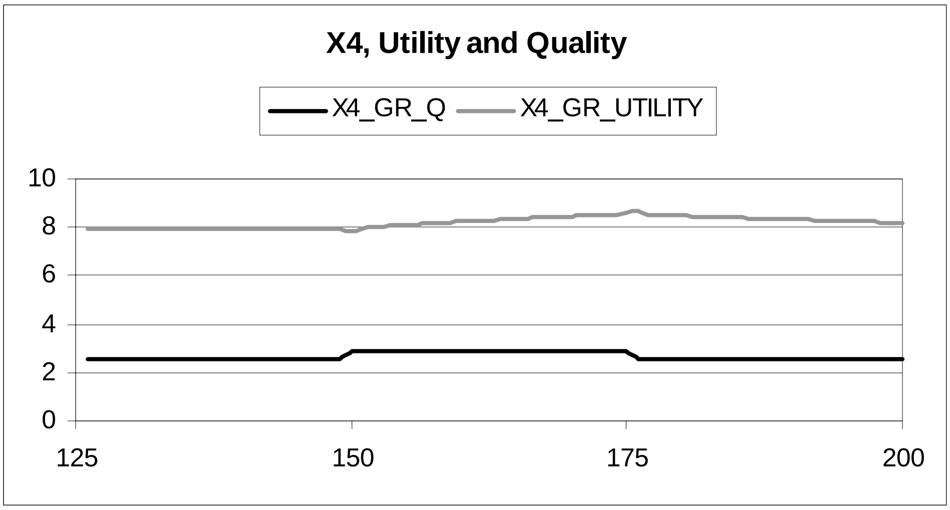

Figure 5.2.10

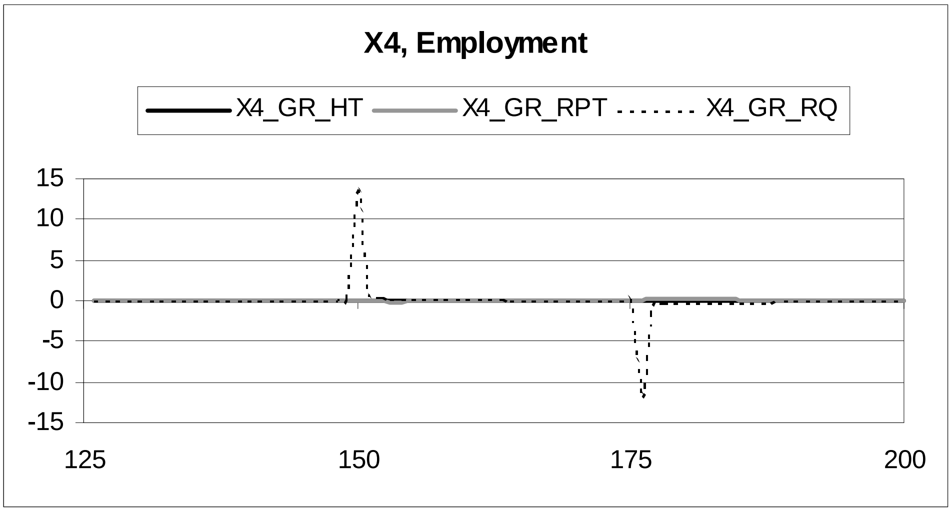

Figure 5.2.11

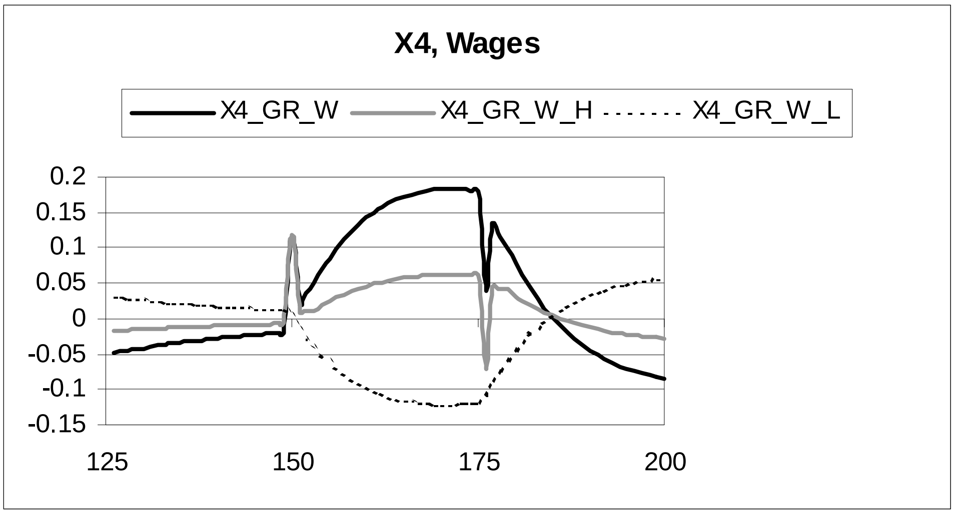

Figure 5.2.12

X5: an increase in δ_P

In this experiment we have increased the productivity of process R&D activities by 10 percent. This leads to a very slight fall in the growth of marginal quality in the short run. In the medium run, however, this is more than compensated by a rise in quality growth above its base run level. This is made possible by the increase in process R&D activity that enables the final output sectors to release high-skilled labour that can be put to ‘growth-uses’ in the product R&D sector. This then enables utility and marginal quality to grow slightly faster than in the base run.

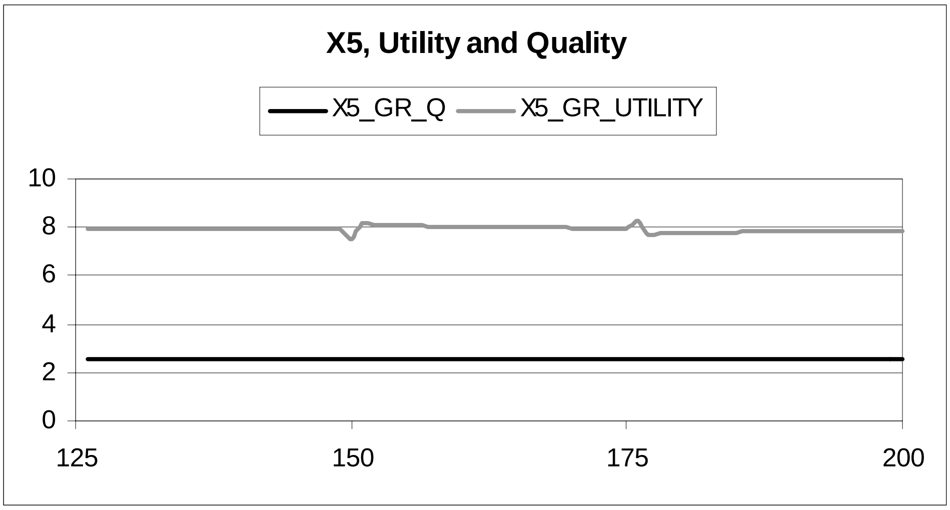

Figure 5.2.13

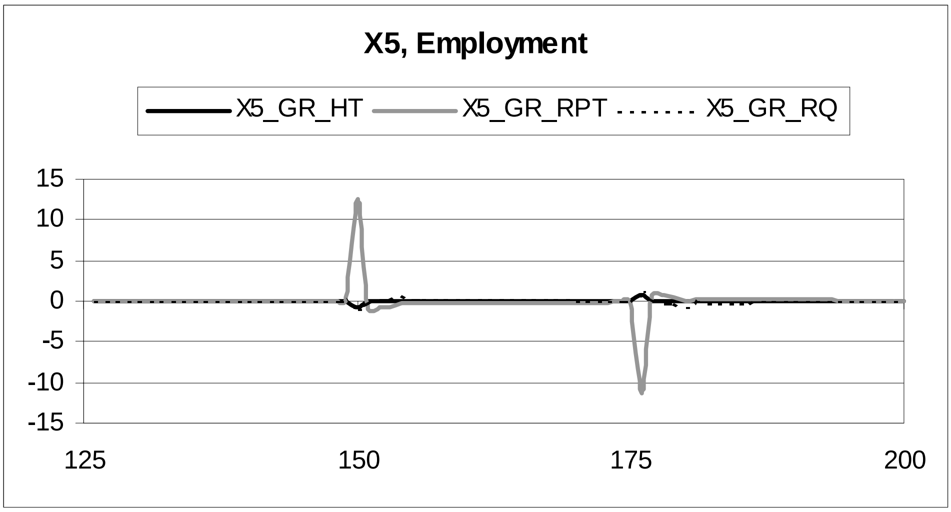

Figure 5.2.14

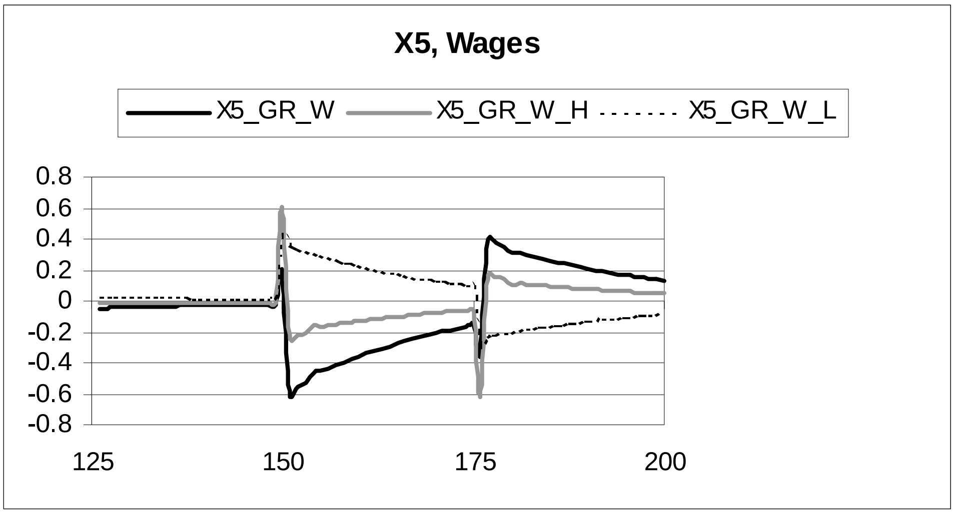

Figure 5.2.15

However, what happens to relative wages is now totally different from the previous experiment. After a one-time increase of relative wages, we notice a permanent drop of about –0.6 percentage points at the beginning of the experimental period that is reduced to about -0.15 percentage points at the end of the experimental period. The rise in the growth rate of low-skilled wages drops from about 0.4 percentage points in period 150 to about 0.1 percentage points in period 175. This improvement in the income distribution for the low skilled is solely due to the fact that the job-composition of employment changes in their favour as the result of the increased level of process R&D.

6 Concluding Remarks

In this paper we have presented the outlines of a fairly straightforward endogenous growth model that focuses on the labour market- and skill-aspects of economic policy measures that may have an impact on technological change, and hence on the effectiveness of the policy measures concerned. The link between skills and technology is two-fold. On the one hand, new technology is high-skilled intensive, while on the other hand, process R&D may actively change the skill-mix of existing production technologies in the direction of a more intensive use of least-cost production factors/skills.

The model as it is, is fairly simple. However, since it is a simulation model, it can easily be extended especially with respect to its production structure, and possibly with respect to the supply of factors of production as well. Despite its simplicity, the a priori growth reactions to parameter changes seem intuitively plausible. In addition, the simulation experiments we have performed indicate that the model, even in its present state, is able to mimic the stylised facts reported by Acemoglu (1997). In various experiments we have shown that a model containing both endogenous product R&D (directly aimed at influencing the demand-side of the economy) as well as endogenous process R&D generates an interesting interplay between both types of R&D that may have important consequences for the design of economic policy. The intricate time-patterns in particular stress the importance of taking a longer-term perspective, but perhaps more importantly, they also underline the need to follow an integrated approach regarding macro-economic and technology policy design.

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Appendix A. The Determination of the Level of Process R&D

Note that *RHS* in equation (15) is a parabola which reaches a minimum value equal to zero for positive *Ri,* at least if the effective rate of discount is positive, as we have assumed it to be the case and if the wage premium increases. If we represent the effective rate of discount by ρ^e equations (15.A) and (15.B) can be represented as follows:

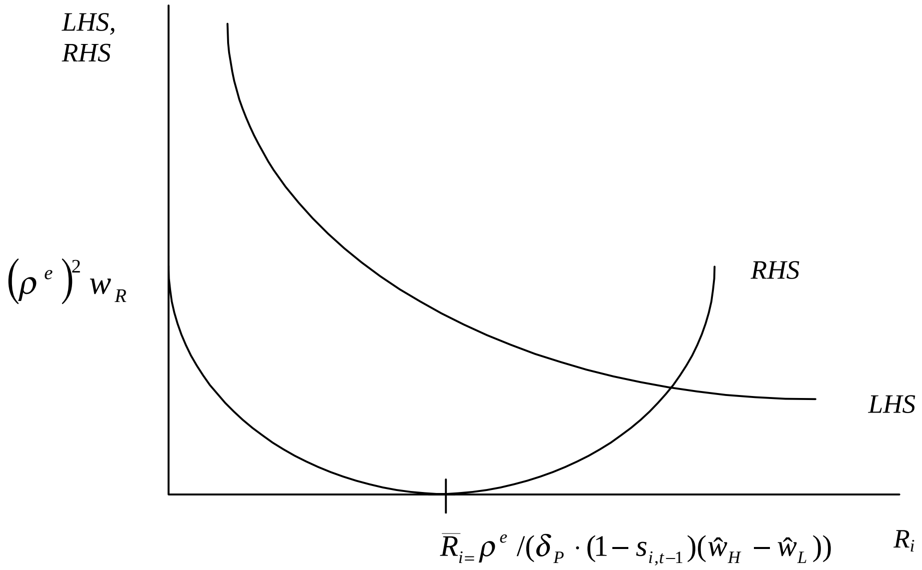

Figure A.1

There are two important variations on this Figure. If the wage premium does not grow, then *RHS* is actually a horizontal line, the height of which is given by $(\rho^e)^2 w_R$. The conclusions regarding the way in which R_i reacts to changes in the parameters that we drew earlier follow immediately. A more interesting possibility is one where *LHS* drops sharply below *RHS* for values of R_i to the left of the minimum of *RHS*. Then the graphs of *LHS* and *RHS* would have three points of intersection, representing three equilibrium allocations. The outer ones would be stable, in the sense that a small deviation from equilibrium would lead to automatic adjustment towards the equilibrium. The middle one would be unstable, since a deviation to the left would lead to marginal benefits from *R&D* being smaller than marginal costs and hence to a further fall in the level of *R&D* activity. The opposite goes for a positive deviation. So, we have in this case a low growth trap as well as a high growth equilibrium. The latter could be reached from the low-growth trap by pushing the economy (through temporary R&D subsidies, for instance) past the unstable equilibrium in the middle.

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