Demand Pull and Technology Push Effects in the Quality Ladder Model

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Abstract:

This paper extends the standard quality ladder model of innovation and quality growth by allowing for heterogeneous industries. This enables us not only to deal with the Schumpeterian hypothesis about market power and innovation, but also to analyze industry specific demand pull and technology push effects. In accordance with the empirical evidence, we show that perspective of large market power, favorable technological opportunities and high demand expectations as well as the economy-wide endowment with qualified labor, unambiguously spur innovative activity.

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1. Introduction

Since the early nineties, endogenous growth theory, as developed by Romer (1986), Lucas (1988) and Barro (1990), was substantially enriched by the so-called Schumpeterian growth models which decisively build on stochastic innovation processes as the engine of market evolution and growth. In contrast to the former models, the quality ladder approach not only explains innovation and growth by intentional R&D activities of private firms, but also formalizes Schumpeter's (1942) vision of a continuing process of creative destruction due to old products becoming obsolescent when new products with higher qualities appear. Aghion, Howitt (1992) were among the first to develop the theory of repeated quality improvements by incorporating an endless sequence of successive patent races, as introduced by Loury (1979) and Lee/Wilde (1980) in Industrial Organization theory, into a dynamic general equilibrium model of innovation-based growth. In this model, technological progress results from a stochastic process of vertical product improvements along a given 'quality ladder'. Since there is only one economy-wide quality ladder, all goods' sectors are synchronized and can thus be treated like a single industry. For this reason, the model is appropriate when analyzing stochastic growth and cycles on the macro level, but it is not suitable to account for industry specific effects of market power, demand expectations or technological opportunities in the multitude of existing industries. This shortcoming would not be more than a justified simplification if the basic conditions in different industries were similar. There is, however, overwhelming empirical evidence in the Industrial Organization literature that the innovative behavior of firms varies in a fundamental degree across industries and that basic industry conditions such as demand, opportunity and appropriability measures explain more than the half of the inter-industry variance (see, e.g. Cohen et al. 1987). Thus, a crucial condition for a descriptive model of innovation-based structural change and growth is a more disaggregated structure of industry sectors.

The multi-sectoral model of Grossman/Helpman (1991a,b), which will be called the standard quality ladder model in the following, fulfills this condition.[1] In contrast to the Aghion/Howitt (1992) model, it is characterized by a continuum of industry sectors and, hence, a continuum of quality ladders. This generalization of the sectoral structure is, however, not motivated by the desire to introduce heterogeneous industries, but rather to generate a smooth and deterministic time path of economic growth which is comparable to the corresponding dynamics of the predecessor models of endogenous growth. In fact, as Stokey (1995) has

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[1] Valuable extensions of the standard quality ladder model are provided e.g. by Segerstrom/Anant/Dinopoulos (1990), Segerstrom (1991), Jones (1995), Stokey (1995), Davidson/Segerstrom (1998) and Cheng/Tao (1999).

already noted, this kind of generality is rather illusory, since the sectors operate completely independently and the aggregated R&D behavior is again exactly that of a one-sector economy. In addition, the distribution of consumer expenditures as well as firms' R&D activities turn out to be uniform across industries. These implications are again in sharp contrast to the empirical findings.

The present paper therefore aims to extend the standard quality ladder model by allowing for sectoral heterogeneity and to derive some testable results about the determinants of innovative activities at the industry level. According to the neo-Schumpeterian hypotheses, as summarized e.g. in Kamien/Schwartz (1982), Cohen/Levin (1989) and Cohen (1995), the set of determinants should include at least market power effects, demand pull effects and technology push effects. The standard model includes expected market power and technological opportunities as essential determinants of the innovation process but – as noted above – only within a symmetric treatment of all industries. Demand pull effects are completely neglected. The extended model presented in this paper captures industry heterogeneity and is therefore able to describe the evolution of the structure of an economy as the result of industry specific innovation processes which themselves depend on some basic industry characteristics of the supply and demand side. Furthermore, even in this generalized quality ladder model, an explicit aggregation over industries can be performed and, therefore, the macroeconomic development can be analyzed consistently and in line with the alternative fundamental models of endogenous growth (see, e.g. the systematic treatment in Barro/Sala-i-Martin 1995 and Aghion/Howitt 1998).

The paper is organized as follows. Section 2 analyzes the structure and the dynamic time path of consumers' expenditures in the sectoral disaggregated economy and introduces the source of demand asymmetry across industries. Section 3 deals with the pricing behavior of incumbent firms and derives inter-industry differences in the firms' expected market power. Section 4 presents the disaggregated patent race approach which accounts for industry specific technological opportunities. Section 5 solves the model and identifies the determinants of R&D activities on the industry level as well as the determinants of macroeconomic growth. Finally, Section 6 concludes the paper.

2. Structure and Dynamics of Consumers' Spending Behavior

In the household sector, we assume that consumers share identical preferences according to the time separable discounted utility function

(1) $$U(C) = \int_0^\infty e^{-\rho t} \ln C(t)\, dt$$

with a unit intertemporal elasticity of substitution where ρ is the common rate of time preference and

(2) $$\ln C = \int_0^1 s(j) \ln\left[\lambda^{m(j)} q(j)\right] dj; \qquad \int_0^1 s(j)\, dj = 1,$$

represents the flow of instantaneous utility where q(j) denotes the quantity and s(j) the partial utility elasticities of consumer goods in each industry j. As in the standard model, we assume that there is a continuum of consumer goods indexed by $j \in [0,1]$. However, we extend the model by removing the restriction s(j)=1 ∀ j, i.e., we allow for an asymmetric demand structure in the economy in order to analyze demand pull effects below.

Each product can potentially be produced in a countable-infinite number of qualities. The quality grades of the goods are arrayed along the rungs of an industry-specific quality ladder. Each new generation of the goods in industry j provides a λ(j) times higher quality, where the λ(j)>1 are assumed to be exogenous and fixed over time but may differ between industries, while the standard model imposes the restriction λ(j)=λ ∀ j. The quality improvements result from successful innovative activities undertaken in a separate R&D sector to be characterized below. If the lowest quality available at time t=0 is normalized to one, the highest available quality of good j is given by $\lambda(j)^{m(j)}$, where m(j) = 0,1,2,... denotes the number of sequential quality improvements in industry j up to the present. At each moment in time, the highest quality levels in all industries define the technological state-of-the-art.

Each household is endowed with one unit of labor and maximizes discounted utility subject to its dynamic budget constraint

(3) $$\dot{A} = rA + w - E,$$

where A denotes the value of asset holdings, r is the certain return on consumers' portfolio, w is the wage rate for labor, and

$$E = \int_0^1 p(j) q(j)\, dj$$

represents the flow of spending where p(j) is the price of product j. As usual, the maximization problem is solved in two stages. In the second stage, consumers maximize instantaneous utility at time t subject to a given level of expenditures E. This yields the static industry demand functions

(4) $$q(j) = s(j)E / p(j).$$

Substituting these demand functions into (1) and (2), the consumers' first-stage maximization problem is solved by choosing the dynamic time path of E(t) subject to (3). Solving this intertemporal optimization problem yields the well-known Keynes-Ramsey rule

(5) $$\dot{E} / E = r - \rho.$$

Because of the homothetic preferences, (5) applies not only to each representative consumer, but also to the aggregate economy when E denotes aggregated spending.

3. Limit Pricing of Incumbent Firms

On the production side, the economy is endowed with the single input factor labor. In all industries, one unit of labor is needed to manufacture one unit of the consumer good, regardless of quality. Thus, an industry leader whose technology is assumed to be perfectly protected by an infinitely lived patent, will set a price sufficiently below the monopoly price so that the closest follower cannot compete without realizing negative profit flows. It is shown in the standard model that industry leaders undertake no research targeted to improve the quality of their own products because the incremental gain of a two-step quality advantage to an incumbent is strictly smaller than the gain of a one-step quality advantage to an external innovator. This result also holds in our extended version of the model. Therefore, in each industry the optimal limit-pricing strategy is given by

$$p(j) = \lambda(j)w$$

where the magnitude of quality improvements $\lambda(j)$ obviously serves as an indicator of the market power of the incumbent firm in industry j. Thus, each industry leader can realize a corresponding profit stream

(6) $$\pi(j) = (1 - 1/\lambda(j))\, s(j)\, E$$

which depends on the aggregated spending of consumers as well as on the basic industry conditions on the supply and demand side. As will be shown below, industry profit flows do not have to be equal in a dynamic equilibrium with R&D engagement in all industries, if incumbent firms face different risks of displacement by an entrant with a higher quality product. In the general equilibrium, derived below, the expected discounted value of a firm in the research sector is zero, independent of the industry to which the R&D efforts are targeted. This implies that the innovation and hence obsolescence rates in industries with higher profit flows will be exactly compensated for either by a shorter time period of realizing this flow or by higher expected costs of R&D. The resulting inter-industry differences in the speed of the quality upgrading process are responsible for the asymmetric evolution of the economy's market structure.

4. R&D Competition of Potential Entrants

The quality of consumer goods can be upgraded by a sequence of innovations, each of which builds upon its predecessors. To produce a higher quality consumer good, a blueprint is needed. These blueprints have to be developed by innovative firms in a separate R&D sector. The lure of monopoly rents drives potential entrants to engage in risky R&D projects to search for the blueprint of a higher quality production. The first firm to develop the new design is granted an infinitely-lived patent for the intellectual property rights. This is why the competition takes the form of a patent race between rival firms. The prize for an innovation is the monopoly profit flow (6) that will last until the next success is achieved in the same industry. There is free entry into each patent race for the next quality improvement. Each potential entrepreneur may target his research efforts at any of the continuum of state-of-the-art products, i.e. it may engage in any industry. If it undertakes R&D at intensity h(j) for a time interval of length dt, it will succeed in taking the next step up the quality ladder for the targeted product with probability h(j)dt. This implies that the number of innovations in each industry follows a memoryless Poisson process with the industry specific arrival rate h(j).

The technology discovered with any innovation opens up the opportunity for all R&D firms to search for the next innovation. This implies an external spillover effect of technological knowledge since even laggard firms can equally participate in each patent race without having taken all of the rungs of the quality ladder themselves. It is only the patent protection which guarantees temporary appropriability of innovation rents. The innovation production function is approximated by a linear specification where one unit of R&D intensity, h(j), requires $\mu(j)$ units of labor $L_h(j)$ per unit of time. Thus, the number of realized innovations in each industry j follows a Poisson process whose arrival rate is given by

(7) $$h(j) = L_h(j) / \mu(j),$$

where $L_h(j)$ is the labor input in the research sector devoted to a quality improvement in industry j, and $\mu(j)^{-1}$ denotes the labor productivity of R&D and will be used as an indicator for the technological opportunities in industry j.[2] In the standard model, $\mu(j)=\mu\ \forall\ j$ is required, i.e. the R&D projects in all industries are assumed to be equally difficult and there are no inter-industry differences in the technological opportunities. At a flow R&D cost of $wL_h(j)dt$ over the time interval of length dt, each firm participating in the present patent race can attain the stock value V(j) of a successful entrepreneur who becomes the technological leader in the industry j with probability h(j)dt. Maximization of $\left[V(j)L_h(j)/\mu(j)\right]dt - wL_h(j)dt$ with respect to labor input would imply an infinite R&D investment if $V(j) > \mu(j)w$, and no R&D activity at all if $V(j) < \mu(j)w$. With free entry into the patent races the former case cannot occur. The latter case, which will be neglected in the following, implies for such industries a stationary equilibrium without any further evolution. The unique equilibrium with positive but finite R&D activities requires $V(j) = \mu(j)w$. It is convenient to choose labor as numéraire, i.e. w=1, so that the stock values of the incumbent firms are determined by

(8) $$V(j) = \mu(j)$$

in each industry. Thus, in contrast to the standard model, the shareholder values of all incumbent firms depend on the technological conditions and will usually differ between industries.

Each firm participating in a R&D race has no internal funds to finance its R&D activities and, therefore, needs to borrow or to issue equity claims. As in the standard model, we assume that innovative firms finance their R&D investments by issuing equity claims on a perfect financial market.[3] These claims pay nothing if the firm's R&D effort fails but yield the profit stream (6), being paid out continuously as dividends, if the firm succeeds in winning the patent race and takes over the industry leadership, until it will itself be replaced by the next entrepreneur in that industry. According to (8), the value of an incumbent firm remains constant as long as the R&D efforts targeted at its industry fail. This event occurs with probability $(1 - h(j)dt)$ in the time interval dt. With probability $h(j)dt$, however, one of the targeted innovation efforts will succeed, the leader will be replaced by an entrepreneur, and

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[2] By extending the basic quality ladder model, Jones (1995) and Stokey (1995) use more general forms of the innovation production function which allow for non-constant returns to scale in R&D. In such specifications, the scale elasticity can be used as an indicator for technological opportunity.

[3] This means that all moral hazard and adverse selection problems which certainly exist when young firms attempt to raise capital funds for risky R&D investments, are completely neglected.

the equity owners will suffer a total capital loss of V(j). Taking the limit as time length dt goes to zero, the no-arbitrage condition in each industry j can be written as

(9) $$\pi(j) - h(j)V(j) = rV(j).$$

Arbitrage in the financial market ensures that the expected rate of return r(j) to the equity owners of an incumbent firm in industry j equals the instantaneous interest rate r on a riskless bond which will turn out to be constant over time. Since research outcomes in the different industries are by assumption uncorrelated, the risks in all industries are idiosyncratic. Therefore, shareholders can earn a riskless return by holding a well-diversified portfolio of shares of firms in the continuum of industries, whereby the portfolio rate of return equals the expected industry specific rates of return.

Substituting (6) and (8) into the no-arbitrage equation (9) yields

(10) $$(1-1/\lambda(j))s(j)E - \mu(j)h(j) = r\mu(j).$$

To close the model, we finally use the labor market clearing condition

(11) $$L = \int_0^1 s(j)E/\lambda(j)\,dj + \int_0^1 \mu(j)h(j)\,dj$$

where the first integral on the right hand side reflects aggregated employment in the manufacturing sector, as can be seen from (4), and the second integral reflects aggregated employment in the R&D sector, as can be seen from (7). According to (11), the only stationary allocation of labor resources implies $\dot{E} = 0$ and thus from (5)

(12) $$r = \rho,$$

i.e. the interest rate equals the rate of time preference and, hence, is constant over time.

5. Determinants of R&D Activities at the Industry Level and Aggregated Growth

Substituting (12) into (10), integrating the resulting expression over the continuum of industries j, yields, using (11), the industry specific innovation rates

(13) $$h^*(j) = (1 - 1/\lambda(j))\ s(j)\ (L + \rho\int_0^1 \mu(j)\,dj) / \mu(j) - \rho\,.$$

In the special symmetric case with $\lambda(j)=\lambda$, $\mu(j)=\mu$ and $s(j)=1$ this solution equation degenerates to the corresponding equation for the standard quality ladder model of Grossman/Helpman (1991a, p. 96):

$$h^* = (1 - 1/\lambda)(L/\mu) - \rho/\lambda\,.$$

It is apparent from this symmetric solution that each industry as well as the whole economy innovate faster the larger is the endowment of the economy with qualified labor, L, the higher is the productivity of labor in R&D, μ^{-1}, the larger is the expected market power, λ, and the lower is the rate of time preference, ρ. So far, these results are certainly in concordance with the empirical facts and provide some essential determinants of innovation and growth in aggregated economy. However, the significant role of heterogeneity between existing industries is completely neglected. There is a bulk of empirical evidence in Industrial Organization literature that demand pull as well as technology push effects have large impacts on the innovative behavior of firms (see, e.g. Kamien/Schwartz 1982, Cohen/Levin 1989, Cohen 1995).

In our generalized model, we are now able to identify such industry specific effects. According to (13), large (expected) market power $\lambda(j)$, favorable technological opportunities $\mu(j)^{-1}$, and high demand expectations $s(j)$ unambiguously spur innovative activities in these industries. The first effect is one of the most fundamental hypotheses originally suggested by Schumpeter (1942). According to this hypothesis, firms require the expectation of some form of transient market power to have an incentive to invest in R&D. Correspondingly, the model implies that no innovation takes place when market power is small, but that there is a positive relationship when market power is large enough.[4] The second effect reflects the technology push hypothesis and states that the less difficult and expensive an innovation project is expected to be, the more R&D resources are invested into these projects. Among others, Geroski (1990) found a highly significant positive impact of industry specific technological opportunity on innovative activities of firms. The third effect is known as demand pull hypothesis and is one of the most reliable empirical regularities in this research area (see, e.g. Flaig/Stadler 1994). The positive effect of the economy-wide resource base, L, which is best

4 It is not easy to find an adequate empirical measure for expected market power. Many studies use for example the Herfindahl concentration index which measures, however, ex ante market power, but not the expectation of ex post market power. Moreover, the empirical results are far from clear. Most studies find a positive or an inverted-U shaped relationship between market concentration and R&D activities, but concentration contributes only little to the explanation of the variance of R&D.

interpreted as qualified labor or human capital, clearly remains. However, the impact of the rate of time preference, ρ, on the innovation rate of a market is now ambiguous. A rise in the discount rate increases current expenditures, E. If some industries are characterized by a large demand share and favorable technological opportunities, innovative activity may therefore rise in these markets.

Using (7) and recalling that we have normalized the wage rate to one, (13) can easily be transformed into an explicit solution equation for industry specific R&D expenditures as

$$L_h^*(j) = (1 - 1/\lambda(j))\ s(j)\ (L + \rho\int_0^1 \mu(j)\,dj) - \rho\mu(j)$$

which depend in the same way on the exogenous factors as discussed with the innovation rates. In contrast to the standard quality ladder model, our generalized model can obviously explain the empirical evidence that R&D expenditures differ significantly across industries. The factors determining the distribution of R&D are attributed to industry specific market power, technology opportunity and asymmetric demand conditions.

Finally, even in this generalized quality ladder model, an explicit aggregation over industries can be performed. The macroeconomic utility growth rate is given by

$$\text{(14)} \qquad \dot{C}/C = \int_0^1 s(j) \ln \lambda(j)\, h^*(j)\,dj .$$

The economy is characterized by perpetual endogenous growth. The equilibrium growth path is characterized by a stationary allocation of labor between the manufacturing sector and the R&D sector as well as constant consumer expenditures. The consumer expenditures are given by the sum of labor income, L (since w is normalized to one), and profit income $\int_0^1 rV(j)\,dj = \rho\int_0^1 \mu(j)\,dj$. Utility growth arises because of a continued quality upgrading in industry specific patent races in an ongoing process of creative destruction.

If one is interested in an explicit analysis of the determinants of macroeconomic growth, one has to impose some restrictions on the industry parameters. This is the reason why the standard model exclusively deals with symmetric industries. Imposing symmetry restrictions on the growth equation (14) yields

$$\dot{C}/C = h^* \ln \lambda ,$$

which is the well-known growth rate in the standard quality ladder model.

6. Conclusion

One of the most intriguing elements of Schumpeterian growth models is that they rely on non-competitive market structures which are, according to Schumpeter, necessary for firms to invest in risky R&D projects. The standard quality ladder model uses the patent race approach which is well established in Industrial Organization theory, to describe the stochastic dynamic process of vertical product innovations. Due to the inter-industry symmetry restrictions, however, the standard model is only suitable for analyzing macroeconomic growth, but not for accounting for industry specific effects on the supply and demand side. This paper has shown that the standard model can consistently be extended by allowing for inter-industry differences to derive some testable hypotheses about the determinants of R&D activities at the industry level.

In its fundamental formulation, the standard quality ladder model is designed to explain vertical product innovations and quality growth. But as is well-known, it can easily be transformed into a corresponding version with cost reducing process innovations (see, e.g. Taylor 1993). A continuing way to generate quantity growth instead of quality growth, which was introduced by Grossman/Helpman (1991b) and Helpman (1992) and is common today, is to reinterpret the continuum of consumer goods as a continuum of intermediate goods which are essential inputs into the final consumer goods production. In these formulations, the macroeconomic development is directly comparable to the alternative endogenous growth models. However, the industry specific effects derived in this paper continue to hold even under such modified conditions.

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