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Technological diffusion patterns and their effects on industrial dynamics

By

Machiel van Dijk and Önder Nomaler
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Machiel van Dijk[†]
Önder Nomaler[†]

Maastricht Economic Research Institute
on Innovation and Technology
P.O. Box 616
6200 MD Maastricht
Netherlands

Tel: ++ 31 43 388 3870

m.vandijk@merit.unimaas.nl

o.nomaler@merit.unimaas.nl

Abstract

By focussing on cumulateness and spillover effects of technological knowledge, theories on technological regimes are predominantly supply side oriented in explaining industrial dynamics. This paper introduces demand side considerations as an additional explanation for industrial dynamics. Given variations in consumer preferences over quality and network sizes of technologies, and different degrees of compatibility between succeeding technologies, we investigate how the resulting differences in the timing and frequency of new technology adoptions effect the industrial dynamics. The simulation results of the model indeed suggest a relationship between different patterns of new technology adoptions and the dynamics of the firm population.

Keywords: technological knowledge, demand, consumer preferences, industrial dynamics

JEL: O31, O14, C15

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1. Introduction

By focussing on cumulateness and spillover effects of technological knowledge, theories on technological regimes are predominantly supply side oriented in explaining industrial dynamics. For instance, low cumulateness and high spillover conditions facilitate the entry process and impede the persistence monopolistic advantages (Breschi et al., 1996; Malerba and Orsenigo, 1996). If such conditions apply to the technological regime of an industry, these theories predict a highly dynamic firm population with a low level of concentration. Hence, causality runs from properties of the technological knowledge base of suppliers to the demographic characteristics of the population they constitute. This paper aims to introduce demand side considerations as a complementary explanation for industrial dynamics.

As in Shy (1996), the degree of substitutability between the quality and the network size of a technology and the degree of compatibility of succeeding technologies are the key determinants of the simulation model presented here. However, Shy (1996) mainly limits his focus to the demand side, as he investigates how varying consumer preferences over technology advance and network size effects the timing and frequency of new technology adoption. Our focus is on the relation between the demand side and the supply side. Given variations in consumer preferences over quality and network sizes, and different degrees of compatibility between succeeding technologies, we investigate how the resulting differences in the timing and frequency of new technology adoptions by consumers effect the dynamics of the population of supplying firms. Furthermore, we will investigate whether these effects are different under various technological regimes.

The structure of the paper is as follows. In the next section the conceptual basis for the model will be explained, and special attention will be paid to how we modelled firm growth. Section three formally presents the simulation model, of which the results will be analysed in section four. Section five focuses on how these results are effected when different technological regimes are considered. Section six concludes this paper.

2. The conceptual basis

As mentioned in the introduction, the primary aim of the present model is to investigate how differences in the diffusion of new technologies affect the dynamics of the population of firms in an industry. Shy (1996) explains the differences in timing and frequency by differences in consumer preferences. In his model, the generation of entering consumers chooses whether to purchase a certain product based on an old technology already used by an older generation of consumers or whether to purchase the product based on the new technology with a higher quality. The young generation chooses the new technology if the utility

from the high quality technology combined with the size of the network associated with the new technology overtakes the utility from the old technology with its associated network size. The size of the network of the new technology is the sum the population size of the young generation and a certain percentage of the old generation of users. This percentage is determined by the degree of compatibility between the old and new technology. Hence, the higher the compatibility, the larger the network size associated with the new technology will be. Shy (1996) then shows that a decrease in the degree of compatibility between new and old technologies will increase the duration of each technology. Further, by varying the degree of substitution between the quality and the network size of a technology, he shows that the duration of each adopted technology is lower and the frequency of technology adoptions is higher the more consumers value quality and network size as substitutes rather than complements.

Hence, his focus on consumer preferences helps us understand “...*why technology is replaced more often in some industries than in others...*” (Shy, 1996, p.786). He also asserts that his model is general enough to capture a variety of market structures. That is, he shows that both a persistent monopoly, as well as a more competitive market structure with the entry of a new firm whenever a new technology becomes available¹, is consistent with his model. Our aim is to further elaborate on the evolution of the supply side of industries experiencing repeated adoption of new technologies. Although previous models on technological change and industry evolution have investigated issues such as the evolution of the firm population², or the diffusion process of (subsequent) innovations³, they have not explicitly linked these two processes. The model presented in this paper attempts to fill this hiatus.

A secondary aim, or perhaps more a constraint, is that the model should preferably be consistent with the stylised facts of industrial organisation. Among these “facts” are: (i) persistence of market turbulence due to entry and exit, (ii) high infant mortality, negatively correlated with firm age, (iii) growth rates of firms that fall with age and with size, (iv) persistence of asymmetric performances, and (v) skewed and stable size distributions.

Besides these stylised facts derived from the empirical literature, two interesting observations from the Dutch manufacturing sector will be captured as well by the model. The first one is that relative labour productivity or profitability cannot explain the growth or decline of firms. There is no evidence that growing firms are more productive (or profitable) than contracting firms. Hence, there seems to be no evidence for the existence of some type of replicator dynamics. However, the second observation is that relative productivity seems to be important in

¹ Shy (1996) assumes that the new firm is endowed with a one period patent right on the new technology, allowing it to (temporarily) charge a monopoly price.

² See, e.g., Nelson and Winter (1982), Winter (1984), and Dosi et al. (1995).

³ See, e.g., Iwai (1984a, 1984b), Silverberg and Lehnert (1993), and Silverberg and Verspagen (1994a, 1994b).

explaining the probability of survival: low relative productivity practically means exit, higher productivity significantly reduces the probability of exiting. Still, even those firms with higher than average productivity levels have a fairly high probability of suddenly experiencing falling productivity, often followed by their exit from the industry.

In order to include these last two issues, we will model firm growth as a random process and therefore abstain from any type of replicator dynamics. Hence, the present model will not attempt to predict the growth process of a firm on the basis of past or current performance levels. Of course, the relative performance of a firm will matter in the model, but only in determining the probability of survival. Therefore, in this model it is really a matter of *survival* of the fittest, as opposed to *expansion* of the fittest. We have several reasons to exclude relative performance as an explanatory variable of firm growth.

The growth or decline of a firm is ultimately a managerial decision: the management decides on how much to invest and how many workers to hire or lay off. Many factors may influence the final outcome of this decision. Past performance is certainly one of them. Besides creating the necessary funds, high profits in the past are a signal of a firm's competitiveness, creating confidence among the management and the potential investors. However, high profits may also indicate a lag in mobilising effective competition, reflecting a windfall gain from being properly positioned to take advantage of a change in level or character of demand. In this last case the high profits may have resulted from mere chance, and are not likely to be as persistent as profits resulting from having been superior to competitors.

But probably more important than a firm's past competitiveness in the growth decision are the expectations of a firm regarding the state of the economy, the condition of the industry, a firm's own performance, et cetera. There are many reasons why firms may have different expectations. First of all, the prospects may differ between industries. When an industry is expected to grow rapidly, a firm will be more inclined to expand than when prospects are less optimistic for the industry. Second, firms within the same industry could have different information sets on which the decision to grow is based. Third, even if firms would have the same information, still they may perceive and interpret it differently, leading to different expectations.

Naturally, different expectations lead to different decisions. Moreover, firms may have different ambitions regarding their (ultimate) sizes or market shares. Some firms may indeed be driven by enormous ambitions and try to capture the total market as much as possible. But other firms may be less ambitious. Their aim could be to acquire a certain amount of profits, and if this goal is reached at a certain size they may decide to keep the size approximately fixed. Perhaps the desire to grow is present latently, but if it is not strong enough no serious attempts will be made to fulfil this desire. Finally, the situation on the markets for labour

and capital goods may differ across industries. A shortage of labourers with skills necessary for a specific firm probably hinders a firm's desire to expand.

Combining the potential differences in expectations, ambitions and input markets makes anticipating the growth paths of firms very difficult. As Geroski (1998) argues, the growth of a firm may very well be understood, but also be hard to describe or predict with any precision. Therefore, we will model the evolution of the size of a firm as following a random walk, however with a declining positive drift. This last property is consistent with the stylised fact that growth rates are negatively correlated to the firm's age.

After having described the two most distinguishing features of the model, i.e., its focus on the repeated adoption of new technologies in relation to the dynamics of the firm population, and the modelling of firm growth as an essentially random process, we now turn to the technical details of the model.

3. The model

Consider an industry where in each discrete time period t , $t = 0, 1, 2, \dots$, the firm population consists of $N(t)$ firms. All firms in the industry are producing a certain product that is defined by its functional characteristics. An essential assumption in the model is that the function the product performs can be based on different technologies. For instance, both the standard compact cassettes as well as the compact disc (CD) are sound recording media, however analogue recording technology underlies the compact cassette, whereas a CD is recorded by using digital technology. However, our notion of a product also extends to producer or capital goods. An example here could be industrial lathes, which can be manually operated or operated by using computer numeric control (CNC) technology.

Every period a random number of new firms enter the industry according to a Poisson process⁴ with arrival rate ρ_{ent} . At birth, each firm i is endowed with a firm-specific organisational competitiveness level λ_i , a product technology Ψ , and a size s_i . The organisational competitiveness level λ_i is a random genotype variable⁵ that sets for each firm a potential limit to its actual competitiveness, creating some (initial) heterogeneity among firms with regard to their organisational capabilities. As mentioned, this variable may limit the firm's actual competitiveness, but whether it actually does depends on its technological competitiveness that is calculated as described below.

⁴ For practical reasons, we have adopted the Poisson process here and approximated it by five hundred Bernoulli trials every period. For analytical convenience, the arrival rate is kept constant over the simulation period.

⁵ This variable is generated as follows. Let $x \sim N(\mu_\lambda, \sigma_\lambda)$. Then $\lambda_i = x$ if $x \leq \mu_\lambda$, and $\lambda_i = \max\{0; 2\mu_\lambda - x\}$ if $x > \mu_\lambda$.

Competitiveness of firms

Assume that at every period K product technologies are available. At birth, every firm is randomly endowed with a technology Ψ ($\Psi = 1, 2, K$), such that the probability of receiving a given technology is equal to $1 / (K)$. These technologies are ranked according to their intrinsic quality level Q_Ψ , such that $Q_K > Q_{K-1} > \dots > Q_1$. Also, there is a class of old technologies $\Psi = 0$ that all have an intrinsic quality level Q_0 . Every β_I periods a pioneering entrant or incumbent introduces a new, intrinsically better product technology that has become available due to exogenous technological change. This introduction causes all technologies to drop one level in their intrinsic quality. Hence, the newly introduced technology becomes K (the technology with the highest quality level Q_K), and $\Psi = 1$ becomes part of the class of old technologies $\Psi = 0$ and degrades to the intrinsic quality level Q_0 . Although firms can employ more than one product technology simultaneously, we will first explain the evolution of some essential variables for a single-technology firm.

A firm's technological competitiveness $TC_{i,\Psi}(t)$ depends on the intrinsic quality Q_Ψ of the product technology it is applying and the total share Γ_Ψ of this technology in the industry in the following way:

$$TC_{i,\Psi}(t) = \alpha \Gamma_\Psi(t) + (1-\alpha) Q_\Psi(t), \quad (1)$$

where $0 \leq \alpha \leq 1$, and $Q_0 \leq Q_\Psi \leq 1$. The parameter α is essential here, as it determines the strength of the network externalities on the demand side. The higher α , the more the total market share of a technology determines the firm's technological competitiveness.

Combining the organisational competitiveness λ_i with the technological competitiveness $TC_{i,\Psi}(t)$ gives us the potential competitiveness $PC_{i,\Psi}(t)$ of a firm, which is:

$$PC_{i,\Psi}(t) = \min \{ TC_{i,\Psi}(t) ; \lambda_i \}. \quad (2)$$

Hence, a firm's potential competitiveness is either bounded by its organisational or its technological competitiveness. We could have modelled organisational and technological competitiveness as (imperfect) substitutes, but this would have implied that, e.g., a firm with a very low level of organisational competitiveness may still survive as long as it has a high level of technological competitiveness. We believe that such a situation is not realistic, as firms will always need a certain level of organisational skills in order to manage the manufacturing and selling of their products. Furthermore, by modelling organisational and technological competitiveness as complementary, we exclude in advance the awkward possibility that the organisational and technological skills of the firms will be

negatively correlated in the simulation results.

Finally, a firm's actual competitiveness $C_{i,\psi}(t)$ evolves according to the following moving average process:

$$C_{i,\psi}(t) = \theta C_{i,\psi}(t-1) + (1-\theta) PC_{i,\psi}(t), \quad (3)$$

where $0 \leq \theta \leq 1$, and $C_i(t) = \beta_2 \lambda_i$ for all firms that enter at period t . The system parameter β_2 puts an entrant at an initially disadvantageous and possibly even dangerous position. To some extent such an entry process corresponds to Jovanovic (1982). Even firms with very low competitiveness levels may decide to enter the industry, simply because they do not know their true competitiveness prior to their entry. Only by actually entering they can gather some evidence regarding their real capabilities, which may subsequently eventuate in a rapid exodus of entrants with low competitiveness levels. It is also consistent with the empirical evidence on the entry process.⁶

Exit rules

If the actual competitiveness is below a certain fraction Φ_L of the industry average \bar{C} , or if size drops below the minimum level \hat{s} , a firm dies with probability one, a higher productivity level reduces the probability of exiting $P_{\text{exit}}(t)$. Survival is guaranteed for the next period if relative competitiveness exceeds an upper level Φ_H . Hence, we have

$$P_{\text{exit},i}(t) = 0 \quad \text{if } C_{i,\psi}(t) \geq \Phi_H \bar{C}(t) \quad (4a)$$

$$P_{\text{exit},i}(t) = \left(\frac{\Phi_H \bar{c}(t) - c_i(t)}{\Phi_H \bar{c}(t) - \Phi_L \bar{c}(t)} \right)^{\beta_3} \quad \text{if } \Phi_L \bar{C}(t) < C_{i,\psi}(t) < \Phi_H \bar{C}(t) \quad (4b)$$

$$P_{\text{exit},i}(t) = 1 \quad \text{if } C_{i,\psi}(t) \leq \Phi_L \bar{C}(t), \text{ or if } s_i \leq \hat{s}. \quad (4c)$$

These exit rules can be interpreted as a mixture of voluntary and forced exit. If relative competitiveness is lower than Φ_L , or if their size drops below the minimum level \hat{s} , firms go bankrupt and are thus forced to exit. However, for those firms that observe that their relative competitiveness lies between Φ_L and Φ_H , the exit decision is voluntary. Depending on their aspiration level, some of them may decide to continue, whereas others may voluntarily leave the industry and perhaps try their chances elsewhere.

Evolution of firm size

⁶ See Caves (1998) for an extensive overview.

As mentioned before, all firms are initially endowed with a fixed size s_i . We interpret this size as a firm's sales capacity and assume for convenience that firms always operate at full capacity. All surviving firms grow each period according to a random process, however their mean growth rates asymptotically reach zero as they mature. The process governing firm growth is

$$\frac{s_i(t+1)}{s_i(t)} = 1 + \left[\beta_4 e^{-\beta_5 a_i(t)} + \chi \left(e^{-\beta_5 a_i(t)} + \beta_6 \right) \right], \quad (5)$$

where $a_{i,t}$ denotes the age of firm i at t . The variable χ is randomly drawn from a normal distribution with mean $\mu_\chi = 0$ and variance σ_χ , β_4 sets the average growth rate of firms at the age of zero. This growth rate gradually declines as the firm matures, a process of which the pace is determined by β_5 . Finally, β_6 assures that even at a high age the size of a firm is still subject to random shocks.

Imitation

Until here, the description of the model has only considered firms employing one product technology. But, as mentioned, the model also allows for firms employing several technologies simultaneously. Let $\Psi = A$ denote the firm's *intrinsically best* technology. As long as $A < K$, a firm may have the opportunity to imitate an intrinsically better technology. Every period, firms randomly receive an imitation draw according to a Poisson process⁷ with arrival rate ρ_{im} . Receiving an imitation draw means that the firm acquires the knowledge of employing one intrinsically better technology. This process is arranged such that on average a firm with a given market share⁸ z_i would receive $\rho_{im} [z_i + \beta_7 (1-z_i)]$ imitation draws in every β_I periods, where $0 \leq \beta_7 \leq 1$. The parameter β_7 sets the inequality between firms with different sizes with regard to receiving an imitation draw. If $\beta_7 = 1$ all firms have equal probabilities to imitate, if $\beta_7 = 0$ the probability to imitate is proportional to a firm's market share.

If an imitation draw is received, the probability of acquiring the knowledge of given other product technology is equal to $1 / (K - A)$.⁹ Every firm that has obtained an opportunity reallocates every period a share $\omega_i(t)$ of its total capacity from its worst available technology $\Psi = L$ (i.e., the technology with the lowest technological competitiveness) to its best available technology $\Psi = H$ (i.e., the

⁷ Again approximated by Bernoulli trials.

⁸ By market share we mean the firm's share in the total capacity of the industry. Hence, we have $z_i(t) = s_i(t) / \sum_{N(t)} s_i(t)$.

⁹ The randomness of this process essentially reflects a bound to the agents' rationality, combined with some degree of technological uncertainty. Hence, the combination of these elements may lead to erroneous decisions of firms with regard to the allocation of their imitation efforts.

technology with the highest technological competitiveness).¹⁰ The size of this reallocation share $\omega_i(t)$ is determined by:

$$\omega_i(t) = \beta_8 [TC_{i,H}(t) - TC_{i,L}(t)] (1 + \eta), \quad (6)$$

where β_8 is a system parameter ($0 \leq \beta_8 \leq 1$), and η is a random variable¹¹ drawn from a normal distribution with mean $\mu_\eta = 0$ and variance σ_η . Hence, on average the share that is reallocated increases with the difference in the technological competitiveness between the worst and the best available product technology.

Whenever capacity is reallocated, part of it gets lost because of adjustment costs. If we denote $s_{i,L}$ as the capacity allocated to the worst product technology, $s_{i,H}$ as the capacity allocated to the best product technology, s_i as the total capacity of the firm (i.e., $\sum_{\psi=L}^H s_{i,\psi}$), and $\Delta s_i (= s_i(t+1) - s_i(t))$ as the capacity growth of the firm, we have:

$$s_{i,H}(t+1) = s_{i,H}(t) + \beta_9 \min \{ \omega_i(t) s_i(t); s_{i,L}(t) \} + \Delta s_i \quad \text{if } \Delta s_i > 0, \quad (7a)$$

$$s_{i,H}(t+1) = s_{i,H}(t) + \beta_9 \max \{ \omega_i(t) s_i(t); s_{i,L}(t) + \Delta s_i; 0 \} \\ + \min \left\{ \sum_{\psi=L}^{H-1} s_{i,\psi} + \Delta s_i; 0 \right\} \quad \text{if } \Delta s_i \leq 0, \quad (7b)$$

$$s_{i,L}(t+1) = \max \{ \min \{ s_{i,L}(t) + \Delta s_i - \omega_i(t) s_i(t); s_{i,L}(t) - \omega_i(t) s_i(t) \}; 0 \}, \quad (8)$$

where $0 \leq \beta_9 \leq 1$. This parameter arranges the fraction of the transferred capacity that gets lost whenever reallocated. Expression (7a) says that if the capacity of the firm grows, it allocates first of all its growth to the best technology. Second, the firm reallocates capacity from the worst technology according to the amount determined by (6). If this amount is not available, it takes away all the capacity that remained for the worst technology¹², and adds it to the capacity of the best technology.

Expression (7b) deals with cases of negative growth of total capacity. In such a case the firm first withdraws the change in capital from the worst technology. If that is not sufficient, it will subsequently take away capacity from the second

¹⁰ Please note that what we call here the ‘best’ technology is not necessarily the technology with the highest intrinsic quality.

¹¹ Again, bounded rationality and technological uncertainty justify the randomness of this process.

¹² For simplicity, we assume that in such a case the firm, only in that period, does not consider reallocation from the second worst to the best technology.

worst, the third worst, et cetera. Only if even the capacity of the second best technology $H - 1$ is divested, the firm will necessarily have to withdraw the remaining part of its total capacity decline Δs_i from its best technology. If, however, $s_{i,L}(t)$ is still positive after subtracting (formally adding) Δs_i , the firm will reallocate again capacity from the worst to the best technology, possible bounded by $s_{i,L}(t) + \Delta s_i$. Expression (8) gives us the amount of capacity available for the worst technology after having gone through the process of reallocation.

With regard to the competitiveness and survival probabilities, we in fact regard a firm employing more than one product technology as a ‘mother’ firm consisting of several subfirms, each of them employing one technology. The actual competitiveness of each subfirm still evolves according to (3). Hence, the organisational competitiveness of the mother firm still applies to all the subfirms. Given the reallocation rules, it may happen therefore that a firm shifts part of its capacity to a certain technology because of its higher technological competitiveness, whereas the actual competitiveness derived from this technology is still bounded by the organisational competitiveness. This can be justified in two ways. First, we could argue that in this way a firm protects itself for the long run. Somewhere in the future the technological competitiveness of the worst technology may fall below the organisational competitiveness if new technologies are introduced, in which case the technological competitiveness will be binding. In order to avoid this a firm may decide already now to transfer some capacity to the best technology. Second, we could assume that a firm only has fuzzy information with regard to its competitiveness. For instance, it may erroneously think it could perform better by switching to a better product technology.

When a firm is employing several technologies simultaneously, the actual competitiveness of the whole firm i is the weighted average of the actual competitiveness levels of all subfirms:

$$C_i(t) = \sum_{\psi} \left[\left(\frac{s_{i,\psi}(t)}{s_i(t)} \right) C_{i,\psi}(t) \right] \quad (9)$$

For the mother firm and all the subfirms the exit conditions expressed in (4) apply. In case of exit the capacity of the subfirm is totally lost, or, in case the mother firm dies, all capacity is gone.

It was already mentioned that every β_l periods a pioneering entrant or incumbent introduces a completely new technology. When this happens, all technologies that a given firm is employing drop one level in their intrinsic quality. Further, the subfirm employing $\Psi = 1$ is merged with the subfirm employing the class of old technologies $\Psi = 0$. Hence, in that period $s_{i,l}(t)$ is added to the capacity allocated to $\Psi = 0$. With regard to the actual competitiveness of the subfirm employing $\Psi = 0$ we calculate a size weighted average of the actual competitiveness levels of

the merging subfirms for that period. Since it is unlikely that, whenever a firm imitates a product technology, it could immediately fully benefit from the imitated technology, we let $C_{i,\psi}(t) = \beta_{10} \lambda_i$ for all firms that imitate technology Ψ at t .

4. Simulation results

Similar to the notion of technological regimes, we introduce the notion of technology adoption regimes to classify cases with different levels of compatibility between old and new product technologies, and different degrees of substitution between the quality and the network size of a technology. In contrast with Shy (1996) however, our concept of compatibility between technologies is not related to the notion of overlapping generations of users. In the interpretation of our model, a consumer, repeatedly buying a given product, is more willing to switch to a newer product technology if its compatibility with the old technology is higher. To use again the example of sound recording media, a consumer that wants to replace his old analogue cassette-player would be more willing to buy a digital compact cassette (DCC) player than a CD-player, simply because his previously recorded tapes can also be played on the DCC-player. Of course, in real life there are many other considerations involved, but purely for the sake of compatibility this consumer would switch easier to a DCC player than to a CD player. Or let us consider a case in which a firm is considering to switch from a manually operated lathe to a CNC operated one. If the CNC lathe requires worker skills that are very different from the skills necessary for manually operated lathes, the much more advanced CNC lathe is still lowly compatible with the old fashioned manually controlled workbench, which could seriously hinder the adoption of this new technology.

In the model, we will simulate different compatibility levels by varying the differences in the intrinsic quality levels between succeeding product technologies. High compatibility between a new and an old technology then implies a high difference in their intrinsic quality levels. For simulating various degrees of substitution between the quality and the network size of a technology, we will of course use the parameter α , which sets the relative importance of a technology's share in the market.

We will simulate three different adoption regimes, in which the number of product technologies available is equal to three ($K = 3$). The first one will be labelled 'quality regime': in this regime, quality and network size are perfect substitutes. This is arranged by setting parameter α equal to zero. Hence, technological competitiveness is only determined by the intrinsic quality of a technology. Further, in this regime new technologies are highly compatible with old technologies. This situation is obtained by setting the intrinsic quality levels as follows: $Q_3 = 1$, $Q_2 = 0.5$, and $Q_1 = 0.25$.

The second technology adoption regime, labelled 'intermediate regime' is

characterised by again perfect substitutability of quality and network size, but here new technologies are less compatible with old technologies than in the quality regime. The lower compatibility of succeeding technologies is obtained by decreasing the differences their intrinsic quality levels: $Q_3 = 1$, $Q_2 = 0.75$, and $Q_1 = 0.5$. Thus, compared to the quality regime, the second best technology is more competitive *vis-à-vis* the best technology available.

The settings of the third adoption regime (the ‘network’ regime) are such that quality and network size are to some extent complementary $\alpha = 0.5$. Further, $Q_3 = 1$, $Q_2 = 0.75$, and $Q_1 = 0.5$. Under this regime, the market share of a technology determines technological competitiveness as well. The other parameters remain constant across the three technology adoption regimes.¹³

Although the three adoption regimes we analyse here are not perfectly consistent with the cases described by Shy (1996), we can still base our expectations with regard to the outcomes of the simulations on the predictions of his model. According to Shy (1996), whenever new technologies are perfectly compatible with old technologies, the new technologies are adopted each period. Further, a decrease in the degree of compatibility between new and old technologies would increase the duration of each technology. Based on this, we may expect that the duration of a technology is higher in the intermediate regime than in the quality regime.

Further, Shy (1996) concludes that when newer technologies are not perfectly compatible with older technologies, new technologies are never adopted if consumers treat network size and technological advance as perfect complements, but may be adopted if they are treated as perfect substitutes. Therefore, we may expect from our simulations that duration will be highest under the network regime, although eventually newer technologies will be adopted, given that our parameters are not consistent with perfect complementarity between network size and quality.¹⁴ Finally, we may expect to see that not always new technologies are adopted whenever they appear in both the quality and, more likely, in the intermediate regime. In both these regimes there is perfect substitutability between quality and network size and imperfect compatibility. However, Shy’s result (of technologies being skipped occasionally under these conditions) very much relies on his notion of compatibility. Therefore, some scepticism with regard to this expectation is appropriate.

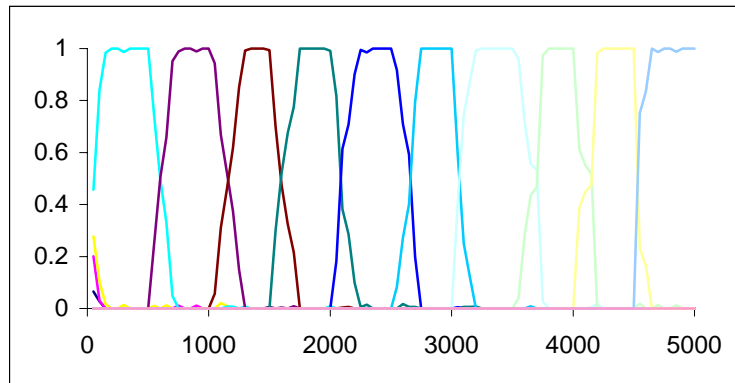
Graphs 1a to 1c show the evolution of the market share of successive product

¹³ The values of the other parameters are: $N(0) = 40$, $\rho_E = 0.15$, $\mu_\lambda = 1$, $\sigma_\lambda = 0.1$, $s_i = 250$, $\beta_I = 500$, $Q_0 = 0$, $\theta = 0.99$, $\beta_2 = 0.6$, $\Phi_L = 0.6$, $\Phi_H = 1$, $\hat{s} = 25$, $\beta_3 = 10$, $\beta_4 = 0.01$, $\beta_5 = 0.0069$, $\sigma_\chi = 0.1$, $\beta_6 = 0.01$, $\rho_{im} = 20$, $\beta_7 = 0.1$, $\beta_8 = 0.1$, $\sigma_\eta = 0.5$, $\beta_9 = 0.05$, and $\beta_{10} = 0.8$. The results of the simulations are robust to small changes in the levels of all parameters.

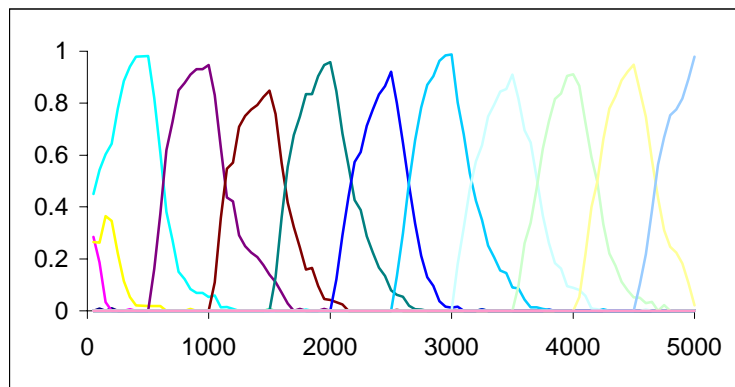
¹⁴ However, when α is set equal to one, the simulations of our model indeed show that new technologies are never adopted.

technologies for the three adoption regimes, resulting from one simulation run of 5000 periods.

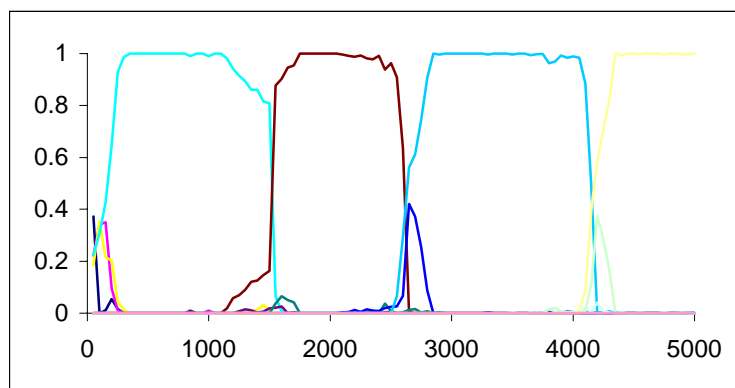
Graph 1: Market shares of successive product technologies



(a) Quality regime



(b) Intermediate regime

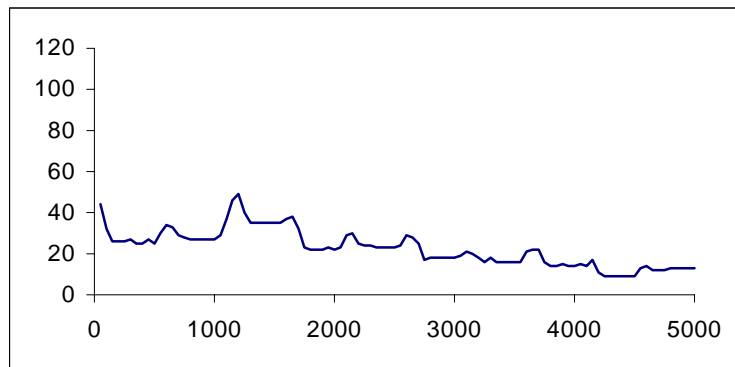


(c) Network regime

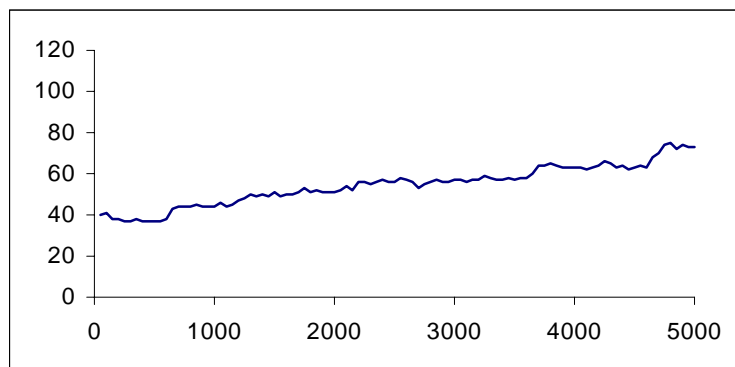
As graph 1a shows, in the quality regime technologies have a rather short life. Whenever a new technology is introduced, it quickly replaces the previous technology and starts to dominate the market until again a new technology becomes available. In the intermediate regime, the replacement process is much slower, implying a longer duration of technologies (see graph 1b). The last graph shows that, after a very short period of coexistence, one technology always

dominates the market until it becomes obsolete¹⁵, after which it is quickly replaced by a new technology that again dominates until its obsolescence. Thus, the outcomes of the simulations are fairly comparable to Shy's predictions. The duration of technologies is higher when compatibility between new and old technologies is lower. However, both under the quality regime as well under the intermediate regime, new technologies are always adopted.¹⁶ Only under the network regime new technologies are never adopted until the existing dominant technology has become obsolete.

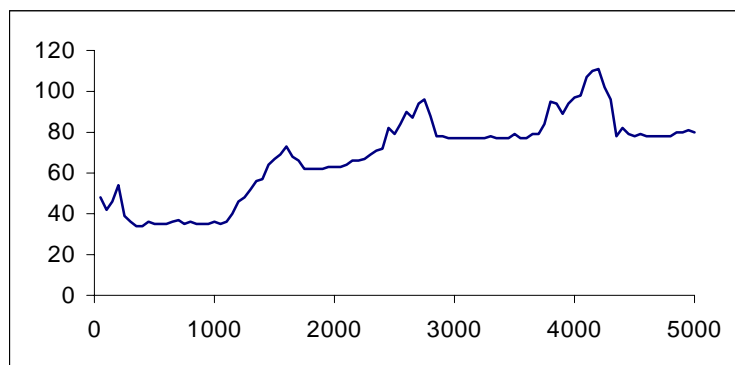
Graph 2: Number of firms



(a) Quality regime



(b) Intermediate regime

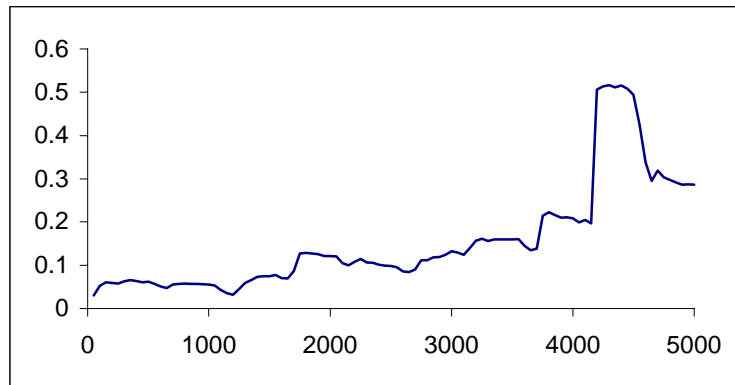


(c) Network regime

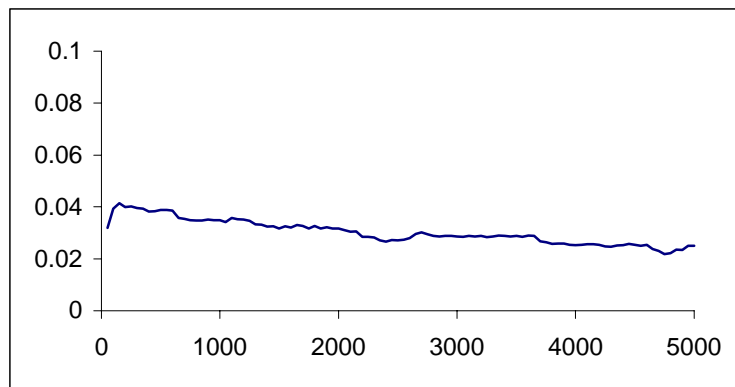
¹⁵ I.e., until it becomes part of the class of old technologies.

¹⁶ As mentioned before, this is due to the different notion of compatibility in Shy (1996).

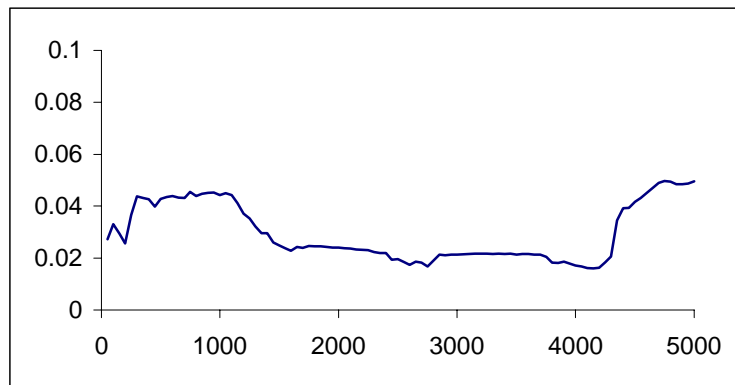
Graph 3: Herfindahl index



(a) Quality regime



(b) Intermediate regime



(c) Network regime

How do the populations of firms evolve under these different regimes, and are there significant differences between the regimes? Graphs 2 and 3 show the evolution of the number of firms and the concentration levels. Under the quality regime, we observe a gradually declining number of firms and increasing concentration levels. The intermediate regime exhibits a gradually growing population of firms with decreasing concentration levels. Finally, under the network regime we see on average a growing population of firms, however the growth rates fluctuates considerably. Further, new technology adoptions in the

network regime are associated with a sharp decrease in the number of firms.

These graphs, derived from one simulation run for each regime, indeed show that the regimes differ with regard to the population dynamics. But for a better assessment of the significance of these differences we calculated a number of statistics on the basis of the output of ten runs per regime¹⁷, shown by table 1.

The first two rows show the average number of firms and the average Herfindahl-index.¹⁸ Next, we calculated the average number of entrants over 50 periods.¹⁹ Entrants are defined as firms absent at the beginning of a 50-period era, but present at the end of the era (*vice versa* for exiters); incumbents are firms present throughout the sample period. Further, we calculated survival rates for entrants, both for the short-run (i.e., the proportion of entrants that survive at least 50 periods) as well as for the long run (proportion of entrants surviving at least 500 periods). Finally, we calculated the weighted²⁰ average age of all exiting firms at their year of exit, and the average age of all firms at $t = 5000$. Table 1 shows the averages of these variables per regime over all the sample periods of the ten simulations (standard error of the mean in parentheses).

<i>Table 1</i>	<i>Quality regime</i>	<i>Intermediate regime</i>	<i>Network regime</i>
<i>Number of firms</i>	21.2 (1.27)	56.1 (2.34)	66.3 (1.70)
<i>Herfindahl-index</i>	12.5 (1.58)	3.57 (0.25)	3.44 (0.22)
<i>Number of entrants over 50 periods</i>	1.24 (0.08)	1.26 (0.06)	2.75 (0.05)
<i>Survival rates</i>			
-short-run	43.9 (1.62)	52.1 (0.99)	49.8 (1.12)
-long-run	31.6 (1.74)	43.9 (0.78)	30.5 (0.63)
<i>Mean age of</i>			
- all exiters	913 (32.8)	1176 (53.3)	840 (41.3)
- all firms at $t = 5000$	1852 (177)	2937 (67.6)	2374 (118)

On average, the largest number of firms is found in the network regime, whereas the quality regime exhibits the smallest population. Not surprisingly then, the highest concentration levels are found under the quality regime, whereas the network regime produces the lowest concentration levels.

The highest number of entrants emerges under the network regime, which is

¹⁷ In order to keep the datasets at a reasonable size we have sampled each run only every 50 periods.

¹⁸ The Herfindahl index is calculated as the sum of squared market shares.

¹⁹ We did not calculate entry and exit rates, because they would not reflect real differences in, e.g., the ease of entry. If a regime is conducive to entrants the simulation results will show a higher number of firms in time than for a regime less conducive to entrants. Since the expected number of entrants in each period is fixed by the arrival rate ρ_E and identical across the three regimes, the entry conducive regime will show lower entry rates than the regime less conducive to entrants.

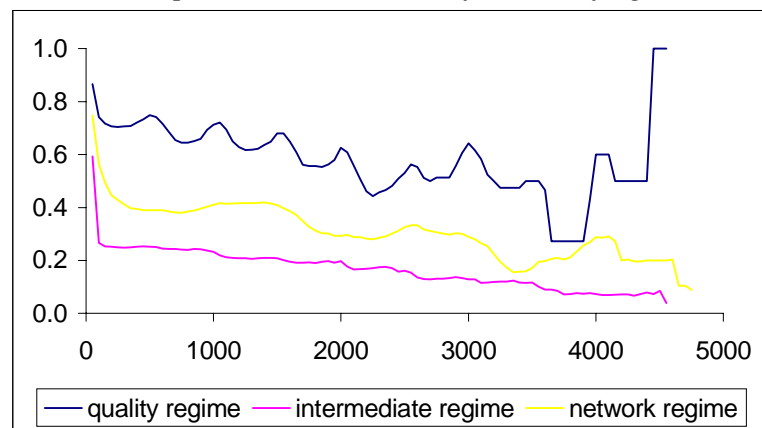
²⁰ For the weights we use the size of a firm (s_i in the model).

approximately twice as high as under the other regimes.²¹ Concerning the survival rates, we see that the intermediate regime produces the highest probability for entrants to survive, both for the short run as well as the long run. The lowest short-run survival rates emerge under the quality regime. Long-run survival rates for the quality and the network regime are virtually similar.

The average age of exiting firms is highest under the intermediate regime, and lowest under the network regime. Further, at the end of the simulation the oldest population is found under the intermediate regime, whereas the youngest population is found under the quality regime.

With regard to the consistency of the model with the stylised facts mentioned in section two, it is obvious that the model reproduces the first one. Under all regimes, there is persistent market turbulence due to entry, and exit. The second stylised fact (high infant mortality, negatively correlated with firm age) also emerges, except for the quality regime. Graph 4 shows the probability of exiting over the full simulation period given the age cohort²² of an entrant for each regime.

Graph 4: hazard rate as a function of age



Under the quality regime, infant mortality initially declines with age, however no entrant is able to live for more than approximately 4,500 periods. This leads to a rise in hazard rates for entrants with ages exceeding 4,000 periods. The other two regimes show very similar hazard rates that indeed decline as entrants mature. Hence, both the intermediate regime and the network regime reproduce this second stylised fact.

The third stylised fact (growth rates of firms that fall with age and with size) is of course to some extent imposed on the model by equation (5). Still, it might be

²¹ Note that we only sample every 50 periods. Therefore, despite the identical entry arrival rate of 0.15 per period, the three regimes produce different numbers of entrants due to variations in the number of firms that die before being observed in the sample. Hence, this number can be interpreted as a ‘very short run’ survival rate.

²² Each age cohort covers 50 simulation periods.

interesting to learn about the emerging econometric regularities of the model. As in Dosi et al. (1995), we therefore run a number of regressions of the following form:

$$\ln\left(\frac{s_i(t+T)}{s_i(t)}\right) = q_0 + q_1 \ln s_i(t) + q_2 \ln a_i(t) + q_3 (\ln s_i(t) \ln a_i(t)), \quad (10)$$

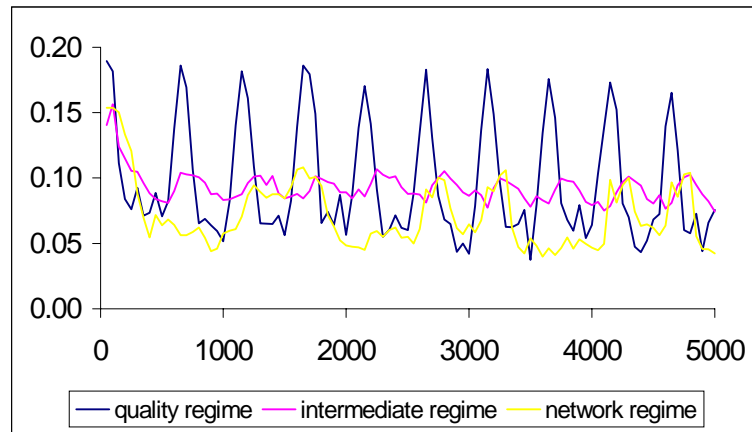
for $t = 50, 100, \dots, 5000$ and $T = 50$ (regression 10a), and for $t = 500, 1000, \dots, 5000$ and $T = 500$ (regression 10b). The results are listed in table 2.

<i>Table 2</i>	q_0	q_1	q_2	q_3	R^2 -adjusted
<i>Quality regime</i>					
10a	0.595	-0.045	-0.085	0.006	0.098
10b	1.306	-0.135*	-0.202	0.020*	0.036
<i>Intermediate regime</i>					
10a	0.595	-0.055	-0.077	0.007	0.119
10b	1.128	-0.099	-0.151	0.012	0.170
<i>Network regime</i>					
10a	0.641	-0.058	-0.086	0.008	0.101
10b	1.707	-0.146	-0.235	0.020	0.204

Under all regimes this stylised fact is reproduced. All parameter estimates are significant at the 1-% level, except for the ones indicated with an asterisk, which are only significant at the 10-% level. Hence, both over the 50 period interval as well as over the 500 periods, initial size and initial age exert a negative impact on firm growth. Surprisingly, the interaction term exhibits in all cases a positive coefficient. Apparently the negative effect of, for instance, age on firm growth is attenuated for larger firms. Given the specification of equation (5), this emergent property is hard to explain. However, this regularity has been observed before in empirical studies on firm growth. Also Evans (1987a, 1987b) found significant positive estimates for the variable indicating the interaction between age and size.

Persistence of asymmetric performances, the fourth stylised fact, also emerges from the model. To show this, we calculated for each 50th period the standard deviation of the mean of relative competitiveness of all firms (i.e., relative to the industry mean). These series are plotted in graph 5. As this graph shows, there is no convergence in the relative competitiveness of firms, hence in all regimes asymmetric performances are persistent. Especially under the quality regime the standard deviation clearly exhibits cyclical fluctuations, associated with the high speed of adoption of new technologies.

Graph 5: standard deviation of average relative competitiveness



The evidence for the last stylised fact mentioned in section two, regarding the skewed and stable size distributions, is shown by graphs 6a to 6c. These graphs plot the log of firm sizes $s_i(t)$ on the vertical axis and the log of the firms' ranks $rank_i(t)$ on the horizontal axis (firms are ranked according to their size, in descending order) for $t = 500, 1000, \dots, 5000$ for the same simulation run underlying graph 1a to 1c.

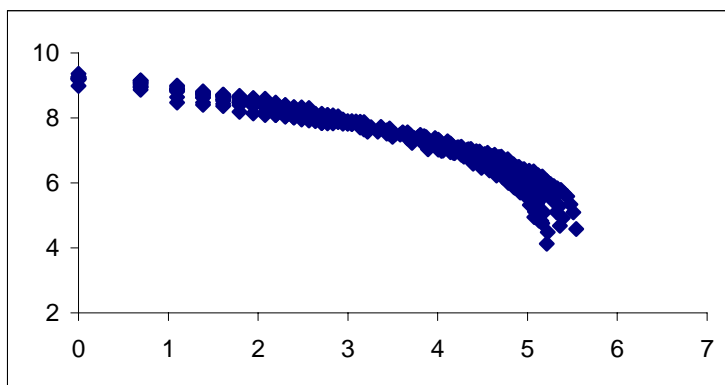
As graphs 6a to 6c show, all three regimes produce skew firm size distributions, but there are some interesting differences. The quality regime seems to produce the most skewed distribution, whereas the least stable size distribution emerges under the intermediate regime. These findings, derived from visual inspection, are corroborated by the results from running the following regression:

$$\ln s_i(t) = A + B \ln rank_i(t), \quad (11)$$

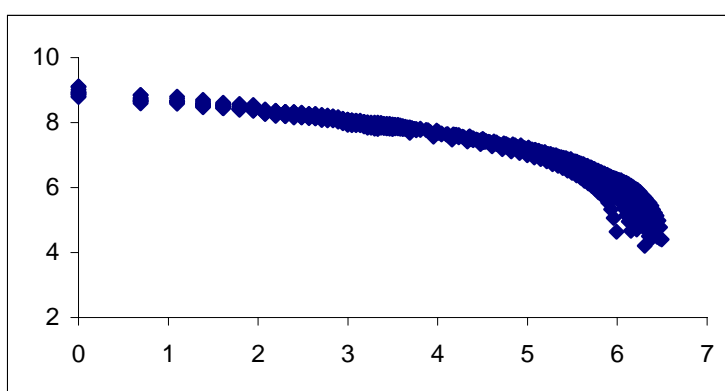
for $t = 250, 750, \dots, 4750$ (regression 11a), and for $t = 500, 1000, \dots, 5000$ (regression 11b) over all simulation runs. Table 3 shows the results (all parameter estimates are significant at the 1-% level).

Table 3	A	B	R ² -adjusted
<i>Quality regime</i>			
11a	10.4	-0.93	0.84
11b	10.5	-0.90	0.83
<i>Intermediate regime</i>			
11a	10.7	-0.80	0.79
11b	10.8	-0.81	0.80
<i>Network regime</i>			
11a	10.9	-0.80	0.75
11b	11.0	-0.82	0.77

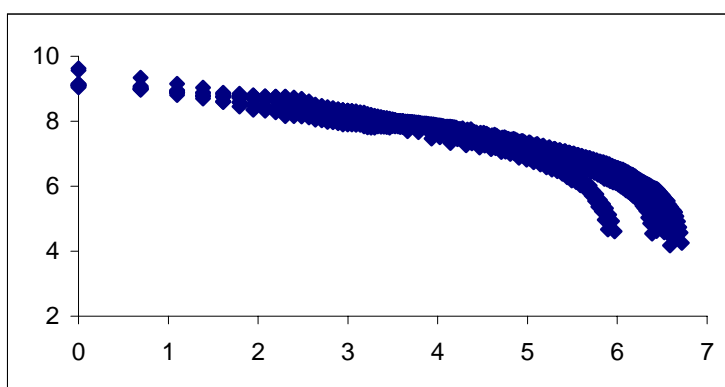
Indeed, the quality regime shows the highest absolute value for B , and hence produces the most skewed size distribution. Further, we observe that it hardly matters when the regressions are executed (i.e., either at the end of a depreciation period or in the middle of it), indicating the stability of the size distribution.

Graph 6: Size distributions

(a) Quality regime



(b) Intermediate regime



(c) Network regime

In conclusion, the simulations of the three technology adoption regimes show significant cross-sectional differences with regard to the static and dynamic properties of the firm population. The quality regime produces the smallest and youngest population of firms, whereas long run survival seems to be easiest under the intermediate regime. Still, because of a higher number of entrants, the largest firm population emerges under the network regime. Hence, these results strongly suggest a relationship between the timing and frequency of new technology

adoptions and the dynamics of the firm population. Also, the model is consistent with a number of stylised facts observed in the empirical literature.

5. Interaction between adoption regimes and technological regimes

As mentioned in the introduction, the aim of this paper was to introduce demand side considerations as an alternative to more supply side oriented explanations for industrial dynamics, like the concept of technological regimes. By varying a number of parameters determining the technological competitiveness of firms, we have designed three technology adoption regimes and investigated the differences in the firm population between these regimes. However, to some extent our model also allows for investigating the impact of different technological regimes on the industrial dynamics, and the interaction between adoption regimes and technological regimes. The present section will deal with these issues. By selecting and varying a number of parameters reflecting the level of cumulateness and spillovers, we will run and compare several simulations of different technological regimes under the three technology adoption regimes.

A technological regime can broadly be defined as a particular combination of cumulateness and spillover conditions, common to specific activities of innovation and production and shared by the population of firms undertaking those activities. Cumulateness conditions refer to the extent to which acquiring technological knowledge is a cumulative process, whereas spillover conditions reflect the ease of technological knowledge to flow from innovators to imitators. In the literature on technological regimes, a distinction is usually made between two major patterns on innovative activities. The first one, called Schumpeter Mark I (SM-I), is characterised by a key role played by new firms in innovative activities, whereas in the second one, Schumpeter Mark II (SM-II), this key role is fulfilled by the large and established firms.

The differences between the two regimes are mainly related to differences in the cumulateness and spillover conditions. For instance, the SM-I regime is characterised by low levels of cumulateness and high levels of spillover effects, whereas opposite conditions hold for the SM-II regime. Given these differences, industries with different underlying technological regimes are likely to differ with respect to their dynamic and structural properties. In SM-I industries, we may expect a turbulent and large population of young and small firms, and low entry barriers. SM-II industries may be characterised by a more stable and small population of large and old firms, and by high entry barriers.

Obviously, the conditions determining the technological regime have a strong impact on the patterns of innovative activities of an industry, as well as on the ease and the impact of imitation. Since in our model innovation is exogenous, we cannot fully simulate the different conditions underlying technological regimes.

Only to the extent that these conditions apply to ease and impact of imitation we can analyse the effect of different technological regimes in our model.

To investigate whether our model is still able to produce the regularities predicted by the technological regime framework, we first have to identify the parameters reflecting the cumulateness and spillover conditions. For cumulateness we have to find the variable that indicates best to what extent the acquisition of knowledge is a cumulative process. We propose to vary the parameter governing the ‘penalty’ rates for continuing firms (β_{10}). This penalty rate can be interpreted as a measure indicating to what extent the knowledge and experiences of a firm with its existing product technologies carry over to the new technology it adopts. For instance, if β_{10} is equal to β_2 (the penalty rate for entrants), the subfirm adopting the new technology starts at a competitiveness level equal to that of an entrant.²³ In this case the subfirm has no direct advantage over entrants with regard to the new technology (the accumulated experience with its existing technologies does not carry over to the subfirm with the new technology). However, the higher β_{10} (relative to β_2), the more the knowledge of new technology is based on the knowledge of previous technologies, and hence the more a new subfirm benefits from its accumulated experience *vis-à-vis* new firms entering with the same technology.²⁴

For varying the spillover effects, it seems natural to vary the parameter determining the probability to receive an imitation draw (i.e., ρ_{im}). Since we have defined imitating as acquiring the knowledge of applying a superior technology, this parameter reflects the ease of knowledge of new product technologies to flow to imitators. However, this parameter only reflects spillovers between continuing firms, not from continuing firms to entrants. Of course, in a strict sense, entrants are considered as continuing firms in the model from the moment they have entered. Thus, when the arrival rate of imitations is higher, also the very young firms have a higher probability to receive an imitation draw. On the other hand, since more continuing firms will imitate, the average competitiveness level will be higher, which decreases the probability for entrants to survive. Several simulation runs with different imitation arrival rates indeed show that this last effect dominates: higher levels of spillovers generally lead to less entry, *ceteris paribus*. Since this inconsistency is due to the fact that entrants do not directly benefit from higher spillover levels, we consider it appropriate to also increase the arrival rate of entrants (ρ_{ent}) when spillovers levels are higher. In that case, more entrants

²³ I.e., relative to the firms’ genotype organisational competitiveness levels λ_i .

²⁴ Of course, it may happen occasionally that an entrant with a certain technology receives an imitation draw quickly after it has entered. If β_{10} is high, this entrant will also benefit from its experience with the inferior technology, despite the short time it has been employing it. This will not seriously effect the results however, because the overall competitiveness of this entrant is at least for some time also determined by the competitiveness of the subfirm employing the inferior technology for which the entry penalty rate β_2 is still effective. Besides that, this firm already employed the initial technology successfully and therefore must possess some crucial knowledge about it.

have access to the knowledge necessary to imitate an existing technology. Also the entering firms will then benefit directly from high spillover conditions.

In the next experiments we will consider three levels of cumulateness and spillover conditions (low, medium, high) for each of the technology adoption regimes of the previous section. The specific parameter settings are as follows. Low cumulateness means no direct advantage for subfirms relative to entrants ($\beta_{10} = \beta_2 = 0.6$). Medium levels correspond to the parameter settings of the previous section ($\beta_{10} = 0.8$), whereas high cumulateness levels are set by $\beta_{10} = 1$. With regard to spillover effects, low levels of spillovers are set by $\rho_1 = 10$ and $(\rho_{ent}) = 0.1$. Medium levels again correspond to the parameter settings of the previous section (hence, $\rho_1 = 20$ and $\rho_{ent} = 0.15$). High spillover conditions are set by $\rho_1 = 30$ and $\rho_{ent} = 0.2$.

Hence, for each adoption regime we will consider nine different combinations of cumulateness and spillover conditions. To get a general impression of the effect of varying the cumulateness and spillover conditions, tables 4 to 9 will show the means and their standard errors of the same variables listed in table one under these various conditions (except for the number of entrants).²⁵ For an assessment of the significance of the effects of different cumulateness and spillover conditions, and to investigate the extent to which these conditions interact, we will additionally perform the following regression analyses. Each of the six variables will be regressed on a number of dummy variables, indicating the various cumulateness and spillover conditions and the potential interaction between them. More specific, for each adoption regime we will estimate the following equation:

$$Y = \beta_1 + \beta_2 Cm_l + \beta_3 Cm_h + \beta_4 Sp_l + \beta_5 Sp_h + \beta_6 (Cm_l \times Sp_l) + \beta_7 (Cm_l \times Sp_h) + \beta_8 (Cm_h \times Sp_l) + \beta_9 (Cm_h \times Sp_h) + \varepsilon, \quad (12)$$

where Y is the dependent variable under consideration, Cm_l equals one if cumulateness conditions are low and zero otherwise, Cm_h equals one if cumulateness is high and zero otherwise, Sp_l equals one if spillover conditions are low and zero otherwise, and Sp_h equals one if spillovers are high and zero otherwise. From this configuration of dummy variables it follows that the technological regime with medium cumulateness and spillover conditions will be the reference regime, implying that the estimates for β_1 will be equal to the means of the variables listed in table 1. The regression statistics can be found in table A to C in the Appendix of this paper.

²⁵ We will not display the evolution of market shares of succeeding technologies for the different technological regime conditions, because these patterns hardly show any differences *within* each technology adoption regime.

Based on the technological regime framework, we would expect that, *ceteris paribus*, higher cumulateness conditions generate a lower number of firms and higher concentration levels, lower survival rates and relatively young exiting firms, leading ultimately to an older population of firms. With regard to spillover conditions we would generally expect opposite regularities to emerge from the simulation. We have no clear expectations regarding the signs of the interaction effects. As mentioned, in the literature on technological regimes often a distinction is made between two regimes (Schumpeter I vs. II) with opposite spillover and cumulateness conditions. However, no explicit reference is made regarding the interaction between them. By impeding the persistence of monopolistic advantages, high spillover conditions hinder innovative firms to become large, whereas low cumulateness conditions facilitates innovative entry (compared to high cumulateness conditions). Therefore, both high spillovers and low cumulateness *independently* impose restraints on concentration levels. To what extent these conditions reinforce each other is unclear, however. Studying the significance of the interaction between the spillover and cumulateness dummies may partly illuminate this issue.

Table 4: Mean number of firms (standard error)

Quality regime			Intermediate regime			Network regime					
	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>		<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>		<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>
<i>Cm_l</i>	22.4 (1.20)	34.4 (1.05)	48.6 (1.53)	<i>Cm_l</i>	51.2 (1.50)	67.6 (3.17)	83.2 (3.38)	<i>Cm_l</i>	46.5 (2.68)	63.0 (1.53)	87.8 (2.89)
<i>Cm_m</i>	17.2 (0.70)	21.2 (1.27)	30.8 (1.15)	<i>Cm_m</i>	40.4 (2.04)	56.1 (2.34)	72.1 (2.39)	<i>Cm_m</i>	48.5 (2.24)	66.3 (1.70)	84.4 (3.91)
<i>Cm_h</i>	10.2 (0.88)	12.1 (1.33)	16.0 (0.74)	<i>Cm_h</i>	31.1 (1.29)	36.8 (1.36)	42.6 (2.09)	<i>Cm_h</i>	39.9 (2.79)	49.2 (1.74)	71.3 (3.78)

Table 5: Mean Herfindahl index (standard error)

Quality regime			Intermediate regime			Network regime					
	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>		<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>		<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>
<i>Cm_l</i>	10.1 (0.79)	6.13 (0.44)	4.64 (0.37)	<i>Cm_l</i>	4.50 (0.44)	3.62 (0.25)	2.97 (0.12)	<i>Cm_l</i>	5.37 (0.54)	3.53 (0.17)	2.77 (0.28)
<i>Cm_m</i>	12.6 (0.97)	12.5 (1.58)	7.70 (1.15)	<i>Cm_m</i>	5.23 (0.48)	3.57 (0.25)	2.90 (0.26)	<i>Cm_m</i>	4.89 (0.41)	3.44 (0.22)	2.99 (0.20)
<i>Cm_h</i>	31.2 (5.61)	23.4 (3.38)	14.9 (1.58)	<i>Cm_h</i>	6.37 (0.28)	5.29 (0.38)	4.89 (0.37)	<i>Cm_h</i>	5.72 (0.67)	4.89 (0.39)	3.39 (0.26)

As expected, in all three technology adoption regimes we see that, *ceteris paribus*,

higher spillover conditions lead to a higher number of firms and to lower concentration levels. Also, with regard to cumulateness conditions, we see that in general the number of firms decreases and the concentration increases with higher cumulateness. Only under the network regime there is no clear relationship between cumulateness on the one hand and the number of firms and concentration levels on the other.

The regression analyses show that with regard to the number of firms the differences due to variations in the technological regime parameters are significant. Only under the network regime the dummy for lower cumulateness is not statistically significant. Interesting differences emerge with regard to the interaction effects. Under the quality regime, the combination of low cumulateness and low spillovers significantly decreases the number of firms. Thus the positive effect of lower cumulateness on the number of firms is almost completely offset by the negative effect of lower spillovers under this regime. In the opposite case, the negative effect of higher cumulateness is again offset by the positive effect of high spillovers, but here the former effect dominates.

In cases with opposite spillover and cumulateness conditions, we observe that the dummy for low cumulateness and high spillover is significantly positive: low cumulateness and high spillovers reinforce each other in this case. However, no significant interaction emerges in the opposite scenario, i.e., no significant interaction is observed between high cumulateness and low spillovers under the quality regime. Under the intermediate regime, this latter interaction is significantly positive. Here, high spillovers and low cumulateness *together* result in a higher number of firms than would be expected on the basis of these two effects individually. The other significant interaction under the intermediate regime emerges with high spillover and high cumulateness. As under the quality regime, the negative effect of higher cumulateness is again offset by the positive effect of high spillovers, where the former effect dominates. Finally, under the network regime no significant interaction is observed between cumulateness and spillovers.

With regard to concentration levels the dummies for lower cumulateness and higher spillovers are insignificant across all adoption regimes. Further, the dummy for low spillovers is insignificant under the quality regime, but significant under the other regimes. Finally, none of the dummies covering the interaction effects is statistically significant under any of the three adoption regimes. Thus, concentration levels are less affected by varying the cumulateness and spillover conditions than the total number of firms, indicating that most of the differences appear in the lower firm size classes.

Table 6: Mean short run survival rates (standard error)

Quality regime			Intermediate regime			Network regime					
<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>			
<i>Cm_l</i>	50.1 (1.46)	49.6 (1.39)	46.5 (1.70)	<i>Cm_l</i>	62.6 (0.77)	56.0 (1.34)	52.1 (1.83)	<i>Cm_l</i>	54.1 (1.70)	49.6 (0.81)	49.4 (0.97)
<i>Cm_m</i>	48.5 (1.54)	43.9 (1.62)	42.0 (1.22)	<i>Cm_m</i>	61.6 (2.37)	52.1 (0.99)	47.8 (1.58)	<i>Cm_m</i>	54.9 (1.81)	49.8 (1.12)	49.6 (0.60)
<i>Cm_h</i>	36.6 (3.01)	30.7 (4.54)	30.0 (0.95)	<i>Cm_h</i>	52.0 (2.02)	34.5 (1.96)	28.2 (2.45)	<i>Cm_h</i>	50.4 (1.54)	45.4 (1.91)	46.9 (1.21)

With respect to short run survival rates, the relationship between cumulateness and this variable is as expected, albeit rather weak under the network regime: higher cumulateness is generally associated with lower short run survival. However, higher spillover levels lead to *lower* short run survival rates (again a rather weak effect under the network regime). Still, this is not surprising, since high spillovers increase the industrial average competitiveness, making it harder for entrants to survive.

The regression analyses generally confirm this. Compared to the technological regime with medium cumulateness and spillover levels, higher cumulateness significantly decrease the short run survival rates. Further, lower spillovers significantly increase the short run survival, except under the quality regime. The dummies for low cumulateness and high spillovers are all statistically insignificant. Finally, only one interaction dummy is significant. Under the intermediate regime, the negative effect of high cumulateness on short run survival is almost completely offset by the (unexpected) positive effect of low spillovers.

Table 7: Mean long run survival rates (standard error)

Quality regime			Intermediate regime			Network regime					
<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>			
<i>Cm_l</i>	31.0 (1.11)	33.2 (1.31)	34.1 (1.22)	<i>Cm_l</i>	46.4 (1.30)	44.8 (1.77)	44.3 (1.83)	<i>Cm_l</i>	29.6 (1.32)	29.4 (0.98)	31.0 (1.06)
<i>Cm_m</i>	29.6 (1.41)	31.6 (1.74)	29.3 (1.63)	<i>Cm_m</i>	50.1 (2.02)	43.9 (0.78)	41.3 (1.55)	<i>Cm_m</i>	30.6 (2.06)	30.5 (0.63)	31.3 (1.30)
<i>Cm_h</i>	25.0 (1.77)	23.2 (3.60)	23.6 (1.50)	<i>Cm_h</i>	42.4 (1.63)	30.9 (2.20)	23.7 (2.12)	<i>Cm_h</i>	29.2 (1.73)	27.7 (1.48)	30.2 (1.48)

For long run survival rates, the picture is rather similar with regard to cumulateness conditions. Under the quality and the intermediate regime, higher

cumulativeness decreases long run survival, whereas long run survival under the network regime is not effected by different cumulateness conditions. Higher spillover conditions only seem to have a (negative) effect on long run survival under the intermediate regime.

Again, these observations are confirmed by the regression analyses. Under the network regime, none of the dummies is statistically significant, whereas under the quality regime only the dummy for high cumulateness is significant. Further, under the intermediate regime the dummies for low spillovers (positive) and high cumulateness (positive) show significant estimates. Finally, all interaction effects are statistically insignificant under all three adoption regimes.

Table 8: Mean age of exiters (standard error)

	<i>Quality regime</i>			<i>Intermediate regime</i>			<i>Network regime</i>				
	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>		
<i>Cm_l</i>	676 (21.2)	759 (17.8)	834 (23.3)	<i>Cm_l</i>	1039 (37.2)	819 (28.1)	444 (24.3)	<i>Cm_l</i>	874 (42.2)	883 (25.8)	814 (39.6)
<i>Cm_m</i>	666 (25.7)	913 (32.8)	890 (35.6)	<i>Cm_m</i>	1297 (43.4)	1176 (53.3)	682 (75.6)	<i>Cm_m</i>	759 (32.3)	840 (41.3)	755 (35.2)
<i>Cm_h</i>	659 (37.0)	745 (51.3)	861 (27.1)	<i>Cm_h</i>	1224 (45.8)	1232 (58.5)	612 (84.1)	<i>Cm_h</i>	699 (34.2)	653 (24.2)	559 (34.9)

For the mean age of exiting firms, the picture is quite diverse. Under the quality regime, higher spillovers tend to increase the average age of exiters (as expected), whereas under the intermediate regime the opposite tendency is observed. No clear relationship between spillover levels and the mean age of exiters emerges under the network regime. With regard to cumulateness, only the regularities under the network regime match our expectations. Here, higher cumulateness decreases the average age of exiters. This relationship seems to be reversed under the intermediate regime, whereas no clear effects of cumulateness conditions are observed under the quality regime.

Naturally, the regression statistics show a dispersed picture too, most notably for the quality regime. Both the dummies for low and high cumulateness are statistically significant, with both being negative. Also the dummy for low spillovers is significant under this regime, with the expected negative sign. Under the intermediate regime, both the dummies for low cumulateness and high spillover are significant, but both have a negative sign where we would expect positive ones. Finally, under the network regime the dummy for high cumulateness and the dummy for low spillovers are significant, with the expected negative sign. Regarding the interaction effects, it is interesting to see that only under the quality regime significant interactions emerge, where the combined effects seem to be less strong than the sum of individual effects. This applies to the combinations of low spillovers and low cumulateness, low

spillovers and high cumulateness, and high spillovers and high cumulateness.

Table 9: Mean age at $t = 5000$ (standard error)

	<i>Quality regime</i>			<i>Intermediate regime</i>			<i>Network regime</i>				
	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>	<i>Sp_l</i>	<i>Sp_m</i>	<i>Sp_h</i>		
<i>Cm_l</i>	1298 (82.3)	1444 (81.5)	1682 (75.5)	<i>Cm_l</i>	1938 (59.8)	2029 (58.4)	2316 (75.6)	<i>Cm_l</i>	2055 (109)	2234 (68.8)	2359 (85.3)
<i>Cm_m</i>	1281 (122)	1852 (177)	2024 (132)	<i>Cm_m</i>	2275 (37.3)	2937 (67.6)	3294 (47.3)	<i>Cm_m</i>	2253 (174)	2374 (118)	2522 (56.4)
<i>Cm_h</i>	2112 (424)	2717 (390)	2365 (183)	<i>Cm_h</i>	2768 (157)	3827 (129)	4098 (120)	<i>Cm_h</i>	2067 (72.9)	2438 (122)	2385 (116)

The average age of the total population at the ultimate period (table 9) generally increases with cumulateness and spillover conditions under the intermediate regime and, to a lesser extent, under the quality regime, whereas no relationships emerge under the network regime.

Also the regression statistics show no significant dummies for the network regime. For the quality regime, only the dummy for high cumulateness is statistically significant. The dummies for cumulateness have the expected sign and are both significant under the intermediate regime. The dummies for spillover conditions are also statistically significant, however their signs do not match the expectations based on the technological regime framework.

Interaction effects are only significant under the intermediate regime this time. The (expected) negative effect of low cumulateness combined with the (unexpected) negative effect of low spillovers results in an older population than we would expect from those two effects individually. The positive effect of high cumulateness on the average age of the total population is more than offset by the negative effect of low spillovers when these are combined.

In conclusion, we observe that with regard to the cumulateness conditions the regularities predicted by the technological regime framework are reproduced by the model. In general, we see a smaller, more concentrated and eventually older population of firms when cumulateness conditions are high. Spillover conditions are in line with the expectations regarding the number of firms and concentration levels. I.e., higher spillovers lead to a higher number of firms and to lower concentration levels. However, they do not increase survival rates or decrease the average age of the population.

A possible explanation for this is that the benefits of the incumbents from high spillovers are such that they easily imitate and survive, thereby increasing the industrial average competitiveness. This process leads both to an eventually older population, as well as to hard survival conditions for entrants. Another reason for

this inconsistency with the technological regime framework is that our model does not allow for analysing the effect of the technological regime conditions on differences between the innovative activities of incumbents and entrants. Innovation is exogenous in our model, and perhaps endogenising the innovation process would make our model more consistent with the technological regime framework.

Finally, we observe that the regularities emerging under the network regime are the least affected by variations in spillover and cumulativeness conditions. Also the interaction effects between spillovers and cumulativeness are never significant under the network regime. Apparently, the emerging regularities under this regime are mainly determined by the network externalities among users and the resulting diffusion patterns of new product technologies. Under the quality and intermediate regime, we have found some significant interaction effects, however they do not appear to systematically affect the results.

6. Conclusions

This paper has shown that sectoral variations in the dynamics of the firm population can be explained by differences in the timing and frequency of new product technology adoptions. Assuming that varying consumer preferences over technology advance and network size effects, and different degrees of compatibility between succeeding technologies explain why in some industries technologies are more often replaced than in others (see Shy, 1996), we analysed, by means of a simulation model, how the different replacement patterns would effect the dynamics of the firm population. We designed and investigated three different technology adoption regimes with the following underlying conditions: *(i)* a quality regime, in which quality and network size are regarded as perfect substitutes and new product technologies are highly compatible with old technologies, *(ii)* an intermediate regime, in which new product technologies are less compatible with old technologies, but where quality and network size are still regarded as perfect substitutes, and *(iii)* a network regime, in which network size and quality are regarded as complementary. By modelling the growth of a firm's competitiveness as a function of both the quality level and the market share of the product technology it employs, and by tuning the parameters of this function to arrange the adoption regimes, the model produces the following results.

First of all, three rather different replacement patterns of technologies emerge. In the quality regime, technologies are continuously and rather quickly replaced by superior technologies as soon as they become available. In the intermediate regime, newer technologies still always replace older ones, but the duration of a technology is higher than under the quality regime. Finally, in the network regime eventually one technology always dominates the market until it becomes obsolete (despite the presence of superior technologies), after which it is quickly replaced by a new technology that again dominates until its obsolescence.

The second result is that the replacement patterns of product technologies clearly affect the dynamics of the firm population. The quality regime produces the smallest, but most dynamic population of firms, whereas the largest firm population emerges under the network regime. The intermediate regime exhibits the most stable population of firms, where long run survival is relatively easy.

The third result is that for all three regimes the model is able to reproduce a number of important stylised facts from industrial organisation. The model produces persistence of market turbulence due to entry and exit; high infant mortality, negatively correlated with firm age; growth rates of firms that fall with age and with size; persistence of asymmetric performances; and skewed and relatively stable size distributions.

The fourth result is that all these outcomes are obtained in the absence of replicator dynamics. There is no explicit relationship in our model between a firm's relative competitiveness and its growth rate. The only selection mechanism in our model is that a minimum level of relative competitiveness is required in order to survive. This rather simple mechanism turns out to be sufficient to produce meaningful results, consistent with the previously mentioned stylised facts.

The fifth and final result is derived from running the model under different technological regimes, represented by various cumulativeness and spillover conditions. In general, we see a smaller, more concentrated and eventually older population of firms when cumulativeness conditions are high. These regularities are in line with the technological regime framework. Spillover conditions, however, are only partly consistent with this framework. Higher spillovers indeed lead to a higher number of firms and lower concentration levels. However, they do not generally increase survival rates or decrease the average age of the population. The explanation for this is found in the trivial effect of high spillover conditions on the competitiveness of incumbent firms *vis-à-vis* entrants. High spillover conditions enable more continuing firms to imitate, which increases the industrial average competitiveness. This, in turn, deteriorates the general conditions for entrants and makes it more difficult for them to survive. Finally, we observed that the regularities emerging under the network regime are the least affected by varying cumulativeness and spillover conditions.

Endogenising the innovation process could make our model more consistent with the technological regime framework. Since innovation is exogenous in our model, we cannot analyse the effect of the technological regime conditions on differences between the innovative activities of incumbents and entrants. Perhaps future efforts in this direction will enable us to better assess the interaction between the demand side oriented adoption regimes and the more supply side oriented technological regimes.

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Appendix: regression statistics section 4

Table A	Number of firms			Herfindahl-index		
	Quality regime	Intermediate regime	Network regime	Quality regime	Intermediate regime	Network regime
Constant	21.2** (18.8)	56.1** (24.6)	66.3** (24.4)	12.5** (5.32)	3.57** (10.8)	3.44** (8.96)
Cm_l	13.2** (8.32)	11.5** (3.58)	-3.36 (-0.88)	-6.42 (-1.93)	0.05 (0.11)	0.09 (0.17)
Cm_h	-9.02** (-5.67)	-19.3** (-5.96)	-17.1** (-4.46)	10.9** (3.26)	1.72** (3.66)	1.44** (2.66)
Sp_l	-4.02** (-2.53)	-15.7** (-4.86)	-17.8** (-4.65)	0.06 (0.02)	1.66** (3.54)	1.45** (2.66)
Sp_h	9.60** (6.03)	16.0** (4.96)	18.1** (4.72)	-4.87 (-1.46)	-0.68 (-1.44)	-0.45 (-0.83)
Cm_l x Sp_l	-8.01** (-3.56)	-0.70 (-0.15)	1.34 (0.25)	3.92 (0.83)	0.78 (-1.18)	0.39 (0.51)
Cm_l x Sp_h	4.63* (2.06)	-0.48 (-0.10)	6.70 (1.23)	3.38 (0.72)	0.02 (0.04)	-0.31 (-0.41)
Cm_h x Sp_l	2.03 (0.90)	10.0* (2.19)	8.55 (1.58)	7.73 (1.64)	-0.57 (-0.87)	-0.61 (-0.80)
Cm_h x Sp_h	-5.72** (-2.54)	-10.3* (-2.25)	4.00 (0.74)	-3.71 (-0.79)	0.28 (0.42)	-1.05 (-1.36)
Adjusted R ²	0.91	0.84	0.78	0.53	0.51	0.39

Note: *t*-values are in parentheses.

* Significant at the 5-% level.

** Significant at the 1-% level.

Table B	Short run survival rates			Long run survival rates		
	Quality regime	Intermediate regime	Network regime	Quality regime	Intermediate regime	Network regime
Constant	43.9** (19.9)	52.1** (29.1)	49.8** (36.4)	31.6** (17.2)	43.9** (25.2)	30.5** (21.9)
Cm_l	5.70 (1.82)	3.89 (1.54)	-0.23 (-0.88)	1.63 (0.63)	0.93 (0.11)	-1.12 (-0.57)
Cm_h	-13.2** (-4.22)	-17.5** (-6.94)	-4.38* (-2.26)	-8.38** (-3.22)	-13.0** (-5.28)	-2.80 (-1.42)
Sp_l	4.57 (1.46)	9.52** (3.77)	5.06** (2.62)	-1.98 (-0.76)	6.17** (2.51)	0.08 (0.04)
Sp_h	-1.87 (-0.60)	-4.30 (-1.70)	-0.24 (-0.12)	-2.26 (-0.87)	-2.57 (-1.05)	0.78 (0.40)
Cm_l x Sp_l	-4.11 (-0.93)	-2.91 (-0.81)	-0.54 (-0.20)	-0.23 (-0.06)	-4.59 (-1.32)	0.14 (0.05)
Cm_l x Sp_h	-1.22 (-0.28)	0.47 (0.13)	0.10 (0.04)	3.21 (0.87)	2.03 (0.58)	0.80 (0.29)
Cm_h x Sp_l	1.29 (0.29)	7.91* (2.21)	-0.11 (-0.04)	3.75 (1.64)	5.32 (1.53)	1.38 (0.49)
Cm_h x Sp_h	1.14 (0.26)	-2.00 (-0.56)	1.74 (0.64)	2.66 (0.72)	-4.69 (-1.35)	1.70 (0.61)
Adjusted R ²	0.51	0.78	0.25	0.26	0.66	0.00

Note: *t*-values are in parentheses.

* Significant at the 5-% level.

** Significant at the 1-% level.

<i>Table C</i>	<i>Mean age of exiters</i>			<i>Mean age at t = 5000</i>		
	<i>Quality regime</i>	<i>Intermediate regime</i>	<i>Network regime</i>	<i>Quality regime</i>	<i>Intermediate regime</i>	<i>Network regime</i>
<i>Constant</i>	913** (28.8)	1176** (22.0)	840** (24.0)	1852** (8.30)	2937** (31.9)	2374** (22.0)
<i>Cm_l</i>	-154** (-3.44)	-357** (-4.72)	43.3 (0.88)	-409 (-1.30)	-909** (-6.98)	-141 (-0.92)
<i>Cm_h</i>	-168** (-3.75)	55.7 (0.74)	-187** (-3.78)	865** (2.74)	890** (6.83)	64.2 (0.42)
<i>Sp_l</i>	-247** (-5.51)	121 (1.60)	-80.8** (-1.64)	-571 (-1.81)	-662** (-5.08)	-121 (-0.79)
<i>Sp_h</i>	-22.8 (-0.51)	-495** (-6.54)	-85.1 (-1.72)	172 (0.55)	357** (2.74)	148 (0.97)
<i>Cm_l x Sp_l</i>	164** (2.58)	98.2 (0.92)	71.7 (1.03)	426 (0.95)	572** (3.10)	-58.2 (-0.27)
<i>Cm_l x Sp_h</i>	98.4 (1.55)	119 (1.11)	16.2 (0.23)	65.9 (0.15)	-69.1 (-0.38)	-22.6 (-0.11)
<i>Cm_h x Sp_l</i>	161** (2.54)	-129 (-1.21)	127 (1.81)	-33.9 (-0.08)	-397* (-2.16)	-251 (-1.16)
<i>Cm_h x Sp_h</i>	139* (2.19)	-125 (-1.17)	-8.83 (-0.13)	-524 (-1.17)	-86.2 (-0.47)	-202 (-0.94)
<i>Adjusted R²</i>	0.44	0.75	0.43	0.26	0.86	0.10

Note: *t*-values are in parentheses.

* Significant at the 5-% level.

** Significant at the 1-% level.

Danish **R**esearch **U**nit for **I**ndustrial **D**ynamics

The Research Programme

The DRUID-research programme is organised in 3 different research themes:

- *The firm as a learning organisation*
- *Competence building and inter-firm dynamics*
- *The learning economy and the competitiveness of systems of innovation*

In each of the three areas there is one strategic theoretical and one central empirical and policy oriented orientation.

Theme A: The firm as a learning organisation

The theoretical perspective confronts and combines the resource-based view (Penrose, 1959) with recent approaches where the focus is on learning and the dynamic capabilities of the firm (Dosi, Teece and Winter, 1992). The aim of this theoretical work is to develop an analytical understanding of the firm as a learning organisation.

The empirical and policy issues relate to the nexus technology, productivity, organisational change and human resources. More insight in the dynamic interplay between these factors at the level of the firm is crucial to understand international differences in performance at the macro level in terms of economic growth and employment.

Theme B: Competence building and inter-firm dynamics

The theoretical perspective relates to the dynamics of the inter-firm division of labour and the formation of network relationships between firms. An attempt will be made to develop evolutionary models with Schumpeterian innovations as the motor driving a Marshallian evolution of the division of labour.

The empirical and policy issues relate the formation of knowledge-intensive regional and sectoral networks of firms to competitiveness and structural change. Data on the structure of production will be combined with indicators of knowledge and learning. IO-matrixes which include flows of knowledge and new technologies will be developed and supplemented by data from case-studies and questionnaires.

Theme C: The learning economy and the competitiveness of systems of innovation.

The third theme aims at a stronger conceptual and theoretical base for new concepts such as 'systems of innovation' and 'the learning economy' and to link these concepts to the ecological dimension. The focus is on the interaction between institutional and technical change in a specified geographical space. An attempt will be made to synthesise theories of economic development emphasising the role of science based-sectors with those emphasising learning-by-producing and the growing knowledge-intensity of all economic activities.

The main empirical and policy issues are related to changes in the local dimensions of innovation and learning. What remains of the relative autonomy of national systems of innovation? Is there a tendency towards convergence or divergence in the specialisation in trade, production, innovation and in the knowledge base itself when we compare regions and nations?

The Ph.D.-programme

There are at present more than 10 Ph.D.-students working in close connection to the DRUID research programme. DRUID organises regularly specific Ph.D.-activities such as workshops, seminars and courses, often in a co-operation with other Danish or international institutes. Also important is the role of DRUID as an environment which stimulates the Ph.D.-students to become creative and effective. This involves several elements:

- access to the international network in the form of visiting fellows and visits at the sister institutions
- participation in research projects
- access to supervision of theses
- access to databases

Each year DRUID welcomes a limited number of foreign Ph.D.-students who want to work on subjects and projects close to the core of the DRUID-research programme.

External projects

DRUID-members are involved in projects with external support. One major project which covers several of the elements of the research programme is DISKO; a comparative analysis of the Danish Innovation System; and there are several projects involving international co-operation within EU's 4th Framework Programme. DRUID is open to host other projects as far as they fall within its research profile. Special attention is given to the communication of research results from such projects to a wide set of social actors and policy makers.

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