A Vintage Model of Technology Diffusion

The Effects of Returns to Diversity and Learning by Using

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Abstract

The diffusion of new technologies is a lengthy process and many firms continue to invest in relatively old technologies. This paper develops a vintage model of technology adoption and diffusion that aims at explaining these two phenomena. Our explanation for these phenomena emphasises the relevance of complementarity between different vintages (or, alternatively, returns to diversity) and learning-by-using. The model is characterised by simultaneous investments in vintages of different quality and endogenously determined scrapping of old technologies. We show that the stronger the complementarity between different vintages and the stronger the learning-by-using, the longer it takes before firms scrap (seemingly) inferior technologies.

1. Introduction

A good understanding of well-documented differences in growth and productivity performance of different countries requires an understanding of the complex process of the development and diffusion of new technologies. Relatively much effort – amongst others in the recent new or endogenous growth theory – has been devoted to endogenising the rate of arrival of new technologies emphasising the importance of R&D and human capital (e.g. Lucas 1988 and Grossman and Helpman 1991). However, a good understanding of the diffusion and adoption of new technologies is in our view at least equally important (see, for example, Jovanovic 1997). In this regard, we know that diffusion of new technologies is a lengthy process, that adoption of new technologies is costly and that many firms continue to invest in old and (seemingly) inferior technologies. The relevance of the latter phenomenon has, for example, convincingly been shown in the literature on the so-called energy-efficiency paradox; the phenomenon that firms do not (exclusively) invest in technologies that according to standard Net-Present-Value calculations yield the highest return (see, for example, Howarth and Andersson 1993, Jaffe and Stavins 1994, and Sutherland 1991). The aim of this paper is to contribute to our understanding of adoption behaviour of firms and of diffusion processes of new technologies.

The question as to why firms do not invest in seemingly superior technologies has already achieved much attention in the literature. We can categorise this literature in four groups. The first category focuses on uncertainty. It emphasises that the combination of uncertainty and some degree of irreversibility creates an option-value of waiting. Thereby, it can explain the relatively slow diffusion of new and uncertain technologies. Uncertainty can be related to the quality and performance of new technologies, the speed of arrival of new and further improved technologies, input prices of technology-specific inputs, etcetera (see, for example, Balcer and Lippman 1984, Dixit and Pindyck 1994 and Farzin et al. 1998 for work in this field). The second line of research focuses on strategic issues in technology adoption. It elaborates on the effects of (expected) rival innovation and imitation on the timing of innovation or adoption in a world characterised by spill-overs and limited appropriability (see, among others, Kamien and Schwartz 1972, Reinganum 1981 and Spence 1984). The third approach focuses on the role of learning and spillovers. Learning improves the performance of existing technologies and can have important spill-overs to the performance of other related technologies (e.g., Davies 1979, Jovanovic and Lach 1989, and OECD/IEA 2000). A final category that we can distinguish focuses on the role of vested interests. It argues that switching to new technologies (temporarily) reduces expertise and destroys rents associated with working with relatively old technologies for particular subgroups in the economy which may therefore engage in efforts aimed at keeping the old technologies in place (see, for example, Canton et al. 1999, Jovanovic and Nyarko 1994, Krusell and Ríos-Rull 1996).

In this paper we emphasise the role of learning as well as the relevance of complementarity between different vintages. Our model has four distinctive features. First, technology is embodied in physical capital. New vintages of capital are - when considered in isolation - more productive than old ones. Second, capital goods of different vintages are imperfect substitutes in production. Firms exhibit a 'taste for diversity' of vintages creating an incentive to simultaneously invest in new and older technologies. Third, firms gain expertise in a technology by using the technologies in the production process. In other words, we incorporate learning-by-using. Fourth, our model allows for the endogenous determination of the number of vintages used by firms, so we offer an economically motivated approach for the scrapping of vintages. We discuss these features more extensively when presenting the model in section 2.

There are a number of related articles in which issues of learning and technological innovation and diffusion are analysed. Without extensive discussion, we refer to, for example, Aghion and Howitt (1996), Aghion et al. (1997, 1999), Arrow (1962), Chari and Hopenhayn (1991), Jovanovic and Nyarko (1996), Parente (1994), Stokey (1988) and Young (1993a,b). The main differences between these studies and ours are that we (i) emphasise the importance of complementarity of vintages, (ii) emphasise diffusion instead of innovation and (iii) provide a supply-oriented explanation for the endogenous scrapping of old vintages (or, alternatively, the modernisation of the capital stock).

The paper is organised as follows. In section 2 we set up the basic model. This model is solved in section 3. The comparative static characteristics of the model, illustrating the importance of complementarity and learning-by-using for understanding diffusion patterns of new technologies, are presented in section 4. Finally, section 5 concludes and discusses roads for future research.

2. The model

The model that we develop is essentially a simple two-sector vintage model that is characterised by learning-by-using and 'returns to diversity'. The two sectors that we distinguish are (i) a final goods sector in which a homogeneous consumption good is produced using labour and capital and (ii) a capital goods sector consisting of (a mass of) T monopolistically competitive firms each producing a particular vintage of capital. The only factor of production in the model is labour which is used for assemblage of final consumption goods and for the production of capital or intermediate inputs.

The model that we develop can be considered as a vintage model in the sense that capital inputs used in production are heterogeneous in their productivity or quality. For simplicity, capital is assumed to be non-durable. The model can therefore also be considered as a model with heterogeneous intermediate inputs. An advantage - at least for presentational purposes - of this assumption is that the coexistence of different vintages can, by definition, not be explained on the basis of incomplete depreciation of the existing capital stock as is common in 'traditional' vintage models. The productivity of vintages depends on its date of 'invention' and the intensity with which it has been used in the past. The latter captures the relevance of learning-by-using. Furthermore, in contrast with the more traditional vintage models, our model exhibits a 'taste for diversity' of vintages. This implies that in our model firms have incentives to invest in older technologies, even if new technologies are available that are 'better' when considered in isolation. Vintages are in other words imperfectly substitutable or to some degree complementary, whereas in traditional vintage models firms only invest in best practice technologies (for example, Meijers 1994). The very reason that old and new vintages coexist in the traditional models is that once firms have incurred the (partly) sunk investment cost, it need not be optimal to replace this capital once a superior technology becomes available. By contrast, we argue that complementarity is an essential ingredient in the process of technological change and an important reason for the coexistence of different vintages. Many new technologies pass through a life cycle, in which they initially complement older technologies, and only subsequently (and often slowly) substitute for the older technologies. A number of historical examples, like for example the replacement of the waterwheel by the steam engine, illustrate the role of complementarities in this 'life cycle view' of technological change (see for example Rosenberg 1976, Young 1993b). One can argue that modern production processes consist of even more interrelated and mutually reinforcing technologies than the documented historical examples. Whereas Young (1993b) employs the idea that complementary innovation is the result of rent-seeking inventive activity on the part of innovators, we focus on the role of adopters that wish to invest in complementary technologies.

In the context of adoption of new technologies, one can think of various underpinnings - not explicitly modelled in this paper - for these complementarities. First, firms may face uncertainty about the performance of new technologies. Older more certain technologies then complement the newer ones by providing the possibility to hedge against the uncertain performance of the new technology. Second, in large firms a range of different techniques coexists and the production process may be seen as a puzzle of a large number of technology pieces. It is then reasonable that firms continually invest in improvement of distinct pieces instead of replacing the whole puzzle at once. Third, when technological improvement takes the form of additional improvement of already adopted techniques (retrofit), there is a reason to invest in older basic techniques. The formulation that we use in our model captures these ideas in a very stylized way. It is inspired by the product-variety theory which started with the seminal work of Dixit and Stiglitz (1977) and was later extended and applied by, for example, Ethier (1982), Grossman and Helpman (1991) and Romer (1990). As first proposed by Ethier (1982), we assume returns to a diversity of capital vintages (of heterogeneous quality) instead of returns to variety of consumer durables or intermediate goods.

2.1 The final goods sector

The final goods sector produces a homogeneous consumption good according to a Cobb-Douglas production function:

$$Y_t = K_t^{\alpha} L_{Yt}^{1-\alpha} \qquad (1)$$

in which Y_t represents output produced in year *t*, and K_t and L_{Yt} are the capital- and labour input in final goods production, respectively. Capital is an aggregate of vintages of capital goods. Vintages are characterised by the first year of their availability τ. The aggregate capital stock is formulated as (building on the seminal work of Dixit and Stiglitz 1977):

$$K_t = \left[\int_{t-T}^{t} \left(A_{\tau,t} K_{\tau,t} \right)^{\frac{\varepsilon-1}{\varepsilon}} d\tau \right]^{\frac{\varepsilon}{\varepsilon-1}} \qquad (2)$$

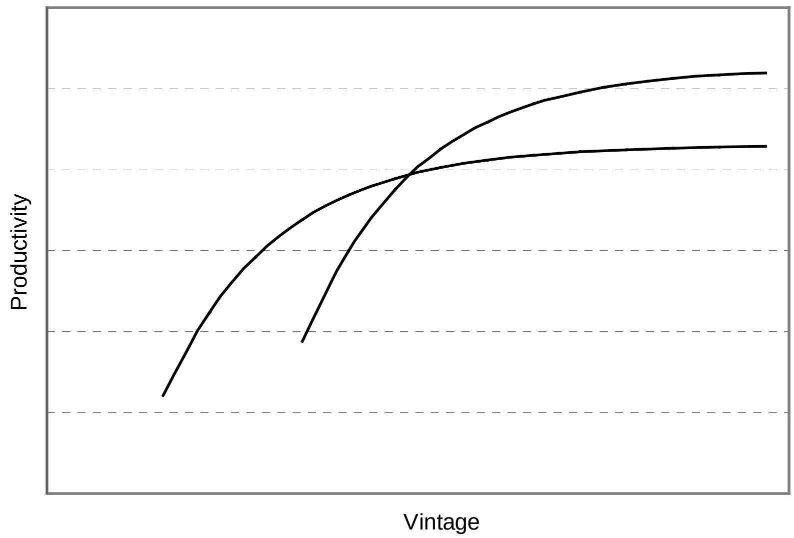
in which *T* is the (endogenous) mass of vintages in use, $K_{\tau,t}$ is the amount of capital of vintage τ used in year *t* (where $t-T \le \tau \le t$) and $A_{\tau,t}$ is a vintage-specific productivity parameter (which is where the model deviates from the standard Dixit and Stiglitz framework). Alternatively, *T* can be interpreted as the age of the oldest vintage in use. Technological change is embodied in new vintages. The elasticity of substitution between any pair of vintages (in efficiency units *AK*) is denoted by ε. Vintages are assumed to be closed but imperfect substitutes ($1 < \varepsilon < \infty$).

The productivity of vintages develops according to two factors. The first is exogenous. Newer vintages - as they are brought on the market - are more productive than older vintages when those were brought on the market. Secondly, vintages improve as they are used. Hence, the productivity endogenously depends on the cumulative investments in vintages. We further label this learning-by-using. More specifically, we assume that the productivity of vintages ($A_{\tau,t}$) develops according to

$$A_{\tau,t} = A_0 e^{g\tau} + \left[1 - (1 + aC_{\tau,t})^{\lambda-1}\right]\left(A_\tau^{\max} - A_0 e^{g\tau}\right) \qquad (3)$$

In this specification, A_0 is initial productivity, *g* is an exogenously given growth rate of the productivity of new vintages, *a* measures the strength of learning-by-using effects, C_t represents past cumulative investments in vintage τ ($C_{\tau,t} = \int_\tau^t K_{\tau,t}\, dt$), λ represents the curvature of the learning-curve and $A_\tau^{\max}$ is the vintage-specific maximum productivity level (that is, the productivity level when the technology has matured). For simplicity, we assume that $A_\tau^{\max}$ is in fixed proportion γ(≥1) to the productivity at the date of introduction of the vintage ($A_\tau^{\max} = \gamma A_0 e^{g\tau}$). In the special case in which γ=1, the learning-by-using mechanism is absent and productivity of vintages purely depends on the exogenous improvements. The assumption that 0<λ<1 implies that the productivity of a technology in the presence of learning-by-using (γ>1) gradually converges to the mature productivity level $A_\tau^{\max}$ once the technology starts to penetrate into the production process.[1] Figure 1 depicts a typical example of productivity development of two different vintages. The newer vintage (starting more to the right) is potentially more productive, but initially the old technology outperforms the new technology due to learning-by-using.

Figure 1. Productivity development with learning-by-using



[1] From equation (3) we can also determine the learning rate. This rate indicates the percentage with which the productivity increases if installed capacity is doubled. In the specification for productivity development that we have chosen, the learning rate depends – among others – on the capacity that has already been installed (C_0). More specifically, we can determine the learning rate as

$$\frac{\gamma - (\gamma - 1)\left(1 + 2aC_0\right)^{\lambda - 1}}{\gamma - (\gamma - 1)\left(1 + aC_0\right)^{\lambda - 1}} - 1$$

This learning rate is declining in C_0 so the learning rate decreases as a technology penetrates further into the economy. Learning ultimately stops as the technology reaches maturity. This pattern is broadly consistent with empirical evidence on learning rates which has convincingly shown that learning rates are – at least – kinked, that is high at low levels of penetration and low at higher levels of penetration (e.g. OECD/IEA 2000).

The above formulation captures the idea that the (potential) productivity level of a new vintage as it comes on the market at t=τ is higher than of an old vintage. For the purpose of this paper, we do not further elaborate on the innovation process that underlies the improvement of new vintages, but focus on the diffusion process. We allow for effects of learning as the product of the utilization of the technology by the final user by allowing productivity to improve with the intensity with which it has been used in the past. This learning-by-using has to be distinguished from the learning in R&D stages and learning in producing the technology, the so-called learning-by-doing (Rosenberg 1976). As a result of the presence of learning-by-using, and in accordance with broad historical evidence (see for example Mokyr 1990, Rosenberg 1976 and Young 1993a), new technologies can initially be inferior to more mature technologies. Learning-by-using improves the productivity and performance of the new technology over time and this learning can - at least initially - be so fast that it dominates the improvement of newly arriving vintages.

For the time being, we assume for reasons of analytical tractability of the model that learning-by-using is absent (γ=1). We generalise and discuss the implications of allowing for learning-by-using for diffusion patterns and adoption of technologies in section 4.2.
The behaviour of producers in the final goods sector is guided by profit-maximisation. They operate under perfect competition and a representative firm maximises profits (π):

$$\pi_t = P_{Yt} Y_t - w_t L_{Yt} - \int_{t-T}^{t} P_{K\tau,t} K_{\tau,t} d\tau \qquad (4)$$

in which P_Y, w and $P_{K\tau}$ denote the output price, the wage rate and the price of capital goods of a specific vintage, respectively (we omit time-indices if possible). Vintage capital is bought from the capital goods sector to which we turn in the next subsection.

2.2 The capital production sector

The capital production sector consists of (a mass of) T monopolistically competitive firms each producing a specific vintage according to[2]

$$K_{\tau,t} = L_{K\tau,t} \tag{5}$$

In addition, firms in this sector have to pay a fixed cost in terms of labour (L_f) before being able to produce. Firms maximise their profits according to

$$\max \pi_{\tau,t} = P_{K\tau,t} K_{\tau,t} - (L_{k\tau,t} + L_f) w_t \tag{6}$$

The model is closed by imposing labour market equilibrium which - assuming a constant and exogenous labour supply L - reads as:

$$L = L_{Yt} + \int_{t-T}^{t} \left(L_{K\tau,t} + L_f \right) d\tau \tag{7}$$

In the next section, we discuss the solution of the model, focusing on the allocation of labour and the determination of the mass of vintages used in the production process.

3. Solution of the model

At the heart of the solution procedure is the notion that the mass of vintages that is used is endogenous. Or, stated alternatively, the age of the oldest vintage in use is endogenous. To understand this intuitively, it is important to notice that newer vintages are more productive than older ones and the producers of vintages have to pay a fixed cost in terms of labour. As a result of the gradual increase in productivity of newer vintages, the (relative) demand for old vintages will gradually decline over time. The

[2] We assume that in each period, a new vintage becomes available due to an exogenous process of technological innovation (see equation 3) and only one firm acquires the right to produce capital of this particular vintage. It is of course possible to generalize here and to model a separate sector producing the brands and selling these to the firms producing the capital. In such a setting, firms in the capital production sector would be willing to buy the patent to produce the specific brand and acquire the monopoly right to produce, provided that the profits that can be earned over time are equal to the costs of the patent (compare, for example, Grossman and Helpman, 1991). Such a generalization, though interesting, would not add to the basic insights we want to emphasise in this paper.

complementarity between vintages of different age is the reason that firms do not immediately shift to the most productive vintage. At some point in time, however, the demand for a vintage becomes so low that it can no longer profitably be supplied by the producer of that vintage. Supply will stop and the vintage disappears from the market. This 'scrapping' of vintages is - in contrast with the more traditional vintage-literature - caused by the impossibilities to profitably *supply* the vintage, whereas the traditional vintage explains scrapping from the fact that at some point in time, the vintage can no longer profitably be *used* by the owner. Note that at this point the demand for this vintage is still positive but small. Our model thereby offers an alternative economically motivated approach for scrapping of vintages that differs from, for example, Den Hartog and Tjan (1980) and Malcolmson (1975).

Let us now turn to the solution of the model more formally. Producers in the final-goods sector perform a standard profit maximisation problem in two stages (maximisation of equation (4)). First, they determine the optimal relative demand for (the composite of) capital and labour. This results in the standard allocation rule for a Cobb-Douglas production function implying constant cost shares of capital and labour:

$$\frac{K_t P_{Kt}}{L_{Yt} w} = \frac{\int_{t-T}^{t} K_{\tau,t} P_{K\tau,t} d\tau}{L_{Yt} w} = \frac{\alpha}{1-\alpha} \tag{8}$$

in which P_K is the price index of the composite capital good. In the second stage, they decide on the optimal amount of capital of each vintage by solving the following maximisation problem:

$$\max_{K_{\tau,t}} \left[\int_{t-T}^{t} \left(A_{\tau,t} K_{\tau,t}\right)^{\frac{\varepsilon-1}{\varepsilon}} d\tau \right]^{\frac{\varepsilon}{\varepsilon-1}} \quad s.t. \quad \int_{t-T}^{t} P_{K\tau,t} K_{\tau,t} d\tau = P_{Kt} K_t \tag{9}$$

Optimisation yields a downward-sloping demand curve for capital of a specific vintage:

$$K_{\tau,t} = K_{s,t} \left[\frac{A_{\tau,t}}{A_{s,t}} \right]^{\varepsilon-1} \left[\frac{P_{K\tau,t}}{P_{Ks,t}} \right]^{-\varepsilon} \tag{10}$$

The relative demand for two vintages of different age thus depends on their relative productivity and their relative prices. This relative demand will be more responsive to productivity differences, the easier the vintages can be substituted for each other.

Producers in the vintage production sector maximise their profits (equation (6)) subject to the downward-sloping demand curve for the vintage that they produce (equation (10)). This results in standard mark-up pricing, according to which the producers of vintages put a mark-up over labour costs.:

$$\frac{\partial \pi_{\tau,t}}{\partial L_{K\tau,t}} = 0 \quad \Leftrightarrow \quad P_{K\tau,t} = \frac{\varepsilon w_t}{\varepsilon - 1} \tag{11}$$

The mark-up is larger the larger the complementarity between different vintages (i.e., the smaller ε).

This basically concludes the description of behaviour of firms in our economy. The model is subsequently solved by essentially determining the mass of vintages that can be sustained in the economy (that is, the age of the oldest vintage that can be sustained). For this, we first need to determine the allocation of labour over the production or assemblage of final goods and the production of vintages, respectively. Using the fact that cost shares of capital and intermediates are constant, we can determine the allocation of labour. Using equations (5), (8) and (11), we derive that :

$$L_{Yt} = \frac{(1-\alpha)\varepsilon}{\alpha(\varepsilon - 1)} \int_{t-T}^{t} L_{K\tau,t} \, d\tau \tag{12}$$

This expression reveals that more assemblage labour will be used relative to labour used for producing vintages, the smaller the share parameter in the production function of final goods and the lower the elasticity of substitution. The latter is caused by the fact that a low elasticity of substitution results in relatively high prices of vintages due to mark-up pricing and results in a shift from capital to labour in final goods production. Substituting this expression in the labour market equilibrium (equation (7)) and rewriting yields an expression for labour use in production of vintage capital:

$$\int_{t-T}^{t} L_{K\tau,t} \, d\tau = \frac{\alpha(\varepsilon - 1)}{\varepsilon - \alpha} \left[L - \int_{t-T}^{t} L_f \, d\tau \right] \tag{13}$$

Firms in the capital production sector continue to produce their specific vintage as long as this is profitable. So they produce as long as

$$P_{K\tau,t}K_{\tau,t} \geq (L_{K\tau,t} + L_f)w_t \qquad (14)$$

Using the production function for vintages and mark-up pricing (equations (5) and (11)), this expression can be rewritten (with equality) as

$$\frac{\varepsilon}{\varepsilon - 1} = \frac{L_{K\tau,t} + L_f}{L_{K\tau,t}} \qquad (15)$$

This expression basically determines the minimally required scale of operation for a producer of vintages (and hence, the minimal demand for a particular vintage that is needed for the producer of that vintage to be able to operate profitably). From (15), this minimal demand can be derived as

$$\overline{K} = \overline{L} = (\varepsilon - 1)L_f \qquad (16)$$

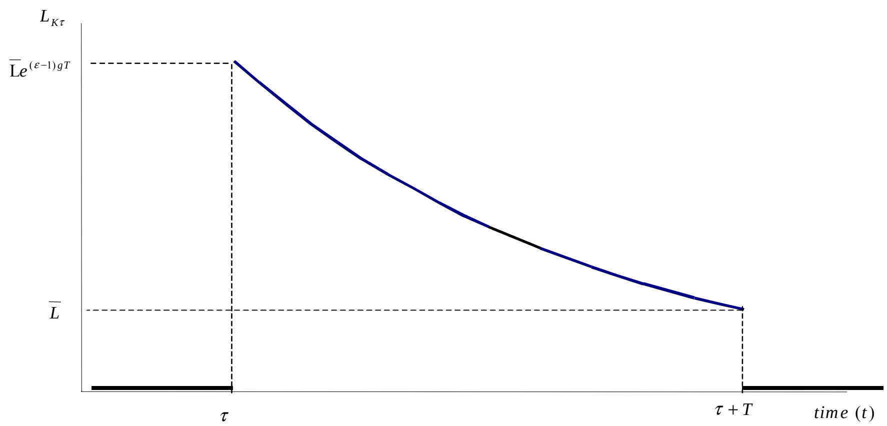
in which $\overline{L}$ is the amount of labour used to produce the oldest vintage which is in use by the final good production sector. Clearly, the minimum scale of operation or the minimal demand for a particular vintage is larger the larger the fixed cost and the larger the elasticity of substitution (and hence the lower the mark-up the producers of the vintages can charge). Any firm that would intend to produce an older vintage for which there would be less demand due to its lower productivity would make losses.

Having determined the production level of the oldest vintage, we can uniquely determine the production levels of more recent vintages which are in use by combining the expression for the relative demand for different vintages and the productivity difference between these vintages. Substituting the expressions for the price of capital (equation (11)) and the growth rate of productivity of new vintages (equation (3)) into equation (10) and rewriting yields (in the absence of learning-by-using; i.e. γ=1):

$$L_{K\tau,t} = \overline{L}e^{(\varepsilon-1)g(\tau+T-t)} \qquad (17)$$

Figure 2 graphically illustrates this expression by displaying the production of one particular vintage (arriving on the market at t=τ) over time. Expression (17) reveals that in the presence of exogenous improvements of the performance of newer vintages (g>0), more labour is used for the production of more recent vintages (higher τ). The effect of improvement of performance on (relative) labour use is reinforced when the degree of complementarity among vintages declines. In the special case in which g=0, vintages are equally productive and we end up with a symmetric solution of the model).

Figure 2. Production of one particular vintage over time



The total amount of labour used for the production of vintages thus equals (using equations (16) and (17)):

$$\int_{t-T}^{t} L_{K\tau,t}\,d\tau = \int_{0}^{T} \bar{L}e^{(\varepsilon-1)g\tau}\,d\tau = \frac{\bar{L}\left[e^{(\varepsilon-1)gT}-1\right]}{g(\varepsilon-1)} = \frac{L_f\left[e^{(\varepsilon-1)gT}-1\right]}{g} \qquad (18)$$

Combining equations (13) and (18) we can now solve for the mass of vintages that can be sustained in the economy (or, alternatively, the age of the oldest vintages in use). This solution for T is given by the following implicit function:

$$(\varepsilon-\alpha)L_f\left[e^{(\varepsilon-1)gT}-1\right] = \alpha g(\varepsilon-1)\left[L-TL_f\right] \qquad (19)$$

The comparative static characteristics of the model will be discussed in the next section.

4. Comparative static characteristics

The aim of this section is to illustrate the comparative static characteristics of the model. This is mainly done by relying on a graphical method that enables us to both illustrate the solution of the model as it was discussed in the previous section and the comparative static characteristics. In section 4.1, we will discuss the importance of the degree of complementarity between different vintages for understanding the adoption and diffusion of new vintages. In section 4.2, we elaborate on the importance of learning-by-using. This is done by generalising the productivity development of vintages, as it was introduced in section 2.

4.1 The effects of complementarity

The degree of complementarity is captured by the elasticity of substitution between the vintages. The consequences of an increase in the elasticity of substitution (that is, a lower degree of complementarity) can best be understood by dividing the total effect into three components. Note that we assume the learning effect to be absent. First, increased substitutability reduces the mark-up that producers of intermediates can charge. Consequently, the minimal demand required for these producers to operate profitably increases. Secondly, increased substitutability implies that the relative demand for vintages is more responsive to increases in productivity of newer vintages. Finally, the increased substitutability lowers the price of intermediates relative to wages. As a consequence, firms in the final goods sector will, ceteris paribus, increase their demand for intermediates. These three effects can be illustrated graphically. This is done in Figure 3.[3]

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[3] Figure 3 is based on a discrete version of the model with the following parametrization: α=0.6, w=1 (numeraire), g=0.05, A_0=1, L=300, L_f=2, and γ=1. The elasticity of substitution is equal to ε=6.87 in the low-complementarity case and ε=5.25 in the high-complementarity case. This results in T=6 and T=8, respectively. Details on the numerical analysis are available upon request from the authors.

Figure 3. Demand for vintages of different age at one point in time - the no-learning case

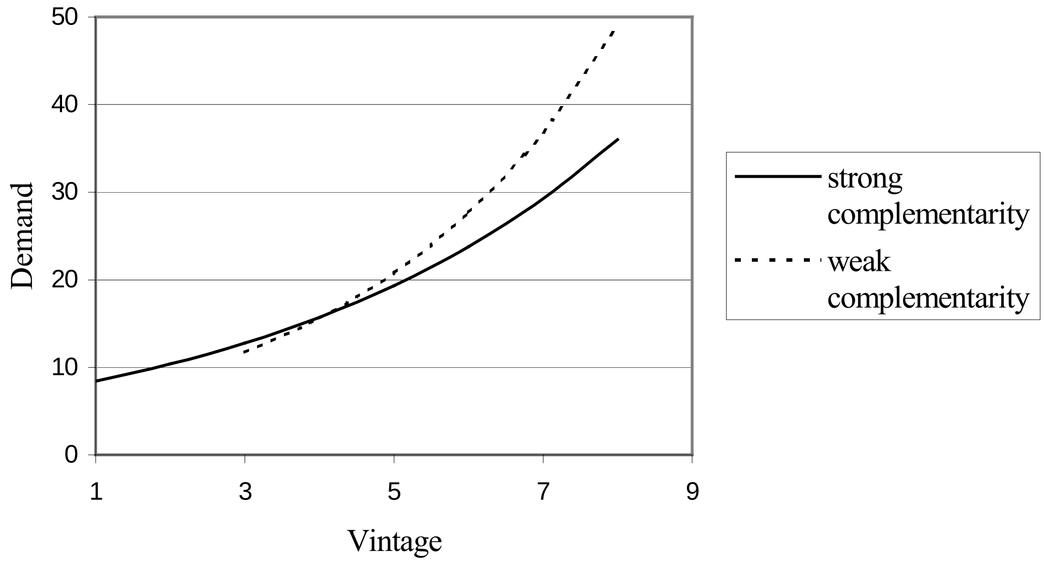

Figure 3 depicts the demand for vintages of different age (on the vertical axis) as a function of the date of introduction on the market (on the horizontal axis). The most recent (current) vintage is located most to the right in the figure. The figure can be understood as follows. Consider first the case in which the elasticity of substitution is low (i.e., complementarity between different vintages is strong). The upward slope of the demand curve reflects the fact that newer vintages (located more to the right) are more productive and consequently have a higher demand. The demand for the oldest vintage is given as the minimal required demand as defined in equation (16) and is represented by the lowest point on the demand curve. The surface below the demand curve is equal to the amount of labour that is available for the production of vintages as it is given in equation (13). Combining these three elements yields a unique solution of the model that is essentially characterised by the age of the oldest vintage.

Let us now consider what happens when the elasticity of substitution increases (i.e., the degree of complementarity declines). In terms of the figure, the minimal required demand increases. This, ceteris paribus, implies a reduction of the equilibrium number of vintages. Secondly, the demand curve gets steeper as users of the vintages become more responsive to productivity differences. Ceteris paribus, this also implies that the equilibrium number of vintages that can be sustained in the economy declines. Thirdly, producers of final goods shift their input towards capital as capital becomes relatively cheap. This is reflected by an upward shift of the demand curve. This effect works opposite to the two previous effects and implies that more vintages can be sustained. However, the former two effects dominate for reasonable parameter values[4] and increased substitutability reduces the number of vintages that can be sustained. Complementarity thus slows down the rate of modernisation of the capital stock.

4.2 The effects of learning-by-using

In the previous section, we have assumed the learning-by-using effect to be absent (γ=1). We will now drop this assumption and assume that productivity of vintages initially increases at a relatively fast rate when the vintage is introduced in order to slow down at later stages and to mature (γ>1 and λ<1). Empirical evidence seems to suggest that indeed the initial learning rate can be quite strong (Argote 1999 and McDonald and Schrattenholzer 2000). This would suggest that situations can arise in which productivity of vintages that have been introduced some periods ago exceeds productivity of vintages that have been introduced more recently. This possibility was already illustrated in Figure 1. The implications of such developments of productivity should now be relatively easy to understand. The productivity development as suggested in Figure 1 implies that there is a vintage of intermediate age that is characterised by the highest productivity. Older vintages are less productive since their learning-by-using potential has declined (or, in other words, those vintages have matured), whereas newer vintages have not yet matured and experienced the productivity improvements due to learning-by-using. The implications of such developments for the diffusion of new technologies are illustrated in Figure 4. This

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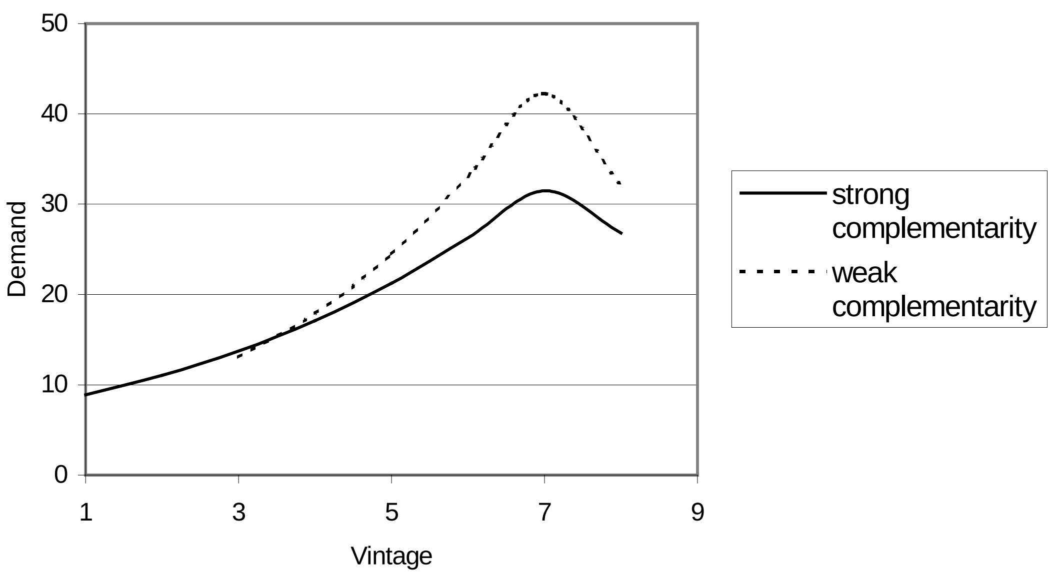
4 This conclusion is based on extensive simulations with the model. The details are available upon request from the authors. Applying the implicit function theorem on equation (19), we derive that the age of the oldest vintage declines with an increase in the degree of complementarity if

$$L_f\left[e^{(\varepsilon-1)gT}\left(1+(\varepsilon-\alpha)gT\right)+\alpha gT-1\right]>\alpha gL$$

figure is comparable to Figure 3, but now learning-by-using is included.[5] Clearly, new vintages are initially demanded at a relatively limited scale due to their low productivity, but as they improve due to learning-by-using they will be demanded more in order to subsequently be gradually phased out of the production process as the vintage matures and ultimately becomes obsolete. Based upon the similar logic as explained in section 4.1, a higher elasticity of substitution will result in fewer vintages being used in the production process and at the same time stronger responses to differences in productivity levels between vintages of different age.

Figure 4. Demand for vintages- the effects of learning-by-using



[5] Figure 4 is based on a discrete version of the model with the following parametrization: α=0.6, w=1 (numeraire), g=0.05, A_0=1, L=300, L_f=2, γ=1.25, a=0.2 and λ=0.5. The elasticity of substitution is equal to ε=5.5 in the low-complementarity case and ε=5.25 in the high-complementarity case. This results in T=6 and T=8, respectively. Details are available upon request from the authors.

5. Conclusion

The widespread adoption and diffusion of new technologies is a lengthy and costly process. In this paper we developed a vintage model to study the diffusion of new technologies and to explain why diffusion is gradual and firms continue to invest in seemingly inferior technologies. A key characteristic of our model is that vintages are complementary; there are returns to diversity of using different vintages. We have argued that this is a potentially relevant part of the explanation for why firms continue to invest in older technologies when newer ones are available. Furthermore, we showed that this effect is intensified when we take a learning-by-using effect into account. The loss of expertise - gained by using a particular vintage and building up experience - which a firm suffers from when switching to a newer vintage provides an extra argument for firms to invest in older vintages. Another important characteristic of the model is the endogenous determination of the number of vintages that is used in the production process. In our analysis we show that the stronger the complementarity between different vintages and the stronger the learning-by-using effect, the longer it takes before firms scrap (seemingly) inferior technologies. Decreased complementarity (or, alternatively, increased competition) in other words speeds up the modernisation of the capital stock.

Clearly, the simple model developed in this paper could be extended in a number of interesting directions. First, we can allow for the endogenous determination of the rate of learning-by-using and the rate of improvement of new vintages. We refer here to Aghion and Howitt (1996) for such a kind of analysis, drawing a distinction between research (developing new vintages) and development (improving existing vintages). Secondly, we intend to introduce a second factor of production, energy, in order to use the model to shed light on the so-called energy-efficiency paradox referred to in the introduction of this paper (e.g. Jaffe and Stavins 1994). Finally, we intend to allow for the incomplete depreciation of capital in order to assess the importance of complementarity in understanding the development of the stock of capital of different vintages and the investment behaviour of firms.

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