Technological diffusion, welfare and growth: technological succession in the presence of network externalities

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Abstract

The paper examines the conditions under which technological successions can occur in the presence of network externalities. A multi-agent model is developed in which the product designs offered by firms co-evolve with consumer preferences. Firms compete though product innovation. The model incorporates a modified genetic algorithm (GA) in which imitation is conducted via a process of selective transfer (a one-way crossover) and internal R&D is conducted via selective mutation. Following an initial period in which old technology firms develop their designs and network externalities accrue, a technological shock occurs in which new technology-based firms enter the market. The findings of the model indicate that a necessary condition for a technological succession are the existence of at least one consumer group that champions the new technology, developing new preferences for its characteristics. Further, the introduction of novel characteristics are have a greater bearing on the probability of a succession than incremental gains in characteristics offered by the old technology. Third, the analysis identifies an inverse relationship between time the probability of a technological succession.

Keywords: technological change, innovation, succession, co-evolution

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Introduction: technological successions and network externalities

Schumpeter laid stress on the importance of technological discontinuities in economic history. In contrast to Marshall, who on the front page of his 'Principles of Economics' stated that *Natura non facit saltum* (Nature does not leap), Schumpeter argued that "evolution is lopsided, discontinuous, disharmonious by nature... studded with violent outbursts and catastrophes... more like a series of explosions than a gentle, though incessant, transformation" (Schumpeter, 1939, p. 102). Schumpeter did not question the existence of long periods of gradual development marked by the incremental development of established technologies. However, he stressed that such periods are punctuated by short bursts in which radically new technologies – such as the steam engine, the dynamo, the internal combustion engine and the integrated circuit - yield alternative products, processes and associated knowledges that displace existing technologies and lead to key structural changes in the economy as old industries are displaced by new industries, and old employment patterns replaced by new ones. It is the appearance of these new major technological breakthroughs that drive the economic system in a new direction. Such a shift "so displaces its equilibrium point that the new one cannot be reached from the old one by infinitesimal steps. Add successively as many mail coaches as you please, you will never get a railway thereby" (Schumpeter, 1939, p.37). Hence, for Schumpeter, economic development occurs when an economy moves from one base technology to another. New technologies are the fuel of economic growth and the source of welfare improvement over the long-run (Figure 1).
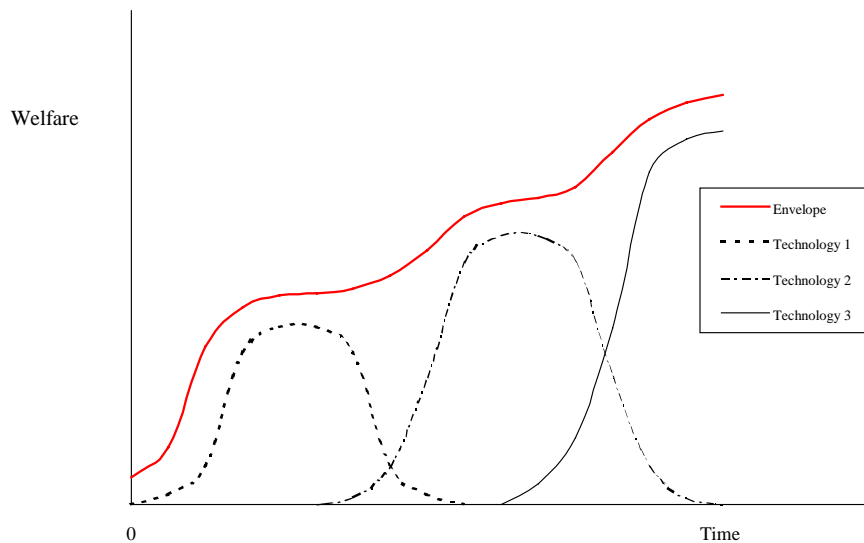

Figure 1.   Increasing welfare through technological succession

The Schumpeterian thesis of economic development has diffused widely since the late 1970s. Important impetus was provided by the work of Mensch (1979), Freeman, Clark and Soete (1982), and Kleinknecht (1990) on long-run economic cycles. Subsequently, important aspects of the Schumpeterian thesis have been adopted within mainstream neo-classical economics, e.g. in the literature on real business cycles (Nelson and Plosser, 1982; Kydland and Prescott, 1982) and in endogenous growth theory (Romer, 1994; Aghion and Howitt. 1992).

The focus of this paper is the conditions under which a new technology can overcome the network externalities enjoyed by an established (old) technology. In this respect, the paper draws together two areas of research that were, by and large, previously treated as separate: competition between sequential technologies and standards competitions. Research on network externalities has tended to consider standards competitions that occur between rival versions of a new technology (e.g. Arthur, 1989; Katz and Shapiro, 1986; Farrell and Saloner, 1985). A notable exception is David's empirical case study of the QWERTY keyboard (David, 1985). The DVORAK keyboard, a later and more efficient typing layout, was unable to displace the established QWERTY technology due to the network externalities enjoyed by the latter.

David's analysis discusses the institutional and behavioural factors that can keep a population locked in to an established technology. In this paper we wish to examine the set of factors that can enable externalities to be overcome. Section 2 of the paper discusses three key factors. The first concerns a differentiation of the characteristics offered by established and new technologies (Lancaster, 1971; Archibald and Eaton, 1989). It may not be sufficient for a new technology to simply offer a higher specification in a limited number of common characteristics (Hotelling, 1929). The second factor is the existence of differential rates of cost reduction due to the scale economies associated with different technologies. Differential falling unit costs of alternative technologies affect demand when these are transmitted to prices, altering the price-quality combinations offered by old and new technology products (Choi *et al.*, 1990). The third factor considered is the role that is played by user groups that are willing to experiment with new technologies leading to the development of new preferences. Herein lies an important distinction between technological successions and technological substitutions. In the former, new preferences emerge through a process of experimentation with new technologies. In the latter, a new technology better fulfils a given, unchanging set of user preferences. The fourth factor considered is time. The time with which new technology providers are able to exploit their superior applications may affect the probably of a technological succession occurring.

Given the large number of parameters involved, and the desire to examine these in a meaningful manner, the paper employs simulation techniques in section 3 in order to develop a model of technological successions. This is an agent-based model containing heterogeneous populations of adaptive users and providers that co-evolve over time. Producers employ various adjustment rules to their production routines while simultaneously innovating through a combination of imitation and internal

R&D. The model incorporates a modified genetic algorithm (GA) in which imitation is conducted via a process of selective transfer (a one-way crossover) and internal R&D is conducted via selective mutation. Section 4 provides details of the implementation of the model, the properties of which are tested through the estimation of a set of statistical models whose explanatory capabilities are compared. The results of this testing procedure are provided in section 6.

2. *Conditions for a technological succession*

An important starting point for the current paper is Shy's (1996) discussion of consumer substitution between network externality and quality in sequential technology competitions. In contrast to earlier papers by Farrell and Saloner (1985) and Katz and Shapiro (1986), the successive generations model developed by Shy focuses on *repeated* technology adoptions by different generations of adopters. Shy's model allows for different preferences between an 'old' consumer type and a 'young' consumer type (although preferences within each generation are assumed to be identical). In so doing, the model introduces an important distinction between a technological succession and a technological substitution. A technological substitution, such as the replacement of manual assembly processes by Taylorist (semi-)automated production processes, raised welfare by shifting the production possibility frontier for a given level of factor inputs. There is no change in consumer preferences. By contrast, a technological succession involves the introduction of new artefacts that alter consumption opportunities for a particular level of output. A succession is associated with change in both the dominant technological artefact produced by firms and the prevailing set of consumer preferences, as a new production-consumption nexus displaces an established production-consumption nexus.

Shy's paper suggests that a technological succession can occur provided the young consumer type treats quality and network externalities as substitutes (the later technology is *de facto* assumed to be of higher quality). If, however, quality and network externalities are treated as complements, then the old technology will be selected. Unfortunately, a number of issues are 'black boxed' in the Shy model: issues that are likely to affect the probability of a succession occurring. To begin with, three aspects of consumer demand need to be considered. First, one must clearly establish the basis on which later rival, technologies can displace an old technology. Second, one needs to carefully spell out the issue of 'quality'. The Shy model assumes that one technology is unambiguously superior to another. This is unlikely to be the case in reality. Indeed, historical studies of technological change indicate that later technologies tend to be better in some aspects of performance but weaker in others (Grübler, 1990). Furthermore, the actual sets of attributes are likely to differ, i.e. some attributes associated with a new technology are not present in the old technology and vice versa. Thus an important stylised fact of sequential technological competitions is differentiation across attributes as well as differences in the quality of shared attributes. Third, the Shy model does not consider the implications of a heterogeneous consumer population. Clearly, in the presence of product diversity, one needs to appreciate the way in which consumers – with heterogeneous preferences – compare rival technologies and make their

selections. On the supply-side, two issues are unexplored by the Shy model. First, the cost of producing these different attributes, or characteristics, will be reflected in the different prices of rival technology designs. A trade-off between new and/or improved attributes and the cost of their production is likely to arise. Second, the rate of falling unit costs due to static and dynamic economies of scale is likely to have important consequences to the result of competition.

2.1 Functional equivalence

A technological succession involves the displacement of an established product or process by a new alternative that fulfils the same basic function. Grübler, for example, has collected data that for primary energy sources and transport (Grübler *et al*., 1988; Grübler, 1990) that clearly show sequential technology successions, with changing relative market shares of successive technologies over time. The horse was replaced by the train, which was in turn succeeded by buses and then cars as the dominant mode of land-based transport in the US and Western Europe. Similarly, water was succeeded first by fuel wood, coal, and then oil as the primary energy source of the industrialised world. These alternative and competing forms of energy and land-based transport can be clustered because they share common functions. In the case of transport, the common function is to move humans and/or goods from one point to another, in the case of basic energy it is to provide heat and power. In other words, there is a *functional equivalence* between the new technologies and the older technologies they displace. Users consider the available alternatives and make choices based on some perceived difference between the relative *fitness of purpose*. Thus for a new technology to succeed an established technology, users must be persuaded that an alternative technology can in some sense *better fulfil* the product or process function. This leads us to the issue of quality and the assessment of quality by consumers.

2.2 Quality of alternative designs

Conventional economics ties the relative fitness of competing products to welfare. The economic literature contains some important precedents for an analytical treatment of how consumers first compare, and then rank, substitutable goods. In the past the analysis has tended to focus on one aspect of a good - its price - in order to explain the relative price elasticity of a commodity. Here we are interested in the process by which consumers compare not just price but also the performance characteristics of rival technologies. To this end a useful link can be made to the literature on consumer choice and product differentiation. The characteristics (or address) approach to modelling product differentiation dates back to Hotelling (1929) and has been used in a number of empirical studies (e.g. Saviotti, 1988; Archibald and Eaton, 1989; Choi *et al*., 1990; Frenken *et al*., 1999). Following Lancaster (1971), the Hotelling model can be adapted in order to describe a commodity in terms of the bundle of characteristics (or attributes) that it embodies. The important insight of

Lancaster is that a commodity is not desired for itself but, rather, because it offers certain performance characteristics that, in combination, translate into functionalities that form the basis of selection according to consumers preferences. For example, the basic function of a car is to transport people and goods from one place to another. Additionally, a car's design may please the user aesthetically, distinguishing it from rival designs.

A firm competes by offering a combination of characteristics that it believes will be more attractive to consumers than those offered by its rivals. In this way a firm effectively offers consumers a distinct point within a multi-dimensional character space. Product innovation is the means by which firms search this *n*-dimensional character space. The ability to offer a set of new, previously unavailable characteristics that are in some sense attractive to consumers is likely to be an important factor for a technological succession.

2.3 Trade-off between quality and price

A trade-off is likely to exist between the quality of the rival technologies and their price, tied to costs of producing these alternative bundles of characteristics. Given that consumer welfare depends on both the relative performance of each technology and their price, this will affect demand and hence the outcome of a technological competition. Indeed, Arthur (1989) has highlighted the importance of scale economies in production as one of the key factors likely to determine the outcome of technological competitions (also see Rosenberg, 1982). While a new technology design may provide previously unavailable characteristics, this is likely to be at an initially higher price. An established technology may enjoy static (level of production) scale economies and/or dynamic economies of scale (due to learning by doing) garnered over time. Both, of course, are initially unavailable to a new technology entrant. Having said this, the initial disadvantages of the new entrant may be overcome if unit costs of the new technology fall at a *faster rate* than those of the old technology. If firms are differentiated by both design quality and unit cost of production, then *ceteris paribus* market selection of the new and old technologies will in part depend on the rate at which unit costs fall over time.

2.4 New consumer preferences

As noted previously, a technological succession is associated with the development of new consumer preferences. By and large, the issue of changing preferences has been avoided by economists. In models of technological diffusion and in traditional consumer theory, for example, user preferences are assumed to be exogenously given and unchanging. In each case, this is a simplifying assumption which facilitates the development of models capable of producing analytically tractable results. In the

current context, however, the issue of changing preferences needs to be addressed directly.

It is interesting to contrast the situation in economics with that in psychology, sociology, anthropology, cultural studies, and marketing, where discussions of changing consumer preferences are well established. There changes in individual tastes have been linked to a range of social, economic and cultural factors. Notable influences include the individual's 'lifestyle' (Giddens, 1991), social class (Bourdieu, 1984), and the influence of prominent figures within cultural/social networks (Becker, 1984). Fashions, for example, are commonly driven by social influences (Simmel, 1957). Individuals belonging to a particular group may seek to establish a collective identity, and simultaneously distinguish themselves from other social groups, via their improvisation with novel technologies. However these consumption patterns may loose their attraction for these 'pioneers' if other groups start to consume these services. Over time then, the values attached to the characteristics offered by a particular product can change (increase or decrease) over time. The marketing activities of companies may also influence individual preferences. In the case of fashion, companies' marketing activities are clearly aimed at influencing users' desires for the characteristics provided by their products. Indeed, the last twenty years has seen the development by firms of innovative front-office tools such as branding, direct mail, loyalty schemes, and relationship marketing through internet-based ICTs, all aiming to cultivate demand for their products.

In order for a novel technology to first take hold, it needs to be supported by at least one group of consumers that is willing, and capable, of experimenting with its novelty (Rosenberg, 1982; Rogers, 1983). A necessary condition for technological succession is thus the appearance of a new 'type' of consumer preference; one that gives weight to the particular characteristics of the new technology. Take, for example, the recent diffusion of the internet. Cultural and social theorists have drawn attention to the innovative role played by distinct forms of youth culture that developed in the early 1980s. The internet facilitates the (virtual) interaction of readers and writers in ways that are very difficult to achieve in print – especially for young people. Publishing on the web by young people aged 13 to 18 is motivated by the desire to participate in, or create, a distinct community (Abbott, 1998). An important strategy for acquiring membership and defining oneself as part of the community, is the ability to sustain contemporary knowledge of the appropriate words, spelling of words, contractions acronyms, emoticons and appropriate and inappropriate terms which change from week to week.

Experimentation with non-standard English is directly related to the supplanting of the print era. "Supposedly proper grammar, dictionary definitions and correct spellings have all been the result of printing press uniformity. The standardised forms did not exist before the advent of the printing press, and they probably won't exert the same hold over our minds as the influence of the printing press declines" (Spender, 1995, p.xx). Computer-culture theorists such as Turkle (1995) go further, seeing in the new uses of computers "fundamental shifts in the way we create and experience human identity" (1995, p.10). Cyberculture on the internet, she argues, was distinct to other

forms of culture and was populated with distinctive species of human beings - hackers, MUDers and cyberpunks. This phenomenon, and the trope of newness/danger, was not unique to the USA or Europe. In Japan there is the phenomenon of the *Otaku-Zokui*: the 'at home tribe'. Otaku are (typically) young men who spend most of their time at home at their computers, assessing, processing and distributing information about a very specific aspect of the world of television, music, movies or comic books (Grassmuck, 1990; Greenfield, 1993). Tobin observes that "cyberculture is a dyadic relationship between young people with computers and older people reacting to them, trying to control them, and worrying about them" (Tobin, 1998, p.111).

Championing of a technology by at least one group of users provides the resources necessary for firms to engage in R&D, further developing the attributes that are distinct to the technology. Subsequently, other groups of users become aware of these distinct attributes and also begin to adopt the technology, leading to a change in their preference sets. These later adopters may be more conservative and less technically competent. As a consequence, technological designs need to become more reliable and more robust. For example, a variety of software packages now exist that enable users to develop web pages and organise websites without the need to write XML script or learn a computer language. Still, while some of the more radical social and political aspirations of its early adopters may become diluted, distinctive aspects of will remain intact as it diffuses amongst other user groups (Pinch and Bijker, 1984). In the case of the internet, for example, it has no central structure or organisation, is hardware and software independent, and is an inherently two-way medium that requires adopters to develop new styles of communication. Indeed, its ubiquitous nature is such that it is remains exceedingly difficult to either legislate and regulate.

2.5 Time

Austrian economists have long emphasised the importance of time as an important variable in economics. On the demand side, the network externality associated with an established technology will continue to increase incrementally over time. On the supply side, the longer old technology firms have to learn about the preferences of preferences of their existing users, and the longer they have to perform R&D in order to optimise the performance of their designs, the greater the probability of their identifying designs that maximise the utility of their customers. Independently, each factor could effectively lock-out a new technology. Together, they represent a significant barrier that increases with time. *Ex ante* one would expect the probability of a technological succession occurring to be inversely related to the length of time during which an older technology establishes itself.

2.6 The adopter's choice problem

From the proceeding discussion we see that there is likely to be a number of factors influencing consumer preferences, and that these interact in a complex manner. Three factors in particular have been highlighted above: production costs, price and performance quality. Formalising this, the probability of adopting the new technology B rather than the established technology A at time *t* is

$$\Pr\{U_A(x_A + e_A) + V_A(m - p_A) < U_B(x_B + e_B) + V_B(m - p_B)\} \quad (1)$$

where *x* is the characteristic vector of a technology design

   e is the network externality

   p is the price of that design

   V is the indirect utility of money that can be obtained in other markets

Here we assume that all other markets are fixed and that this function has a constant form. *U(x)* is the direct utility of consuming the good with characteristic vector *x*. Note that the utility of not buying a good is *V(m)* and so a consumer will only accept offer *(x, p)* if $u_i(x) > V_i(m) - V_i(m-p_i)$. That is to say, an adopter only makes a purchase when direct utility outweighs the lost in indirect utility, or opportunity cost, of the purchase.

In the presence of heterogeneous preferences, an analytically tractable solution for equation 1 is unlikely to exist in all but the simplest of circumstances. Multiple equilibria solutions can exist in which it is impossible to predict *ex ante* whether there will be a technological succession, a technological substitution, a mixed solution in which both old and new technologies coexist, or even a technological lock-out. First, multiple equilibria solutions will exist, even when the performance characteristics of one technology are absolutely superior to those of another, if there is a high frequency of intermediate valuations within the consumer population. Second, rival technologies typically offer different relative strengths across a set of performance characteristics. Again, given heterogeneous preferences, it is impossible to predict *ex ante* whether a technological succession will occur. One way of tackling the problem is to construct a simulation model with which one can analyse the consequences of heterogeneous consumer preferences, and the co-evolutionary dynamics of changing consumer preferences and the innovative activities of competing firms.

3.   A model of technological succession

3.1 The Market

After initialisation, overall control of the model passes to a market object that runs the model for the number of time periods specified in the model configuration. In each period this market object proceeds as follows,

1. It brings the consumer groups to market in a random order and gets the groups to determine their demands and purchases.

2. It initiates the replicator dynamic for that period to redistribute the consumer population across the groups.

3. It gets firms to adjust their capacity, level of production and to redesign their goods.

3.2 Consumers dynamics

There are M consumer groups. Associated with group $i = 1,...,M$ is a utility function u_i is defined over the offer space, namely the Cartesian product $X \times P$ of design space X and the price space P (positive real numbers) of the form

$$U_i(x,p) = \sum_k \alpha_{ik} v_k(x_k) + \beta_i w(m-p) = \alpha_i \cdot v(x) + \beta_i w(m-p) \qquad (2)$$

Here m is the budget of the consumer and is assumed to be the same for all consumers. The term $\beta_i w(m-p)$ is the indirect utility obtained by spending the residual budget in other markets. All consumers in the same group are assumed to adopt the same utility function. Each firm offers to sell a good with some design x at some price p. Consumers use these utility functions to rank alternative offers and as a measure of well-being. Note that consumers always have the option of not accepting any of the offers and may keep all of their budget for use elsewhere. The utility of this option is $\beta_i w(m)$ and will be called the *null utility*. It can be seen that the utility functions differ across groups only in having different values for the coefficients α_i and β_i. Currently we use a simple square root function for the component functions, i.e.

$$v_k(x_k) = \sqrt{x_k} \quad \text{and} \quad w(m-p) = \sqrt{(m-p)} \qquad (3)$$

The population of consumers in each period is G and a form of the replicator dynamics described below governs the distribution across the M groups. Let G_{it} be the number of consumers of type i at time t. We use the subscript t only when

necessary to distinguish between periods. In each period firm j offers a quantity Q_j of a particular design-price combination (x_j,p_j). After firms have 'posted' these offers, consumer groups appear in the market in a random order. Let $I(i)$, with $i = 1,...,M$, be a permutation of the indices $\{1,...,M\}$ so that $I(1)$ is the first group to come to market. Note that this permutation will differ from period to period. Given the utility function $U_{I(1)}$ associated with this group, the consumers rank the offers (x_j,p_j) in descending order of preference.

Let $J(j)$ with $j = 0,1,...,M$ represent this ranking, so that $J(j)$ is a permutation of $\{0,1,...,M\}$, where 0 represents the 'null offer', i.e. buy none of the goods. If the null offer is best (*i.e.* $J(0)=0$) the consumers in that group exit the market without buying anything. If the firm ranked highest by the consumers has an offer which dominates the null offer (*i.e.* $J(0)>0$) then all consumers in that group will 'post' a demand for one unit of that offer. If firm $J(0)$ has produced a sufficient quantity of the good (*i.e.* $Q_{J(0)} \geq G_{I(1)}$) then all these demands will be converted into sales, all consumers in the group exit the market and the available quantity of the good is reduced by the volume of sales, i.e. $Q_{J(0)} \Leftarrow Q_{J(0)} - G_{I(1)}$.

If demand exceeds supply (*i.e.* $Q_{J(0)} < G_{I(1)}$) then $Q_{J(0)}$ demands are converted into sales, $Q_{J(0)}$ of the consumer leave the market and the available quantity of the good becomes zero and the remaining consumers $G_1 - Q_{J(0)}$ consider their next best option $J(1)$. The interaction of these remaining consumers with this offer is identical to interaction with $J(0)$. If $J(1) = 0$ they leave the market, otherwise they post demands for the goods and these are met fully or partly depending on the quantity $Q_{J(1)}$ on offer. This process for group $I(1)$ continues until all consumers in the group have left the market. Group $I(2)$ enters the market and interacts with firms in the same way apart from the fact that the quantities available to this group will be reduced by any sales made to group $I(1)$ consumers. This continues until all groups have entered and left the market. When group $I(i)$, $i > 1$, enters the market the quantities available will be the Q_j's minus any sales made to consumer groups $I(k)$ for $k = 1,...,i-1$.

After this process in period t each consumer group will have attained an average level of utility W_{it}. This is the average utility of the consumers in the group after they have consumed any good bought in this market. Note that all consumers will attain a utility no less than the null utility and thus W_{it} will be no less than the null utility.

Let $\rho_{it} = G_{it} \div G$, where G is the total population, be the proportion of the consumer population in the ith group. Given these utilities the new distribution ρ_{it+1} is calculated as

$$\rho_{it+1} = \rho_{it} \times rW_{it} \div \Sigma_k (\rho_{kt} \times rW_{kt}) \quad (3)$$

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where r is factor determining the strength of the replicator effect of the differing utilities. Groups with above-average utilities grow larger and groups with below-average utility decline *i.e.* they have a negative grow rate.

3.3 Firms: prices, profits, wealth, production and capacity

Firms adjust to excess demand by altering output and production capacity. In the beginning of period t, firm j has monetary wealth or cash M_{jt}, capacity or capital K_{jt}, design x_{jt}, a level of production y_{it} and an inventory of unsold goods q_{jt}. The unit variable cost of production is given by the cost function

$$C(x) = \Sigma_k \gamma_k c_k(x_k) \qquad (4)$$

Note that the cost function is common to all firms and is seen to represent the available technology available to all firms. Note also that this cost is independent of the level of production. The cost function is available to firms in the sense that they can calculate the cost of a design prior to production. Currently the component functions are

$$c_k(x_k) = x_k^2 \qquad (5)$$

It is assumed firms face a fixed cost Φ so that the average total cost of producing output y of design x is $C(x) + \Phi/y$. Hence with $\Phi > 0$ there are increasing returns to scale in the sense that these average total costs are falling.

Firms set prices according to a simple mark up rule, namely

$$p_{jt} = (1+\eta_{jt}) \times (C(x_{jt}) + \Phi \div y_{jt}) \qquad (6)$$

In current simulations there is a common and constant mark up so that $\eta_{it} = \eta$, but the model allows the mark up to adjust to excess demands and supplies.

At the start of the model, firms start with the same capacity and wealth but have their designs are randomly and independently generated. The variety between firms is initially in their designs and in their target consumer group; see the discussion of innovation below.

Given the design and level of production the firm offers a quantity $y_{jt} + q_{jt}$ of the design x_{jt} at a price p_{jt}. After consumers have made their choices, signalled their demands and made their purchases, firms adjust their capacities, their levels of production and consider modifications to their designs. Given its sales s_{jt} and level of

production, each firm calculates its net revenue or current account profit for the period, namely $\Pi_{jt} = p_{jt}s_{jt} - y_{jt} C(x_{jt}) - \Phi$. This profit is added to its monetary wealth: $M_{jt+1} = M_{jt} + \Pi_{jt}$. If profit is negative and this monetary wealth becomes negative, then the firm has to sell capital sufficient stock to return monetary wealth to zero. If the firm has insufficient capital stock to restore zero monetary wealth then it becomes bankrupt in the sense that wealth and capital go to zero and the firm can no longer produce.

A the firm calculates a new target level of production y^*_{jt+1} as follows:

$$y^*_{jt+1} = \chi d_{jt} + (1 - \chi) s_{jt} \qquad (7)$$

where $\chi \in [0,1]$ is partial adjustment term and d_{jt} is the level of demand for the jth firm's design in period t. The firm adjusts its capacity given this target level of output. Essentially, the firm aims to make capacity match this target level of output subject to the constraints that any increase in capacity cannot exceed its monetary wealth and that capacity cannot be negative. Given this target capacity, the firm partially adjusts its capacity toward this target,

$$K_{jt+1} = K_{jt} + \delta(K^*_{jt+1} - K_{jt}) \qquad (8)$$

where δ is a partial adjustment term and K^*_{jt+1} is the target level of capacity. $K^*_{jt+1} = y^*_{jt+1}$ if $(y^*_{jt+1} - K_{jt}) \leq M_{jt+1}$ otherwise $K^*_{jt+1} = K_{jt} + M_{jt+1}$.

Note that, after adjusting capacity, monetary wealth is adjusted as follows:

$$M_{jt+1} = M_{jt} - (K_{jt+1} - K_{jt}) \qquad (9)$$

3.4 Design innovation by firms

Firms modify their designs in two stages. In the first stage all firms consider mutations, while in the second stage all firms consider one-way transfers. Both are subject to filtering by firms' mental models. Each firm targets one of the consumer types. In this version of the model we simply by assuming the firm knows the utility function of that consumer type. An innovation, mutation or transfer, is implemented only if it increases the utility of the target consumer type.

Mutations are carried out in isolation of other firms. Given design x for the jth firm at period t, the firm considers a mutated design x^*. Each component x^*_i mutates with probability μ and if it does mutate it has the value $x_i + \kappa \varepsilon$, where κ is a mutation factor and ε is a random number drawn from a standard normal distribution. The mutated design replaces the current design only if it increases the utility of the firm's target consumer type.

After mutation, firms consider further innovation based on imitation of rival firms. Each firm picks another firm in a biased random draw from the existing set of firms. Selection is biased toward to the more profitable firms, and is based on Goldberg's 'roulette wheel'. Here the probability of firm j being selected is proportional to the profit made by the firm j in the current period. Having selected a rival, the firm creates a new candidate design x^* by transferring part of the rival's design x^r to replace the matching elements of its current design. A random set H of characteristics is selected and $x^*_h = x^r_h$ for $h \in H$ and $x^*_h = x_h$ for $h \notin H$.

This selective transfer operator is different to crossover in genetic algorithms. Here there is no mutual exchange of elements, selective transfer is a one-way emulation[1]. Hence the firm that is being emulated does not have to adjust its design as a consequence of this operator. The new design x^* replaces the current design x only if this increases the utility of the target consumer type.

3.5 Technological Shock

Central to the Schumpeterian thesis is the periodic occurrence of major technological shocks that drive economic growth. Innovative entrepreneurs seek to enter existing market niches through the introduction of alternative products based on radical technological breakthroughs and/or new scientific discoveries. In this way, a new wave of innovative entrepreneurs simultaneously challenge the existing leading-edge of technology and the dominant market players that produce the established technology.

New market entrants provide a second major source of new variety in the model. As previously discussed, Schumpeter highlighted the role played by new entrants who seek to enter existing market niches through the introduction of alternative products. When successful, these lead to changing market shares and the demise of old technology firms. Following Schumpeter (1912), we assume that barriers to entry for new start-up companies are low, new firms being able to freely access the existing, common knowledge domain. In turn, the new knowledge generated by their innovate behaviour spills over into this common knowledge pool and so can be built upon by subsequent innovators.

In the current model there is a technological shock at some period T_1. This shock has three features. First, the design space qualitatively changes, i.e. the set of characteristics associated with the new technology differs to that of the old technology. More specifically, up to time T_1 the design space involves characteristics or dimensions 1 to h_1 while after T_1 the design space involves characteristics or

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[1] See Windrum and Birchenhall (1998) for a detailed discussion of the one-way selective transfer operator.

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dimensions h_2 to h, where $1 \leq h_2 \leq h_1 < h$. Furthermore, before T_1 there is a limit x_{max} on characteristic values. We use D_1 and D_2 to represent the design spaces before and after T_1 respectively. Before T_1 all designs must belong to D_1 and consumers place positive weight on characteristics 1 to h_1 and zero weight on characteristics h_1+1 to h.

Second, whereas firms prior to T_1 are producers of the old technology, after T_1 there is a set of new entrants and these new entrants use the 'new' technology producers. At the same time all new consumer groups born after T_1 are 'new' technology consumers. This is done in the following way: at T_1 'dead' firms and 'dead' consumer types are replaced by new generations of firms and consumer types. A firm is treated as 'dead' if its market share has fallen below a cut-off value and a consumer type is 'dead' if its share of the consumer population has fallen below a cut-off value. The new firms created at time T_1 must provide designs in D_2. New consumer types place positive weight on characteristics h_2 to h and zero weight on characteristics 1 to h_1-1. Third, picking up on the earlier discussion of the possible importance of the relative rate of falling unit costs due to static and dynamic economies of scale, the cost of production for new technologies is reduced by a factor θ, i.e. after T_1 all γ_k are reduced by a factor θ.

4.   *Implementation details*

The current model uses three independent random number generators, *RC*, *RF* and *RM*, which are used to initialise and modify the consumers, firms and the market respectively. These are independent in the sense that each has its own set of seeds. In a run of the model these generators are used as follows,

- *RC* is used to assign values for parameters α, β in the utility functions both at the start of the model and for new consumer groups at T_1. All values lie between 0.0 and 1.0.

- *RF* is used to assign initial designs and cost parameters γ_k as well as control the mutations and transfers. Apart from initial designs before T_1 all values lie between 0.0 and 1.0. Initial designs before T_1 are truncated at x_{max}.

- *RM* is used to randomly shuffle the order in which consumer groups arrive at the market.

A batch job is used to control multiple runs of the model. This batch job has its own random number generator *RB*. The role of *RB* is outlined below.

To study the properties of the above model, a batch job was used to run 400 versions of the model. Here we describe this batch job and in the next section we present a statistical analysis of the model. Before running the batch job a configuration file was used to set default values for the various parameters of the model (see Table 1 in

Appendix for key default values). During the batch job, the following parameters were set randomly as follows.

Symbol	Description	Random Range
x_{max}	Maximum value of x_i before T_1	[0.3, 1.0]
T_1	Time of technological shock	[100, 200]
h_1	$x \in D_1$ has $x_i = 0$ for $i > h_1$ and $\beta_i = 0$ for $i > h_1$	[5, 8]
θ	Cost reduction factor	[0.0, 0.3]
$CS1$	First seed for RC	[1, 10000]
T_2	Number of periods after T_1	$2 \times T_1$
T	Total Number of periods $T_1 + T_2$	$3 \times T_1$

All random values were generated by a uniform distribution over these ranges.

5. Results

First, we report that the model is capable of producing technological successions. When these occur, changes in the aggregate level of consumer welfare conform to the pattern illustrated in Figure 2. The envelope of aggregate utility is raised as the new technology displaces the previous incumbent within a particular market niche. Hence, the model is capable of generating observed patterns of improvement illustrated in Figure 1 above. The model therefore conforms to an important stylistic fact of long-run economic development: the displacement of old technologies by new, more efficient technologies, raises consumer welfare over time.
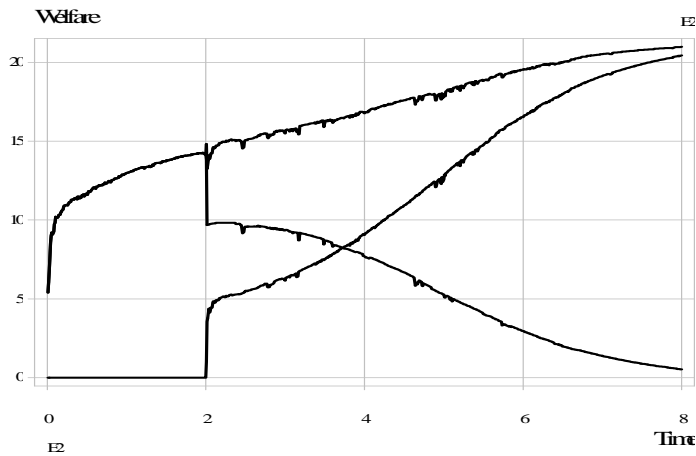

Figure 2. Succession by a new technology providing higher welfare

The ability of the model to produce results that accord to important stylised facts increases ones confidence in the model. Of course, we are not simply concerned with the replication of stylised facts. We are interested in exploring the conditions under

which technological successions are likely to occur. As the model is rich in its parameters, we report a series of experiments that explore the dimensions of design characteristics h_1, the upper bound on the values of characteristics offered by the old technology x_{max}, time T_1, and the cost reduction factor θ as potential explanatory variables for a technological succession occurring. To this end, we constructed a logit model of the probability of succession P. To estimate the models we take the 400 simulations as observations on the model.

As discussed in sections 1, 2 and 3, an important distinction needs to be made between technological 'succession' and a 'substitution'. A 'succession' occurs when, at the end of a simulation run, a new, 'type two' firm-consumer coupling has displaced an established, 'type one' firm-consumer coupling, i.e. only new technology firms remain and these sell all their output to new consumer types. By contrast, a 'substitution' occurs when type two firms displace type one firms but there is no change in consumer preferences, i.e. type two firms sell their output to type one consumers.   A third possibility is a mixed solution where type two firms displace type one firms and sell to a combination of both type one and type two consumers.

Here we are here interested in separating out technological successions from all other cases. Hence, we shall henceforth refer to the case of successions as 'Successions' and cluster both substitutions and mixed solutions under the term 'Substitutions'. For each simulation we can use the observed values of sales and consumer population to classify the outcome as 'succession', 'substitution' or 'lock-out'.

Summary Statistic	Value
In Sample Successions	111
In Sample Substitutions	160
In Sample Total	360
Out of Sample Succession	16
Out of Sample Substitutions	21
Out of Sample Total	40

Here we present the logit model that considers the factors influencing a technological succession. The model sets the dependent variable to 1 if there is succession and to zero otherwise. When estimating the model we used 360 'in sample' observations to select and estimate the models and 40 'out of sample' observations to test the prediction capacity of the selected logit model. Before selecting variables and estimating model the explanatory variables are normalised as follows. For each variable we subtract the in-sample mean and divide by the in-sample standard deviation. Variable selection involves a stepwise elimination of variables in an attempt to minimise the Schwartz Information Criterion (SIC), which is a form of Penalised Maximum Likelihood Model Selection (PMLMS) (see Birchenhall *et al.*, 1999 for a discussion of this method). Sin and White (1996) show that PMLMS leads asymptotically to the selection of the 'best' model, i.e. the model with the smallest Kullback-Liebler Distance from the true model even if all models are misspecified.

Using this method of variable selection for the succession model, the variables are eliminated in the following order: θ, x_{max}, T_1 and h_1. The best model includes T_1 and h_1, the estimated model being

$$P = \text{logit}(1.01 + 0.82\, h_1 - 0.72\, T_1)\ .$$

The summary statistics for this model are

Statistic	Value
SIC	383.9
Log Likelihood	180.2
In Sample Succession Errors	26%
In Sample No Succession Errors	18%
In Sample Total	21%
Out of Sample Succession Errors	19%
Out of Sample No Succession Errors	5%
Out of Sample Total	12%

6.   Conclusions

The paper represents a first attempt to develop a multi-agent model of technological succession in the presence of network externalities. The initial findings presented in the paper indicate the approach offers significant promise in terms of its ability to construct and probe complex models containing high degrees of non-linear interaction between multiple agents whose behaviour changes over time. Stylised facts of production and consumption have been integrated within the model. In the presence of imperfect capital markets, firms with finance R&D investments out of past profits. This establishes a strong positive feedback between past success in offering deigns with attractive quality-price characteristics, improved sales and profitability, current investment in R&D, and the future development of yet more attractive designs. The existence of static and dynamic economies of scale adds a further spur to successful firms since those firms with market shares that grow faster than average, enjoy above-average reductions in fixed operating costs (Nelson and Winter, 1982; Silverberg *et al.*, 1988; Metcalfe, 1994; Klepper, 1996).

Turning to the stylised facts of consumers, individual preferences are nested within group relationships and preferences evolve over time (Simmel, 1957; Bourdieu, 1984; Becker, 1984; Giddens, 1991). Just as collectively firms learn about consumers, so consumers collectively also learn over time as they experience rival products offered in markets. Hence, preferences and technological designs co-evolve through learning

and experimentation by heterogeneous populations of adaptive consumers and firms. When a technological shock occurs, and a radically new technology product is introduced into the market, at least some consumers will experiment with it and compare it with old technology designs. Indeed, a necessary condition for a technological succession, is its initial championing by at least one group of consumers.

The logit model that has been estimated is statistically respectable and conforms to a number of intuitive expectations. Where firms engage in mark-up pricing, they will adjust to a demonstrable demand for their designs and compete through product innovation. Whether a technological discontinuity leads to a technological succession, a substitution, or else is locked-out by the old technology, ultimately depends on the evolving preferences of consumers. In the model, a replicator dynamic is placed on consumer preferences. Preferences that are well serviced will diffuse over time while those that are poorly serviced tend to disappear. Consequently, new technology firms must quickly develop designs that satisfy their target customers. For a succession to occur in the model, new (type two) technology firms must quickly develop designs with quality-price combinations that provide their targeted (type two) consumers with higher levels of utility than those enjoyed by (type one) consumers serviced by old (type one) technology firms. If not, then the network externalities accruing to the old technology continue to increase, locking out the new technology.

In addition to highlighting the co-evolutionary interaction between technological designs and consumer preferences that drive emergent market structures, the paper explored the effect of four factors on the probability of a technological succession occuring. First, superior performance by new technology designs in characteristics also offered by old technology designs; second, the introduction of distinct characteristics by new designs that are unavailable in old technology designs; third, different rates of reductions in fixed production costs between new and old technologies; and fourth, time. Only the first factor was considered by Shy's model. In our estimated logit model, the availability of new characteristics has a higher significance than the ability to offer improved performances over existing characteristics. Intuitively, given diminishing marginal utility over the entire characteristic space, the initial gain arising from the consumption of a new characteristic is likely to be greater than that due to an incremental improvement in an existing characteristic.

Turning to differential rates of cost reduction in the production of new and old technology designs, these do not appear to be a significant factor in the estimated succession logit model. It may well be that relative costs prove to be a key factor in technological substitutions, where new technology firms sell to established (type one) consumer groups. Certainly, this is an issue that needs to be considered in future research. By contrast, time was found to be an important explanatory variable in the estimated logit model. As one would intuitively expect, a negative relationship exists between the probability of a succession occurring and the length of time in which the old technology is able to establish itself. Not only do the network externalities accruing to an old technology increase but longer periods of investment in R&D by old technology

firms improves the chance of their identifying designs that satisfy the preferences of (type one) users. Hence, the longer the time period prior to the introduction of a new technology, the higher the differential in quality required of the new designs in order to overcome these lock-out effects.

To summarise, the multi-agent model presented in the paper complements and extends Shy's discussion of technological successions in the presence of network externalities. Notably, its findings support the proposition that the simultaneous championing of a new technology by new firms and by one or more consumer groups that develop new preferences for its characteristics are necessary conditions for a technological succession. Further, the findings suggest that the result does not depend on the assumption of homogeneous consumer preferences amongst later generations of adopters. Investigation of the multi-agent model has also extended the discussion in a number of important respects. Notably, it suggests that the introduction of novel characteristics are likely to have a greater bearing on the probability of a succession occurring than incremental performance gains in characteristics also offered by the old technology. In addition, it highlights the importance of time as a variable. Not only do network externalities accruing to an old technology increase over time but the ability of old technology firms to innovate and develop good quality designs increases over time. Both act to reduce the probability of a technological succession occurring.

Appendix

Table 1: Glossary of notation and Default Batch Values

Symbol	Description	Default
$U_i(x,p)$	Utility function for ith consumer group	
X	Design vector	
N	Number of characteristics in a design	8
x_{max}	Maximum value of x_i before T_1	Random
T_1	Time of technological shock	Random
D_1	Design Space up to T_1	Random
D_2	Design Space after T_1	Random
e	Network externality in period T_1	Random
h_1	$x \in D_1$ has $x_i = 0$ for $I > h_1$ and $\beta_i = 0$ for $i > h_1$	Random
h_2	$x \in D_2$ has $x_i = 0$ for $i < h_2$ and $\beta_i = 0$ for $i < h_2$	1
P	Price of good	
α	Vector of utility coefficients	
β	Coefficient on indirect utility of money	
M	Monetary budget of consumers	20
v_k	Component function of utility function	
W	Indirect utility function	
G	Total population of consumers	60
M	Number of consumer groups	8
G_{it}	Number of consumer in group i at time t	
Q_{jt}	Quantity of good from firm j at time t	
W_{it}	Average utility attained by group i at time t	
ρ_{it}	Proportion of population in group i at time t	
R	Strength of replicator effect	0.1
$C(x)$	Unit variable cost of producing design x	
γ_k	Coefficients in $C(x)$	
θ	Cost reduction factor	Random
$c_k(x_k)$	Component functions in $C(x)$	
Φ	Fixed cost of production in each time period	2.0
y_{jt}	Level of production of firm j in period t	
η	Mark up on costs	0.25
p_{jt}	Price of j'th firm's output in period t	
q_{jt}	Inventory of goods for firm j in period t	
Π_{jt}	Current account profit for firm j in period t	
s_{jt}	Sales for firm j in period t	
M_{jt}	Monetary wealth of firm j in period t	
d_{jt}	Demand for firm j's output in period t	
χ	Partial adjustment factor for output	0.1
K_{jt}	Capital = capacity for firm j at period t	
δ	Partial adjustment factor for capacity	0.25
μ	Probability of mutation	0.3
κ	Mutation size factor	0.05
ε	Draw from a standard normal distribution	

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