AN EVOLUTIONARY MODEL OF STRUCTURAL ECONOMIC DYNAMICS

By Esben Sloth Andersen

Draft version: Dec. 12, 1996. Do not quote.
Comments to: esa@business.auc.dk

Paper to be presented to the Danish Research Unit for Industrial Dynamics Conference, January 8-10, 1996.

Dept. of Business Studies, Aalborg University.

ABSTRACT: This paper presents a model of evolutionary endogenous growth. The model represents an attempt to provide an evolutionary economic microfoundation to Pasinetti's scheme of the structural economic dynamics of a labour economy. Like this scheme the model deals with an economic system with a varying number of sectors, each of which is producing a homogeneous consumption good. Consumers have a hierarchy of goods, and they first consume a higher-order good when they are fully provided with the lower-order goods. The goods are produced within consumer-producer firms which organise both production and consumption for their workers. Production takes place by means of labour and knowledge. Through innovative activities firms increase their productivity with respect to individual goods. The long-run consequence of this is that labour becomes available for the production of new consumption goods. The model is first presented in a verbal form in relation to a simple Robinson Crusoe economy. Then the model is formalised, and finally it is provided with a relatively complex set of innovative mechanisms.

KEYWORDS: Endogenous growth, structural economic dynamics, evolutionary modelling, innovation systems, Pasinetti, Robinson Crusoe. JEL CLASSIFICATION: E20, O30, O41.

ACKNOWLEDGEMENTS: The paper has been prepared in relation to the DRUID project on "Dynamic Reconstruction of Unfolding Industrial Diversity by Interactive Computing" (DRUIDIC). The paper is partly designed to be followed up by DRUIDIC simulation experiments in the Nelson and Winter tradition. The overall analytical framework and the models draw upon discussions with and comments from Chris DeBresson, Ina Drejer, Nicolai Juul Foss, Keld Laursen, Bengt-Åke Lundvall and Morris Teubal. A version of the Robinson Crusoe story has earlier been used in Andersen and Lundvall (1994).

1. From Pasinetti's scheme to an evolutionary model

This paper presents a model of evolutionary endogenous growth in a way which can serve as a framework for the clarification and computer implementation of the structural dynamics of an economic system. The model has many purposes and backgrounds (including new growth theory), but it can most easily be understood as an attempt to provide an evolutionary economic microfoundation to Pasinetti's (1981; 1993) scheme of the structural economic dynamics of a labour economy. This relationship builds a common purpose of both Pasinetti's and the present model. This purpose of both models is to bring out clearly one of the best documented stylised facts of economic growth: that long-term growth is always related to major changes in the composition of the economic system. The two models also take serious another, somewhat more disputed, stylised fact, namely that increased complexity of the economic system is an integral part of long-term economic growth.

Pasinetti tries to formalise the story of learning and accumulation of useful knowledge in relation to the economic concerns of humanity. He presents an abstract scheme for the exploration of the economic consequences of man's propensity to learn from experiences. To him it is the "widespread phenomenon of individual and social learning which constitutes the *primus movens* of industrial societies." (Pasinetti, 1993, 36). In other words (Pasinetti, 1981, 23), "[i]t is this learning activity that represents the spring moving the whole system, by its constant application to improving the production processes and to starting new productions." The outcome of learning is the structural dynamics of the economic system.

The concrete implementation of Pasinetti's vision is surprisingly simple, a fact that is especially emphasised in a recent book (Pasinetti, 1993). For the present purposes this simplification has been driven too far, however. Compared with earlier versions of his analytical scheme (Pasinetti, 1981), there is an omission of useful notions like vertically integrated sectors and the increase in the number of sectors.

For the present purposes we shall consider the following short-term aspects of the Pasinetti scheme. First, we split the economic system into n[t][1] sectors, each of which is producing a homogeneous consumption good. Second, we determine the size of output of the n[t] goods of the economy by means of a per capita consumption coefficient, Q[i,t] = c[i,t]N[t], where C[i,t] is the consumption coefficient of good i and N[t] is the size of the population. Third, we assume that production takes place by means of labour and knowledge; the intermediate goods relating to a certain consumption good are assumed to be produced within a vertically integrated sector. The sectoral production function determines that L[i,t] = Q[i,t]/A[i,t], where L[i,t] is the number of workers employed in sector i and A[i,t] is the labour coefficient. Fourth, we assume that the whole population is fully employed. The employment per capita in the economy is L[t]/N[t] = Sigma[i, 1..n[t]](c[i,t]/A[i,t]) = 1,[2] and the full-employment condition is L[t]/N[t] = 1.

---

1 [All mathematical expressions are, un fortunately, typeset for exchange between different computer platforms. Sorry about the inconvenience.]

2 [... Sigma[i, 1..n[t]](c[i,t]/A[i,t]) means the sum with i from 1 to n[t] of the expression c[i,t]/A[i,t] ...]

Within this framework we can study the consequences of human learning with respect to both production and consumption. To do so Pasinetti makes the following steps. First, it is emphasised that learning in production means that the labour coefficients increase over time, partly because of more and more "roundabout" methods of production. Second, it is assumed that there are physical limits to the consumption of any good. This means that consumption coefficients cannot continue to grow as a reflection of the increased productivity of the economy. Sooner or later an economy with a fixed number of goods will reach a stage where production coefficients dominate over consumption coefficients. This means that $L[t]/N[t] < 1$, i.e. we observe what might be called "technological unemployment". Third, we come to the formulation of a core policy issue of an industrial economy: how to react to "technological unemployment". One strategy is to reduce labour time (i.e. $L[t+1] < L[t]$); another strategy is to try to introduce new consumption goods (i.e. $n[t+1] > n[t]$). In both cases there is a need of consumer learning: how to exploit extra leisure time and how to utilise new goods.

The short description of long-term dynamics within the Pasinetti scheme demonstrates that is captures in the simplest possible way the stylised facts of the structural transformation and the increased complexity of the economic system. This result is, however, obtained by a exogenous changes in production coefficients and consumption coefficients. This treatment of the core issue (learning) as a *deus ex machina* is only satisfactory as a first approximation. But the scheme has shown no changes in this respect since its original presentation thirty years ago (Pasinetti, 1965). This obviously delimits the applicability of the scheme although it immediately suggests a large number of ideas.

As an example of the difficulties of applying Pasinetti's scheme, we may take the SPRU[3] study of the 1980s on technology and employment. In one of the early publications from this project an attempt was made to use the scheme for clarifying a large number of questions (Freeman, Clark and Soete, 1982, 138-146): the long-run dominance of income elasticities over price elasticities, the structural demand problems in recessions, inflation due to stickiness of prices in industries with supernormal productivity growth, the localised spread of productivity gains, etc. However, when the SPRU project came to an end, Pasinetti was not included or just mentioned in the passing (Soete, 1985; Freeman and Soete, 1987). This is just an example of the difficulties of transforming an early inspiration from Pasinetti's scheme of structural economic dynamics into a guide-line for concrete research. But it might also be taken as an indicator of the need for providing a micro foundation for Pasinetti's purely formal scheme. If such a foundation can be provided, there is a chance that the scheme may help integration the rapidly increasing but quite scattered literature on learning and innovation, growth and structural change, competitiveness and employment.

With respect to the evolution of labour coefficients, the Nelson and Winter tradition of evolutionary economic modelling supplies a potential micro foundation for the Pasinetti scheme. From this tradition we know that economic evolution can be depicted as a process in which firms follow rules or procedures that can occasionally be mutated or adapted. We also know that an important example of economic evolution takes place within an industry (or a one-sector economy) where new process techniques are

3 Science Policy Research Unit, University of Sussex.

introduced and imitated. These and other aspects of the Nelson and Winter model have to some extent defined a "paradigm" for further research, even in the form of an evolutionary growth theory (see Silverberg and Verspagen, 1995; Nelson, 1995, 67-72). But this tradition has been weak in supplying foundations for a treatment of the evolution of consumption coefficients. There is, however, a possibility of making a major extension of the evolutionary research agenda in this respect (see Andersen, 1996b). The idea is that innovation may promote interfirm specialisation in terms of a complex and fluctuating division of labour between firms. Specialisation and exchange may help to confront analytically the evolution of the consumption coefficients.

The evolutionary model of structural economic dynamics will be presented in three steps. First, Pasinetti's idea of an institution-free or "natural" level of analysis (in the tradition of classical economics) will be driven to its extreme by analysing the structural economic dynamics of a Robinson Crusoe economy (section 2). Then a simple version of the model of evolutionary endogenous growth will be presented (section 3). This version of the model is simple because it, in analogy with learning by doing, treats innovation as a by-product of production work. Finally, the paper presents an extension of the model that includes a more complex innovation system.

2. The fable of the innovative Robinson Crusoe

Ever since Mandeville's (1970) discussion of the division of labour in terms of "The Fable of the Bees", a good fable has had an important double role in economic theorising: it helps the modeller to focus on core issues and it helps the users of the resulting model to get a quick impression of the underlying ideas and visions. Robinson Crusoe is the person that most often figures in the fables of economists (White, 1987). Especially after the marginalist revolution radicalised the split of the economic agent into a pure producer and a pure consumer, Robinson's one-man economy helped to treat important issues that are most obvious to an integrated consumer-producer agent. But if we look back at the many applications by economists of Robinsonian stories, it is obvious how limited a use that has been made of Defoe's original and of the later rich literature of Robinsonades.

The starting point for the present fable of structural economic dynamics is that "Robinson Crusoe Was Not Mainly a Resource Allocator" (Simon, 1989, 471). Contrary to the normal use of him in economics any thorough reading of Defoe demonstrates that Robinson was not mainly engaged in dealing with known and existing resources. It was rather his efforts in "creating new ways of dealing with his environment [that] kept him alive and eventually comfortable. Such creating is a proper model for the economic history and future of humankind; allocation is only its handmaiden." (Simon, 1989, 471) This is a nice summary of the vision and stylised facts that underlies the model of the present paper. The underlying fable starts with Robinson Crusoe as a boundedly rational man with a high degree of creativity. It is such a Robinson that builds a complex production and consumption system, and to do so he needs to emphasise innovative activities.

This reinterpretation of the fable of Robinson is one of the ways of making sense of Pasinetti's multisectoral model of growth and transformation. The ease by which Robinson's economy can be related to Pasinetti's economic system is largely due to the latter's concentration of the basic "natural" facts without any institutional specification. This means that we are dealing with a full-blown analytical scheme rather than an economic model. This scheme describes a growth process that is driven by a large number of exogenously determined labour coefficients and consumption coefficients. Also the basic full-employment condition is exogenously imposed rather than an endogenous result.

The fable of Robinson is probably the simplest way of providing the Pasinetti scheme with a minimal amount of decision-rules and driving forces. As soon as we relate the Pasinetti system to Robinson's decision-making, it is easy to understand the meaning of the full-employment condition and it is also possible to make a crude endogenesation of the changes in labour coefficients and consumption coefficients. Thus we arrive at a model where the main problem is how the resources of the Robinsonian "innovation system" are divided between increasing productivity in production of existing consumption goods and creating new consumption goods. The growth process will be slowed down or halted if one of these two tasks becomes dominating.

It must be admitted that it calls for a good deal of abstraction to go from Robinson's island economy to Pasinetti's pure labour economy with no constraints from nature and capital. But at a closer look it becomes obvious that Daniel Defoe (1938), as later Adam Smith (1976), wanted to emphasise that the wealth of nations is much more constrained by the knowledge and organisation of labour than by natural resources. In order to come to this result, we need to classify Robinson's tasks according to the consumption goods to which they are directly or indirectly connected.[4] This classification is not as easy as it sounds since a given task (e.g., production of corn) may contribute to final consumption as well as to intermediate production (e.g., as an input to the production of goat meat). In this case we have to split the labour time of corn production in proportion to the quantities used for the two purposes.[5] When the classification is finished, all the tasks which are related to the supply of a particular consumption good are said to belong to the vertically integrated sector whose output is that good.

According to Defoe (1938), Robinson made good book-keeping with respect to the allocation of his labour time and to his production during his 28 years in the deserted island. Therefore, we should have no difficulty in calculating for each year the input of labour hours, L[i,t], the output of consumption goods, C[i,t], and the roughly defined labour productivity for each vertically integrated sector, A[i,t]. We may also calculate for each year the total amount of labour hours (L[t] = 1) and the composition of "demand" measured in terms of labour costs embodied in the output of the different final goods (L[i,t] = A[i,t]/c[i,t]). From these data (and especially the ever-increasing number of sectors, n[t]) it becomes clear that Robinson has to a surprising degree replicated much of the overall evolution of economic life – in a much less automatic way than in biology where the individual ontogenesis to some extent is programmed to replicate the population-level phylogenesis (Gould, 1977).

4 Here we relate to Pasinetti (1981) since the idea of vertically integrated sectors is omitted from Pasinetti (1993).

5 A rough measure of the vertically integrated labour coefficients of the different final-demand sectors can be obtained by inverting the empirically given matrix of input-output coefficients (Pasinetti, 1981, ch. 6).

Contrary to the traditional interpretation among economists, the present assumption is that Robinson's success should mainly be attributed to his "system of innovation" rather than to his behaviour with respect to savings and investments. The idea that Robinson's final wealth is founded in his preferences for savings and for investment in inventories and capital stocks (cf. Böhm-Bawerk, 1891) is simply not convincing. For instance, Robinson starts a very long-term project of creating a corn production before he even knows whether he will ever be able to obtain the goal: bread (since he lacks yeast and oven techniques). Instead we see Robinson as a lonesome Schumpeterian entrepreneur who is simply addicted to near-impossible projects which he completes because of his self-confidence, reason, open-mindedness, and creative powers. Behind his behaviour may also be a mix of "Protestant ethics" (in Weber's sense), a Faustian thirst for knowledge (in Goethe's sense), and a strong wish to catch up with his home country (Britain). In other words, the most important characteristic of Robinson's behaviour is his high level of innovative activity (due to his preferences for creative learning and for catching up with Britain) while the emergence of high rates of investment and saving is mainly a means of implementing the resulting innovations (as argued in another context by Schumpeter, 1934, against Böhm-Bawerk, 1891).

Robinson's many parallel innovative activities can best be described in terms of an innovation system that is related to the multisectoral growth process of an individual (and later two-person) economy. First, he engages in innovative activities which relate to needs which have hitherto been unsatisfied but for which crude production methods may be found. Here he largely applies his previous knowledge of goods from Britain,[6] and for selected goods he tries to find an adequate process of production through "reverse engineering". Second, he performs innovative activities which relate to problems emerging from the production within each vertically integrated sector. He applies his innovative mind to major areas of productivity advance based on his loose knowledge of productive activities in Britain, and on this background he decides on projects which often lead to an innovative deepening of the set of tasks related to a particular activity (that becomes a sector), and to a related increase in the productivity of labour. Third, he performs a less goal-directed search for new goods and thus new sectors. During this search he has a whole set of potential product and process innovations the back of his head. Thus, for Robinson "chance favours the prepared mind" (to use Pasteur's dictum). Even the goal-directed search in a certain sector may from the viewpoint of other sectors be a source of "externalities" (in a loose sense) – which obtains increasing importance as the economy becomes increasingly complex.

Given an innovation system with these diverse functions, it is not difficult to depict the overall process of growth and transformation of the Robinsonian economy as driven by an interplay between the two major results of the Robinsonian system of innovation: process innovations which decrease unit costs within each vertically integrated sector and product innovations which create new sectors. The consequences of process innovations are fairly obvious. First, the results of intrasectoral innovative activities increase the productivity of existing sectors. Given an unchanged amount of aggregate labour, this leads to increasing wealth but also to a decreasing marginal utility of the existing goods. Some of the existing goods will ultimately reach income elasticities equal to or below unity. Second, the application of the results of general search activities

6 He also applies tools that he brought with him to the island. This problem is avoided in later Robinsonades like that of "Robinson Junior" (Campe, 1977).

("fundamental research") and of intersectoral "externalities" from the knowledge production will tend to create a further speed up of productivity increase in existing sectors. The two kinds of process innovations drive more and more of Robinson's wants to saturation – at least when they are satisfied by the given set of goods.

If Robinson sticks to a given set of consumption goods, the result will be more and more labour time that cannot be meaningfully applied in productive activities, i.e. $L[t]/N[t] < 1$, where $N[t] = 1$. If he wants to uphold a given distribution of his time between accountable work and leisure time, he will be facing something like "technological unemployment". However, the finding of methods for the production of new goods and the related creation of new sectors ($n[t+1] > n[t]$) free him from this "problem". In other words, the "revival" of the Robinsonian economy springs from innovative activities which directly or indirectly are oriented towards the application of methods for the production of new consumption goods (or consumption goods of increased quality). During a large part of Robinson's stay at the deserted island, the introduction of new products is relatively easy since he can apply his knowledge of wants and goods from Britain, and the apply "reverse engineering". But still his creation of new sectors presupposes many innovative activities. The situation after he has reached a substantial degree of catching up with Britain is different from the previous situation in degree rather than in kind. Thus, we cannot explain the tendency towards a steady-state situation during Robinson's last years on the island in terms of an absolute saturation of wants. On the contrary: "The whole history of man shows that his wants expand with the growth of his wealth and knowledge." (Marshall, 1949, 186) But Robinson has lived up to the British standards of life and, furthermore, he has become an old man who starts to transfer his knowledge to Friday, i.e. to the next generation.

The long-term evolution of the Robinsonian economy demonstrates that innovation systems are not only relevant in a process of Schumpeterian competition. The role of British knowledge in the Robinsonian evolution also demonstrates that the transfer of knowledge may benefit one country without hurting the other country. If Robinson decides to remain on his island after being "rescued", this knowledge transfer may show up to be continuous and not totally one-sided (since Robinson may obtain knowledge of some (marginal) relevance for the British economic system). If Robinson, furthermore, decides to develop trade with Britain, he is facing a whole new set of questions about how he is best advised to specialise. However, the present approach to long-term economic growth suggests that Robinson should consider to specialise in a way which maximises his learning in production and consumption (cf. Pasinetti, 1993, ch. 9) rather than in a way which maximises the static gains from trade. His specialisation decisions should thus include reflections on his innovation system and not just his comparative advantages in performing given routines of production.

3. Endogenous structural economic dynamics based on new goods, process innovation and specialisation

3.1. Motivation and overview

To develop further the lessons from the Robinsonian economy, it is helpful to develop a model that depicts an economic system which is placed between Pasinetti's scheme of a "natural" or institution-free economic system and full-blown capitalist systems with money, labour markets and financial markets. The in-between model has none of these capitalist characteristics. Instead it has "firms"[7] that organise the production and consumption of their fixed labour force; and these firms can engage in bilateral exchange (in this respect inspiration has been drawn from Yang and Ng, 1993). In other words, we are dealing with "consumer-producer firms" which in this respect is similar to Robinson's "firm".

To establish a rapid intuition about consumer-producer firms, the reader may think of firms in an economic system where very-long-term labour contracts have come to dominate, but there are several alternative interpretations. One possibility is that firms are consumer-producer cooperatives, another that we are facing consumer-producer households of the peasant and artisan type. It is even possible to interpret a consumer-producer firm as a country and thus explicitly to relate to the classical theory of international specialisation; but this country-oriented interpretation misses some of the model's insights of how an economic system may be created from scratch through an innovation-driven process.

The success of a consumer-producer firm with respect to (heuristic) utility maximisation for its members is not only determined by its specialisation but also by its innovative activities. In the first version of the model (presented in this section) productivity change is the outcome of innovative activities that are not professionalised by can rather be seen as a by-product of production (innovating by doing). This basic form of innovative activities functions as a starting point for the emergence of specialised research activities of firms which are treated in an extended version of the model (section 3).

Basically, both models functions like the about description of the evolution of Robinson Crusoe's economy except that we now take into account the possibility of specialisation. The outcome of a successful innovation is the introduction of a new "algorithm" about the process of production with respect to a particular activity (like one of the Robinsonian sectors). The productivity differentials between firms that emerge due to technical change are the background for their specialisation and bilateral exchange between them. As income increases, consumption is expanded to encompass an ever-increasing range of products. Thus a more complex economic system emerges.

To go a little more into details, the model depicts an economic system that produces a variable range of consumption goods by means of labour and firm-specific knowledge. Each of the n firms can, in principle, produce all products; the productivity in the production of a particular product is determined by the firm's activity-specific knowledge (an algorithm on the production of each good). The economic system has no market for labour, so the allocation of labour between firms does not vary; furthermore, the members of a firm supply a fixed amount of labour. The members of a firm have no personal income but they are equal-share owners. The firm obtains consumer goods for its owner-members by means of production and exchange; these goods are distributed equally between the members. The goal of the boundedly rational firm is to maximise the utility of its members.

---

7 A theory in the modern firm should include its relationship to the factor markets. Since this is not the case in the model, we are obviously talking of "firms" in a metaphorical sense.

3.2. The basic structure of the model

Let us start by formalising the short-term utility maximisation problem of the consumer-producer firm j, which supplies its members with bundles of consumption goods. The firm can produce an infinite number of types of goods, and the specification of all these goods are known to the model builder. The firm and its members are, however, much more myopic. The reason is that all L[j] members have identical utility functions that orders the consumption goods hierarchically (like in Pasinetti, 1993; Verspagen, 1993, Ch. 7). This hierarchy is reflected in an ordering of the set (I) of index numbers for consumption goods, 1, ..., i, ...: a good is more basic than another if it has a lower index.

The model has a very simple interpretation of the (Austrian) notion of a hierarchy of consumption goods. For each good there is a physical maximum per capita which is equal for all individuals and all goods, C = 1. Although it is not necessary, we shall often specify the good that is consumed with an index, C[1] = C[2] = ... = C[i] = ... If maximum utility has been obtained from goods 1 ... i, then the utility increases in proportion to the consumed quantity of good i + 1 up to its physical maximum. Expansion beyond that maximum does not influence utility. Expansion of the quantity of good i + 2 before good i + 1 has reached its maximum does not increase utility. The historically given level of diversity of consumption of the firm is characterised by the consumed good that has the maximum index, G[j,t].

These specifications of the utility function (which are loosely compatible with Engel's law) cannot be seen independently of the production conditions in the economy, e.g. the assumption that all consumption goods can be produced with "reasonable" initial productivities (see section 3.4), constant returns to scale and the possibility of productivity increases.

The production constraints of the consumer-producer firm j relate both to labour and production knowledge. Each member of each firm supply one unit of labour services. All firms have exactly the same labour force. However, for reasons of clarification we still use an index so that the labour force of firm j is L[j].

With respect to the different goods the consumer-producer firm has to acquire knowledge about their production methods before they can be produced. This acquisition of production knowledge has to follow the sequence defined by the consumption hierarchy. The firm is thus able to produce the goods 1 ..., i, ..., H[j,t], where H[j,t] is the index of the highest-ordered good that firm j is able to produce in period t.[8] Production takes place by means of labour and firm-specific knowledge, and it is characterised by constant returns to scale. More specifically, if L[i,j,t] units of labour are allocated to the production of the i'th good, then the output of this good is Q[i,j,t] = A[i,j,t]L[i,j,t], where A[i,j,t] is a labour coefficient which reflects the algorithm used by

8 When we turn to an exchange-based system with the possibility of full specialisation, the assumption that the firm has to follow the consumption hierarchy in the expansion of its production capabilities seems very unrealistic. It should, however, be noticed that we are dealing with consumer-producer forms with no ability to go bankrupt. If the market for a specialised firm disappears, it has (at least for a period) to supply its members by means of self-produced goods.

the firm in the production of the good.[9] The firm's overall knowledge is characterised by a list of activity-specific labour coefficients, A[1,j,t], ..., A[i,j,t], ..., A[H[j,t],j,t], A[H[j,t]+1,j,t], ..., where all the missing capabilities have a labour coefficient equal to zero: A[H[j,t]+1,j,t] = A[H[j,t]+2,j,t] = ... = 0.

With respect to bilateral exchange the model includes a simple form of transaction costs. These costs emerge a gap between quantity of good i that seller j supplies and buyer k receives: if firm j supplies Q[i,j,k,t], then firm k receives (1 - K[i,j,t])Q[i,j,k,t]. The simplest interpretation of K[i,j,t] is that it represents the amount of the good that disappears or is delivered in an unusable form. It stems from a general and a firm-specific component, i.e. K[i,j,t] = K[t] + k[i,j,t]. The general transaction costs, K[t], are determined by the overall level of the economic system; such a type of transaction costs is often found in development economics. The firm-specific transaction costs with respect to individual goods, k[1,j,t], ..., k[i,j,t], ..., k[H[j,t],j,t], may stem from inadequate product design or insufficient quality control of goods for exchange.

3.3. Short-term decision-making

We start in an autarkic, Robinson Crusoe like, situation where "every farmer must be a butcher, baker, and brewer for his own family" (Smith, 1976, Bk. I, Ch. 3). Here it is easy to see how the consumer-producer firm allocates its production labour, L[j], across the different productive activities so that short-term utility is maximised. The task is simply to go through the hierarchy of goods and see how many of them can be supplied, given the labour force and the labour coefficients of the different activities. Since with respect to good i each member of the firm at maximum consumes C[i] (= 1), the maximum amount of labour for activity i is L[i,j,t] = C[i]/A[i,j,t]. The task of the firm is simply to produce the maximum amount of as many goods as possible. With respect to the last good in the hierarchy that the firm produces it might not be possible to reach the maximum.

The firm may reach its maximum capacity for two reasons: either it has used up its labour force or it has reached a point in the hierarchy of goods where it lacks production knowledge. In the case where the labour force is the effective constraint, the last good that is fully supplied is called G[j,t] if there is no residual of labour, and G[j,t] - 1 if there is extra labour for producing the next good (i.e. G[j,t]). In the case where knowledge is the effective constraint, there is a residual of labour that cannot be employed, U[j,t]. The reason is that it is the last good for which the firm has production knowledge (H[j,t]) that determines the last good that is fully supplied (G[j,t]). We are facing a type of unemployment that may be called technological unemployment in the sense of Pasinetti (1993).

Compared with autarky the cases with exchange between consumer-producer firms are, of course, much more complex and manifold. The only possibility allowed for in the model is direct exchange between firms. In the beginning of each period firms make contracts, and goods are exchanged at the end of each period. Each firm fulfils its part of the contract (e.g. because of reputation effects). However, in contrast to in-house production all exchanges in the system are characterised by transaction costs.

9 This expression emphasises that all firm members are assumed to be equally suited for performing the activity. In other words, there is a large transferability of the algorithm between individual workers, and this implies a low degree of "tacitness" of production knowledge.

Even in the context of direct exchange, there are many ways of modelling the negotiation process. One solution is to assume price-taking behaviour and use Walrasian auctioneer to find a general equilibrium with well-defined properties (but the model is not designed for this purpose; cf. Yang and Ng, 1992). We instead suggest a hierarchical negotiation process characterised by price-making behaviour and different prices within each market. The choice of a concrete hierarchical solution is not intended to be realistic but to clarify the sensitivity of the outcome of the concrete way buyers and sellers are matched.

The negotiation process starts in the market for the first consumption good (with index 1), and then it runs through the markets one by one. Inside each market another hierarchical process proceeds in a way which is based on the firm-specific labour coefficients. An exchange of good i from firm j against good k from firm l is acceptable to firm j if Q[i,j,l,t]/A[i,j,t] < [(1 - K[i,j,t])Q[k,l,j,t]]/A[k,j,t], where the left hand side is the amount of labour spent for fulfilling the contract and the right hand side is the amount of labour made spared because of the supplied goods (excluding transaction costs). From the condition follows directly that the price of k in terms of i must be less than [A[i,j,t](1 - K[i,j,t])]/A[k,j,t]. An exchange is only possible if both parties find it acceptable. From the condition for firm l follows that the price of k in terms of i must also be higher than A[i,l,t]/[A[k,l,t](1 - K[i,j,t])]. Taken together the conditions mean that [A[i,j,t](1 - K[i,j,t])]/A[k,j,t] > A[i,l,t]/[A[k,l,t](1 - K[i,j,t])].

To clarify the implications of this conclusion it is helpful to introduce the classical notion of comparative advantage in the exchange between two firms j and l with respect to two goods i and k. First we define firm j's relative performance in the production of good i to be V[i,k,j,l,t] = (A[i,j,t]/A[k,j,t])/(A[i,l,t]/[A[k,l,t]). Firm j is said to have a comparative advantage in the production of i if V[i,k,j,l,t] > 1. This is, however, no sufficient condition for a specialisation of j in i and l in k. In the context of an economy with transaction costs, the condition for an exchange is that [(1 - K[i,j,t])^2]V[i,k,j,l,t] > 1.

We are now ready to consider the market process as a whole. We start with good 1 and allow potential sellers to enter negotiation one by one, starting with the firm with the highest performance and then moving through the firms in descending order. The first seller (j) asks for exchange rates, and each potential supplier makes an offer terms of another good. Then the seller heuristically selects the offer that gives it the highest gains from trade. Finally the parties make a contract (in terms of two quantities). If the quantity obtained does not cover buying firm's total demand for the good (C[i]L[j]), it turns to the next-best offer to see whether it is acceptable. Then comes the second seller of the first good, etc. Then comes the negotiation process starting from good 2, etc.

The whole short-term market process is time consuming (from an algorithmic point of view) and unrealistic (considered as a negotiation process). It can, however, get much worse if we leave the hierarchical market process (and the underlying individual heuristics and social organisation of the market). In this case it is difficult to avoid a computational explosion, i.e. a use of computational resources that grows exponentially with the number of firms. This is the major reason for sticking to the present market process that teaches us several lessons about our primitive economic system, lessons that seem to be rather robust to changes in the negotiation process. Most importantly, the model functions as a starting point for the exploration of a number of novel problems in relation to the function of the firm's innovative activities.

3.4. Innovation as a by-product of production and exchange

The short-term analysis demonstrates the importance of productivity differentials between firms. To be more specific, exchange between firms will only take place if two conditions are fulfilled: firms must differ with respect to productivity, and these differences must be sufficiently large to overcome the costs of transactions between firms. Since transaction costs are likely to be large in the exchange of a good that has not been exchanged before, the core question is how the correspondingly large productivity differentials come about. The model's answer is: through innovation.

Innovative activity can be organised in different ways (see section 3), but it is both realistic and convenient to start from the most simple form: innovating by doing. In this case we consider innovative activity to be an integrated aspect of production. This innovative aspect means that the production of a certain good leads to two results: a certain quantity of the good and a (small) probability of obtaining a new algorithm of production. More formally, when firm j with respect to the production of good i allocates a certain amount of labour, L[i,j,t], the result is not only the quantity Q[i,j,t] (= A[i,j,t]L[i,j,t]) but also a possibility of obtaining a new labour coefficient, Anew[i,j,t]. There is no guarantee that the new algorithm represents is a real improvement, i.e. that Anew[i,j,t] > A[i,j,t]. But if the innovation increases productivity, it is applied by the firm in the next period. Thus the condition is A[i,j,t+1] = max(Anew[i,j,t], A[i,j,t]), where it is assumed that new algorithm can be fully applied in the period after it has been obtained.

This version of innovating by doing apparently excludes learning by doing (Arrow, 1962a). The problem is that once a new algorithm is introduced, it cannot be improved gradually by learning; it can only be replaced by another new algorithm. This means that the evolution of production technology is discontinuous: a given productivity level is fixed until it makes a jump due to the introduction of an innovation. However, this does not mean that production learning is not taking place. On the contrary, production learning reveals many problems, faults, limitations and bottle-necks. The new algorithm represents a (partial) solution to these problems. It inherits many aspects of the old algorithm, and it is thus not a totally new technological paradigm. Learning by doing is a limit case where the improvements in the old algorithm take the form of arbitrarily small increments. Innovating by doing takes into account that the process of change is uncertain and may include an element of creative destruction.

To find the total number of innovations obtained by firm j during a period, we start from the average number of innovations Rprod[t] that during a period is obtained by an individual production worker. We shall simply assume that Rprod[t] is determined by the exogenously given level of education (identical to all members of all firms). We shall also assume constant returns to the scale of the innovative aspect of production, so the firm's average number of innovations is Rprod[t]L[j]. More specifically, the arrival of innovations is modelled as a Poisson process in which Rprod[t]L[j] is the mean of the number of innovations obtained by firm j in period t.

The result of each innovation relates to a particular production coefficient. The innovations obtained by a firm during a period is randomly distributed across the different activities according to their amounts of production work. If the firm obtains an innovation with respect to a particular activity, the outcome depends on a normal distribution with a fixed standard deviation, sigma[P], and a time-varying mean, mu[i,j,t]. The mean of the distribution of determined by the firm's labour coefficient, i.e. mu[i,j,t] = A[i,j,t] (or, to obtain scale independence, we can use mu[i,j,t] = ln(A[i,j,t]) and then transform the Result back by exp(Result)). The result is introduced if it represents an improvement in comparison with the old algorithm.

We now have all the elements that determine the rate and direction of a firm's innovative results. First, the firm's production effort determines in a probabilistic way the number of innovations. Second, each innovation is assigned to an activity according to the firm's employment in the different activities. Third, the labour coefficient that comes out of the innovation (Anew[i,j,t]) is calculated. Fourth, it is checked whether the innovation improves the firm's productivity. If this is the case, we come to the fifth and last task: to set the new productivity that is applicable to its full extent in the next period, i.e. A[i,j,t+1] = Anew[i,j,t].

There are strong limitations to innovating by producing. The most obvious is that workers will not find an algorithm that concerns a production activity that they are not performing. Seen from the viewpoint of the firm the problem is that innovations only increase labour productivity with respect to a given range of goods. Thereby, technological unemployment (U[j,t]) increases. The unemployed workers will only have the task of looking for an algorithm that allows the firm to produce the next good in the hierarchy (H[j,t] + 1). Since they are unaccustomed with this task, the probability of success is small although they spend all their time in performing the task. The most easy specification is that the unemployed contributes as if they were full-time workers in activity H[j,t] + 1. If they obtain an innovation, the new labour coefficient Anew[H[j,t] + 1,j,t] = Aintro/(H[j,t] + 1), where Aintro is a constant and H[j,t] + 1 is the index number of the good for which the new production capability is being acquired.

Since the model is not only dealing with production but also with exchange, it is possible to supplement the notion of innovating by producing with the notion of innovating by exchanging. The idea is that the outcome of exchange-related work is not only the actual transactions but also new algorithms that serve to reduce transaction costs. Since we have no explicit treatment of exchange-related work, it shall simply be assumed that it is proportional to the employment in the production of goods for exchange between firms. If epsilon is the share of good i that is used for exchange, then exchange-related employment is E[i,j,t] = epsilonL[i,j,t]. For each period the average number of transactions-related innovations is Rexch[t]E[i,j,t]. The outcome of an individual innovation is simply the reduction of transaction costs with a given fraction kappa, i.e. k[i,j,t+1] = kappa k[i,j,t].

3.5. Autarkic and exchange-based structural dynamics

The long-term evolution of the structure of our economic system can be discussed in terms of sectors whose output and employment is found by aggregation of firm data, rather than from data on exchange. Thus production sector i that produces good i has output Q[i,t] = Sigma[j](Q[i,j,t]), employment L[i,t] = Sigma[j](L[i,j,t]) and productivity 1/A[i,t] = L[i,t]/Q[i,t]. To study the dynamics of these sectors we start by defining the conditions for period t = 0 in a standard way: all firms are equal in all respects (except when it comes to luck in the innovation lottery). They have the same sizes of labour force, have the same labour coefficients and the same (substantial) transaction cost coefficients, and produce the same small number of goods (larger than 1).

According to the initial conditions we start with the case of autarkic firms. If there is only one firm, we have the Robinson Crusoe case. At present it is, however, assumed that n is large. Even in this case it is easy to make calculations for the sectors in which all members of all firms get the maximum quantity. The employment in such an sector i is L[i,t] = Sigma[j](C[i]/A[i,j,t])L[j], where C[i] (defined = 1) is maximum consumption, A[i,j,t] is the labour coefficient and L[j] is the number of members of a firm. Since all firms are identical, this can be simplified to L[i,t] = (1/A[i,.,t])L, where A[i,.,t] is the average productivity in the economy with respect to sector i, and L is the total number of workers.

Given that the autarkic firms have non-zero probabilities of making innovations, a typical story of the employment of a sector i (which is not included in the initial set of production sectors at T[0]) is the following: The employment L[i,t] is zero until period T[1] where the production of the i'th good is introduced in at least one firm. Then comes a period where employment decreases because of productivity increases in the incumbent firms and increases because of the entry of new firms. The sector may in period T[2] reach a stage where all firms supply all their members at the maximum level. From that period the employment can only decrease. In the intermediate period between T[1] and T[2] the growth rate of the sector depends in an S-shaped manner on the fraction of firms that are engaged in the sector. The productivity of the sector will show a slow initial improvement and then the improvement will become more rapid until it reaches its maximum at time T[2]. After time T[2] there will be a small but long-term slowdown in productivity improvements (because of the sector's decreasing share of employment and thus of innovation).

The evolution of a system of autarkic consumer-producer firms is slow because of the relative inefficiency of innovating by producing while an economic system with exchange between firms shows a much more rapid and complex structural economic dynamics. In the study of these patterns computer simulation can be of great help. Some general conclusions can, however, be drawn, even from the present specification of the model. In the first round they concern the fraction of the employment which is engaged in production for exchange. Given that we start from the autarkic situation, this fraction starts from zero. The basic question is therefore whether exchange-based come to its "take-off" phase, or whether bilateral exchanges will continue to be non-existent or sporadic phenomena. In other words, will the autarkic system become transformed into a system with wide-spread exchange?

There will (see section 3.3) be no exchange if all firms are alike as in the initial situation. Since innovating by producing is the only way of changing the labour coefficients, there would never be any exchange in the model if the probability of success was zero. But innovation not a sufficient condition for exchange to emerge. Another condition is that transaction costs are not too high. Transaction costs, K[i,j,t], help us to understand the problem of take-off. They depend both on an exogenous factor and on innovating by exchanging.

Assume that due to random events with respect to innovation, exchange is introduced in a period called T[1]. Since there has been no learning about the problems of exchange, k[i,j,T[1]] is very high for all i. This means that there are only few cases in which the comparative advantage in the exchange between two firms is sufficient to compensate for the difference between the quantity produced by the delivering party and the quantity consumed by the receiving party. However, if there is any exchange taking place, we sometimes have that k[i,j,t+1] < k[i,j,t]. At the same time K[t] will also decrease. Basically this happens because of positive externality from exchange. Although this externality is crucial, we shall not try to endogenise it.

Given that there has been a take-off into an exchange-based economic system, we (like the national accounting systems) might concentrate on the structural dynamics of the exchange-oriented part of the production sectors. To simplify comparisons with the autarkic system it is, however, helpful to stick to the above definition of sectors that include production for intrafirm consumption. Given this set-up and given a large number of firms, it becomes obvious that the structural dynamics of an exchange-based system is much quicker than that of the autarkic system. The reason is that the results of the research sector is much more effectively applied when firms are allowed to specialise and thereby to exploit their innovations more effectively. When the possibility of specialisation is introduced, the firm has (unless it is already fully and adequately specialised) the chance of changing its specialisation pattern so that the use of the innovation is spread over a larger volume of output. And this enhances growth of the diversity of goods in the economy.

4. Extending the model with a complex economic system

4.1. Allocation of innovative labour

In the case of innovating by producing innovative activities were performed as a by-product and in a given proportion to productive activities. As soon as we introduce specialised research, it is necessary to specify how part of the firm's labour is allocated to research according to a strategy. This strategy is simply specified as the firm's research intensity, r[j,t]; the amount of labour in research is L[0,j,t] = r[j,t]L[j].

Another problem with the firm's specialised research is how to relate it to the different productive activities. This will be specified as focusing method f[t] (an algorithm) that determines the distribution of this research effort over the different activities. The simplest algorithm is to allocate research work equally over the different activities. An alternative is to let the allocation of researchers to a particular activity depend on the amount of production labour allocated to this activity. Finally, the allocation of researchers may depend on the firm's relative strength in the activity according to some measure of "revealed technological advantage". Another issue is the emphasis on anticipatory acquisition of capabilities with respect to the production of goods that have not yet been produced by the firm, i.e. improvements of the technical coefficients A[H[j,t] + 1,j,t], A[H[j,t] + 2,j,t], ... In the standard algorithm only good H[j,t] + 1 is included (see below).

4.2. Innovative and imitative results

The outcome of a firm's research is new process technologies that are reflected in potential changes its technical coefficients. The result of an innovation with respect to activity i is Anew[i,j,t]. There is no guarantee that it is an improvement, i.e. that Anew[i,j,t] > A[i,j,t]. But if the innovation represent an improvement, it is applied by the firm in the next period. Thus the condition is A[i,j,t+1] = max(Anew[i,j,t], A[i,j,t]), where it is assumed that new technology can be fully applied in the period after it was obtained. The innovative result can only be improved through further innovations, and in this as well as in other characteristics the model comes close to Nelson and Winter (1982) and Winter (1984).

In the model the research activities of the firm are treated as a whole. To find the total number of innovations during a period, we start from the average number of innovations R[t] that during a period is obtained by an individual research worker (the determination of R[t] is described below). Since we assume constant returns to the scale of research, the firm's average number of innovations is R[t]L[0,j,t]. More specifically, the arrival of innovations is modelled as a Poisson process in which the mean of the number of innovations obtained by firm j in period t is R[t]L[0,j,t].

The result of each innovation relates to a particular production coefficient. The coefficients that can be improved are the firm's given set of coefficients. Furthermore, the innovation can add a new labour coefficient that implies that the firm has obtained the capability of producing the next good in the hierarchy of goods. Thus, an innovation relates to one of the goods indexed 1, ..., H[j,t], H[j,t] + 1. The innovations obtained by a firm during a period is randomly distributed across the different activities according to their amounts of research work. Furthermore, they are distributed between imitation-based innovations ("imitations") and innovations in the narrow sense (often called "innovations"). This split depends on the closeness of the firm to the economy-wide maximum of labour coefficient with respect to the activity, Amax[i,t] = max(A[i,j,t], j=1..n). More specifically, the probability that Anew[i,j,t] is based on an imitation is 1 - A[i,j,t]/Amax[i,t]; otherwise it is based on an innovation in the narrow sense.[10]

Imitation functions as a conditional spillover from the leader to its followers, but only with respect to technology related to a given activity. If firm j through its research obtains an imitation with respect to activity i, this implies that the firm tries to copy the best-practice technology. However, the result decreases in proportion to the difference between the difference between the firm's labour coefficient and the best-practise labour coefficient. Thus, Anew[i,j,t] = Amax[i,t] - iota(Amax[i,t] - A[i,j,t]). An extreme type of imitation is obtained when iota = 0; this type of imitation is used by Nelson and Winter (1982, Chs. 12-14). If the firm obtains an innovation in the narrow sense, the outcome depends on a normal distribution with a fixed standard deviation, sigma, and a time-varying mean, mu. The mean of the distribution of determined by the firm's labour coefficient, mu[i,j,t] = A[i,j,t] (or, to obtain scale independence, we can use mu[i,j,t] = ln(A[i,j,t]) and then transform the Result back by exp(Result)).

10 We shall soon consider the special cases of A[i,j,t] = 0 and/or Amax[i,t] = 0.

It is a problem in itself how firms come to know about the production technology necessary for the production of a good that they have never produced before. For the pioneering firm j that first acquire the technology for good i,[11] the new labour coefficient Anew[i,j,t] = [Aintro(1 - r[j,t])]/(H[j,t] + 1), where Aintro is a constant, r[j,t] is the firm's research intensity, and H[j,t] + 1 is the index number of the good for which production capability is being acquired. For a follower firm[12] the method of obtaining a new production capability is through an imitation.

4.3. The productivity of research and the determination of the research intensity

Imitations are obvious cases of spillovers. However, even innovations in the narrow sense are also characterised by some degree of spillovers, although these spillovers are not direct by mediated through the probabilistic labour coefficient of research work, R[t]. This coefficient determines the extent to which an innovation in the general sense will be obtained by the firm. In its turn R[t] is determined by two stocks of knowledge: the stock of technology-based general knowledge, A[t] ("algorithms"), and the stock of science-based general knowledge , B[t] ("basic laws"). The stock of algorithms is not cumulative in a simple sense since each new labour coefficient represents a new algorithm that replaces the old one. Instead the stock of algorithms is assumed to be proportional to the number of sectors in the economic system, A[t] = max(G[j,t], j=1..n).[13] The stock of basic laws is (against Thomas Kuhn) assumed to be cumulative. It is determined by the cumulative output of the public basic research sector (and thus exogenous in the present model). It grows at a constant rate b (per period).

Taken together the stocks of algorithms and basic laws are assumed to determine research productivity according to a Cobb-Douglas function: R[t] = A[t]^alphaB[t]^beta, where alpha and beta are constant exponents. This function is likely to show increasing returns to scale (alpha + beta > 1) because innovation is to some degree a matter of making "new combinations" (Schumpeter) and the materials for making these combinations are taken from the stocks of knowledge.[14] This function depicts the interdependence between algorithms and basic laws in research work: If a researcher has only concrete algorithms, she is in trouble applying these algorithms in new areas. If she has only basic laws, it is next to impossible to create concrete artefacts. If she has both in an adequate mix, things are much easier and her research work is much more productive. This interaction between technology and science has recently been re-emphasised by Nelson and Romer (1996).

We now have all the elements that determine the rate and direction of a firm's innovative results. First, the overall research productivity is calculated. Second, the firm's research effort determines in a probabilistic way the number of innovations. Third, each innovation is assigned to an activity according to the firm's focusing algorithm. Fourth, it

11 I.e. for the situation A[i,j,t] = Amax[i,t] = 0).

12 I.e. for the situation A[i,j,t] = 0, Amax[i,t] <> 0.

13 The inclusion of a sector from the moment that one firm starts production in it, is not realistic. The measure especially overestimates the stock of available algorithms in a system where a few firms have a number of goods much larger than the rest. However, when vertical differentiation is introduced (cf. Andersen, 1996a; 1996b), the number of sectors related to a particular good becomes dependent on its size.

14 This is not surprising since the basic checks against ever-increasing rate of growth (especially national resources) have not been dealt with in the model.

is decided whether an innovation becomes an "imitation" or an innovation in the narrow sense. Fifth, the labour coefficient that comes out of the innovation (Anew[i,j,t]) is calculated. Sixth, it is checked whether the innovation improves the firm's productivity. If this is the case, we come to the seventh and last task: to set the new productivity that is applicable to its full extent in the next period, i.e. A[i,j,t+1] = Anew[i.j.t].

Given this description of the research process, we can now consider the firm's motivation for doing research and thus study the rule underlying the determination of the research-intensity strategy for the next period, r[j,t+1]. Loosely formulated this rule could be "select a research intensity that maximises the present value of present and future consumption". A more precise formulation of the rule has to take into account that bounded rationality, which is permeating the whole model, is _a fortefiori_ characterising to the determination of the research strategy. Not only are the laws underlying the outcomes of research imperfectly known to the firm, but the results of the research race is also dependent upon the timing of the innovations of other firms. Furthermore, the firm could consider to change the focusing strategy or method, that should then be called f[j,t]; but we shall ignore this possibility in the present account.

The idea of satisficing behaviour provides simple rules of how to change r[j,t] (cf. Winter, 1984). The rule applied in the model reflects that the satisfaction of the members of a firm depends on the relative performance of their firm with respect to the introduction of new consumption goods. They make for the last tau years a comparison of the number of new products in their consumption, g[j,t] = G[j,t] - G[j,t-tau], and the average of the same number for the whole of the economy, g[.,t], where . (dot) means the operation of taking the average. The performance indicator can thus be defined as X[j,t] = gamma(g[.,t] - g[j,t]); it is initialised to 1. If X[j,t] < 0, then r[j,t+1] is changed with the increment r[j,t]delta; at the same time the satisfaction index is reset (X[j,t] = 1) in order to give the new research strategy time to be tested in practice. The direction of the incremental change of r[j,t] depends on the average research intensity, r[.,t]. If r[j,t] > r[.,t], then the firm decreases its research intensity; else it is increased. However, if performance at time T is still negative after a number of changes in research intensity, then research intensity is fixed to a very low size (i.e. r[j,t+1] = r[j,t] for t > T).

This mechanism for heuristic optimisation of the research intensity of a firm is obviously very primitive. It is especially problematic when competitive conditions are rapidly changing. Under these conditions (which are likely in an exchange-based economy with rapid technological change), it is dangerous for firms to adopt a wait-and-see heuristics and a fixed-size reaction to unsatisfactory conditions. One partial solution it to let delta[t] grow with the proportion of the production that is exchanged between firms as well as with the average research intensity.[15]

---

15 In a system where a firm might be wholly dependent on its knowledge about the production of a few goods, it is dangerous to rely of corrective steps of a given size. The ability to make major changes in the research intensity in a serious situation at time T[1] is, however, not a general solution. One reason is that the probabilistic character of research might imply that results come too late to prevent a catastrophe for the firm and its members. Another reason is that a major increase in research is likely to imply a temporary decrease in research productivity (R[T[1] + 1] < R[T[1]], etc.). Given these problems, it is obvious that it is dangerous to wait for an unsatisfactory performance at time T[1]. Instead the exchange-based economy suggests that successful firms should be able to use other mechanisms than satisficing to determine their level of research. To deal with this problem is the task of a later paper.

4.4. The innovation system and nonrival aspects of technologies[16]

The difficulties for the public sector in dealing with the innovation system call for a discussion of the basic economic principles for the evaluation of innovation systems. The reason why these principles are still under discussion is that the technologies that come out of the research process are difficult to handle in terms of standard economic analysis because they often represent a peculiar mix of private and public goods (Romer, 1993a; 1993b; Nelson and Romer, 1996). Technologies differ from conventional goods by not being destructed by their use. Instead a formalised technology (a product design or a process algorithm) can be freely applied for any scale of production. The (probabilistic) costs of creating a technology can thus be spread over a larger volume of output without incurring additional costs, and this means that an increased scale of application leads to decreased average costs. The advantage from the scale of adoption is not restricted by the size of an individual firm. Instead the nonrival character of a technology means that it can be adopted by extra firms without influencing the production result of the present adopters. Thus a technology is it a potential public good.

Technologies differ from pure public goods by having some degree of excludability (or appropriability) since a firm has several methods (tacitness of technical knowledge, non-disclosure, patenting, etc.) for holding its technology to itself. This excludability explains how the expected revenues from a more or less monopolised new technology can more than outweigh its (probabilistic) costs, and thus why private firms may undertake innovative activities. However, the fact that the exclusion is often partial means that an externality, a knowledge spillover, arises from the creation of technology within a firm. In some cases a relatively low degree of excludability allows the free-rider strategy of the imitators to become dominant while private production of the technology becomes impossible.

To policy-makers the placing of technologies on the scale between private and public goods suggests an Arrowian dilemma (Arrow, 1962b) or a Schumpeterian dilemma (Nelson and Winter, 1982, ch. 14). On the one hand, a strengthening of the private good aspect of technologies by increased excludability gives incentives to corporate R&D but also to monopoly power and slow diffusion of technology. On the other hand, an emphasis on technologies as public goods with low excludability avoids static inefficiencies; but if growth is to be upheld in the long run, government gets the near-impossible task of being a major supplier of technologies.

It should be observed that individual technologies differ with respect to their intrinsic degree of excludability. Some technologies are so idiosyncratic that they are mainly applicable within a specific firm; they can either be inherently idiosyncratic or their basic logic can intentionally kept unformalised and tacit. Other technologies are not protected in these ways, so they have to be made excludable through a more systematic effort with respect to patenting, etc. Still other technologies are related to the many minor activities that a firm perform, and no special effort is made for avoiding spillovers; on the contrary, they can allow the firm's access to "clubs" for the exchange of minor technological results. Finally, there are technologies for which the intrinsic excludability is so small that they are either avoided or produced through publicly

16 [This section has not yet been developed and fitted into the argument of the paper.]

supported R&D. These different approaches to excludability are not purely theoretical. On the contrary, economic life and economic policy demonstrate continuous attempts to cope with the problems - nor least through trial and error. Innovation systems reflect historically given, preliminary solutions.

4.5. The innovation system from a public sector perspective

To understand the development of innovation systems it is not sufficient to explore the endogenous evolution in relation to the private sector. As emphasised in section 4.5. there are elements of this sector that can only be developed by a public sector. To avoid an assumption of the behaviour of this sector according to inherent fulfilment of the general interest, a simple background of its behaviour is assumed. Especially, it is assumed that the public sector employs workers that are at the same time members of the labour force of individual firms; each firm takes care of the consumption of the members it has transferred to the public sector.

The size of the public sector is determined by two taxes, a poll tax and a turnover tax. The head tax functions in a way similar to the research intensity rule of private firms: a given fraction of the labour force is transferred to the public sector. This tax obviously puts the heaviest burden on weak firms and their members. The turnover tax is related to exchanges between firms, and it functions in the same way as the model's transaction costs: it creates a gap between the costs of the supplier and the benefits of the user. Because of the way the two taxes have been specified, the public sector can be dealt with by introducing a few minor complications into the specification of the model. In the main we may think of the public sector as being already implicitly present in the above accounts for the model.

The actual function of the public sector is to supplement the self-organising forces of the private sector in two respects: enhancement of the production and distribution of technology, and reduction of transaction costs. The former task applies even to a system of autarkic firms while the latter task is only relevant where there is at least a chance of developing an extended exchange. No attempts will be made to endogenise the public sector into the model. However, at couple of stories about the functioning of the public sector will help to motivate the following analysis of innovation systems and the public sector's role in them.

The first story concerns how the emergence of the technological role of the public sector can be traced back to the case of autarkic firms. The story starts once upon a time when all firms were alike (see section 3.5). At that time the public sector was just a luxury to society. However, as productivity differentials started to emerge, the different "employees" in the public sector considered their different consumption levels. An individual in the public sector who came from firm j consumed the range of goods 1..G[j,t]. The most lucky individuals consumed the range 1..max(G[.,t]). If G[j,t] < max(G[.,t], the individual from firm j (just as nearly all other "employees") had an interest in understanding how the gap came about and what could be done about it. Together with self-organised institution-building, the result of these reflections was a diffusion-oriented innovation system. When productivity differentials started to vanish and new differentials did not emerge to a sufficient degree (because of the difference between private and social returns to research), the innovation system was redesigned to include innovation-creation in the public sector and to some extent in the private sector (based on subsidies in terms of a lower tax).

The second story is about the public sector's role in the expansion of trade between firms. It begins at a time when firms had begun a sporadic exchange. The employees of the public sector had found out that their well-being was not only dependent on the consumption they got from their home-base firms. They had found out that their utility was positively and directly influenced by the size of the public sector. Therefore, they were happy to find out that a turnover tax was a means of expanding their sector. However, when they too often had spoilt the emerging exchanges, they finally found out that it was better to help the self-organising forces of the economy to fight the kinds of transaction costs that were rival to the turnover tax. As it became gradually more costly for the public sector to help in the decrease transaction costs, new methods were invented. First of all, it was observed that the innovation system could contribute to the reduction of transaction costs by inventing methods of measurement and quality control, etc. Next it was observed that not only the size of their research effort but also the focusing algorithm of firms influenced their creating of productivity differentials that were large enough to overcome the burdens of transaction costs and taxation. Therefore, a series of changes in the innovation system were made. These changes tended to emphasise innovation-creation rather than innovation-diffusion, e.g. by the assignment of strong property rights (e.g. patents) to innovating firms. However, it was soon recognised that technology was accumulated in firms that could not exploit all the potentials of an increased level of exchange. As a correction the innovation-diffusion aspects of the innovation system were strengthened once more.

The third story is about promoting exchange between firms of different economies (countries). This exchange was particularly easy to tax by the public sector, but it was also characterised by huge transaction costs. Although these costs to some extent could be limited, it appeared more obvious to create very large productivity differentials. The innovation system was oriented towards the needs of this kind of "technological mercantilism" by emphasising innovation-creation. But it was soon recognised that the intra-economy diffusion of innovations was at least as important. Thus the public sector helped to create "technology centres" that functioned as clearing-houses of technologies between firms engaged in a particular "national" sector. In this way a large international trade was promoted and taxed - apparently in the same way as intranational trade. However, there was a huge difference in the feed-back from economic growth to public policy in the two cases. As long as the public sector was coupled to all sides of the economic system, there was a certain check against the merchants' potential "conspiracy against the public". In the case of international trade, the checks were much less strict and the approaches were often one-sided. Therefore, the use of innovation systems for export promotion and import substitution was often problematic, and a return to the basics of the role of innovation systems in national economic growth was often necessary.

5. Conclusions

In a well-known computer game[17] we build a civilisation from scratch and try to bring it from the bronze age to industrialism, from despotism to democracy. The paper has presented an evolutionary model that allows us to do similar things with an economic system: we create the units of the system in a way so that they may spontaneously innovate and establish economic relations; we help the economic units by lowing transaction costs; we see how an emphasis on the creation of knowledge emerges spontaneously, but also how we can support this tendency; we recognise the increasing wealth of our economy and consider how this wealth can be exploited for further progress; finally we are challenged by other economic systems and have to design inter-economy relationships. In short, we behave as if we were Adam Smith by trying to reconstruct and analyse the economic system from scratch.

The model has been presented as a further development of Pasinetti's (1981) work with the subtitle *A Theoretical Essay on the Dynamics of the Wealth of Nations*. In contrast to Pasinetti's scheme the model has an explicit, but primitive, micro foundation. In this respect the paper has exploited the fact that we learn, and are at the same time entertained, by constructing the objects that we study. In the most abstract sense the building blocks are human activities relating to human needs. But in decision-making terms, the unit is consumer-producer firms. They help us to reconstruct the evolution of the economic system in a pragmatic, and apparently naive, approach. This approach may be called constructivist like Brouwer's school of mathematical philosophy.[18] It assumes that our best understanding and explanation is obtained when we are able to make reconstructions of given phenomena. When we deal with extremely complex phenomena like the emergence and evolution of an economic system, our simple reconstructions are of course not full reconstructions of real processes.

A pragmatic kind of constructivism and realism is by no means a novelty within the history of economic thought. On the contrary, it was already present in Adam Smith's *Wealth of Nations*. What is new today is that we have the computer to keep track of many of the repetitive details of our reconstructive work. Beneath our economic aggregates we can uphold finely reconstructed firms in a way that has not hitherto been considered feasible. At the same time we begin to recognise that it is a modelling advantage that our economic decision-makers have no absolute rationality and God-like level of information. If the economic system is to evolve from scratch, it is instead important that firms have a more complex inner structure than the decision-making agents we meet in e.g. neoclassical economics and most of formal game theory. This complexity of our agents allows the building of a complex economic macrocosm through a sequence of interdependent modifications of the microcosms of individual economic agents.

---

17 The game "Civilization". This computer game has an evolutionary flavour because of the role of random events in the coevolution (competition and cooperation) between different civilisations and between the government and its population. However, the major part of the underlying model is simple systems dynamics (systems of first-order differential equations) as can more clearly be seen from a predecessor of Civilization, namely SimCity that was explicitly based on Forrester (1969). See also Forrester (1971).

18 The approach has nothing to do with the Social Construction of Technology School within technology studies.

It is not the purpose of the paper to suggest a model in which economic growth is fully endogenised, to make a Wealth-of-Nations game as a self-evolving Game of Economic Life. Such a game would not only be boring for the players (in contrast to the game of Civilization). As we have already suggested in the section on specialised innovative activities there are many areas of government intervention. The most obvious problem of decision making is how governments could and should always avoid the temptations of mercantilist policies. Other issues are connected to the creation of the labour market, the monetary system, standardisation systems, patent law, general and sectoral promotion of basic and applied science, skilling of workers, and how to balance the level of taxation with the economic benefits that can be obtained by spending the incomes of government. Other policies may concern contractual law and the general levels of e.g. honesty, risk-taking and entrepreneurship. There are obviously many trade-offs between these different policies, and this leaves plenty of room for judgements from the player. Even experienced players will not be able to come up with optimal solutions because of the level of randomness of events and the lack of knowledge of the full structure of the game. But this is not to say that there is no policy conclusions based on evolutionary theorising and modelling.

References

Andersen, Esben S. (1996a), "From Static Structures to Dynamics: Specialisation and Innovative Linkages", in DeBresson, Christian (ed.) *Economic Interdependence and Innovative Activity: An Input-Output Analysis*, Elgar, Aldershot, pp. 331-353.

Andersen, Esben S. (1996b), The Evolution of an Industrial Sector with a Varying Degree of Roundaboutness of Production, Paper presented at the International Schumpeter Society Conference, Stockholm, 2-5 June, Department of Business Studies, Aalborg University.

Andersen, Esben S., and Lundvall, Bengt-Åke (1994), Innovation Systems and Economic Evolution: A Division-of-Labour Approach, Precedings of the EUNETIC Conference on Evolutionary Economics and Technological Change: Assessment of Results and New Frontiers, Strasbourg, October 6-8, Université Louis Pasteur, Strasbourg, pp. 1491-1520.

Arrow, Kenneth J. (1962a), "The Economic Implications of Learning by Doing", *Review of Economic Studies*, Vol. 29, pp. 155-73.

Arrow, Kenneth J. (1962b), "Economic Welfare and the Allocation of Resources for Invention", in Nelson, Richard R. (ed.) *The Rate and Direction of Inventive Activity*, National Bureau of Economic Research, Princeton University Press, Princeton, N.J., pp. 609-625.

Böhm-Bawerk, Eugen von (1891), The Positive Theory of Capital, Stechart, New York.

Campe, Joachim H. (1977), *Robinson der Jüngere*, Ein Lesebuch für Kinder (1779). Mit den Bildern von Ludwig Richter (1848), Weismann, München.

Defoe, Daniel (1938), *The Life and Strange Surprising Adventures of Robinson Crusoe of Yorks, Mariner*, Penguin, Harmondsworth.

Forrester, Jay W. (1969), *Urban Dynamics*, Wright-Allen, Cambridge, Mass.

Forrester, Jay W. (1971), *World Dynamics*, Wright-Allen, Cambridge, Mass.

Freeman, C., Clark, John, and Soete, Luc (1982), *Unemployment and Technical Innovation: A Study of Long Waves and Economic Development*, Pinter, London.

Freeman, C., and Soete, L. (eds.) (1987), *Technical Change and Full Employment*, Basil Blackwell, Oxford.

Gould, Stephen J. (1977), *Ontogeny and Phylogeny*, Harvard University Press, Cambridge, Mass.

Mandeville, Bernard (1970), *The Fable of the Bees*, edited from the 1724 edn., Penguin, Harmondsworth.

Marshall, Alfred (1949), *Principles of Economics: An Introductory Volume*, reset version of 8th edn., Macmillan, Basingstoke and London.

Nelson, Richard R. (1995), 'Recent Evolutionary Theorizing about Economic Change', *Journal of Economic Literature*, Vol. 33, pp. 48-90.

Nelson, Richard R., and Winter, Sidney G. (1982), *An Evolutionary Theory of Economic Change*, Belknap Press, Cambridge, Mass. and London.

Nelson, Richard R., and Romer, Paul M. (1996), "Science, Economic Growth, and Public Policy", *Challenge*, Vol. 39, pp. 9-21.

Pasinetti, Luigi L. (1965), "A New Theoretical Approach to the Problems of Economic Growth", in *Study Week on the Econometric Approach to Development Planning*, North-Holland (Pontificiae Academiae Scientiarum), Amsterdam, pp. 571-685.

Pasinetti, Luigi L. (1981), *Structural Change and Economic Growth: A Theoretical Essay on the Dynamics of the Wealth of Nations*, Cambridge University Press, Cambridge.

Pasinetti, Luigi L. (1993), *Structural Economic Dynamics: A Theory of the Economic Consequences of Human Learning*, Cambridge University Press, Cambridge.

Romer, Paul M. (1993a), "Implementing a National Technology Strategy with Self-Organizing Industry Investment Boards", in Baily, Martin Neil, Reiss, Peter C., and Winston, Clifford (eds.), *Brookings Papers on Economic Activity: Microeconomics*, Vol. 2, Brookings Institution, Washington, D.C.

Romer, Paul M. (1993b), Two Strategies for Economic Development: Using Ideas and Producing Ideas, Proceerings of the World Bank Annual Conference of Development Economics, 1992: Supplement to the *World Bank Economic Review*, March, pp. 63-91.

Schumpeter, Joseph A. (1934), *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest and the Business Cycle*, Oxford University Press, London.

Simon, Julian L. (1989), "Robinson Crusoe Was Not Mainly a Resource Allocator", *Social Science Quarterly*, Vol. 70, pp. 471-478.

Smith, Adam (1976), *An Inquiry into the Nature and Causes of the Wealth of Nations*, 2 vols., ed. R.H. Cambell and A.S. Skinner, Clarendon, Oxford.

Soete, Luc (ed.) (1985), *Electronics and Communications*, Gower, Aldershut.

Verspagen, Bart (1993), Uneven Growth Between Interdependent Economies: An Evolutionary View on Technology Gaps, Trade and Growth, Avebury, Aldershot.

White, M. W. (1987), "Robinson Crusoe", in Eatwell, John, Milgate, Murray, and Newman, Peter (eds.), *The New Palgrave: A Dictionary of Economics*, Vol. 4, Macmillan, London and Basingstoke, pp. 217-218.

Winter, Sidney G. (1984), "Schumpeterian Competition in Alternative Technological Regimes", *Journal of Economic Behavior and Organization*, Vol. 5, pp. 287-320.

Yang, Xiaokai, and Ng, Yew-Kwang (1993), *Specialization and Economic Organization: A New Classical Microeconomic Framework*, North-Holland, Amsterdam.

Appendix.
Transcending the dilemma for appreciative theorists

Because of their emphasis on bounded rationality and on technology as a very special kind of good, many economists dealing with the economics of technical change and the broader field of evolutionary economics tend to apply a form of theorising that de-emphasise formal abstraction and the related modelling criteria of rigour, consistency and robustness. Instead they emphasise relevance for description and policy-making in relation to the real world. The term used by Nelson and Winter (1982, 46) for this style of research is "appreciative theorising". For ambitious researchers, like e.g. Nelson and Winter, this style of research is not an attempt to avoid formal modelling *per se*. For them it is often the only way of theorising about important economic phenomena, given the gap between these phenomena and the scope of available formal modelling tools. There is, however, an inherent contradiction in ambitious appreciative theorising: it tries with rather simple and informal means to capture phenomena that are more complex that the ones treated by mainstream modelling tools. This is especially obvious in the recent writings on innovation systems (Nelson, 1993; Lundvall, 1995; Carlsson, 1995; Edquist, forthcoming). Therefore, the emerging theory of innovation systems is to a high degree confronted with classical dilemma of non-standard economics: either to become formalised in a way that tends to remove its interesting contents or to be kept in an unsatisfactory loose form and thus to foresee that the theory will sooner or later be forgotten.

It is well known that the old Schumpeter was marred with this dilemma - made obvious by the intellectual failure of his intended *magnum opus*, *Business Cycles* (1939). Although he sought help from his formalist friends and students (Frisch, Samuelson, Goodwin), the advice he got was at best of little help. So he was stuck with his verbalised vision. Krugman (1995) has recently pointed out that the main contributors to "high development theory" in the 1940s and 1950s (Rosenstein-Rodan, 1943; Myrdal, 1971; Hirschman, 1961) faced the same problem and choose the same, seemingly hopeless, solution as Schumpeter: to stick to the not-too-formalised version of their theory. According to Romer (1993, 553 ff.) the "appreciative theorists" in the economics of technical change and evolutionary economics (Nelson and Winter, 1982; Dosi, Pavitt and Soete, 1990; Dosi and Freeman, 1992) face the same problem: "If this work continues to operate in isolation from the formal modelling traditions of mainstream economics, it too may be lost and ignored." Romer is, however, quick to point out that the present-day situation has new possibilities for theorists who emphasise empirically oriented modelling and untraditional visions.

To start with, modern appreciative theorists may try to develop Nelson and Winter's (1982) suggestions of computer modelling and simulation as a middle ground between appreciative theorising and simplistic formal models. But this is not necessarily sufficient, since to survive the insights from "theory on the computer" might depend on "being codified in simple formal models that supplement the simulations and the appreciative theory" (Romer, 1993, 555) Here they can turn to endogenous growth theory which might help "to codify some of the insights from the appreciative theory of development" since it recognises that "ideas" (e.g. technology) are of central importance. Especially the "second-round or 'neo-Schumpeterian' models of growth with monopoly power", like the models of Romer (1990), Grossman and Helpman (1990), "may help to bridge part of the gap between the mainstream theorists and appreciative theorists"

(Romer, 1993, 556) On this background Romer (1993, 569) concludes with the suggestion of "a natural division of labour in future research" where mainstream theory tries to include more and more elements in "simple abstract models" while the outsiders (like Rosenberg, 1976; Fagerberg, 1987; David, 1991; Mokyr, 1991; Nelson, 1993) "push the kind of evidence that they have collected" towards aggregative statistical analysis and in-depth case studies. This work includes the further development of the "studies of national innovation systems in a variety of industrial and newly industrializing countries". (Romer, 1993, 561)

Romer's analysis of the situation of appreciative theorists, econometricians and historians in the Nelson and Winter tradition (and similar traditions) is surprisingly precise. But he tends to de-emphasise their need for a process of formalisation and simplification of theories and computer models which is closer to their traditions than new growth theory is likely to come for a long time. Such a effort is helped by the possibilities of an interaction with the works of the new growth theorists, but Romer obviously overestimate the contribution that comes from new growth theory. To allow for at more interesting treatment of technology (cf. Verspagen, 1993, Ch. 7), the effort should follow the tradition in appreciative theorising of being open to other "heterodox" theorists. The present paper follows this strategy by suggesting a middle ground between different types of theorising. It is based on the premise that many appreciative theorists have chosen their research strategy not because they are against simple formal models but because they are interested in core economic issues like increasing returns, spillovers of different types, and first and foremost "technology" and other "ideas" that do not behave like normal economic goods (especially because they are not really rival goods). With respect to these topics of central importance to modern knowledge-based economies - and thus to the whole modern world - new growth theory is a central ice-breaker, but it has just started to scratch the surface of the underlying problems.

The starting point of the present paper is not only that there is now a substantial number of studies of innovation systems, but that these studies are relatively isolated. Not only have they not been connected to mainstream economics, but they have not been connected systematically to the modelling in the Nelson and Winter tradition or to other "heterodox" kinds of modelling (like Pasinetti, 1993; Yang and Ng, 1993) and history-near theorising (like Hicks, 1969; Rosenberg, 1976; 1982; 1994). In this situation there is some very basic work to be done: to clarify the concept on innovation systems and related concepts; to suggest a simplistic growth model in which these concepts make sense; to enhance the understanding of the concepts in relation to an analysis of the transformation of innovation systems in relation to changes in the underlying economic system. It is obvious that a single paper cannot confront all these issues in a satisfactory way. The basic proposition of the paper is, however, that the we are on the way towards a theory of innovation systems. If this proposition on one of the more difficult issues in appreciative theorising is correct, then the door has been opened to a multitude of other issues.

References to Appendix

Carlsson, Bo (ed.) (1995), *Technological Systems and Economic Performance: The Case of Factory Automation*, Kluwer, Dordrecht.

Dosi, Giovanni, and Freeman, Christopher (1992), The Diversity of Development Patterns: On the Processes of Catching-up, Forging Ahead and Falling Behind, University of Rome La Sapienza, Rome.

Dosi, Giovanni, Pavitt, Keith, and Soete, Luc (1990), *The Economics of Technical Change and International Trade*, Harvester Wheatsheaf, New York.

Edquist, Charles (ed.) (forthcoming), *Systems of Innovation: Technologies, Institutions and Organisations*, Pinter, London.

Fagerberg, Jan (1987), "A Technology Gap Approach to Why Growth Rates Differ", *Research Policy*, Vol. 16, pp. 87-99.

Grossman, Gene M., and Helpman, Elahan (1990), "Comparative Advantage and Long-run Growth", *American Economic Review*, Vol. 80, pp. 796-815.

Hicks, John (1969), *A Theory of Economic History*, Clarendon, Oxford.

Hirschman, Albert O. (1961), *The Strategy of Economic Development*, paperback edn., Yale University Press, New Haven, Conn.

Krugman, Paul (1995), *Development, Geography, and Economic Theory*, MIT Press, Cambridge, Mass. and London.

Lundvall, Bengt-Åke (ed.) (1995), *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*, Pbk. edn., Pinter, London.

Mokyr, Joel (1990), *The Lever of Riches: Technological Creativity and Economic Progress*, Oxford University Press, New York and Oxford.

Myrdal, Gunnar (1971), *Economic Theory and Underdevelpoed Regions*, Harper, New York.

Nelson, Richard R. (ed.) (1993), *National Innovation Systems: A Comparative Analysis*, Oxford University Press, New York and Oxford.

Nelson, Richard R., and Winter, Sidney G. (1982), *An Evolutionary Theory of Economic Change*, Belknap Press, Cambridge, Mass. and London.

Pasinetti, Luigi L. (1993), *Structural Economic Dynamics: A Theory of the Economic Consequences of Human Learning*, Cambridge University Press, Cambridge.

Romer, Paul M. (1990), "Endogeneous Technological Change", *Journal of Political Economy*, Vol. 98, pp. S71-S102.

Romer, Paul M. (1993), "Idea Gaps and Object Gaps in Economic Development", *Journal of Monetary Economics*, Vol. 32, pp. 543-573.

Rosenberg, Nathan (1976), *Perspectives on Technology*, Cambridge University Press, Cambridge.

Rosenberg, Nathan (1982), *Inside the Black Box: Technology and Economics*, Cambridge University Press, Cambridge.

Rosenberg, Nathan (1994), *Exploring the Black Box: Technology, Economics, and History*, Cambridge University Press, Cambridge.

Rosenstein-Rodan, Paul (1943), "Problems of Industrialization in Eastern and South-eastern Europe", *Economic Journal*, Vol. 53, pp. 202-211.

Schumpeter, Joseph A. (1939), *Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process*, 2 vols., McGraw–Hill, New York and London.

Verspagen, Bart (1993), *Uneven Growth Between Interdependent Economies: An Evolutionary View on Technology Gaps, Trade and Growth*, Avebury, Aldershot.

Yang, Xiaokai, and Ng, Yew-Kwang (1993), *Specialization and Economic Organization: A New Classical Microeconomic Framework*, North-Holland, Amsterdam.