

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

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Abstract

In an earlier paper (Windrum and Birchenhall, 1998), the authors examined the dynamics of co-evolving product designs and user preferences leading to the horizontal segmentation of new technology markets into distinct ‘niches’. In this paper the generic framework is applied to the issue of how new technologies are able to overwhelm the network externalities enjoyed by established technologies (Arthur *et al.*, 1987; Arthur, 1989; David, 1985; Katz and Shapiro, 1986; Farrell and Saloner, 1985).

The analysis builds on earlier discussions of technological substitutions and explores a number of issues not normally considered but which are likely to have a bearing on the probability of technological substitutions occurring. First, we consider differentiation in the characteristic sets offered by the old and new technologies (Lancaster, 1971; Archibald and Eaton, 1989). This contrasts with the possibility of a new technology offering higher specification over the same characteristic set (Hotelling, 1929). Second, we consider differential costs due to scale economies. 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, DeSarbo, and Harker, 1990). Third, we consider time as a possible explanatory variable. Altering the time in which new technology suppliers are able to exploit their superior applications is likely to affect the probably of a technological substitution occurring.

Given the large number of parameters involved in the analysis, and the desire to examine these in a meaningful manner, the paper employs simulation techniques on an agent-based model containing heterogeneous populations of adaptive users and suppliers that co-evolve over time. In the spirit of Nelson and Winter (1982), producers employ various adjustment rules to their production routines, while simultaneously innovating through a combination of

imitation and internal R&D. Whereas Nelson and Winter modelled these using a replicator dynamic algorithm, the current paper employs a modified genetic algorithm in which imitation is conducted via a process of selective transfer (one-way crossover) and internal R&D is conducted via selective mutation.

The paper identifies a number of necessary conditions for technological substitutions, leading to higher welfare and growth. These compliment earlier suggestions while also highlighting new issues; functional equivalence of the alternative technologies, quality of the alternative designs, the trade-off between quality and price, new user preferences, and time.

Keywords: technological substitution, innovation, co-evolution

1. Introduction: technological substitutions and punctuated equilibrium

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).

We suggest that the concept of punctuated equilibrium developed in the ecological sciences can be usefully applied to this discussion of the relationship between incremental change and technological substitutions. The ecological theory of punctuated equilibrium was originally put forward by Gould and Eldridge (1977). They observe that "once they appear, species tend not to change very much at all. They may last 5 or 10 million years - sometimes even longer - and yet, while a few might undergo the sort of gradual, 'progressive' modification we have come to expect of evolution, most will stay pretty much as they were when they first evolved... But the mid-Paleozoic period shows us that the individual instances of species-stability 'punctuated' by occasional bursts of speciation... have immediate consequences for the ecological organisation, and thus the ecological history, of life" (Eldridge, 1987, p.82). In their discussion of species substitutions in ecological systems, Nicolis and Prigogine (1977) add that the new invaders must have a better capability of exploiting the same resources offered within an ecological niche. In other words, they must be able to do something 'more' or 'better' - whether it be capturing a certain type of prey, reproducing or avoiding death - than the previous incumbent. As a consequence, the fitness of successive species occupying a

given niche will increase over time. The envelope of overall fitness is raised as more efficient species displace earlier incumbents within an ecological niche (Figure 1).

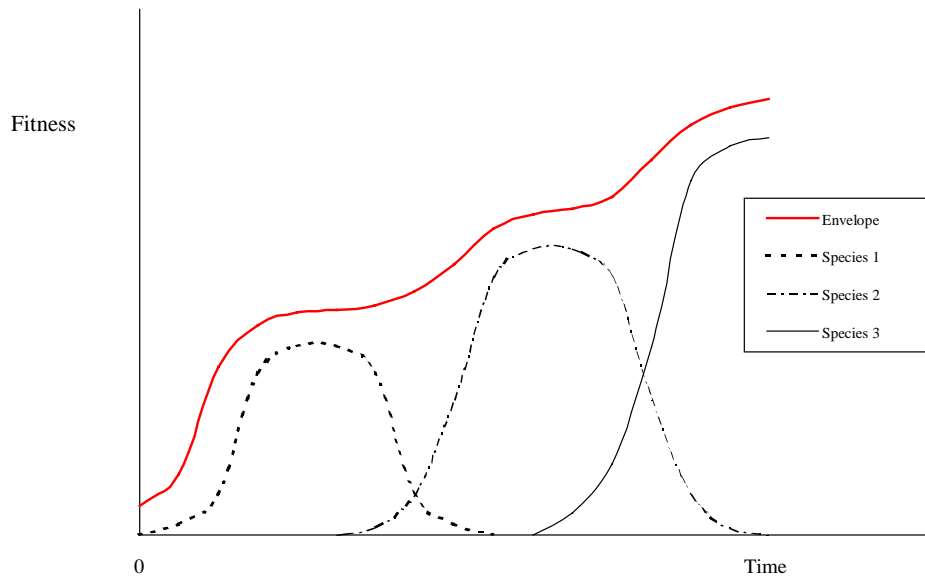


Figure 1. Substitutions by successive species with increasing fitness

Schumpeter's discussion of economic evolution has much in common with the ecological theory subsequently developed by Gould and Eldridge. As noted, Schumpeter similarly discussed economic history in terms of punctuated equilibrium, the economic system spending long periods in one equilibrium state and then suddenly shifting to a new equilibrium. Economic history, according to Schumpeter, is marked by a sequence of such punctuations brought on by the development of radically new technological products, processes and associated knowledges. We suggest that punctuated equilibrium offers a useful general framework in which to bring together the discussions of radical and incremental technological innovation developed over the last couple of decades. Product competition can operate at two levels, between rival old and new technological artefacts and between rival variants of a technological artefact. In the remainder of this paper we shall address the conditions under which the advantages that have accrued to an established technology over time may be overcome by a new, alternative technology.

2. Conditions for a technological substitution

Nelson and Winter (1982) argue for engagement in *appreciative theorising* as an initial step in the process of developing formal models. One must be clear about what is, and is not, being modelled. As well as identifying a set of *stylised facts* which the model is expected to replicate – notably, in this case, the ability of a formal model to replicate Figure 1 - appreciative theorising provides the basic conceptual and theoretical elements which form the core of the model. An important starting point for the current paper is Shy's (1996) discussion of consumer substitution between network size and quality in sequential technology competitions. In contrast to earlier

papers by Farrell and Saloner (1985) and Katz and Shapiro (1986), the overlapping generations (OLG) model developed by Shy focuses on *repeated* technology adoptions. The model allows for different preferences between the ‘old’ consumer type and the ‘young’ consumer type, although preferences within each generation are assumed to be identical (i.e. homogeneous). The key question addressed by the model is whether the young consumer type will treat quality and installed user networks as substitutes and, hence, select the later technology (which is *de facto* assumed to be of higher quality) or alternatively treat them as complements, in which case they will select the old technology. In this paper we address a number of issues that are ‘black boxed’ by Shy but which are likely to have important implications for the general thrust of his argument.

The first issue is that of *functional equivalence*. A technological substitution involves the substitution of an established product or process by a new alternative that fulfils the same basic function (Grübler *et al.*, 1988; Grübler, 1990). Second, there is the *quality of alternative designs*. The standard economics model of choice ties relative fitness to the welfare associated alternative commodities. The economic literature contains some important precedents for an analytical treatment of how users first compare, and then rank, substitutable goods (e.g. Frenken, Saviotti and Trommetter, 1999). A third issue is the *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 user welfare depends on both the relative performance of each technology and their prices, this will affect demand and hence the outcome of a technological competition (Arthur, Ermoliev and Kaniovski, 1987; Arthur, 1989). Fourthly, we address is the existence of *new types of users*. This is likely to be a key factor affecting the complex dynamics of emergent market structures.

We see that there is likely to be a number of factors influencing user preferences, and that these interact in a complex manner. Three factors in particular were 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

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

where x is the characteristic vector of a technology design

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 user 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 loss in indirect utility (i.e. the opportunity cost) of the purchase.

In the presence of heterogeneous preferences, a simple analytically tractable solution for equation (1) is unlikely to exist in all but the simplest of circumstances. Multiple equilibria solutions may exist in which it is impossible to predict *ex ante* whether there will be a technological substitution, a technological lock-out, or a mixed solution (i.e. a partial substitution with market sharing between the old and new technologies). First, multiple equilibria solutions can exist - even when the performance characteristics of one technology application are absolutely superior to those of another - if there is a high frequency of intermediate valuations within the user 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 substitution will occur. One way of tackling the problem is to construct a simulation model in

order to analyse the consequences of heterogeneous user preferences, and the co-evolutionary dynamics of changing user preferences and the innovative activities of competing suppliers.

3. A formal model of technological substitutions

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,

- i) It brings the user groups to market in a random order and gets the groups to determine their demands and purchases.
- ii) It initiates the replicator dynamic for that period to redistribute the user population across the groups.
- iii) It gets suppliers to adjust their capacity, level of production and to redesign their goods.

3.1 User dynamics

There are M user groups. Associated with group $i = 1, \dots, M$, 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

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

Here m is the budget of the user and is assumed to be the same for all users. The term $\beta_i w(m-p)$ is the indirect utility obtained by spending the residual budget in other markets. All users in the same group are assumed to adopt the same utility function. Each supplier offers to sell a good with some design x at some price p . Users use these utility functions to rank alternative offers and as a measure of well-being. Note that users 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.

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

The population of users 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 users of type i at time t . We use the subscript t only when necessary to distinguish between periods. In each period supplier j offers a quantity Q_j of a particular design-price combination (x_j, p_j) . After suppliers have ‘posted’ these offers, user groups appear in the market in a random order. Let $I(i)$, with $i=1, \dots, M$, be a permutation of the indices $\{1, \dots, M\}$ 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 users rank the offers (x_j, p_j) in descending order of preference.

Let $J(j)$ $j = 0, 1, \dots, M$ represent this ranking, so that $J(j)$ is a permutation of $\{0, 1, \dots, M\}$, where 0 represents the ‘null offer’, i.e. buy none of the goods. If the null offer ($J(0) = 0$) is best, the users in that group exit the market without buying anything. If the supplier ranked highest by

the users has an offer which dominates the null offer (*i.e.* $J(0) > 0$) then all users in that group will ‘post’ a demand for one unit of that offer. If supplier $J(0)$ 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 users 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 user leave the market and the available quantity of the good becomes zero and the remaining users $G_1 - Q_{J(0)}$ consider their next best option $J(1)$. The interaction of these remaining users 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 users in the group have left the market. Group $I(2)$ enters the market and interacts with suppliers in the same way apart from the fact that the quantities available to this group will be reduced by any sales made to group $I(1)$ users. 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 user groups $I(k)$ for $k=1, \dots, i-1$.

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

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

$$\rho_{it+1} = \frac{\rho_{it} r W_{it}}{\sum_k \rho_{kt} r W_{kt}} \quad (4)$$

where r is the 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.

3.2 Suppliers: prices, profits, wealth, production and capacity

Here we present a model of production that is distinctly Keynesian in flavour as adjustments to excess demand occur primarily through changes in output and production capacity rather than price. In the beginning of period t , supplier j has monetary wealth M_{jt} , capacity or capital K_{jt} , design x_{jt} , a level of production y_{jt} and an inventory of unsold goods q_{jt} . The unit variable cost of production is given by the cost function

$$C(x) = \sum_k \gamma_k c_k(x_k) \quad (5)$$

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

$$c_k(x_k) = x_k^2 \quad (6)$$

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

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

$$\rho_{jt} = (1 + \eta_{jt}) \left(C(x_{jt}) + \frac{\phi}{y_{jt}} \right) \quad (7)$$

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

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

Given its sales s_{jt} and level of production, each supplier calculates its net revenue 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 supplier has to sell capital sufficient stock to return monetary wealth to zero. If the supplier 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 supplier can no longer produce.

The supplier calculates a new target level of production y^*_{jt+1} as follows:

$$y^*_{jt+1} = \chi d_{jt} + (1 - \chi) s_{jt} \quad (8)$$

where $\chi \in [0, 1]$ is partial adjustment term and d_{jt} is the level of demand for the j th supplier's design in period t . The supplier adjusts its capacity given this target level of output. Essentially, the supplier 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 supplier partially adjusts its capacity toward this target,

$$K_{jt+1} = K_{jt} + \delta(K^*_{jt+1} - K_{jt}) \quad (9)$$

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:

$$M_{jt+1} = M_{jt} - (K_{jt+1} - K_{jt}) \quad (10)$$

3.3 Suppliers: Innovation

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

Mutations are carried out in isolation of other suppliers. Given design x for the j th supplier at period t , the supplier considers a mutated design x^* . Each component x^*_i mutates with probability μ and if it does mutate it has the value $x_i + \kappa\epsilon$, 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 supplier's target user type.

After mutation, suppliers consider further innovation based on imitation of rival suppliers. Each supplier picks another supplier in a biased random draw from the existing set of suppliers. This selection is biased toward to the more profitable suppliers. In fact it is based on Goldberg's 'roulette wheel' in that the probability of supplier j being selected is proportional to the profit made by the supplier j in the current period. Having selected a rival, the supplier 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, as shown:

$$x^*_h = x^r_h \text{ for } h \in H \text{ and } x^*_h = x_h \text{ for } h \notin H. \quad (11)$$

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. Hence the supplier 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 user type.

3.4 Technological Shock

In the current model there is a technological shock at period T_1 . This shock has three features. First, the characteristic space qualitatively changes, i.e. the set of characteristics associated with the new technology application differs from that of the old technology. More specifically, prior to time T_1 , the characteristic space has characteristics dimensions 1 to h_1 . After T_1 , the characteristic has 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 users place positive weight on IS application characteristics 1 to h_1 and zero weights on characteristics h_1+1 to h .

Second, whereas suppliers prior to T_1 are producers of the old technology, after T_1 all market entrants are 'new' technology producers. At the same time, the user groups that emerge after T_1 are 'new' technology users. New generations of users and suppliers are generated in the following way; at T_1 'dead' suppliers and 'dead' user types are replaced by new generations of suppliers and user types. A supplier is treated as 'dead' if its market share has fallen below a cut-off value and a user type is 'dead' if its share of the user population has fallen below a

cut-off value. The new suppliers created at time T_1 must provide designs in D_2 . New user types place positive weight on IS application 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 .

3.5 Implementation details

The current model uses three independent random number generators, RC , RF and RM , which are used to initialise and modify the users, suppliers 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,

- i) RC is used to assign values for parameters α , β in the utility functions both at the start of the model and for new user groups at T_1 . All values lie between 0.0 and 1.0.
- ii) 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} .
- iii) RM is used to randomly shuffle the order in which user 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 .

4. Results

The first step is to establish whether the model is capable of producing technological substitutions of the type illustrated in Figure 1 above. In the tests conducted it is found that the model does indeed produce the patterns associated with technological substitutions within a market niche. As illustrated in Figure 2 below, the envelope of aggregate utility is raised as the new technology displaces the old technology in the market niche. A substitution occurs when a new, ‘fitter’ technology (i.e. one offering higher levels of welfare) displaces an older, ‘less fit’ technology (i.e. one offering lower levels of welfare).

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

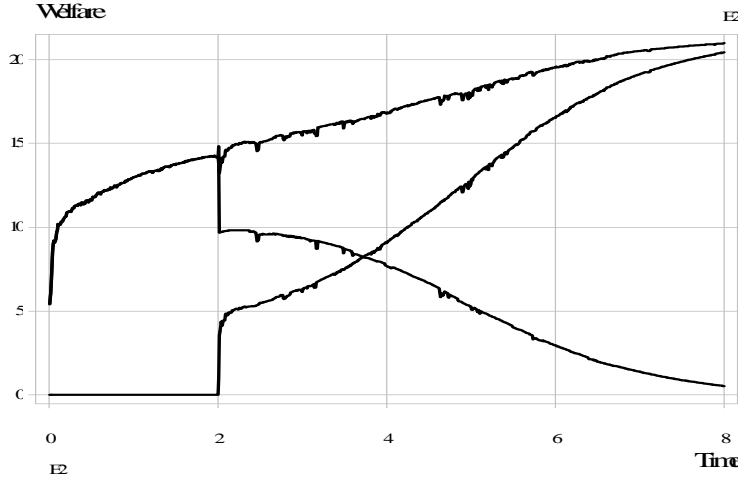


Figure 2. Substitution by a new technology providing higher welfare

Following the discussion in section 2, we should distinguish between two types of substitution. In the first case, which we shall call the ‘Type A’ case, an old technology - old user group is displaced by a new technology – new user group. In the second case, which we shall call the ‘Type B’ case, a new technology application replaces an old technology application but these are sold to an established (old) consumer group. For each simulation we can use the observed values of sales and user population to classify the outcome as ‘Type A’, ‘Type B’ or ‘no substitution’ (Table 1).

Summary Statistics	Value
In Sample Type A Substitutions	111
In Sample Type B Substitutions	160
In Sample Total	360
Out of Sample Type A Substitution	16
Out of Sample Type B Substitutions	21
Out of Sample Total	40

Table 1. Summary statistics for occurrence of Type A and Type B substitutions

Here we present the logit model that considers the factors influencing a Type A substitution. The model sets the dependent variable to one if there is a Type A substitution 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 SIC (Schwartz Information Criterion) which is a form of Penalised Maximum Likelihood Model Selection (PMLMS) (Birchenhall *et al.*, 1999). 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 mis-specified.

Using this method of variable selection for the Type A substitution 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 (Table 2).

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

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

Table 2. Summary statistics for best fit model of Type A substitutions

5. Concluding remarks

The paper has made a case for a re-examining Schumpeter's reading of economic history as one of punctuated equilibrium; long periods of incremental innovation are punctuated by bursts of rapid change associated with the introduction of radically new technologies. To this end we have developed an agent-based simulation model of technological substitution that contains heterogeneous populations of adaptive consumers and firms that co-evolve over time. This is a hybrid Neo-Schumpeterian - Keynesian model of technological innovation. The various adjustment rules applied by firms can be interpreted as Nelson and Winter 'routines'. 'Technological transfers' are a form of technological dissemination and in this sense firms do *not* earn monopolistic profits. As each firm targets a different consumer group the model typically leads to an 'emergent' monopolist market, with one firm most successfully servicing a consumer group which in turn becomes the dominant consumer type. The model contains an imperfect capital market, all investment being financed from the firm's stock of wealth. Prices in the model are 'sticky' in that they do not adjust to excess demands and the market does not necessarily clear in any single period. The use of a fixed mark-up can be interpreted as an adaptive firm's attempt to ensure a 'normal' return. This gives the model a particularly Keynesian flavour.

The simulation model represents a first attempt to develop a systematic modelling of the probability of technological substitutions occurring. While there is clearly room for further development, we suggest that the basic methodology shows much promise. The estimated logit model is statistically respectable and conforms to a number of intuitive expectations. Given the fixed mark-up, firms will happily adjust to a demonstrable demand for their design and price combinations. Hence the key to substitution is the replicator dynamics and the utility of the targeted consumer group. Type A Substitution tends to occur if a new Type Two firm can quickly generate a design and price combination that will make its targeted Type Two consumer better-off than the current dominant Type One firm-consumer alliance. This highlights the co-evolutionary interaction between technological designs and consumer preferences that drive emergent market structures. A necessary condition for a technological substitution in this model is new market entrants, offering previously unavailable performance characteristics, *and* a consumer group that is willing to experiment with these new characteristics.

Four variables have been explored in the paper: the new characteristics offered by new technology designs, improved performance in one or more characteristics commonly offered by both new and old technology designs, differential production costs, and time. In the estimated logit model, the availability of new characteristics has a higher significance than the ability to offer improved performances over existing characteristics. Given diminishing marginal utility over the entire characteristic space, the initial gain arising from consumption of a new characteristic is likely to be greater than that arising through an incremental improvement of an existing characteristic. This issue is not considered in the Shy model. Indeed, as far as we are aware, the issue has not been considered by previous formal models. Neither does the Shy model consider the likely implications of relative production costs. Interestingly, costs do not appear as a significant factor in the estimated Type A substitution logit model. It may well be that relative costs prove to be a key factor in Type B substitutions, where new technology firms are selling to established Type One consumer groups. This is an issue that will be investigated in future work.

The estimated model also considers time as a possible explanatory variable. By varying T_1 one can alter the time allowed for a new technology to become established in a market niche. Time T_1 was found to be the second most important explanatory variable in the estimated logit model. Finally, the results generated by the simulation model support a number of aspects of Shy's earlier analysis of technological substitutions. Notably, it highlights the importance of a co-existence of new technological products, championed by new market entrants, and one or more consumer groups that are willing to experiment with these new products. Additionally, it supports Shy's (previously untested) hypothesis that technological substitutions can occur in the presence of heterogeneous consumer preferences.

To conclude, the simulation model developed in this paper complements and extends, Shy's analysis of technological substitutions, focussing on a number of potentially important variables not considered in that earlier work. The current analysis represents a first effort in an ongoing research programme that seeks to re-open the research agenda on technological substitutions, and to frame the discussion in meaningful way, through the development of agent-based models that can assist in the analysis of this complex phenomenon.

Appendix

Table 1: Glossary of notation and Default Batch Values

Symbol	Description	Default
$U_i(\mathbf{x}, p)$	Utility function for i th consumer group	
\mathbf{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
\mathbf{D}_1	Design Space up to T_1	Random
\mathbf{D}_2	Design Space after T_1	Random
h_1	$\mathbf{x} \in \mathbf{D}_1$ has $x_i = 0$ for $i > h_1$ and $\beta_i = 0$ for $i > h_1$	Random
h_2	$\mathbf{x} \in \mathbf{D}_2$ 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
$C(\mathbf{x})$	Unit variable cost of producing design \mathbf{x}	
γ_k	Coefficients in $C(\mathbf{x})$	
θ	Cost reduction factor	Random
$c_k(x_k)$	Component functions in $C(\mathbf{x})$	
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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