A COMPUTER SIMULATION OF TECHNICAL PROGRESS AND ECONOMIC EVOLUTION IN A MULTISECTORAL ECONOMY

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ABSTRACT

The thesis takes as its aim the analysis of the micro foundations of economic growth, focussing particularly on the role of technical progress. The discussion argues the case for adopting a non-equilibrium, evolutionary, approach to the issues, based upon the behavioural theory of the firm and a dynamic theory of competition. These principles are embodied in a microeconomic based computer simulation model, which is used to analyse the technological and industrial development of an economy.

The thesis begins with a discussion of the nature and measurement of technical progress, in which the need for a multisectoral analysis of change is argued. It then moves to consider growth paths in multisectoral economies, and the problems of incorporating technical progress into linear models of economic growth. The need for a non-equilibrium multisectoral model of growth and technical progress is made apparent.

Models which describe the main elements of an evolutionary explanation of economic development are then developed: firm behaviour based on rules of thumb for production decisions and profit seeking search for technological advances in investment decisions is then developed; economic selection and dynamic competition based upon firms' revealed performance; technological evolution in the economy. The principles of these models are incorporated into a computer simulation model. The problems of using such models in economic enquiry are also discussed.

The final chapters of the thesis present results from running the computer simulation. The results first analyse the individual elements of the model focussing on a single firm and a single industry. The evolution of the economy as a whole is then examined. Results are presented for individual simulation runs, and as comparative dynamic exercises as various parameters are changed.

The principal conclusions are:

(i) That the model produces results with stable macro performance arising out of diversity and change at the micro level. Such results therefore add weight to the evolutionary explanation of economic development.

(ii) That the success of industrial economies is to a large extent determined by their technology. Investing in new technology is a primary determinant of a firm's and ultimately an economies success. Induced innovation is a major factor in economic growth and industrial change.

(iii) That the long run dynamic behaviour of economies may be very different to short run. Policy designed to promote some end may succeed in the short run but have the opposite effect in the long term.

No part of this thesis has been submitted in support of an application for any other degree or qualification of the University of Manchester or of any other University or institution of learning.

Since graduating with BA (Economics) from the University of Essex in 1972, my education and research experience relevant to this thesis has been:

(i) 1974: MA (Economics) University of Essex.

(ii) 1974 to date: Lecturer II and then Senior Lecturer in Economics, Department of Social Studies, Liverpool Polytechnic.

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CHAPTER 1 TECHNICAL PROGRESS AND ECONOMIC DEVELOPMENT

1.1 Introduction

One of the most notable features of industrial economies is their ability to sustain long periods of economic growth. One of the main engines of economic growth is technical progress, which allows more efficient production of existing products and the introduction of new and improved products. Accompanying growth at the macro level will be a changing structure of firms and industries at the micro level. The economy is constantly evolving as a result of technical progress. Our intention is to advance understanding of the growth process by examining the relationships between technical progress, industrial change and economic growth.

Studies of technological change have tended towards two extremes. On the one hand there have been highly aggregated macroeconomic studies of economic growth. On the other there have been many micro economic examinations of firms, studying invention, innovation and the diffusion of new processes through an industry. Our aim is to help in the synthesis of these two approaches; to enhance understanding of the micro foundations of economic growth. In this chapter we set an agenda for our study.

1.2 The Neo-Classical Approach to the Study of Economic Growth

As a first step we briefly consider the 'orthodox', neoclassical, approach to growth and technical progress, and some criticisms of it. This will provide us with a starting point for the development of our study.

The principal 'facts' to be explained by growth theory are generally agreed. At the macro level they may be summarised in Kaldor's stylised facts (Solow (1970) pp2-3). When we disaggregate to the industry level it is clear that some sectors have developed much more quickly than others, and that sectoral patterns of growth have varied over time.

The foundations of neoclassical analysis are to be found, according to Simon (1986) in; Say's law, the Quantity Theory of Money, and a principle of rationality, which ensures that markets clear by providing an opportunity for profit or increased utility whenever markets are out of equilibrium. The central elements of the neoclassical descriptions of economic growth derive from the theory of the firm and production in a competitive industry. Here profit maximising firms make optimal choices on inputs and outputs over a well defined and known choice set. Prices adjust freely to keep all markets continuously at equilibrium, and thus convey 'correct' signals back to economic agents. Competition is essentially passive, with firms being price takers, and earning normal profits at market equilibrium. The sources of economic growth are the accumulation of capital, increases in the labour supply and technical progress (Solow 1970, Wan 1971). Technical progress is that part of economic growth which is not accounted for by increased inputs.

In order to explain the 'residual' of technical progress, it is necessary to incorporate firms' profit maximising decisions on research and development, either for innovation or for imitation purposes. Firms are postulated to search over well defined sets of potential new processes or products, spending money on search activity until marginal cost equals marginal present value of revenue, given expected prices and outputs. The process of search is thus seen as qualitatively the same as any other activity carried out by the firm. In this rational world innovation is made endogenous to the model by means of an innovation production function.

As new processes are discovered, firms will adopt them at the ideal moment. In the neo-classical perspective, competition will ensure that all firms behave in this way, since those that do not will be forced out of business. If some firms should have defective information, their rational choices will be incorrect for their true context, and market forces will move to eliminate them. Economic selection will ensure that profit maximising behaviour will dictate the path of economic evolution.

1.3 Critique of the Neoclassical Approach.

The aim of a theory is to find fruitful simplifications and abstractions. Theories should be judged by both their predictive ability and the theoretical understanding which they confer. Understanding should be in terms of causal structure at a level deeper than that required for useful prediction. In the language of Nelson and Winter (1980), theories should provide us with correct 'structural equations' as well as 'reduced forms' which can yield good predictions. By these criteria neoclassical models have serious weaknesses and criticism of the orthodox approach to economic problems is widespread. Nowhere is this criticism more justified than in the study of economic growth, which focuses, by its very nature, on change rather than equilibrium.

Various models of economic behaviour are able to predict the basic facts of economic growth described above. Thus resort to empirical testing, by perhaps ever more sophisticated methods, will not be able to distinguish the models. We need therefore to consider the extent to which the models give us understanding. Simon (1986) is unequivocal: "Existing uncertainties about the correct explanations of economic growth and business cycles cannot be settled by aggregative analysis within the neoclassical framework. Current disputes in theory rest largely on ad hoc, casually empirical, assumptions about departures from perfect rationality under uncertainty" (p 21). He argues that "to build an interesting and useful theory of long term economic growth, even for developed countries, we have to go behind the principle of rationality" (p28). Similarly Kay (1984, p1) sees the problems of neoclassical economics as being rooted in bounded rationality and system nondecomposability (that the whole cannot just be regarded as the sum of the parts). Pasinetti

(1981) sees the problem arising because neo-classical theory emphasises trade, which is essentially about short run considerations, rather than industry and production, which is dynamic and requires a long run perspective.

In this light, so far as neoclassical growth theory is concerned, Nelson and Winter (1980) see the critical problem as a misapplication of the conventional static theory of the firm in a competitive market. This was developed, for microeconomic analysis, as a reduced form, for making predictions about behaviour in competitive markets within a given economic and technological environment. In the context of a growth model it is a major building block within the larger structure, where it incorporates the basic ideas as to what molds industry behaviour. Crucial features of the theory are inappropriate to this task, and severely limit the understanding which the neoclassical model can confer.

Bounded rationality and uncertainty are principal elements of the innovation process, which has a major role in explaining technical change and economic growth. The very idea of innovation implies something previously unknown, and thus not likely to be a part of a well defined choice set. Imitation implies that some firms do things better than others, something difficult to incorporate into a world of perfect knowledge. Nelson and Winter (1974) contend that "there is a sharp inconsistency (between) the macro growth literature and the micro literature on technical change per se that calls into question the basic tenets of neoclassical theory" (p886). They cite studies showing much evidence of the role of insight in the invention process, of differential ability to use knowledge, of considerable differences among firms in the technology they use and in their profitability.

These ideas also imply a very different type of competition to that of the neoclassical model. Once firms become differentiated, as a result of bounded rationality and uncertainty, competition becomes a dynamic process involving struggle and disequilibrium. In a Schumpeterian model of competition, innovation is a method by which firms may seek to gain advantage over others, and so increase their profit. The development of the industry is now dependent on three forces; profit seeking behaviour by firms in their current production decisions, profit seeking by firms by search over uncertain terrain, and from selection of the most profitable firms through their higher rates of growth. It is the continued diversity of behaviour, as a result of innovation, and chronic disequilibrium that drives the process of economic growth.

These alternatives to the neo-classical conception need to be explicitly incorporated into a model of economic development if the growth process is to be truly understood.[1] Our purpose is to develop such a model. Our model will clearly be required to predict the agreed facts of economic growth, but

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[1] We will not discuss here reasons for the dominance of the neo-classical approach. These issues are briefly raised in chapter 6.

now arising from a more realistic description of firm's behaviour.

Matthews (1984) discusses in general terms the consequences of including non-optimisation into models of economic change. Non-optimisation may be due to inertia (firms keep on doing what they have done in the past), due to satisficing, bounded rationality, risk aversion and so on. This coupled with competitive selection is sufficient to lead to qualitatively similar predictions to the orthodox model. Whilst Matthews and others emphasise that a variety of model types, consistent with various degrees and types of non-optimisation and competitive selection, will yield useful extensions to the neoclassical theory, we will concentrate on one such group of models, which seek to describe a process of economic evolution. Evolutionary models have proved to be a particularly fruitful source of enquiry into the processes of technical progress, as evidenced in particular by the work of Nelson and Winter.

1.4 Elements of an Evolutionary Model.

The core of evolutionary theory is the dynamic process by which firm behaviour and market outcomes are jointly determined over time[2]. At each point of time firms exist in given states, a legacy of past decisions. Firms operate in the context of given market conditions, and produce outputs,

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[2] Day and Eliasson (1976) give a concise discussion of the elements of an evolutionary model.

invest in new capacity and undertake search for new products or processes. The firm's transition to its state in the next production period is determined by two factors. First, its profitability, which is one determinant of the firm's growth rate. Competitive selection has the function of ensuring that the most profitable firms tend to have higher than average growth rates. Second, by the success of its search activity in finding new modes of behaviour (including production routines). The nature of search will be partly determined by the economic environment of the firm. Thus prices determine both the profitability of firms and, through induced innovation, the nature of search. Some search may be directed towards imitation of successful behaviour. Search and selection are simultaneous, interacting aspects of the evolutionary process. Through selection and search, firms evolve over time. Each firm's actions help determine its future. "The condition of the industry in each time period contains the seeds of its condition in the following period" (Nelson and Winter (1982) p19).

The major building block of an evolutionary model of economic growth is a 'behavioural' theory of the firm. The dynamics of the economic system depends critically on just how economic agents make their decisions, so these must be modelled in a plausible manner. A firm consists of boundedly rational people who together use their knowledge and abilities to operate a set of decision rules, which determine the firm's response to a given environment, given its current state; its revealed performance. The firm's decision rules are the outcome of previous decisions. They are stable in the short term, but susceptible to change over time as a result of learning, chance and from goal-orientated search. The rules governing the firm's search procedure are necessarily qualitatively different from the others. Evidence cited by Winter (1971) suggests that firms make day to day production and pricing decisions by routine application of established rules, procedures and policies. Search, by its very nature implies dissatisfaction with existing rules. Search is a remnant of behaviour motivated by the profit consequences of a contemplated course of action; the innovating remnant.

Profit maximisation over a well defined choice set is thus a special case of this more general model. Winter (1971) discusses a satisficing case. Description of the rules which determine production, investment and search activity is the means by which we model firm behaviour. Simon (op cit) would see such description as essentially empirically based. Rules perform an analogous role to genes in biological evolution, and need to be observed in the first instance.

The second main element of an evolutionary model is the explicit description of the selection mechanism, by which the most profitable processes will eventually come to dominate. The selection mechanism consists of a set of rules which translate each firm's performance into expansion or contraction. The 'selection environment' determines the profitability of each firm, including its market share, and the nature of the financial and capital markets in which firms operate. The selection environment is the arena in which firms interact with each other. The specification of the environment will depend on the scope of the model; in the evolutionary equivalent of general equilibrium analysis all demands and supplies and all prices but one will be endogenous. The financial and capital markets determine the extent to which each firm's profits can be transformed into new capacity. In partial models some of these elements will be exogenously specified.

An evolutionary scenario of technological progress and economic growth is as follows: New discoveries are first incorporated into production at the level of the individual firm and will be used at first in parallel with older techniques. Over time new processes supplant the old, until in turn they are themselves supplanted. Individual firms rise and fall in terms of their relative importance, and similarly industries rise and fall as a proportion of total production. Technological progress in an industry will typically lower the costs of production for a given quality of product and, in a competitive market, price will fall. The effect of this will be felt in other industries, both as patterns of demand change and as the economic viability of industrial processes changes. The process as a whole does not converge to an equilibrium but continues to evolve.

1.5 The Nature of Our Study.

From our discussion so far we conclude that our explanation of economic growth should be set in the context of individual firm's decision taking, which must be modelled explicitly. Given our intention of examining the relationships between technical progress, industrial change and economic growth, it is clear that our model must be multisectoral in nature, in order to capture the interaction of technical progress between industries. The model should, of essence, be non-optimising and non-equilibrium in nature, as in the evolutionary approach. Our intention is to develop and analyse such a model.

The degree of complexity which is introduced means that clear analytical results will not be achieved. The problem of intractability in micro to macro models, particularly those incorporating non-optimisation and disequilibrium is cited[3] as one explanation for the continued dominance of the neo-classical approach. Our results will be obtained from a computer simulation of the workings of a multifirm, multisectoral economy, and by controlled experimentation with the evolutionary path of our economy. We will seek to discover the effects of new innovations as their potential is realised throughout the economy. We will consider the importance of induced innovation and structural change, the

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[3] See for example McCloskey (1986), Simon (1986), Nelson and Winter(1974).

role of investment and finance and various economic strategies to more effectively extract the benefits from new ideas.

As described, our study seeks to synthesise elements of the micro and macro economic analyses of economic growth and technical change. In order to put our discussion in the context of this other work, we proceed by, in Chapter 2, a discussion of methods used to describe and measure technical progress. In Chapter 3 we discuss various models of multisectoral economic growth. These models have been used principally for the study of economic growth within a given technological environment. Our purpose is to examine how growth affects the industrial structure and also to provide a framework for developing a simulation study. In chapter 4 we begin to develop our evolutionary model, considering various approaches to modelling the behaviour of the individual firm. Chapter 5 takes the discussion on to the evolutionary behaviour of the industry and then the economy as a whole. Chapters 2 to 5 describe the economic theory and models underlying our simulation study.

Chapter 6 introduces simulation with a discussion of the merits of this approach to economic enquiry, and a look at some other studies which help to inform us as to good practice in simulation modelling. In chapter 7 we describe in detail the actual model used to generate our results. The function of chapter 8 is to describe the workings of the model, beginning with the behaviour and performance of an individual firm and moving on to greater degrees of aggregation. In chapter 8 we carry out closely controlled experiments on the separate elements of our model economy. On the basis of our previous analysis, in chapter 9, we carry out experiments with the whole simulation model. We first examine the nature of economic evolution and in particular the role of induced innovation. Second we consider the nature of economic long waves. Finally in chapter 10 we consider the implications of our study for the understanding of the nature of technical progress.

CHAPTER 2 THE NATURE AND MEASUREMENT OF TECHNICAL PROGRESS

2.1 Introduction

In this chapter we discuss what we understand by technological change, and how it may be described and measured. This, together with chapter 3, will provide a theoretical basis, and practical techniques, for constructing our simulation study and for examining the results from it. A small number of issues are raised in this chapter, but discussion deferred to the next, where they are more easily dealt with. We introduce the subject with some definitions of technological progress.

Kennedy and Thirlwall (1972) define technology as useful knowledge pertaining to the act of production. Hence "technical progress implies advances in knowledge which improve human welfare, quantitatively through increases in real income per head and qualitatively through widening mans choice of goods and extending his leisure" (Kennedy and Thirlwall op cit p11). The effect of technical progress or technical change (used synonymously here) is, ceteris paribus, to move out the production frontier of society. In this sense technical progress will arise from knowledge creating processes, resulting in new products and new forms of organisation and production. The impact of technical progress is created not by the invention of new industrial processes but by their incorporation into production. We need therefore to extend our definition of progress to include the diffusion of already known techniques and the run down of less efficient ones.

Productive techniques in use at any time will comprise a mixture of current best practice, down through older and less productive techniques to those on the verge of obsolescence. Current average productivity will therefore be a weighted average of the productivity of these techniques. Changes in productivity represent relative changes in total outputs and total inputs. Improvements in average productivity within an industry, meaning more output is produced from a given quantity of inputs, can therefore occur in three ways. First, by scrapping the oldest, least productive techniques. Second, by firms investing in currently available best practice techniques. Third, the productivity of a firm's best practice can be increased through research and development or another learning process. All of these lead to a shift in observed production coefficients, and this allows us to describe (and measure) technical change which improves production of existing products by its effect on (average) production coefficients.

Many macroeconomic studies of technical change utilise the concept of an aggregate production function. Technical change is then defined as a shift in the function and is measured by changes in the parameters of the function. In our analysis below we will consider firms developing and using a range of production processes, each with discrete fixed technical coefficients. Technical change is then described by observed differences in relationships of inputs to outputs, or by dual measures based on factor earnings. We will have occasion to use both approaches below, a particular process being thought of as the outcome of a decision based on an isoquant and a set of input prices.

In this chapter we commence by briefly considering the mechanisms by which technological progress can come about, and how the benefits from change are conferred on society. We then move on to the description of change in terms of overall efficiency of an industry or economy, and the rate and direction of change.

2.2 Mechanisms of Advance

The techniques in use at any time are a subset of all those that are technically feasible. The subset is chosen on the basis of economic viability, both at the time research and development is carried out which determines those processes which are developed, and prices at the time of production which determine whether capital is to be operated. For the economy as a whole, improvements in one industry may allow different and more productive techniques to become economically viable in other sectors. Improvements in average productivity occur both through a continuous process of small changes and through major breakthroughs leading to fundamentally new basic production processes.

Better knowledge about production technology is the starting point for improved best practice. This may come about through deliberate search, through learning by doing, or serendipity. Improved best practice results when this new knowledge is actually implemented in production, ie. innovation. These matters are the subject of chapter 4, so here we merely note the various different sources of improvement.

In the real world an industry will typically have some firms who are innovators and are developing the next best practice technology, and some who are imitators whose best practice is still somewhat behind the leaders. A typical firm will also tend to be using a number of processes. Thus advance can come from each firm abandoning its old processes and replacing them with one already known to the firm, or from imitating firms catching up, as well as from innovation. The existence of adjustment costs in finding, developing and incorporating new techniques ensures the continuation of this diversity of techniques, at least in the short run.

Salter (1969) gives a model to explain the economic lifetime of a technique within a perfectly competitive industry (as well as discussing implications of relaxing his assumptions). Firms taking the decision to invest, do so on the basis of the total expected return to that investment. All investment is in the current best practice technology available to the firm and involves the building of a new plant (not a crucial assumption). New investment takes place until the expected return to new investment is equal to normal profits. Thus the price of the goods will equal operating costs plus a gross trading margin to cover a normal return, depreciation etc. For capital already in existence, the fixed costs have (mainly) already been incurred. The decision is therefore only whether or not to scrap. Thus existing capital will remain in use so long as price of output exceeds operating costs plus a return on the scrap value of the plant, anticipated over the production period. Existing capital therefore has the short term nature of a primary input and it earns a quasi rent. Through its lifetime capital becomes progressively more outmoded and is scrapped when its quasi rent becomes negative.

We can see that it is the existence of fixed capital embodying a given technology which gives rise to lags in introducing new technology and therefore to some technical inefficiency (as defined in section 2.4). The economic lifetime of a plant is a function of relative factor prices and the degree of capital intensity. As the price of new capital and produced inputs falls relative to the wage rate, so old plant and techniques more quickly become obsolete. The greater the capital intensity of a plant the longer the economic lifetime will be.

Average productivity within each sector of the economy will be continuously changing. The exact nature of the technical change within each sector will depend on the technically feasible possibilities and on relative prices. Whilst these are exogenous to each sector, the relative prices are endogenous to the economy as a whole. Consequently analysis of productivity changes for the economy as a whole must take into account this extra dimension. Carter (1970) refers to factor substitution arising from relative price changes as adaptive structural change. Adaptive changes may trigger off a new round of innovations which were not worth developing at the old factor prices. Adaptive changes may also speed the obsolescence of old plant (as compared to constant prices) by allowing new plant to use new cheaper inputs more intensively, leading to lower output prices for the industry. An example of how this may occur is found in section 3.4 of chapter 3.

2.3 The Benefits of Technical Change

One observation in most empirical studies of technical change is the predominance of labour saving in the whole process of productivity change. In part this reflects a problem in measuring quality changes in produced inputs, however it is also a reflection of economically directed change. Labour is the only factor input that tends not to have been produced more cheaply as a result of technical progress, as measured by real factor prices. The search for technical advances may therefore be directed towards direct labour saving within the industry. Capital and other produced inputs have been produced more cheaply (with less direct and indirect labour input) and this leads to substitution of these for labour. One effect of this is that as the amount of capital rises relative to that of labour its relative price falls, (and for any produced input the same is true).

As prices are at the centre of this evolutionary process, it is necessary to consider their formation. In the short run prices may be determined by the interaction of demand and supply, with market structure playing a part. In the long run, we expect that supply factors will play a dominant role, and price will reflect total production costs. In Pasinetti's (1981) discussion of this question, price is equated to the total labour costs, direct and indirect, embodied in the good, together with interest payments in compensation for waiting. Indirect labour costs come from flow inputs and capital inputs, and their importance as a proportion of all inputs will differ from process to process, and in particular between new and old processes.

It is useful to distinguish, as Pasinetti does, between capital intensity, K/Y, and the degree of mechanisation, K/L. K/Y is the most relevant for price formation, giving in essence the ratio of physical quantities of labour locked up in capital to that used in total during production. The level of capital intensity and degree of mechanisation will be those which lead to cost minimisation (taking the rate of interest as exogenous to the firm). Clearly these will differ between processes and especially between industries.

Historically the time path of K/L has been increasing whilst K/Y has shown no consistent trend. Consequently new technologies are likely to be more mechanised than old, but because of increased labour productivity new techniques will have a similar fraction of their overall labour requirements in the form of capital as old ones.

In any time period, firms will choose from their existing capacity which techniques to operate. These will also provide the foundation from which new investment opportunities will be researched and implemented. Such search activity will be on the basis of cost minimisation, even in firms with no other profit orientated strategy (Winter, 1971), so that given the above we can see that the general nature of technical progress is an improvement in the overall productivity of labour.

The benefits from technological progress are increased real factor incomes as more output is produced from a given input. Consequently it will be in an economy's interest to organise its development in such a way as to achieve the most rapid rate of progress possible, given savings decisions. We have seen that progress is likely to require investment in search activity and in new capital goods, and in any economy such funds are limited. The task of an economic planning agency in this context is to direct resources such as to maximise the discounted social welfare of the community over the planning period. One of the purposes of our simulation exercise will be to consider the inefficiency which may result from a free market allocation of investment funds. From discussing the nature and benefits of technical progress we now move to its measurement and description, by which means we may monitor the extent of change. This will give us concepts and tools which will be useful in describing our simulation results.

2.4 Best Practice Technology and Efficiency.

In practice new techniques may be introduced in a piecemeal way within existing plant. For the purposes of this section however, we will treat a new best practice technology as being the introduction of a complete new productive process in completely new plant. We consider first a single industry.

New processes coming into use reflect both technical possibilities and input prices, all of which are taken here to be exogenous to the firm. With constant input prices, a new improved technique moves the best practice isoquants nearer to the origin. The shape and steepness and rate of curvature of the isoquant may also change in the case where substitution between inputs is possible. In the case where only a single process (point) on the isoquant of potential processes is actually developed into a real world process, we observe only one set of production coefficients. We can measure changes in best practice productivity either through direct estimation of the parameters of the production function or through an index of total factor productivity. Because factor prices are held constant we can treat this as measuring the improving technical productivity of best practice techniques, which

Nishimizu and Page (1982) identify as the true measure of technical progress.

As we noted above best practice techniques represent only one of (possibly) many techniques in use at a given time. We might therefore wish to consider the efficiency of these, or the current average productivity in relation to the best practice. It is useful to have a purely technical measure of efficiency, based only on the technical conditions of production for the various processes.

Considering the case of firms which can choose their input coefficients from the whole range offered by a production function, in the manner described by neo-classical economic theory, Farrell (1957) identifies a firm's overall efficiency as being the sum of its technical efficiency and price efficiency. Price efficiency measures the extent to which the firm has adopted the currently available best practice optimum factor proportions. Technical efficiency measures the ratio of current inputs to best practice inputs for some output keeping input proportions constant. We can similarly measure the technical efficiency of an industry (though because all firms will use inputs in different proportions this will be less than the weighted average of individual firm's technical efficiency). The structural efficiency of an industry compares current inputs per unit output with a current best practice input per unit output derived from the constituent firms. Technical efficiency, by keeping input proportions constant is a purely technical measure of efficiency. We could also measure technical efficiency by the ratio of actual to best practice outputs keeping inputs constant, as Nishimizu and Page do.

The efficiency of a firm defined in this way is very dependent on the nature of the best practice process. An industry with uniformly inefficient (in world terms say) firms will have a high domestic structural efficiency. An industry with no technical progress over a long period, so that all plant through a process of depreciation and replacement, is of the best practice type will have a technical efficiency of 100%. It follows therefore that low technical efficiency is not necessarily a problem. A low level of technical efficiency is indicative of a failure to make use of best practice technology, but this may be due to rapid technical progress and the existence of fixed capital and other adjustment costs.

Price inefficiency within an industry, will vary over time as relative input prices change as a result of technical progress throughout the economy. The existence of price inefficiency within an industry may therefore be indicative of failure to make adaptive changes as described in section 2.2. Failure to recognize the potential for adaptive change will lead to a misallocation of investment funds between the various sectors of the economy. This will manifest itself both in lack of investment in some sectors and in premature obsolescence in others. Overall, the increase in productivity will be reduced. We may term this loss adaptive inefficiency, which may be measured by the extent to which productivity would have been increased by following an optimal investment strategy (supervised with perfect foresight by an ideal observer!) using world best practice technology.

Soete and Turner (1984) have devised as a dual measure of technical change the improvement in average rate of profit in the economy, all other prices held constant. An improvement in rate of profit comes either from improvements within each process in use or from increased efficiency as firms move from low to high profit processes. This is more general than Nishimizu and Page's formulation which only considers one best practice technique in the industry. Their approach is discussed more fully in chapter 3.

2.5 The Measurement of Technical Progress

Economic growth can occur because of a quantitative change in the volume of inputs. Such economic growth is said to be explained. Economic growth may occur in excess of that explained by the volume of inputs. This residual growth is assumed to be the result of technical progress. The problem of measuring technical progress is thus resolved into one of accurately defining and measuring this residual[1].

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[1] Product innovations do not fit easily into this definition of progress. To some extent it is possible to consider new products as providing a new combination of basic product characteristics, thereby resolving them into process innovations.

From our definition of technical progress and our discussion so far we observe that progress has two manifestations; it allows more output to be attained from the same input and it results in higher real factor incomes. Measures deriving from these are termed primal and dual measures respectively. Our most important measure will be the rate of improvement in total factor productivity, which (abstracting from quality changes) is the rate of growth in value of output minus the rate of growth in the value of inputs. Inputs may be placed in three categories; flow inputs, capital inputs and (non-produced) primary inputs. This allows us to formulate alternative conceptions of productivity improvements on which to base measurement, following Rymes (1971) and Peterson (1979).

The 'neo-classical' conception treats capital as a primary input, with the capital stock given exogenously. In the case where there are no flow inputs productivity changes are then measured by changes in

$$P'Y/(W'L + r'K)$$

where Y is net output, L is non-produced inputs, K is capital inputs and P,W,r are the respective price vectors. The neo-classical view seems most appropriate to a short run analysis. In the long run capital is obviously a produced input, and productivity improvements will occur in the capital goods producing sectors. The 'Harrodian' conception of productivity change measures changes in

$$(P'Y - r'K)/W'L.$$

In this section we examine various different methods of measuring the rate of technical progress. Early approaches considered aggregate output and aggregate inputs linked via an aggregate production function. The work of Solow (1957) described below is an illustration of such a study, in which the residual is the difference between the growth rate of aggregate output and a weighted average of the inputs.

Studies of the Solow type suffer from a number of problems. First it is necessary to specifically consider the problems of aggregation and of measurement of inputs. Second we need to consider, via the theory of optimum production, the relationship between inputs and outputs and hence the precise definition of the residual. We will consider the work of Domar (1961) and Jorgenson and Grilliches (1967) and thereby come to consider the problems of measurement of total factor productivity both for the economy as a whole and for each sector. We also consider measures of technical progress which focus explicitly on real factor incomes.

In the context of a particular production process, technical progress will manifest itself as a change in the technical coefficients of production. We can construct an index of such changes, for each firm, industry and the economy as a whole. This index of structural change will give us another measure of technical change.

Finally in this section we will see that changes in Total Factor Productivity, real wages and the index of structural change are equivalent in the context of an Input Output model.

2.5.1 The Aggregate Production Function Approach

We describe briefly here the work of Solow (1957) for the purpose of contrast with later studies. We define the aggregate production function for the economy as

$$Q = F(K,L,t).$$

This function is assumed to exist and is not justified "by calling on fancy theorems on aggregation and index numbers" (Solow op cit p315). All inputs and output are measured in physical units.

Technical change is defined as any kind of shift in the production function. If we confine ourselves to the case where technical change leaves all rates of marginal substitution unchanged, that is it is Hicks neutral (as defined in the next section), then the production function can be written in the form

$$Q = A(t).f(K,L).$$

Differentiating this totally with respect to time and dividing by Q we find

$$\frac{\dot{Q}}{Q} = \frac{\dot{A}}{A} + A\frac{df\ \dot{L}}{dL\ Q} + A\frac{df\ \dot{K}}{dK\ Q}$$

The relative share of labour in total output is $W_L = dQ/dL.L/Q$ if labour is paid its marginal product, and similarly for capital $r_K = dQ/dK.K/Q$. We obtain therefore

$$\frac{\dot{A}}{A} = \frac{\dot{Q}}{Q} + W_L \frac{\dot{L}}{L} + r_K \frac{\dot{K}}{K}$$

If the production function is linear homogeneous then $W_L + r_K = 1$. The rate of technical progress is then the rate of growth of output minus the weighted average of the rate of growth of inputs.

So far we have considered only aggregates of output, labour and capital, explicitly ignoring index number problems arising from heterogeneous output, labour and capital. We now want to consider these problems. In particular, as Domar (1961) discusses, the size of the residual should be invariant to the process of aggregation and integration.

With Solow's method and a linear homogeneous production function, the measure of technical progress $\dot{A}/A$, takes an arithmetic mean of input changes and subtracts this from output changes. If the production function has the Cobb-Douglas form

$$Q = A L^a K^b$$

and is linear homogeneous ($a + b = 1$), then output is the value weighted geometric mean of L and K. We can see that

$$A = Q / L^a . K^b$$

The shift parameter A(t) of the production function is the ratio of Q to the geometric mean of inputs. If 'conventional' index numbers such as GNP are used to construct Q, K and L then these aggregates will in essence be arithmetic means of inputs. This lack of uniformity in the method can lead to errors in the measurement of the residual (though to some extent the errors may cancel each other out).

Domar shows that the residual will be invarient to the process of aggregation if the residuals calculated for each sector are weighted by the ratio of that sector's value of product final to it, divided by the value of final product for the whole economy. A similar principle applies to aggregation of industries within an industrial sector. Thus in general all weights should be in share of value terms, resulting in Divisia indices. Rather than Solow's aggregate approach, it will be preferable to consider the rate of technical progress for each firm and industrial sector separately and then aggregate these. This is the approach used in our computer simulation. Within each industry we would ideally prefer geometric averages of inputs, but if arithmetic means must be used, the problems are likely to be less than for following such a procedure for the economy as a whole. The weights used to aggregate inputs should be W_L and r_K in the example described.

2.5.2 Total Factor Productivity (TFP)

Measurement of TFP is based on the theory of optimal production in the context of the linear homogeneous production function, ie. that factor inputs are chosen at the point of tangency between the isoquant and budget line, and that factors are paid their marginal products. Using data on both price and quantity of inputs and outputs we can separate movements along the production function from shifts of the function. The latter constitute changes in TFP. The rate of growth of TFP, $\dot{T}/T$, is the rate of growth of real product minus the rate of growth of real factor inputs.

Defining P' as a row vector of final output prices and C as a column vector of net outputs, W' as a row vector of input prices and V a column vector of inputs, then under optimum conditions of production

$$P'C = W'V$$

Differentiating this equation totally with respect to time we find, (where $\hat{X}$ is a diagonal matrix of the vector X):

$$(P'C)^{-1}.P'\hat{C}(d\log C + d\log P) = (W'V)^{-1}.W'\hat{V}(d\log V + d\log W)$$

Defining a' and b' as the value weights for outputs and inputs and T as the ratio of outputs to inputs:

$$P'\hat{C} / P'C = a' \qquad W'\hat{V} / W'V = b' \qquad T = P'C / W'V$$

we find $\dot{T}/T$ as the overall rate of increase in total factor productivity for the economy as follows:

$$\dot{T}/T = a'd\log C - b'd\log V = -(a'd\log P - b'd\log W)$$

We notice that because inputs are related to outputs via the production function and factors are paid their marginal products, shifts in the production function can equally be measured by shifts in the factor price frontier. Also because growth in outputs and inputs are measured as Divisia indices, the index $\dot{T}/T$ will remain zero unless an actual shift in the production function occurs.

Various studies, eg. Richter (1966), Hulten (1978), Jorgenson and Grilliches (1967), have shown that if we define technical progress as the increase in output, prices and inputs constant, then a Divisia index of inputs is an appropriate measure of inputs. The same applies to outputs in the case of more than one output. There are two problems in using this index. First, as Usher (1980) describes, we may get biased measurement of input changes unless the shift in isoquants, due to technical progress, is as if we move over time through a homothetic set of unit isoquants (eg. if progress were Hicks neutral). The Divisia index locates an isoquant as the point of tangency with the budget line, and then 'treats' that isoquant as if it were linear, that is as if there is perfect substitutability between inputs. When for a firm, its production processes are specified by points in the input space, marginal products are indeterminate (within certain limits) for each process, so that unless the new process chosen has the same input proportions as the old, we may have bias in our measure of inputs. Usher shows that if the conditions on the isoquants do not hold, it is possible for the Divisia index to remain unchanged even when the isoquant (and prices and quantities of inputs) have changed. He shows that we should use base period marginal products for calculating weights to allow for the fact that input combinations along our (Divisia) linear isoquant were not available in the base period but are 'assumed' by the index to have been available. Failure to allow for this results in over estimation of inputs and consequent under estimation of technical progress. These issues are taken into account in our computer simulation, when production processes are identified as points in the input space, and technical progress changes input proportions (see subroutine TFP in the appendix).

Second we have the problem of measuring input prices themselves. In the economy as a whole, capital plays a dual role as an output and as an input. The output (stock) price of a unit of a capital good is just the production cost of the machine in our perfectly competitive model. The price of the flow of capital services is more difficult to determine. If the firm takes r as exogenous, then z_i^0, the rental cost of a new machine, whose purchase price is p_i^0 is given by

$$z_i^0 = (rp_i^0 + d_i p_i^0 - \dot{p}_i^0)$$

where d_i is the fraction of physical deterioration in the machine. Hall (1968) describes how the price of an old machine, of age t, can be found for the special case in which there is a general rent for a capital good independent of its vintage. (If capital goods of a particular type produce the same basic service, but appropriate to use in different factor proportions the requirements for this special case are met). This requirement is equivalent to assuming that the ratio of marginal products of different vintages is independent of the amount of labour, and this also means that we can find an aggregate measure of the capital stock for each type of capital.

If firms buy and sell machines to maximise the present value of the firm's assets, and if the present value of a machine in the future tends to zero the further forward we look (ie. there is no speculation in old machines) then Hall finds that:

the price of a machine vintage t.	=	price of a new machine * fraction of the services, M(t), provided by an old one given technical change, wear and tear.	-	an adjustment to take account of the fact that old machines require more replacement expenditure, in turn dependent on future prices, technology and reliability.

Hall shows that if both deterioration and technical change are exponential, then the adjustment term is zero. Assuming this to be the case, the rental price of a machine of vintage t is

$$z_i(t) = rP_i^0 \; M(t) + d_i P_i^0 \; M(t) - \dot{P}_i^0 \; M(t) = M(t)z_i^0$$

We can now use z_i as the prices in constructing our Divisia index. Dropping the superscripts and defining the vector a_j as the capital coefficients in production of good j, we have KI_j as the index of capital used in production, and ZI_j as the price index for capital used in production of good j, as follows:

$$KI_j = (\overline{za_j}'K/(z'a_j) \quad \text{and} \quad ZI_j = z'a_j/\Sigma a_j$$

It may be noted that all the problems of constructing prices for old capital can be avoided if we adopt a Von Neumann type of technology, as described in the next chapter, in which capital is completely used up in production and one period older capital is produced as an output. Which approach we take depends on the degree of aggregation needed.

$\dot{T}/T$ is the rate of increase for the whole economy. We can also consider each sector in turn. Whilst for the economy as a whole all inputs must be primary (non-produced) in the final analysis, this will not be true for individual sectors. Thus for sector h, where Q_h is gross output and $\dot{t}_h/t_h$ the rate of change in TFP, we have:

$$P_h Q_h = \Sigma_i P_i Q_{ih} + \Sigma_i W_i V_{ih}$$

$$\frac{\dot{t}_h}{t_h} = d\log Q_h - \frac{\Sigma_i PP_i Q_{ih} d\log Q_{ih}}{P_h Q_h} - \frac{\Sigma_j W_j V_j d\log V_j}{P_h Q_h}$$

For any one sector we have not really distinguished produced and non-produced inputs. This distinction becomes important when we come to aggregate the sectoral rates of TFP change, since in the aggregation we need to take account of the fact that improvements in all sectors will influence $\dot{t}_h/t_h$. Domar (1961) and Peterson (1979) show that the rule for aggregation is again that each sector should be weighted by the ratio of total gross output to final demand to obtain

$$\frac{\dot{t}_h^*}{t_h} = \frac{Q_h}{C_h} \frac{\dot{t}_h}{t_h}$$

This new index can then be aggregated using final demand weights

$$\frac{\dot{T}}{T} = \frac{\Sigma P_h C_h}{P'C} \frac{\dot{t}_h^*}{t_h}$$

The adjustment of the sectoral indices is needed because some sectors may supply little to final demand, but through their contribution to intermediate outputs, contribute greatly to overall TFP improvements. This weight clearly requires all sectors to produce a positive net output. It is justified since if the original indices $\dot{t}_h/t_h$ were combined using final demand weights the contribution of industries producing mainly intermediate goods will be underestimated, because the indirect benefits of the increase to consumers will be ignored. Effectively the weight allows sectoral rates to be aggregated according to the contribution to gross rather than net output. Steedman (1983b) shows that this weighting system will understate the importance of sectoral advance where there is a lag between the purchase of an input and the production of the output, ie. where interest charges are accrued. In this case the appropriate weights are the ratios of gross output (at which progress is being measured) to the wage bill for each sector, which is clearly less than the contribution to the national income when interest rates are positive. This point is more fully illustrated in section 3.4 of the next chapter, in the context of the model developed there. Steedman also notes that any measure of progress is dependent on the standard of value (bundle of goods) involved in the measurement of output. If technical progress occurs in a sector which is not required to produce our standard of value its effect on measured productivity increase will be zero.

2.5.3 Real Wage Measures

Whilst total factor productivity considers the contribution of all inputs to output growth, we saw above that in aggregating $\dot{t}_k/t_k$ it was necessary to take into account the technological changes in producing produced inputs. Another approach therefore to the measurement of technical change is to consider explicitly the productivity of non-produced inputs. To illustrate this, assume that labour is the only such input, and its real wage, W, is the amount of output, Y, paid per unit of labour. Calling the matrix[2] of outputs B, the matrix

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[2] This allows for joint production.

of produced inputs A and the vector of labour coefficients a, the system of labour commanded prices is given by

$$P'B = a + (1 + r)P'A$$

and hence $P' = a(B - (1+r)A)^{-1}$

P' thus represents the direct and indirect labour requirements for unit output. Thus for wages paid as commodity bundle Y, the real wage of each worker is $W = (P'Y)^{-1}$. Differentiating this totally with respect to time and dividing by W we obtain as a measure of aggregate technical progress:

$$\frac{\dot{W}}{W} = \frac{[P'\dot{B} - \dot{a} - (1+r)P'\dot{A}][B - (1+r)A]^{-1}Y}{P'Y}$$

and hence $\dot{W}/W = -\dot{P}'Y/P'Y$ for constant r. That is to produce a given commodity bundle Y, which corresponds to the "Golden Rule" activity vector, requires less labour as productivity increases, and hence $\dot{P} < 0$ or (equally) output per worker increases $\dot{W} > 0$.

Just as with TFP we need to consider how each sector's productivity improvements contribute to the overall improvement. Analogously to TFP, we define the improvement in sector h as $\dot{s}_h/s_h$,

$$\frac{\dot{s}_h}{s_h} = \frac{P'\dot{B}_h - \dot{a}_h - (1+r)P\dot{A}_h}{P'B_h}$$

that is the change in the value of outputs minus the change in the value of inputs, (all values in labour commanded prices), where $\dot{B}_h$, $\dot{A}_h$ and $\dot{a}_h$ are column vectors of changes in outputs and inputs. From this definition and writing $(\hat{\dot{s}}_h/s_h)$ as a diagonal matrix of the $\dot{s}_h/s_h$ we find

$$\frac{\dot{W}}{W} = \frac{P'B}{P'Y}\frac{\hat{\dot{s}}_h}{s_h}[B - (1+r)A]^{-1}Y \qquad (2.1)$$

Just as with the measure $\dot{T}/T$, aggregating sectoral rates only by weights of final demands will seriously understate the overall rate of progress. The reason is again that we need to take into account improvements in productivity in producing produced inputs. Steedman (op cit) illustrates how ignoring the $(1+r)A$ term in equation 2.1 can easily result in an underestimation of six times in the rate of overall real wage increase.

In the above we have considered the output from each separate industrial sector. However not all sectors need produce for final demand. Also since all sectors have used some produced input, whilst we are interested in the contribution of non-produced inputs, we might usefully take the sectoral improvements for vertically integrated sectors. We define H a matrix of direct and indirect produced inputs, and l' a vector of direct and indirect labour inputs and as follows:

$$H = A(B - A)^{-1}$$

$$l' = a'(B - A)^{-1}$$

Thus $$P' = l' + rP'H$$

Define the sectoral rate of progress (with $\dot{r} = 0$) $\dot{N}_h/N_h$, as the reduction in labour input to produce unit net output for the sector.

$$\frac{\dot{N}_h}{N_h} = \frac{-(\dot{l}_h + rP'\dot{H}_h)}{p_h}$$

If $\hat{N}$ is a diagonal matrix of the N_h then we can show that

$$\frac{\dot{W}}{W} = P'\frac{\hat{\dot{N}}}{N}\,\frac{[I - r\dot{H}]^{-1}Y}{P'Y}$$

If r = 0, $\dot{W}/W$ is just the final demand weighted average of the $\dot{N}_h/N_h$. If $r > 0$, ie inputs purchased at t-1, to produce outputs at t become more expensive, then improvements in any sector count more heavily, $d(\dot{W}/W)/dr > 0$.

Finally, we can consider the relationship between $(\hat{\dot{N}}/N)$ and $(\hat{\dot{S}}/S)$. Steedman shows that

$$P'(\hat{\dot{N}}/N) = P'B(\hat{\dot{S}}/S)(B-A)^{-1} \qquad (2.2)$$

That is the value weighted average of vertically integrated sectoral rates is equal to the value weighted average of the sectoral rates if these are first weighted by the ratios of gross to net output, $(B - A)^{-1}I$ for each user of a commodity.

Allowing only real wage change is clearly only one way of looking at the improvement in factor incomes. We can also examine changes in the rate of profit at constant real wage, or other, intermediate, combinations. One such alternative, the change in the rate of profit, is postponed until section 3.4 of the next chapter, where it is developed as one part of a more general analysis of investment and efficiency.

2.5.4 Leontief's Index of Structural Change

We have seen that technical change is manifested by a shift in the production function. One method of considering the parameters of the production function, at an instant of time, is the observed square matrix of input output coefficients, **A**, whose columns represent the inputs required to produce a unit of gross output in the static input output model. Since technological change is a continuous process, with new commodities introduced and production techniques changing, the matrix at time t+1, A_{t+1} will have evolved gradually from the previous one, A^t. Thus by measuring the coefficients in the matrix $(A^{t+1} - A^t)$ we have a method of measuring the rate of technical change. Similarly, if l is a vector of labour coefficients , the change in l represents technical change.

In the input output system Q = AQ + C where Q is gross output and C net output, an index of relative change for each coefficient is

$$\overline{a}_{ih} = 2\,\frac{a_{ih}^{t+1} - a_{ih}^{t}}{a_{ih}^{t+1} + a_{ih}^{t}}$$

its average value over the two periods. This average is valid, since Domar (1961) shows that the choice of base period is unimportant, and averaging avoids any problems if either coefficient is measured as zero.

In addition to produced inputs AQ, there will be non-produced inputs l at price W. These will also change as a result of technical change and we define $\overline{l_{ih}}$ as the relative change.

To obtain the sectoral index of change we need to aggregate the inputs, using the relative value of each input as weights.

Since there are no capital stocks in this model, the price system is given by

$$P' = P'A + W'l$$

Thus the sectoral rate of improvement is

$$\overline{a_h} = -(1/P_h)\{\Sigma_i P_i \overline{a_{ih}} + \Sigma_i W_i \overline{l_{ih}}\}$$

The minus sign is introduced to aid interpretation, since in the presence of technical progress on average inputs will decrease. $\overline{a_h}$ measures the change in inputs required to produce a unit of output of good h.

Leontief suggests that to aggregate the $\overline{a_h}$ to give $\overline{a_L}$ for the whole economy, we merely weight the $\overline{a_h}$ by the ratio of final demand for each good to total final demand. However doing this creates the same problems as before, since in measuring $\overline{a_h}$ produced and non-produced inputs are not distinguished. Thus to obtain an aggregate which is invarient to the method of aggregation and which accurately measures the change in inputs we need to weight each $\overline{a_h}$ by the ratio of gross to net output for that industry, to obtain $\bar{\bar{a}}$. Since Q > C the following are true:

$$\overline{a_L} = (1/P'C)(\Sigma_h P_h C_h \overline{a_h})$$

$$\bar{\bar{a}} = (1/P'C)(\Sigma_h P_h Q_h \overline{a_h})$$

Since Q > C $\bar{\bar{a}} > \overline{a^L}$. The continuous analogue of $\overline{a_h}$ is

$$\dot{a}_h / a_h = -(1/P_h)(\Sigma_i P_i \, d\log a_{ih} + \Sigma_j W_j \, d\log l_{jh})$$

2.5.5 Comparison of the Measures in the Context of the Static Input Output Model

Above we have considered three measures of technical progress, each derived from a different aspect of production theory. TFP is derived from the theory of optimum production, real wage changes from the identity of prices with non-produced input requirements and the index of structural change from a descriptive analysis of input output tables. We will now demonstrate that these three measures, different approaches to the same problem, have the same numerical value in the case of the static input output model, where there are no capital inputs.

Consider first the sectoral rates of change. For TFP

$$\frac{\dot{t}_h}{t_h} = d\log Q_h - \frac{(\Sigma P_i Q_{ih}\ d\log Q_{ih})}{P_h{}'Q_h} - \frac{(\Sigma W_j v_j\ d\log v_{jh})}{P_h{}'Q_h}$$

In an input output system

$$d\log Q_{ih} = d\log a_{ih} + d\log Q_h$$

$$d\log V_{jh} = d\log l_{jh} + d\log Q_h$$

Hence: $$\frac{\dot{t}_h}{t_h} = \frac{-(\Sigma_i P_i Q_{ih} d\log a_{ih} + \Sigma_j W_j Q_{jh} d\log l_{jh})}{P_h Q_h}.$$

Since we are considering the production of unit output we find:

$$\frac{\dot{t}_h}{t_h} = \frac{1}{P_h}(\Sigma P_i d\log a_{ih} + \Sigma W_j d\log l_{ih})$$

ie. the Leontief index of structural change is equal to TFP.

For the real wage measure, we start from

$$P'B = a + (1+r)P'A$$

In the context of the input output model; B = I and r = 0. In this case the sectoral rate of change is

$$\frac{\dot{s}_h}{s_h} = \frac{P'\dot{B}_h - \dot{a}_h - (1+r)P'\dot{A}_h}{P'B_h} = \frac{n\dot{l}_h - P'\dot{A}_h}{P_h}$$

thus $$\frac{\dot{s}_h}{s_h} = \frac{-1}{P_h} \left(\Sigma h_j \ \dot{l}_{jh} + \Sigma P_i \ \dot{a}_{ih} \right)$$

Since in the above, the vector n plays the same role of weighting labour changes as W in the TFP equation, we see that:

$$\frac{\dot{s}_h}{s_h} = \frac{\dot{t}_h}{t_h} = \frac{\dot{a}_h}{a_h}$$

The equivalence of the measures vertically integrated sectors follows from this result.

2.6 The Bias of Technical Change

So far we have considered all technical changes as having the same basic quality of allowing the same output to be produced from less inputs. Technical progress may have the effect of making some or all inputs appear to be more productive, and in this case it is said to be factor augmenting. Typically however technical change will result in a changing mix of inputs and this leads to the categorisation of different types of change, according to its effect on input proportions. Sato and Ramachandran (1980) define progress to be neutral in some sense, if the relationship of two variables is unchanged through time. Thus many different possible categorisations exist. We can define bias and neutrality for any degree of aggregation, from the process level up to the whole economy.

We illustrate the most commonly used concepts of neutral progress by considering an economy or process with a single output, Q, and two inputs; capital K and labour L. Neutrality in a multisectoral economy is discussed in the next chapter.

(i) If the economy develops such that the capital-output ratio remains constant and if factor shares are not affected by the technological change, then the change is said to be Harrod neutral. It can be shown that Harrod neutral change is equivalent to progress which has the sole effect of augmenting the efficiency of labour, leaving capital efficiency unchanged.

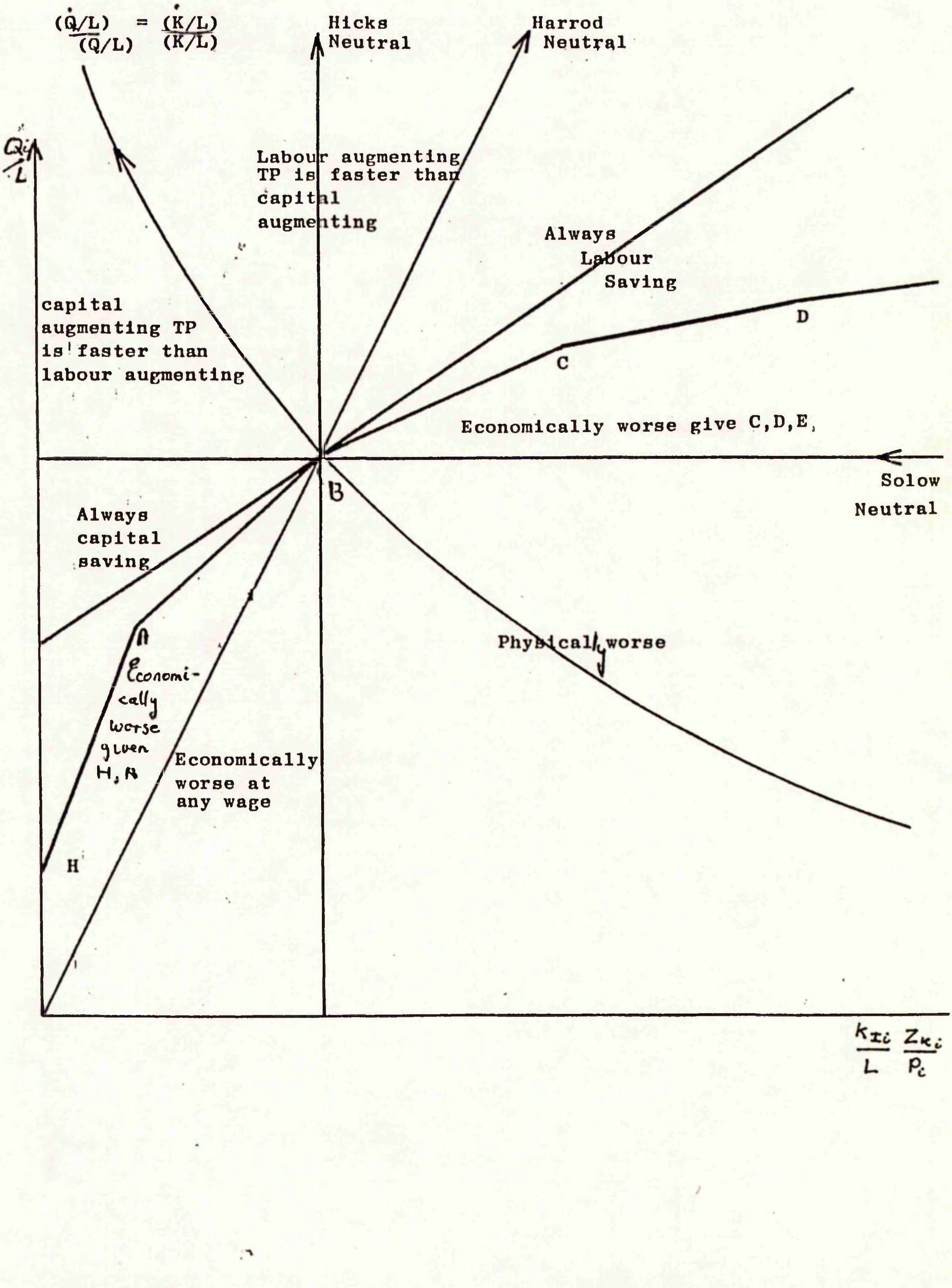
(ii) If the economy develops such that the labour-output ratio remains constant and if factor shares are not affected by the change, then the change is said to be Solow neutral. It can be shown that Solow neutral change is equivalent to solely capital augmenting technical progress.

(iii) If the economy develops such that the capital-labour ratio is constant and if factor shares are not affected by the change, then the change is said to be Hicks neutral. It can be shown that Hicks neutral change is equivalent to the efficiency of both capital and labour being increased at the same rate.

Relative to the chosen definition of neutrality, bias is defined as a falling share to one factor. This progress is labour saving if the relative share of labour is falling. In the type of economy discussed in later chapters, we consider firms using particular production processes, with fixed input coefficients, so that marginal products of the inputs are not uniquely defined. In this case bias will be measured ex-post. Figure 2.1 shows a firm using two inputs, K and L to produce output Q. There are five processes available H,A,B,C,D,E. At the ruling wage W (paid in terms of output), process B is in use. The diagram categorises the possible changes which may take place. The direction in which input coefficients must change for Harrod,Solow and Hicks neutrality are shown.

In a multisectoral economy, technical change will affect the relative importance of each sector, (in terms say of the labour they use), and the relative prices of the goods. We can most easily discuss this in the context of the models described in the next chapter, where this issue will be raised.

Figure 2.1



$\frac{(\dot{Q}/L)}{(Q/L)} = \frac{(\dot{K}/L)}{(K/L)}$
Hicks Neutral
Harrod Neutral
$\frac{\dot{Q}i}{L}$
Labour augmenting TP is faster than capital augmenting
Always Labour Saving
capital augmenting TP is faster than labour augmenting
D
C
Economically worse give C,D,E,
Solow Neutral
B
Always capital saving
A
Economically worse given H, A
Physically worse
Economically worse at any wage
H
$\frac{K_{Ii}}{L}$ $\frac{Z_{Ki}}{P_i}$

CHAPTER 3 A FRAMEWORK FOR ANALYSIS

3.1 Introduction

In chapter 2 we discussed, in general terms, the concept of technical change. The discussion was placed in the context of various models and analytical devices which have been developed to give structure to the issues and to more clearly analyse the consequences of change. Our intention to develop a synthesis of the micro economics of technical change at the level of the individual firm's decisions, with the sectoral and macro-economic performance of the economy will be usefully illuminated by a similar discussion of multisectoral models of economic growth. We thereby examine the industry in the context of a multisectoral economy. Additionally we will want to examine how technical progress can be incorporated into such models and how it can there be measured and described. It is the purpose of this chapter to discuss these issues.

Of the many approaches to modelling the time path of a multisectoral economy we consider four, which are all linear models and which illustrate well issues relevant to our objectives. Typically these models have been developed to analyse the progress of an economy along a balanced growth path, and within a given technological environment. We will evaluate the models as to their suitability for our purposes. We consider in particular the choice of production technique and its characteristics and how these change over time. Finally, we discuss one model in more depth, explicitly developing the consequences of technical progress and problems of measurement in a multisectoral model. The intention is to provide a structure for our simulation, rather than to examine the understanding the four models discussed give of the process of technical change.

3.2 Assumptions

As is usual in abstract discussions of economic growth, our four models will require a range of simplifying assumptions. To avoid undue repetition these are stated here and will be assumed to hold throughout this chapter unless stated otherwise.

We assume a free enterprise closed economy in which perfect competition exists in all markets. All economic agents therefore have perfect knowledge. Land is in plentiful supply and all rents are zero. The labour force is homogeneous and thus perfectly mobile. Consumers have constant tastes. Production takes place under conditions of constant returns to scale, and in discrete time periods of one week. The models do not incorporate a monetary sector and so all transactions are assumed to be by barter, though this does not inhibit trade, and all prices are accounting prices.

3.3 The Four Models

3.3.1 Bensusan-Butt

Of the models to be discussed, it is most appropriate to begin with this, since it is the only one of the four to take as its starting point an economy with zero capital stock, and hence to describe the complete path of economic growth. Bensusan-Butt (1960) begins his discussion with very rigourous assumptions which he then relaxes, and we follow this approach. As well as the assumptions made in section 3.2 we assume no population growth. Two types of good are produced; consumption goods which are produced and consumed within a single week and capital goods which are produced and installed within a single week and become productive the following week. There may be many types of consumption and capital good. There is no depreciation and capital is equally productive throughout its infinite life. Consumption goods may be produced by handicraft technique using labour alone, or by mechanical techniques using capital and labour. There are no intermediate inputs. Each technique has fixed input proportions. Capital is produced only by handicraft. We assume that machines are perfectly malleable at the start of each period and can thus be used to produce any consumption good.

We define the weekly wage as numeraire, so W = 1. A unit of any good is defined as the amount which can be produced by one man in a week using the handicraft technique. At the start of economic development there is no capital and so the price of each good is 1. At this time all incomes are just above subsistence and are equally distributed. Savings are zero at this level of income. An individual begins to save only when his income reaches some minimum level, and then saving increases as income increases. Savers must also receive some minimum return, but otherwise saving is perfectly interest inelastic. (Bensusan-Butt discusses several alternative motives and strategies for saving, but we need not go into these here).

To start the accumulation process we can suppose either some windfall appearing as manna from heaven, or a social process in which an unequal distribution of income appears (for example loans of income over subsistence) such that some individuals begin to invest. Saving equals investment, which will go to that technique which offers the best return. In producing good i, technique ij combines R_{ij} units of capital with one man week of labour to produce O_{ij} units of good i. The use unit value worth of capital increases the productivity of its labour by an amount S_{ij}, which we call the physical productivity of capital.

$$S_{ij} = \frac{(O_{ij} - 1)}{R_{ij}}$$

We can rank all techniques by their physical productivity. For ease of exposition we number techniques so that technique j has a higher productivity of capital than technique j+1, and number goods according to their initial productivity of capital so that $S_{i1} > S_{i+1,1}$. For each good we call handicraft technique 0.

Industrialisation thus begins with technique (1,1). This will happen so long as S_{11} is greater than the rate of interest which borrowers who merely wish to increase their current consumption are willing to pay. We assume that this is the case. As industrialisation of sector 1 takes place, labour will be released to go into production of those commodities (including capital) which are in demand at the new income distribution. The growth of each sector will be dependent therefore on its income elasticity of demand. So long as sector 1 is only partly industrialised, the price of good 1, P_1 will remain at 1, as will all other prices. Consequently, all the benefits of early industrialisation accrue to capitalists.

Eventually industrialisation of sector 1 will be complete. Assuming that further savings continue, there are now three possibilities; either sector 1 re-equips with a more capital intensive technique, or sector 2 begins industrialisation or investment only in technique (1,1) continues. Initially it will be the latter, since the return to investment in technique (1,1) is still S_{11}. However this expansion of capacity will eventually result in a falling price for good 1, all other prices remaining unitary. The return to capital in sector 1 is now $\frac{(P_1 O_{11} - 1)}{R_{11}}$ which is less than S_{11}. Eventually this return will fall to either S_{12} or S_{21} and a new phase of re-equipment or industrialisation begins. There is no way in which we can tell, a priori, which of these two alternatives will occur first, and it is possible that some sectors may go through a series of industrial techniques before others even begin industrialisation.

Figure 3.1

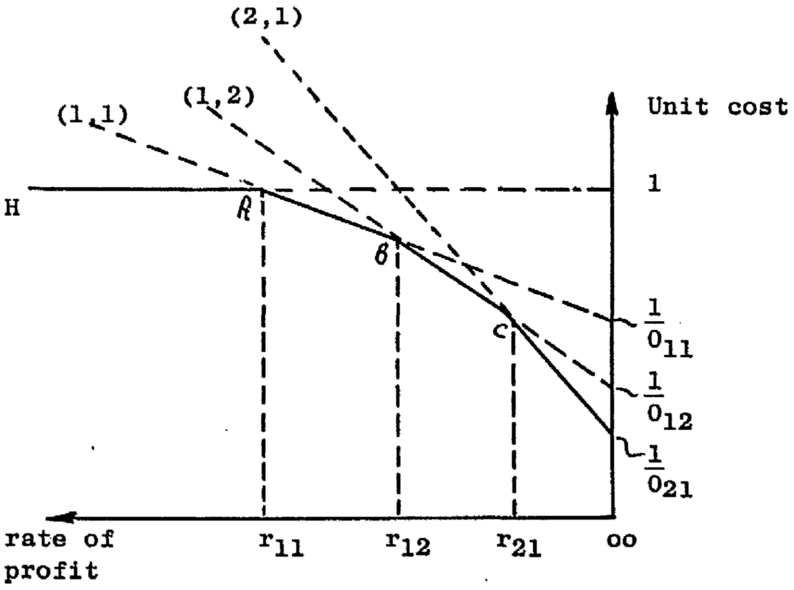


Figure 3.2

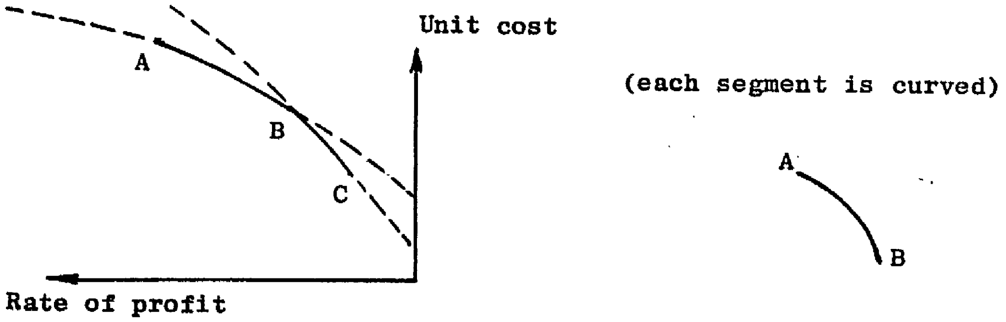
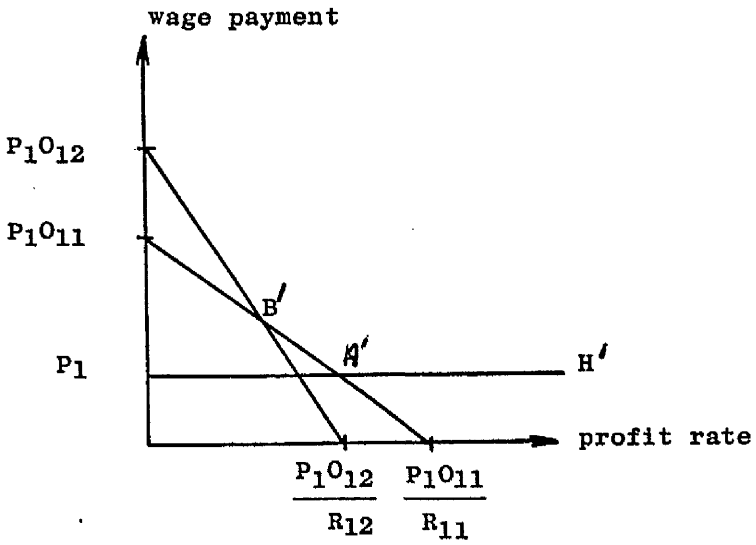


Figure 3.3



We can illustrate the phases of industrialisation with a simple diagram, figure 3.1. Initially we have a handicraft technique shown by HA. Once technique (1,1) is introduced it gives return r_{11}. It stays at this point until industrialisation is complete and then falls over time until r_{12} is reached. At this point we stay at r_{12} whilst re-equipment of sector 1 is completed. Technique (1,2) is more capital intensive than (1,1), as shown by the slope of BC being greater than the slope of AB, whilst its output per man is greater as given by the intercepts on the vertical axis. As industry 1 is re-equipping, we can consider the return accruing to the extra investment ie. $r_{12} = \frac{(O_{12} - O_{12})}{R_{12} - R_{12}}.$

Capital intensity remains constant along AB until the marginal product of capital becomes equal to the rate of profit. Once this happens capital deepening can begin.

We have envisaged each technique with a constant capital to output ratio, however it is fairly easy to incorporate increasing mechanisation within each technique, so that our line looks like figure 3.2

Once re-equipment of sector 1 is complete, then from figure 3.1, further expansion will take place, P_1 will fall and with it the rate of profit until eventually r_{21} is reached, when industrialisation of sector 2 begins. This process will continue, and industrialisation and capital deepening will spread through the economy so long as savings are positive.

Falling prices result in rising real wages, so that savings will begin to come not only from capitalists, but also now from the wage earners. So long as the rate of profit does not fall below some minimum level, or savings fall to zero, the economy will grow.

Before moving on it is useful to consider figure 3.1 from a different perspective. For any technique (i,j), unit cost is given by $(R_{ij} + 1)/O_{ij} = P_i$. For any given value of wage payments from production, there will be a corresponding rate of return which can be achieved with each technique. Figure 3.3 illustrates the three techniques for good 1. For any given real wage ruling in the economy, each technique offers a corresponding return. The technique chosen is that which offers the highest return. We will see that H'A'B' corresponds to the wage curve in the Hicks model described in the next section with good 1 as the only consumption good.

The frontier is linear for each technique because so far we have assumed that all capital is produced only by handicraft methods. Relaxing this assumption is clearly a major step towards realism in our model. Bensusan-Butt approaches this by introducing a new type of industry, a machine tools sector. Initially we assume that machine tools are only made by handicraft techniques, and that machine tools provide an array of techniques through which capital can be manufactured (in the engineering industry).

Beginning again from our starting point of no capital equipment in the economy, initially investment will proceed as before, since due to lack of demand for machines engineering will not be the first sector to industrialise. At some stage mechanisation of engineering will begin, and subsequently will be completed. It is only at this stage, when the price of capital falls below 1 that the story differs from our previous one. The fall in the price of capital will increase the return to capital, both for newly industrialising sectors and for those sectors considering re-equipping with a more capital intensive technique. The result will thus be more capital intensive production. This is also a basic illustration of the potential for induced innovation in this model. If we give the subscript C to the capital good and call the rate of interest r, we find

$$P_i = \frac{1 + R_{ij} P_c . r}{O_{ij}} = \frac{1}{O_{ij}} + \frac{R_{ij} . r}{O_{ij} O_c} + \frac{R_{ij} R_c r^2}{O_{ij} O_c} \qquad (3.1)$$

This function is nonlinear in r, although the exact shape of the wage curve depends on the coefficients. If we make the machine tools industry into a manufacturing one then a similar extension of the analysis can be applied. We do not pursue this, except to point out the alternative assumptions. One possibility is to have the machine tool sector reliant on another sector which is a handicraft. In this case the expression for P_i will have a similar form to equation 3.1 but will include r^3. A more realistic assumption is to allow machine tools to use machine tools and capital in their manufacture. This approach is much more appropriate to our purposes and is taken up when we discuss the Hicks model.

Once we have a falling price of capital in an economy with many investment opportunities, an important problem arises with the Bensusan-Butt model as it currently stands. If we assume each sector has an infinite number of possible techniques then, assuming free entry and perfect knowledge, each industry should have the same rate of profit. (With a finite number of techniques profit rates may differ slightly for short periods). Since capital lasts for many periods, these equal returns across sectors should persist throughout the lifetime of capital, ie the net present value of any investment project should be the same. Whilst in any one period it is possible for this to happen, when we come to the next period, with a lower price of capital then cheaper investments will be earning the same rents. Relying on the assumption of malleable capital to overcome this difficulty is no solution, since it is the physical quantity of old capital (in whatever form) that would have to increase to compensate for the price fall. The only ways out of the problem are to assume 100% depreciation of capital each period, not really a solution, or to abandon the assumption of perfect foresight. Bensusan-Butt discusses in some detail various strategies for this and for depreciation. We need only note the impossibility of perfect foresight and consequently the need for bounded rationality, or a limited time horizon in decision making.

Incorporating technical progress into the Bensusan-Butt model.

Since, as we have seen, economic progress moves the economy through a series of techniques, there is in principle no real problem in introducing technical progress into the model. Technical progress results in a wider body of knowledge which presents itself in economic terms as new innovations. Technical progress in the model is the introduction of new superior techniques. Whether or not the capital goods industry is mechanised, we can reduce improvements in technology to improvements in labour productivity, as described in the previous chapter. In the context of figure 3.3, at some real wage a superior technique will provide a frontier to the right of the existing frontier. In the model described above, capital was assumed to be malleable and infinitely durable. One consequence of this was that as the capital stock grew via continued savings, the rate of interest will fall in a series of steps. If we retain these assumptions about the capital stock, then technical progress will result in new techniques offering higher returns, and so the rate of profit may rise if current savings are not sufficient. However, should this happen, our malleable capital will leave the least profitable processes. This is an unacceptable feature, and we see therefore that a realistic treatment of technical progress requires at least some aspects of technology to be embodied in the capital stock. If the change is not fully expected then capital may need to be revalued as described above. Thus again a bounded decision process is required.

Once we have introduced embodied technical change, then installed capital has become specific to its particular role. If we assume that capital is of the putty-clay type then it is still only necessary to have a single capital good produced for each role. If we develop a model with three basic sectors; machine tools, capital and consumption, we can include all the main features of the model. In effect we just have two distinct types of capital.

In Bensusan-Butt's basic model, the limitation on re-equipping an industry or industrialisation is just the supply of capital. Two techniques can coexist in an industry only for a limited period, during which price is constant. If we now introduce embodied technical progress, old techniques will persist only so long as they earn a non-zero quasi-rent. Embodiment of technology in capital has introduced adjustment costs into the model, and may result in a variety of vintages coexisting. A more refined treatment of adjustment costs can be introduced in a similar way, introducing a non-homogeneous labour force specific to various types of capital, and also by allowing learning by doing.

One assumption which it was necessary to relax even with constant technology, was that of perfect knowledge. With technical progress uncertainty is further increased. One consequence of this is that our assumption of a perfect capital market, in which investment funds go to those projects offering the highest returns, looks less plausible. A firm's expansion may need to be more tied to its current profits, and new knowledge may earn a quasi rent. This is discussed again in the final section of this chapter, and is the approach adopted in our simulation model.

We have seen that the Bensusan-Butt model provides a framework with which analysis of technical progress can be undertaken. However a number of fairly fundamental changes, especially in the nature of the capital stock must be introduced. To consider these further we move on to our second model.

3.3.2 Hicks

Our starting point is the model of economic growth described by Hicks in section II of his "Capital and Growth". We will take the particular case of an economy with one consumption good and two capital goods. The two capital goods are combined with homogeneous labour to produce each of the three goods.

Each good may be produced by many different processes. Each process is characterised by fixed input coefficients, and so processes are distinguished by their differing factor proportions (as well, perhaps, as total factor productivity). Given the ruling wage each firm in an industry will choose that process which offers the highest return to capital. If capital is perfectly malleable and there are no other adjustment costs, all firms will choose the same process for producing each good. We assume this to be the case throughout this section, relaxing it in section 3.4.

It will prove useful for diagrammatic representation of the model to combine the capital goods input into a single index. Given our purpose of investigating technical progress, we construct a Divisia index, K_{Ii}, of the capital used in the production of good i, as described in chapter 2 section 2.5.2, with the proportions of total expenditure on capital inputs attributed to each capital input as weights. Since different processes may use the two capital goods in different proportions, we must select one process at which to measure the weights. We choose the process currently in use as the most practical and sensible. We will be able to construct a separate capital index for the production of each good and also for the economy as a whole using this principle. We also construct a price index ZI_i for capital services used to produce good i, in which the weights are the amounts of each capital good used in the selected process as discussed in the previous chapter.

Figure 3.4a

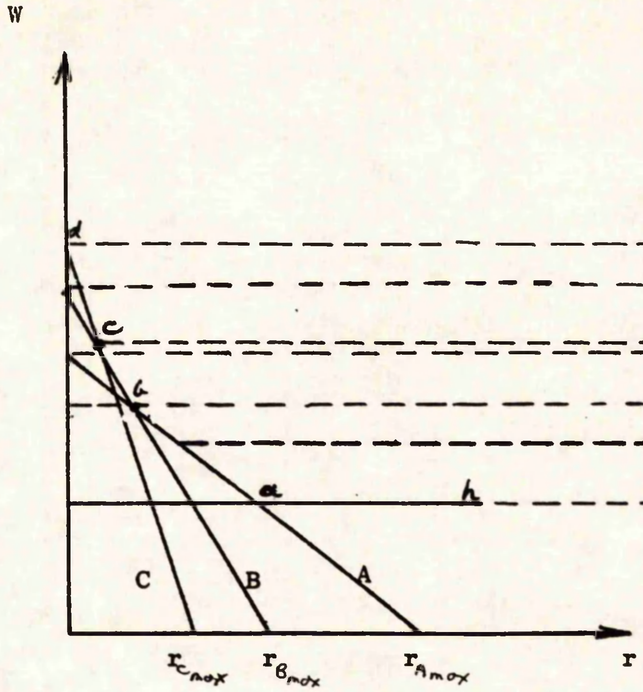
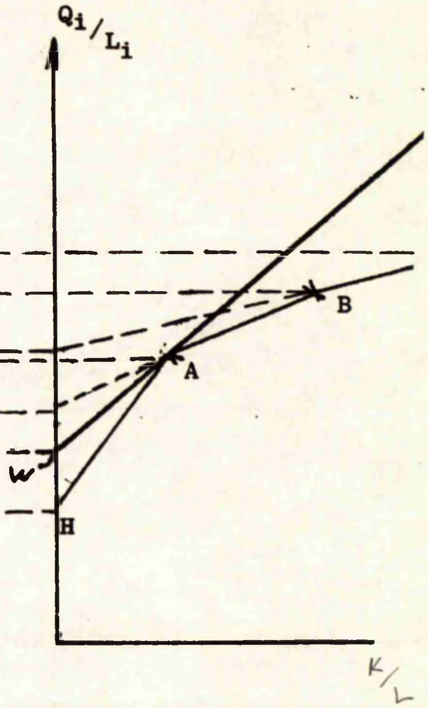


Figure 3.4b



The firm's choice of process can be considered either directly in terms of a factor price diagram or in terms of factor earnings. Figure 3.4 shows for good i, the choice between four processes, handicrafts (h) and three manufacturing processes, A,B,C. Figure 3.4a shows the rates of return each technique offers for any wage rate. The current overall frontier is given by the line h,a,b,c,d. The points a,b,c show the wage rates at which processes offer the same rate of profit, and hence where switching occurs.

Figure 3.4b shows the output per unit of labour for each unit of the index of capital inputs per unit of labour, multiplied by the ratio of capital input to final output prices. The points H,A,B,C represent the four processes. Any other processes which lie below the line H,A,B,C are dominated by these four and will never be chosen (see below), whilst all points above the line are currently unavailable. The set of points below H,A,B,C is necessarily convex.

We can measure the payments to each factor on the vertical axis of figure 3.4b. For a given price of the final product P_i, there will be an amount of good i which corresponds to the existing real wage, so that W represents the wage rate. Profits are then given by the remainder of output, so that for each process the rate of profit is given by the slope of the line to the intercept the wage rate. For each rate, one process will offer the highest rate of profit (A in the diagram). The intercepts of the lines AB, BC with the vertical axis show the real wage rates at which the two techniques offer the same rate of profit.

Relative prices and the composition of output. In the above linear case we have taken each good separately. We now turn to the general equilibrium system and in particular the dual systems of relative prices and relative outputs for the chosen processes. We call the consumption good good 0, and the two capital goods goods 1 and 2. We identify the production coefficients and prices as follows:

	consumption good	capital goods
capital coeffs	$a_0 = \begin{bmatrix} a_{01} \\ a_{02} \end{bmatrix}$	$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$
labour coeffs	b_0	$b = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$
prices	p_0	$P = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}$
output	x_0	$X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

labour supply = L   capital stock = $K = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}$

rate of interest = r   growth rate = g

<u>The set of equations 3.2a to 3.2i describe this model:</u>

$$p_0 = rP'a_0 + Wb_0 \qquad \text{(a)} \qquad\qquad P = rP'A + Wb' \qquad \text{(b)}$$

$$L = b_0 x0 + b'X \qquad \text{(c)} \qquad\qquad K = a_0 x_0 + AX \qquad \text{(d)}$$

$$X = gK \qquad \text{(e)}$$

<u>From which we derive:</u>

$$P' = Wb'(I - rA)^{-1} \qquad \text{(f)}$$

$$\overset{*}{p_0} = rWb(I - rA)^{-1} a_0 + Wb_0 \qquad \text{(g)}$$

$$K = (I - gA)^{-1} a_0 x_0 \qquad \text{(h)}$$

$$L^* = b'g(I - gA)^{-1} a_0 x_0 + b_0 x_0 \qquad \text{(i)}$$

For corn production the Divisia index of capital inputs and capital price index are given by

$$K_{I0} = \frac{\overline{Pa_0}\,'K}{P'a_0} \qquad\qquad ZI_0 = \frac{P'a_0}{\Sigma a_{0i}}$$

Using these two indices we can show the relationships between the consumption and capital goods sectors diagrammatically for the dual systems. Figure 3.5b shows the composition of outputs. For the current stock of capital K_{I0} the corresponding level of employment is L^*. Of this b_0x_0 is devoted directly to corn production and $(L^* - b_0x_0)$ to capital production, so that the balanced growth rate g can be maintained. Thus the composition of output depends on the growth rate, which in turn depends on savings behaviour. From figure 3.5a, we see that the equilibrium price of the consumption good depends on the amount of labour used (directly plus that used indirectly via the capital inputs) and on the roundaboutness of production through the rate of interest. Once either r or w is established all other prices follow.

Figure 3.5a

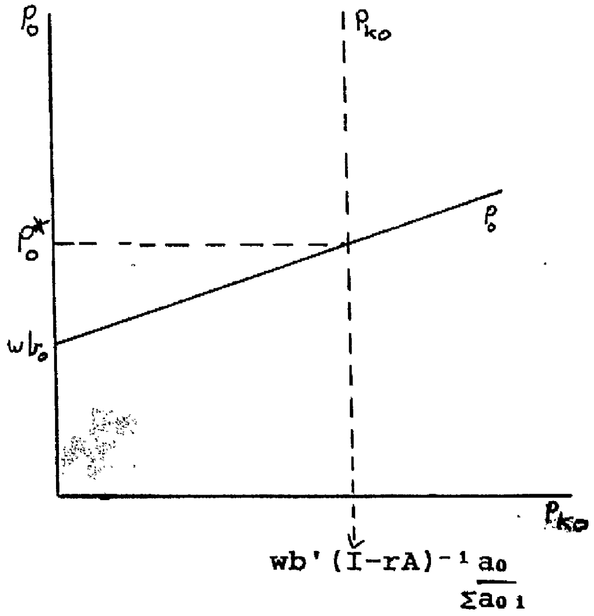
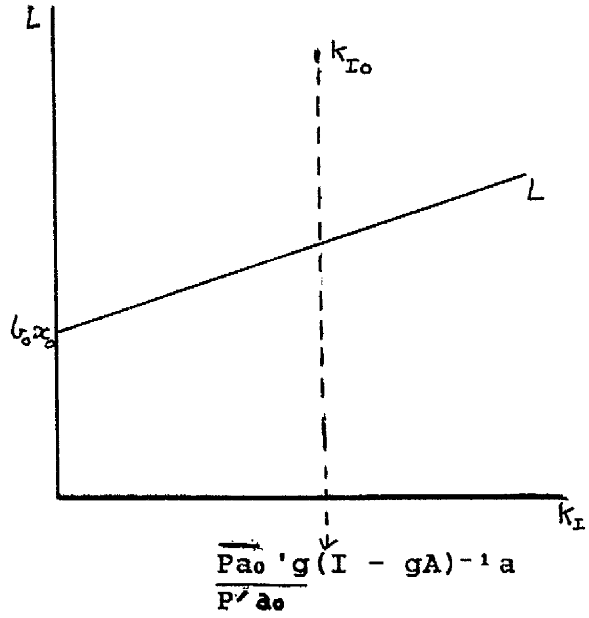


Figure 3.5b



Technical progress in the Hicks model. Hicks does not discuss in any depth how technical progress can be incorporated into this model. In so far as he does so, his concern is principally on whether change is neutral in some sense, which is not central to our concern.

For our purposes the wage curve is of more interest. Clearly new techniques will provide new facets on the wage curve, to the right of the old ones if they are economically relevant. Thus many of the points raised in regard to technical progress in the Bensusan-Butt model apply here. The most notable changes from that model are the introduction of the single composite consumption good, but the disaggregating of the capital stock. Given that our concern is induced innovation and the analysis of technical change, this seems a better approach. It also allows us to move more easily away from the need to have any handicraft sectors at all. We do however still have a need to distinguish vintages of capital, whilst a_0 and A represent only average coefficients across all vintages in use.

3.3.3 The Dynamic Leontief Model

This is an extension of the static model mentioned in the previous chapter, and provides a useful link back to that discussion. We distinguish n goods, each of which may be used in any of three ways; for consumption, as intermediate input or as capital input. Each good is produced by only one technique and there is no joint production. Inputs are required in fixed proportions, given by the n x n matrices, A for intermediate inputs, and B for capital inputs. Intermediate inputs are produced and completely used up within a single production period, whilst capital goods must have been produced in a period prior to their use and may last for more than one period. In this formulation, each type of capital good is homogeneous, and can be switched costlessly from one sector to another. Thus we have an overall constraint on production , where X is the activity vector and S the vector of capital stocks, given by:

$$BX(t) \leq S(t)$$

We also define D, a matrix of depreciation rates, C, a consumption vector, 1 a vector of labour requirements, W the wage rate and P the price vector, we can derive the balance and price equations 3.3.

$$X(t) = (A + D)X(t) + C(t) + B(X(t+1) - X(t)) \qquad 3.3a$$

$$P(t) = P(t)(A + D) + rP(t)B + (P(t+1) - P(t))B + W(t)l \qquad 3.3b$$

If labour is in perfectly elastic supply at the given wage rate and if consumption (saving) is a constant fraction of income then the economy is capable of balanced growth. With constant prices then we can rewrite equation 3.3b as wage payments being the remainder of the value of output not paid out in profits, in the manner of equation 3.1 in the Bensusan-Butt model.

$$W(t)l = P(t)(I - A - D) - rP(t)B \qquad 3.4$$

If there is a choice of many techniques, then that giving the highest return at a given wage will be chosen. From matrices of large size, the single dominant technology A,B,l will be chosen.

Technical progress in the Leontief model

The above represents the bare outline of the model, sufficient for us to contrast it with the previous two. As presented here, only one technique for any good will ever be in operation at any time. For a realistic discussion of technical progress, we must introduce adjustment costs and specific capital as with the Bensusan-Butt model. In this case observed production coefficients will represent weighted averages of individual techniques. This in turn leads to measures of technical progress as described in chapter 2. The greatest problems arise with the treatment of the capital stock. First we treat fundamentally different types of capital, embodying different technology, as broad aggregates. This was a problem with Hicks' model also. With the Leontief model, one way round this problem is to deal with hyper-vertically integrated sectors as Pasinetti (1981) does, since the fundamental quality of a technology is the total amount of labour it requires per unit of output. This approach, however, introduces new problems in the investigation of technical progress, since the whole structure of capital becomes subsumed in the labour coefficient. A second problem with the model is that the matrix B will almost certainly be singular. A third difficulty is that the model is very much supply orientated and a whole new structure of demand needs to be built in, adding to complexity and posing adjustment problems if we also have specific capital and fixed coefficients as demand changes.

3.3.4 Models with joint production

All the above models have had, explicitly or implicitly, only techniques which produce only one commodity. It is useful to introduce joint production into a discussion of technical progress for a number of reasons. First, it is manifestly a move towards realism. Second, it can provide a useful way of introducing a vintage structure of capital and third we can introduce features such as skill creation or learning by doing as joint products.

(i) The Von-Neumann Model Production possibilities are given by matrices A and B whose columns comprise respectively the input and output vectors of the activities run at unit level. Every activity requires at least one produced input (each column of A has at least one positive element) and every good is produced by at least one activity (each row of B has at least one positive element).

Commodities are defined such that all ages of all capital goods are considered as distinct. We can also define activities so that processes producing the same final products, but with different ages of capital good, are considered as separate activities. If the level at which the n activities is run is X(t) and prices are P(t), then since all inputs must have been produced in the previous period then

$$AX(t+1) \leq BX(t)$$

If there is free disposal and perfect competition then

$$P(t+1)B \leq P(t)A$$

With a constant technology this economic system is capable of balanced growth. As with other growth models, this result is much less likely if technical progress is occurring

Technical Progress in the Von-Neumann Model The Von-Neumann approach has the valuable characteristic of allowing all types of capital good to be kept distinct. New techniques are thus easy to introduce. However this will result in changing the size of matrices A and B each period. The result is a structure within which the productive elements of the Bensusan-Butt model may be formulated.

The sectors of the Von-Neumann model may be aggregated into a Leontief type structure, where the resulting coefficients are dependent on the relative importance of each component sector. This synthesis could be useful in a simulation study, allowing a realistic capital structure in the actual model, but providing the path to aggregation in order to allow the sort of description of technical progress discussed in chapter 2.

In the original formulation of the Von-Neumann model non-produced inputs are included in A. In a discussion of technical progress it is useful to separate labour from other inputs so that technological developments in terms of increasingly roundabout production and labour saving investment can be investigated. This may also help in allowing the introduction of a separate demand side to the model and a separate savings function.

(ii) Joint Production with a Labour Sector Steedman's (1983b) model discussed in chapter 2 enables technical progress to incorporated in a model where a non-homogeneous labour force (given by coefficients E) is employed at constant relative wages (h with $h_1 = 1$). Labour is combined with n previously produced inputs to produce n outputs in the n industries. The matrices of inputs and outputs of activities run at unit level are A and B respectively. The prices of the goods are given by equation 3.5, from which we may derive the wage curve.

$$PB = hE + (1+r)A \qquad 3.5$$

In this model all inputs are completely used up in production.

Technical Progress Most of the points made in relation to the Leontief model also apply here. In aggregation of Von-Neumann activities, this model provides a half-way house on the road to the no joint production Leontief model.

3.4 An Appropriate Model for Further Investigation

We recall that our eventual purpose is to investigate the evolution of the technology of a simple economy. On the basis of section 3.3 we will formulate a structure, at the industry level, for a simulation model. We develop the decision making aspects of the model in the next chapter.

In our simulation we need to limit the number of sectors, whilst at the same time preserving the key features of a multisectoral economy, with a range of produced inputs. In particular to investigate induced innovation we need to include at least two produced inputs and a non-produced input in our model. Following Bensusan-Butt and Hicks, it will also be useful to distinguish consumption and capital goods, so that the differential effects of technical progress at various levels in the economy can be analysed. Thus at a minimum our model will have three sectors. Each firm, and hence industry, is envisaged as using a variety of processes and as having a spread of capital stocks of various vintages. In describing technical change we have seen that it is crucial to have technology embodied in the capital stock if a reasonable picture of the adjustment issues is to be obtained. The role of intermediate inputs is less important to this description, and these may be excluded from our model.

We will treat the supply of labour as being exogenous. If we have a heterogeneous labour force then we can assume that the supply of each type of labour is perfectly elastic within plausible ranges, so that relative wages are constant. We are in effect reducing high wage labour down to a simple multiple of low wage, basic, labour. With constant relative wages we may define the wage of basic labour as numeraire.

Prices of produced goods will comprise their total basic labour content, compounded by interest charges accruing from waiting plus any surplus profit that may be earned by particularly productive processes. We may be faced at some stage with a mismatch of supply and demand, particularly when new products are introduced. However this will be a transitional problem, rather than one inherent in the whole process of technical change. Pricing rules to overcome this problem are not discussed here, but are incorporated in our simulation model.

These observations lead us towards the structure of the Hicks model in designating the types of input and good produced. In consequence we may use the Hicks type of analysis to examine change at the sectoral level in our model economy, for example using average technical coefficients from the processes in use to account for the level of prices and profits, and the combination of products. We now move to a discussion technical progress using this framework.

The existence of adjustment costs, which mean that at any time more than one process will be in use within an industry, adds an extra element of complexity to our examination of technical progress within the Hicks framework. We deal first with the case of no adjustment costs.

3.4.1 Technical Progress With No Adjustment Costs

We suppose that a new set of processes becomes available at the start of each period. The new processes may be improvements on old ones or completely new, with very different factor proportions.

In the production of each good we will want to consider separately the effects of changing technical coefficients, ie technical progress within that sector, and the effects of changing input prices due to technical progress in other sectors. However in our diagrammatic representation of change below we cannot separate processes with different mixes of capital input but the same value for the capital index. We also exclude the possibility of qualitatively new inputs with no base period price.

Progress within a sector For any existing process, developments may take place in one of many different directions. Figure 2.1 in the previous chapter illustrates the possible changes from the process currently in use.

For just one process the elasticity of substitution is zero. When we have a choice of techniques this is no longer the case. To describe the various possibilities we suppose that the firm has available to it, a number of fundamentally different, 'basic' production processes. The result of technical progress may be either a new basic process, or incremental improvements in existing processes. The final outcome of technical progress will depend on the relative progress in each process and what happens to factor payments. Figures 3.6 and 3.7 show two possibilities.

Points A,B,C,D,E,F show basic processes, and the subscripts show the time period. Figure 3.6 shows the simplest case.

Figure 3.6

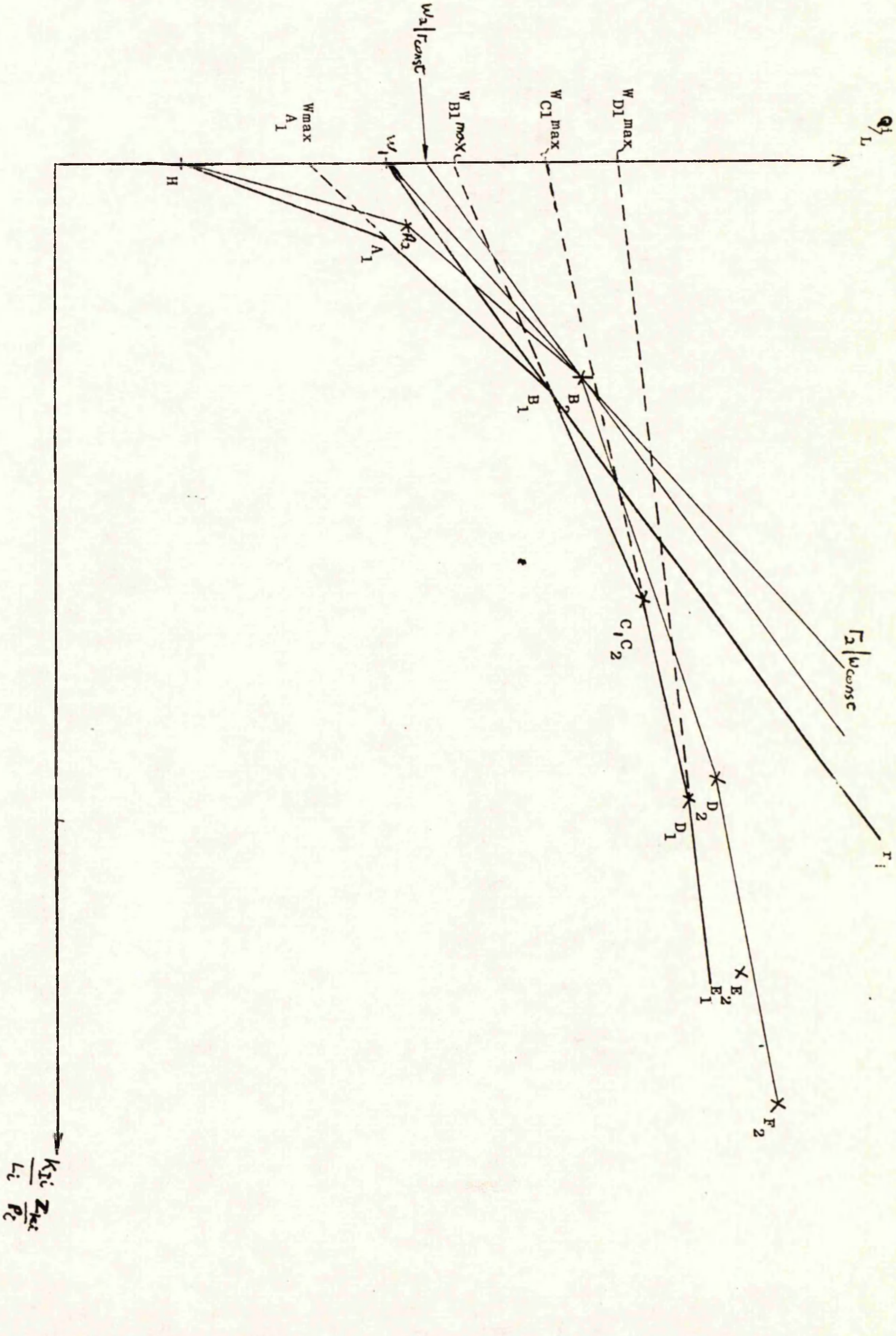
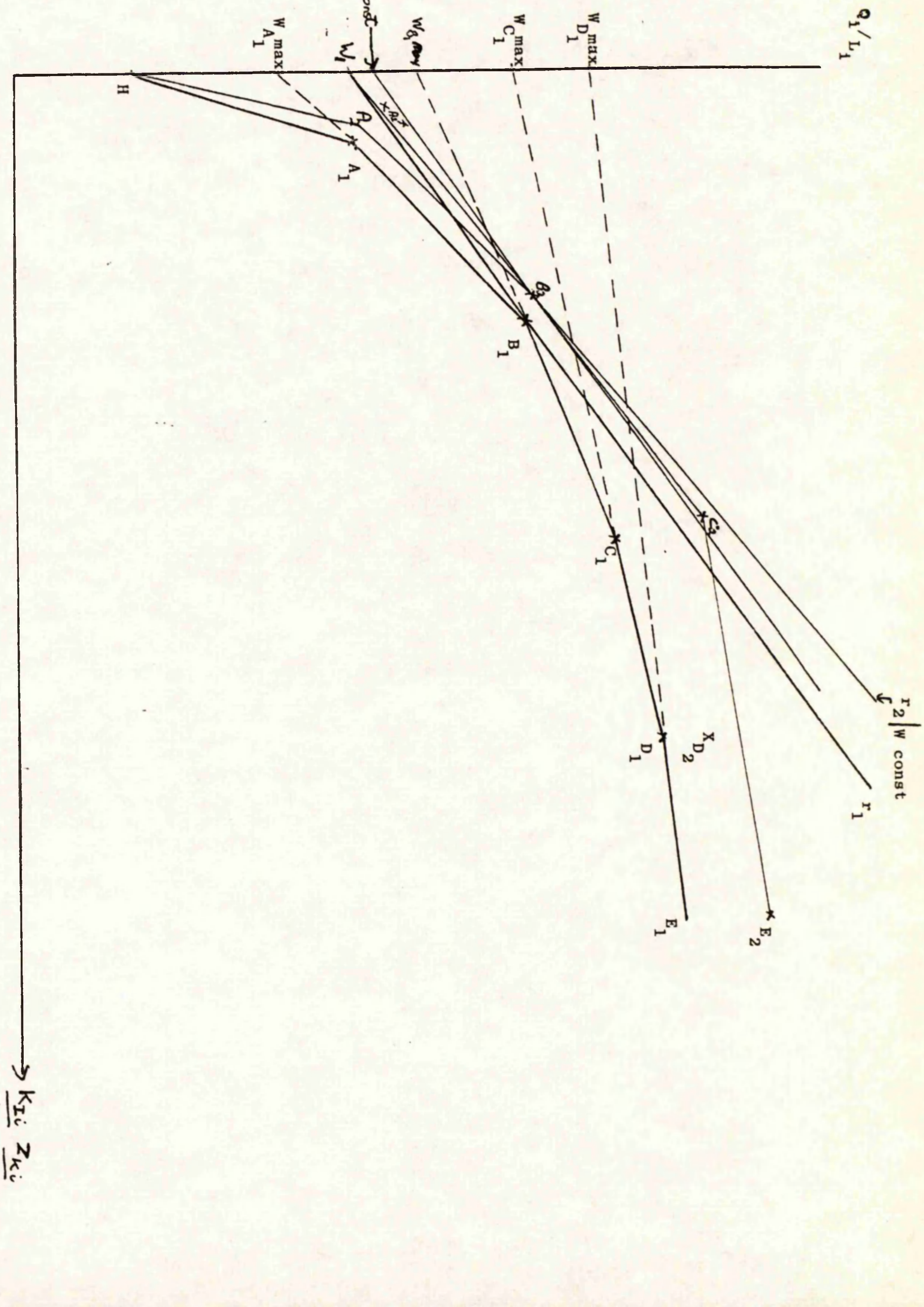

Qi/L
W D1 max
W C1 max
W B1 max
w2|r const
Wmax A1
w1
H
A2
A1
B2
B1
C1C2
D2
D1
E2
E1
F2
ri
r2|w const
Kii/Li Zhi/Pi

Figure 3.7


Q1/L1
W max D1
W max C1
Wd max
ω2|r const
W1
W max A1
H
A2
A1
B2
B1
C1
C2
X D2
D1
E1
E2
r2|W const
r1
KIi/Li ZKi/Pi

There is progress in all processes except C. Two processes, C and E, have become obsolete, since they are now dominated at all wage levels by other processes. E has been made obsolete by the introduction of a new capital intensive process, F. If wages remain unchanged at W_1 (for example they are exogenous to this sector), then basic process B remains dominant so long as the output price is also held constant. The effect of the technical progress is then to increase the rate of profit. The effect of the higher profit, in comparison to other sectors of the economy, will be to encourage more investment in the production of this good, which ceteris paribus will force down the price. In terms of figure 3.6 this will change the horizontal axis, but the effect can be interpreted as an increase in wage payments as a share of output. In our example, even if all the benefits of technical change go to labour, technique B will still be chosen for production and investment.

Figure 3.7 shows a slightly more complex case. At wage W_1, process B_2 is selected. However as the wage payment rises, and before the original rate of profit is restored, process C_2 becomes that offering the highest rate of profit. We could have considered a similar situation in which process A_2* was initially chosen, but then as wage payment rises the most profitable process switches back to B.

<u>General Equilibrium and the Choice of Technique</u> We now turn to the economy as a whole. At any time a number of processes

are available for producing each good. Of these, one triplet of techniques (one for each good) will be dominant, requiring the least input per unit of output, and the lowest price of consumer goods (highest real wage). For expositional purposes we again aggregate the two capital goods and consider production of the consumption good.

Figure 3.8a

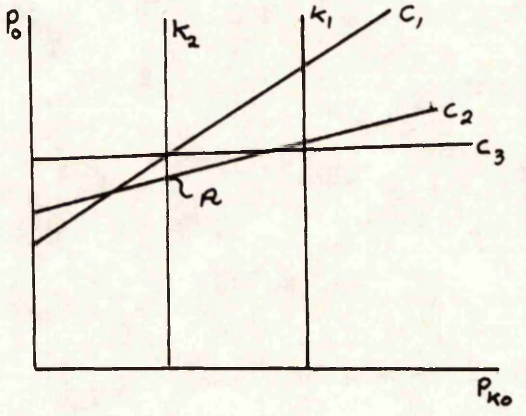


Figure 3.8b

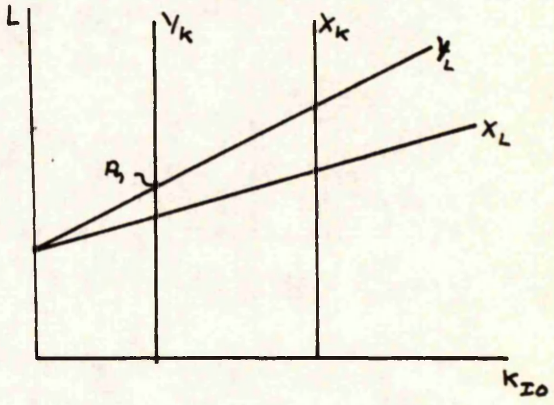
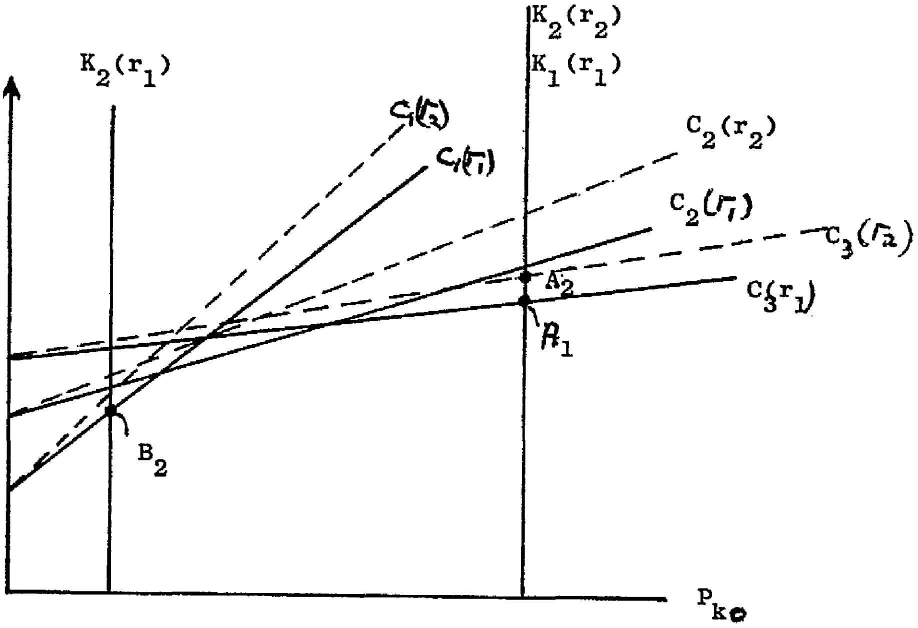


Figure 3.8 shows the dual systems of input utilisation and relative prices. In 3.8a lines C_1 C_2 C_3 represent three corn producing processes and K_1 K_2 two 'processes' giving a particular index value of capital prices. In figure 3.8b there will be six corresponding pairs of lines. X_K X_L show processes K_1 C_2 and lines Y_K Y_L show processes K_2 C_2, with the other lines omitted for clarity. Points A A^1 indicate the optimum choice of processes as K_2 C_2, so that the general equilibrium set of relative prices and input utilisation is determined.

When technical progress takes place, the resulting dominant triplet of processes depends both on the physical nature of the progress, in terms of changed production coefficients, and on how the benefits of progress are distributed between wage and profit payments. With a fixed money wage increased productivity in the production of a good can result in constant price of output and hence a higher share for profit, or reduced price of output and an increased share for wages or some combination of the two. Competitive forces should ensure a single real wage for basic labour rules in the economy as a whole. Whether there can be uniform rate of profit is more problematic, even in this case of no adjustment costs, as we discussed for the Bensusan Butt model. During technical progress the rate of profit may rise in some sectors, and more particularly for some advanced firms. If technical progress takes place in any one sector, then in the economy as a whole the rate of profit may rise, with perhaps some prices rising, or prices may fall, including those of consumption goods resulting in higher real wages, or some combination of the two may occur.

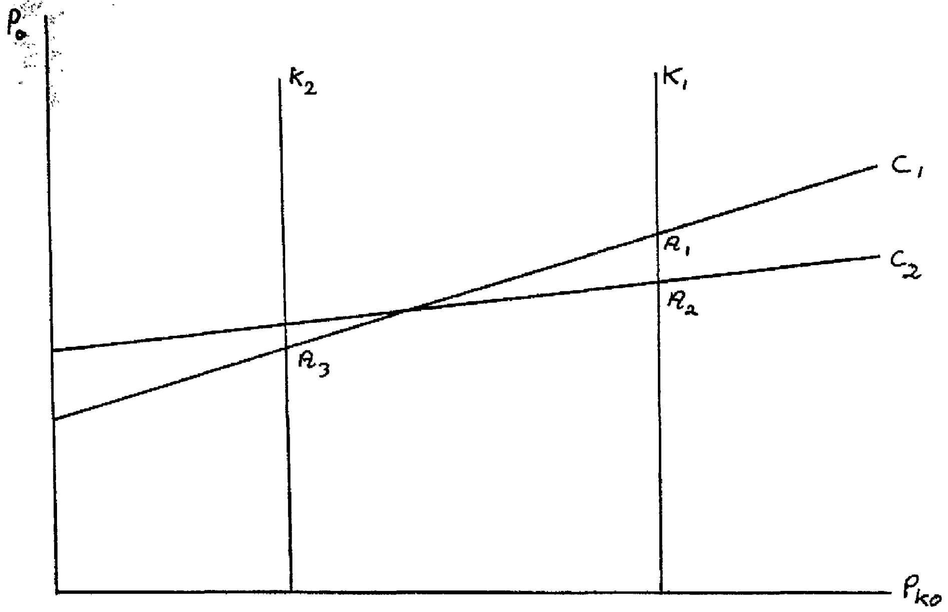
Figure 3.9 illustrates the possible outcomes following technical progress in the capital goods sectors. Line $C_i(r_j)$ shows the i'th process for producing the consumption good, at rate of interest r_j. $K_1(r_1)$) shows the original position whilst $K_2(r_2)$ and $K_2(r_1)$ show the price of capital after technical progress in the two extreme cases of all change being in profits and price falls respectively.

Figure 3.9



The original optimum is A_1. The final position may be A_2 or B_2 or points in between, including use of process C_2. As figure 3.9 shows technical progress can make profitable, processes which were not previously so. Simon (1982) refers to this as a trigger effect. Additionally, although outside the scope of our model, this trigger effect may make scarce, factors which were previously not so and vice versa.

Figure 3.10



Fugimoto (1983) describes a perverse case, shown in figure 3.10. Originally processes C_1 and K_1 are in use. Technical progress of a capital saving, labour utilising type takes place in the corn sector and C_2 becomes available. The best combination changes and relative prices move from A_1 to A_2. Following this further technical change takes place, this time in the capital goods sectors and K_2 becomes available. The new best position is now A_3 in which process C_1 is re-introduced. As figure 3.10 makes clear, this case can only arise when the new process C_2 is more labour intensive than the old process C_1, so that at low capital prices C_1 is the cheaper process.

The ability of the economy to successfully carry out the necessary adjustments, and thus to avoid price and adaptive inefficiencies, as defined in chapter 2, depends on the efficacy of market structures in this no-adjustment costs case.

The Neutrality of Progress. We discussed in chapter 2 how technical progress within a firm or sector may be neutral in some sense. Here we look at the economy as a whole. Following Kennedy (1962) we put sectors in a hierarchy according to the extent to which they provide inputs for other sectors. In our model the consumption good is at the top of the hierarchy and the two capital goods may be in the sector below or one each in two lower tiers, according to their interrelationship. This hierarchy reflects the fact that progress in consumer good production affects only that sector, whilst progress in a lower tier affects that and all higher tiers. This observation was also crucial when attributing overall technical progress to particular sectors, as discussed in chapter 2.

A neutral change for the economy as a whole leaves factor shares constant. In terms of figure 3.11a this means that we move down the ray AO, towards the origin. Such a move is consistent with either a move along A'O',A'B' or A'C' in figure 3.11b

Figure 3.11a

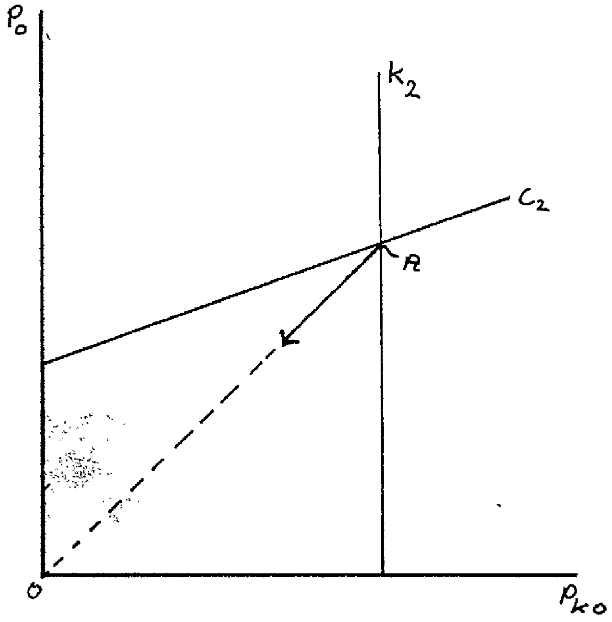
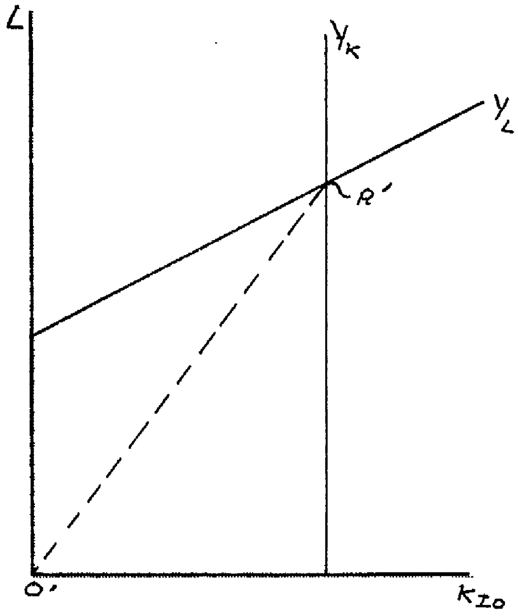


Figure 3.11b



Kennedy (1962) discusses the equivalence of the Hicks and Harrod definitions of neutrality. As we saw in figure 3.9, the final outcome of technical progress depends on what happens to relative factor prices. In terms of figure 3.11a progress along ray AO can be obtained by many sets of changing factor price ratios. A Harrod neutral change, with constant W/r, needs the line C_2 to move down parallel to itself and K_2 to move in, ie that in equations 3.2 the coefficients b_0 and b all fall in equal proportions, with a_0 and A constant, which is labour augmenting progress. From equations 3.2 this shifts the line Y_L making it have both a lower intercept and a flatter slope. The equilibrium moves down the line A'B' of figure 3.11b.

A change which reduces b_0,b and a_0 in the case where the coefficient matrix A = 0, is also consistent with a movement along OA in figure 3.11a, but then from equations 3.2f and 3.2g, r should increase at the same rate as a_0 falls to maintain constant relative prices, and g rises also at this rate. As these input coefficients fall in the same proportion as we move down the line A'O' in figure 3.11b. The rising rate of profit and falling capital inputs counter balance each other and maintain the constancy of factor shares. This is Hicks neutral progress, K/L constant. If matrix A is non zero, then the line A'O' still indicates the Hicks neutral path, and this will occur if the combined effects of changes in coefficients A and b have the effect just described, but now for the economy as a whole coefficients will no longer be falling in the same proportions.

<u>Measuring technical progress.</u> We use here some of the measures identified in the previous chapter. In the case of no adjustment costs, all improvements in productivity come from technical progress. We wish to measure advance at

different levels of aggregation, from process to economy. At the overall level we will be interested in improvements in Total Factor Productivity, $\dot{T}/T$, from both primal and dual perspectives. In our usual notation the value of net output is $p_0 x_0 + P'X$, and the value of total inputs is $wL + rP'K$, where L is total labour input and K_i is the input of capital good i. In continuous terms we derive the following:

$$\frac{\dot{T}}{T} = \frac{1}{p_0 x_0 + P'X}\left[p_0 x_0 \frac{\dot{x}_0}{x_0} + p_1 x_1 \frac{\dot{x}_1}{x_1} + p_2 x_2 \frac{\dot{x}_2}{x_2} - wL\frac{\dot{L}}{L} - rp_1 K_1 \frac{\dot{K}_1}{K_1} - rp_2 K_2 \frac{\dot{K}_2}{K_2}\right] \quad 3{\cdot}6$$

$$\frac{\dot{T}}{T} = \frac{-1}{p_0 x_0 + P'X}\left[p_0 x_0 \frac{\dot{p}_0}{p_0} + (p_1 x_1 - rp_1 K_1)\frac{\dot{p}_1}{p_1} + (p_2 x_2 - rp_2 K_2)\frac{\dot{p}_2}{p_2} - wL\frac{\dot{w}}{w} - (rp_1 K_1 + rp_2 K_2)\frac{\dot{r}}{r}\right] \quad 3.7$$

Equation 3.6 is the primal measure, gauging directly the effect of changing production coefficients. Equation 3.7 gives the dual measure. As discussed above, depending on the nature of the markets, technical progress can result in falling goods prices, rising profit rates, rising money wages or a combination of all three. Thus alternative measures of technical progress, in terms of the factor price frontier are $\left.\frac{\dot{W}}{W}\right|_{r\ \text{const}}$; $\left.\frac{\dot{r}}{r}\right|_{w\ \text{const}}$; or on any ray from the origin in the economy wide version of figure 3.4a, for example $\frac{\dot{W}}{W} = \frac{\dot{r}}{r}$ or in terms of output prices, w and r constant.

Each sector's technical progress, $\dot{t}_i/t_i$, can be similarly measured. If we assume that W and r are exogenous, then we can define for each capital good sector (and analogously for corn production), with K_{ij} equal to sector i's use of capital good j:

$$\frac{\dot{t}_i}{t_i} = \frac{1}{P_iX_i}\left[P_iX_i\frac{\dot{X}_i}{X_i} - wL_iL\frac{\dot{L}_i}{L_i} - \sum rP_jK_{ij}\frac{\dot{K}_{ij}}{K_{ij}}\right] \qquad 3.8$$

$$\frac{\dot{t}_i}{t_i} = \frac{-1}{P_iX_i}\left[P_iX_i\frac{\dot{P}_i}{P_i} - rP_i\ K_{ii}\ \frac{\dot{P}_i}{P_i}\right] \qquad 3.9$$

Only if r = 0 will the overall rate of progress just be a simple weighted average of the sectoral rates (weights being each sectors share of the value of total net output). If r > 0 then we need to take account of the effects of cheaper production of a capital good for all other sectors, which results in $\dot{T}/T$ being greater than the weighted average of the $\dot{t}_i/t_i$ as discussed in chapter 2.

Weighting $(\dot{t}_i/t_i)$, as in Peterson (1979) by the ratio of gross to net output, we find, where $(\hat{t}/t)$ is a diagonal matrix:

$$\frac{\dot{T}}{T} = \frac{(a_0\ \ A)\ \frac{\hat{t}}{t}\left[(I - \ )r\begin{bmatrix}a_0\\A\end{bmatrix}\right]^{-1}\begin{bmatrix}x_0\\X\end{bmatrix}}{(a_0\ \ A)\begin{bmatrix}x_0\\X\end{bmatrix}} \qquad 3.10$$

As in chapter 2 we can follow Steedman (1983b) who shows that the true weights for a Harrodian measure of technical progress are the ratio of gross output to wage bill, which gives equation 3.11

$$\frac{\dot{H}}{H} = \frac{(a_0\ \ A)\ \frac{\hat{t}}{t}\left[(I - \ )r\begin{bmatrix}a_0\\A\end{bmatrix}\right]^{-1}\begin{bmatrix}x_0\\X\end{bmatrix}}{W\ (b_0\ \ b)\left[(I - \ )r\begin{bmatrix}a_0\\A\end{bmatrix}\right]^{-1}\begin{bmatrix}x_0\\X\end{bmatrix}} \qquad 3.11$$

3.4.2 Technical Progress Where There are Adjustment Costs

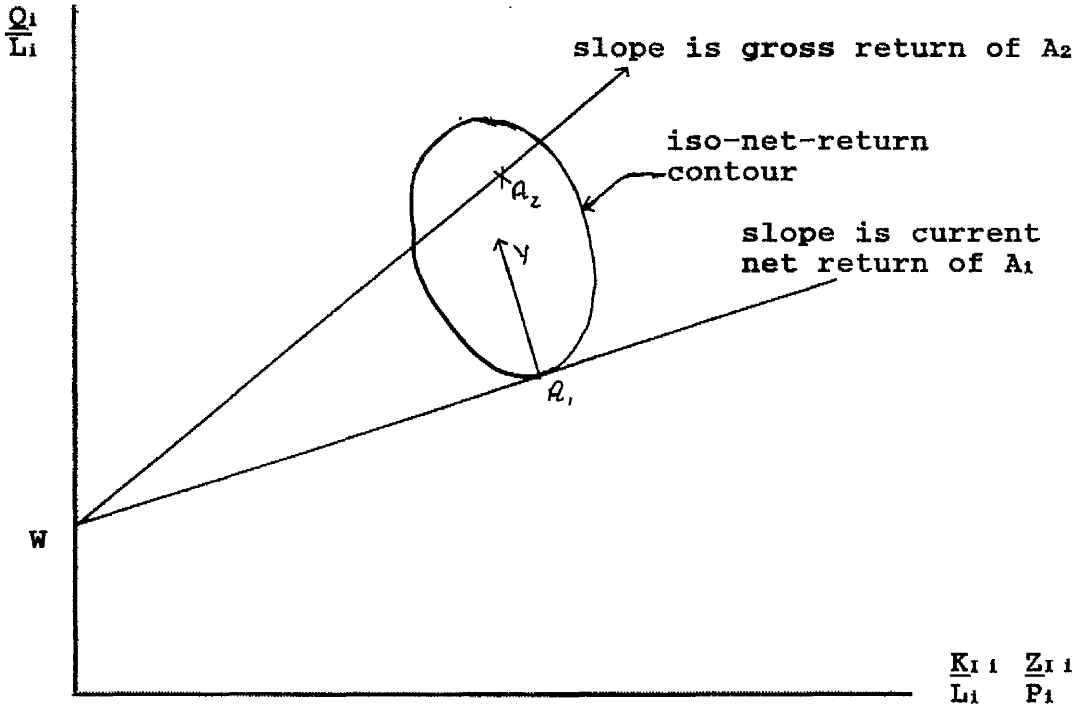
In their widest sense adjustment costs are costs which inhibit firms from changing from one production process to another. They may take three forms. First, if capital is not malleable, changing to a new process will involve scrapping existing capital and thus foregoing any rents it may earn. Second to find a new process may involve search costs. Third if firms become familiar with routines associated with one process, there will be costs in adjusting to new routines and the loss of any economies accrued through learning by doing. This third type of cost differs from the other two, in that the reduction in current profits may be offset by learning economies with the new process, whilst for the other two types the reduction in profits is irredeemable.

If any of these costs are present, firms in an industry will no longer all be using the same process, and as new processes become economically feasible firms may or may not use them. Because of their past history, firms may be using any of the techniques A_1, B_1, C_1, D_1, E_1 shown in figure 3.7. If search and adjustment costs exist then the more local is search, the more innovators and imitators amongst the firms will move only to nearby techniques, one of $A_2, B_2, C_2, D_2, E_2, F_2$ according to the technique currently in use, so that diversity of techniques will continue.

In terms of any one process, we make a distinction between the net and gross rates of profit, where the difference between the two is accounted for by any adjustment costs (in the widest sense) which must be paid. For a process currently in use, the two rates of return are equal (treating learning by doing as an adjustment cost), whilst for a new process, or one where learning may still take place, gross return must exceed net return by sufficient to cover adjustment costs, before it will be adopted. These points are illustrated in figure 3.12.

A_1 is the current process in use at wage W, with a net return given by the slope of the line WA_1. Technical progress will

Figure 3.12



result in higher gross rates of return being available, with the fastest improvement in rate of return for a given proportionate change in production coefficients being in direction A_1Y. If adjustment costs are related to the proportionate change in production coefficients and if they are the same for a given change in any direction, then the locus of points giving the same net return as A_1 is an ellipse with A_1 at the lower end as shown. Points within the iso-net-return contour such as A_2 offer a higher net return. We see therefore that the existence of adjustment costs inhibits the introduction of radical new processes.

The shape of the iso-net-return contour will be dependent on the firm's technological environment at any time. The greater are adjustment costs, from whatever source, the more the ellipse will collapse to a point at A_1. If the price of an input falls then the physical coefficients to which the iso-net-return locus relates will change. If W changes then the slope of A_1Y (along which the epicentres of the ellipse lie) will change. If ZI_i falls, each point on the ellipse in figure 3.11 will move to the left by a proportionate amount. In this way induced innovation can be incorporated into the model.

Measurement of Technical Progress

Clearly in the presence of adjustment costs firms will be using processes that would be otherwise obsolete. We need therefore to distinguish between improvements in best practice technology (technical progress proper) and improvements in average productivity. As noted in chapter 2 Nishimizu and Page discuss this in terms of a primal measure of total factor productivity. They find that the rate of improvement in TFP is the sum of the rates of technical progress, rate of improvement in efficiency and a term relating to different factor proportions involved with average and best practice processes. It is not intended to discuss this model in detail, except to note again that inefficiency may arise from failure to incorporate new technological developments or from failure to adapt to changing input prices arising from productivity improvements in other sectors.

Soete and Turner (1984) discuss measurement of technical change in terms of a dual measure. They consider an economy producing only a single good, but with many processes. They use as a measure the improvements in the rate of return (all other prices constant), each process weighted by the proportion of capital stock which it accounts for. They find that the overall improvement in rate of return is the weighted average of the process rates of return plus a term reflecting the spread of techniques in use (a diffusion or efficiency term). For our purposes it will be necessary to also take account the interindustry effects and the problems of measuring capital stocks in a multisectoral economy as discussed above.

Considering the Soete and Turner approach in more detail, each good j has N_j processes by which it is currently produced. A typical process v_j for production of good j uses labour input b_{vj} and capital inputs A_{vj} to give return r_{vj} at prices P such that

$$P_j = Wb_{vj} + r_{vj}(P_1 a1_{vj} + P_2 a_{2vj}) = Wb_{vj} + rP'A_{vj} \qquad 3.12$$

As before we call good 0 the consumption good. The real wage is defined in terms of the consumption good, and is held constant, so that we can make P_0 numeraire. From 3.12 we see that the rate of return is dependent on prices and so we need to describe how P_1 and P_2 are determined. In our model capital is fixed, so that old capital earns a quasi rent. We must therefore look towards the output produced on newly installed capital for the determination of prices and hence rates of return, as in the Salter (1969) model.

Investment in any sector is not limited by the expansion of demand since scrapping may take place costlessly. The expected net return depends on expected prices (perhaps formed on the basis of a rational expectations mechanism, or by rule of thumb) and expected search and adjustment costs. A firm which finds a particularly profitable process will bid for additional investment funds and expand its capacity. Expansion may also incur adjustment costs (described more fully in the next chapter), and these reduce net return. The existence of these adjustment costs ensures the equalisation of net returns, though not of gross returns, across all new investment projects, and the allocation of investment funds.

Once investment funds have been allocated firms compete for market share. Price cutting forces the least profitable capital into obsolescence until current capacity matches demand. The least profitable capital in use earns a zero quasi rent, and price is determined by its operating costs. New price expectations for next period's investments will then be formed.

Once prices are determined in any period, the average rate of return in the economy can be found as a weighted average of the r_{vj} over all the processes in use. Hence with X_{vj} the gross output from process v_j we find

$$r = \frac{\sum_{j} \sum_{v_j} P_j A_{j\,v_j} X_{v_j} r_{v_j}}{\sum_{j} \sum_{v_j} P_j A_{v_j} X_{v_j}} = \frac{\sum_{j} \sum_{v_j} K_{v_j} r_{v_j}}{K} \qquad 3.13$$

Here we have followed Soete and Turner in weighting processes by their fraction of total capital at current prices. This will be satisfactory if we have a 'Von-Neumann type' treatment of capital, in which used capital is produced as a joint product. Alternatively we might weight processes by their share of total output. Technical change is measured by

$\left.\frac{\dot{r}}{r}\right|$ w constant.

In order to develop a more deterministic analysis of the rate of technical progress Soete and Turner move away from a stochastic search process. Following their approach we define s as the savings rate from profits (which is universal). Hence from process v_j the funds going to investment are $sr_{vj}(P'A_{vj})X_{vj}$. These funds may be reinvested in process v_j

or they may go to a process y_i if $r_{yi} > r_{vj}$. The fraction of investment funds from v_j going to y_i is f_{yivj}. Similarly process v_j may attract funds from elsewhere, so that total investment in process v_j is given by

$$I_{v_j} = sr_{v_j}(P'A_{v_j}X_{v_j} - \sum_{r_{yi} > r_{vj}} f_{y_i v_j} sr_{v_j} P'A_{v_j}X_{v_j} + \sum_{r_{vj} > r_{yi}} f_{v_j y_i} sr_{y_i} P'A_{y_i}X_{y_i} \qquad 3.14$$

Soete and Turner suggest that the f_{yv} are proportional to $(r_y - r_v)/r_v$. This proportionality does not really reflect a possible local nature of search, since it seems plausible that a large difference $(r_y - r_v)/r_v$ reflects a distant technique, so that the firm itself may not carry out the alternative investment, and so the proportionality represents a particular degree of imperfection in the capital market. Second, Soete and Turner suggest that any f_{yv} is proportional to the fraction of total capital used by a particular process, reflecting the fact that knowledge is easier to find about processes in wide use. Whilst strict proportionality as used by Soete and Turner means that new processes will never be introduced, the principle is useful.

$$f_{y_j v_j} = \frac{n'K_{y_j}(r_{y_j} - r_{v_j})}{K\, r_{v_j}} \qquad 3.15$$

Incorporating 3.15 into 3.14 and calling n's = n we find

$$I_{v_j} = sr_{v_j}K_{v_j} - \sum_{r_{yi} > r_{vj}} n'sr_{v_j}K_{v_j}\frac{K_{y_i}(r_{y_i} - r_{v_j})}{K\, r_{v_j}} + \sum_{r_{vj} > r_{yi}} n'\, sr_{y_i}K_{y_i}\frac{K_{v_j}(r_{v_j} - r_{y_i})}{K\, r_{y_i}}$$

From which we derive

$$I_{vj} = sr_{vj}K_{vj} + n\sum \frac{K_y K_v}{K}(r_v - r_y) \qquad 3.16$$

Equation 3.16 is exactly the same as Soete and Turner's equation 14, and as a consequence we conclude that our multisectoral framework can be fitted to their approach to measuring technical change. The growth of each process is given by

$$dK_{vj}/dt = (sr_{vj} + n(r_{vj} - r))K_{vj}$$

so that a process grows at a fraction of its profits plus a fraction of its existing capital proportional to its relative profitability. Again we observe that if $K_{vj} = 0$ then $dK_{vj} = 0$, so that an additional element of search is required to introduce a new process.

From this analysis, Soete and Turner derive 3.17 as the expression for the rate of change of technology, and since we have arrived at their notation in 3.15, the same formula is applicable to our multisectoral model.

$$\left.\frac{dr}{dt}\right|_{w\ \mathrm{const}} = \sum \frac{K_{vj}}{K} \left.\frac{dr_v}{dt}\right|_{w\ \mathrm{const}} + (s + n)\sum (r_v - r)^2 \frac{K_{vj}}{K} \qquad 3.17$$

Equation 3.17 tells us that technical change has two components, improvements within each process and a diffusion term as production moves from low to high profit processes. Whilst this distinction is useful, and provides a more general breakdown of change than that of Nishimizu and Page (1982), since it allows improvements in all processes not just the best practice ones, equation 3.17 does reflect very much the simplicity of the search process implicit in 3.15. In particular 3.16 and 3.17 suggest a process of convergence to best practice in the absence of new techniques becoming available. Our simulation study will allow more complex diffusion processes to be examined.

The use of a dual measure of technical progress overcomes many of the measurement problems inherent in a primal measure, as Lydall (1969) points out. From the set of dual measures the rate of return seems most appropriate to the analysis of a multiprocess, multisector economy, since it introduces the heterogeneity of processes in a sensible and useful way. The use of the matrix f_{vv} to introduce search into the measurement of change yields Soete and Turner good results. Another approach might be to incorporate the outcome of a stochastic search process into such a matrix. This may well yield a more diverse set of outcomes and in particular allow more easily for the introduction of new processes.

3.5 Summary

Chapter 2 examined the nature of technical progress; its characteristics and how it can be described and measured. This chapter has considered various multisectoral models of economic growth, and how technical progress can be analysed at the industry and macro levels. We have seen how growth and technical progress affect the structure of output and of prices. The results from these chapters will provide one means of appraising the results of our simulation study.

A second outcome of our discussion is that methods of modelling, describing and measuring technical change have been identified. In the case of model building, we have identified an appropriate structure of industries. We have also seen that features, such as embodied technical progress, adjustment costs and bounded rationality are necessary elements of the simulation model. In the case of description and measurement, we have identified appropriate methods of aggregation, and have seen how the various alternative measures of technical progress relate to each other and to the growth process.

CHAPTER 4 MODELLING FIRMS' BEHAVIOUR

4.1 Introduction

In this chapter we develop a theory of the firm. In line with our discussion in chapter 1, firms are not considered as neo-classical profit maximisers pursuing strategy over a well defined terrain. Rather, they seek to attain their goals over a limited time horizon by directing such resources as they command with the best of their ability, operating in a world where the outcomes of decisions are uncertain. They are satisficing firms in a continual process of transition as their environment changes.

We begin by considering what it means for a firm to be in a given state, moving on to examine the decision processes of firms. As discussed below, production and pricing decisions are likely to be rules of thumb, whilst decisions on search and investment are more actively profit seeking. We concentrate, therefore, particularly on the mechanisms by which firms incorporate new technology through search and investment, and develop a detailed model of search, to be used later in our simulation study. Finally, we describe the evolution of a firms state.

4.2 The Firm's State and Environment

We consider a typical firm in a representative industry. In a period model the firm begins each period with its current state defined by; its stock of capital equipment, stocks of final product, a labour force appropriate to the various types of capital and an organisational structure capable of implementing decision rules to operate current capacity and plan for the firm's future. The firm's state is a legacy of decisions made within the firm in previous periods.

We assume that each type of capital currently available to the firm has its own specific fixed input-output coefficients. Within a firm we may identify a number of qualitatively different types of basic productive process, each with distinct factor proportions, as described at the industry level in chapter 3. From each basic process a number of techniques may be developed, each corresponding to a given level and direction of incremental improvement. The organisational structure allows all the various component groups within the firm to operate effectively together.

At any time, the firm faces a given economic and technological environment. The firm's technological environment determines its ability to increase its knowledge of production routines which can be incorporated in new capital equipment installed by the firm. This depends on the extent of current scientific knowledge, the current extent of use of various existing production processes throughout the economy and on the firm's current knowledge, and so is specific to the firm. As the economy evolves so the firm's environment will change.
The economic environment determines the prices at which the firm buys inputs and sells outputs and the market structure

and levels of demand and supply at which transactions are carried out. This again is specific to the firm. Depending upon expected prices, the firm operates capital and makes investment decisions to attain its objectives.

4.3 Decision Making Within the Firm

A firm is an organisation comprising perhaps many different groups, whose basic objectives in participating in the firms's activities may be very different. However we assume that all these groups will benefit from a prosperous, profitable and growing firm, and hence they will all work towards this end.

In order to analyse the firm's response to change it will be useful to consider what being in a given state means to a firm. This has two aspects, the skills of each separate group, and the organisational structure. We consider the operators of the firm's stock of each vintage as a separate and identifiable group. Within each group, subgroups will exist. The operation of a given vintage of capital will demand a specific set of skills, which have been acquired by the labour force. A skill or routine is a sequence of steps, which once learned can be undertaken in a fairly automatic way. Nelson and Winter (1982) stress that holders of skills need not be capable of articulating them. Indeed the need to do so, for example to teach others, may so interrupt the automatic implementation of the routine's sequence of steps as to cause a breakdown in the routine. This sort of problem may be important when analysing the expansion of a process and the retraining of labour to acquire a new repertoire of skills.

The organisation of the various production groups into a coherent whole can be considered to be the function of the management group. The management has essentially two tasks, organising current production and planning for the future. Organising production involves sending messages to the production groups to institute their production routines. As such, managers need not be able to carry out any production routine, but they must have a vocabulary of skill names. Developing such a vocabulary and developing effective channels of communication constitutes a major routine for the management group. As with production routines, it is likely that these skills are firm and time specific.

An important implication of this view of firm organisation is that there will be inertia to change from within the firm. Firms create structures, commitments and loyalties which are impervious to change in the short run. Satisficing behaviour rules tend to ensure that people stick to patterns of behaviour that they find successful, rather than continually trying to improve. Some firms may lull themselves into a false sense of security and fail to adapt to new rival products or techniques.

At any time a decision the managers face is whether to instruct each production group to begin production. An appropriate decision rule is to operate profitable capacity to meet current demands and to maintain stocks at an acceptable level. In the short run at least firm's tend to adopt fairly simple pricing strategies, such as a fixed markup over costs. Evidence suggests that firms respond to changing inventories by output changes in the first instance, and change pricing rules less frequently (Cyert and March (1963), Winter (1971)). If the firm is unable to meet demand from production and stocks it will need to increase price in order to reduce market share, or market demand in the case of a monopoly. Such changes may also be instituted by a simple rule of thumb.

The second task of the management group is to make planning decisions. To produce at time t+1, the firm must have capital carried over from time t, (which may also last for some period into the future, possibly well beyond the planning horizon). One possible plan is to keep all capital stocks as at present. This incurs no financial cost. Any other plan incurs financial costs to the firm. One way of looking at the planning process is to consider it as a search for profitable production opportunities. The firm then develops routines such as a research and development and marketing to seek out these opportunities. Winter (1971) presents a convincing argument, that whilst day to day production decisions may be made according to rules of thumb, search activity, by its very nature, requires the active pursuit of some goal. "The innovating remnant assumption requires that some behaviour derive from hypothetical calculations rather than realised results" (p247).

Search will need to be carried out in two separate areas, the creation of expanded markets with the consequent potential to profitably increase overall capacity and changes in the structure of the vintages which comprise the firm's capital stock (including the introduction of new processes and techniques). To change the firm's organisational routine will involve disruption of its smooth operation. As with production routines, the need to instruct new members of the management team disrupts the routine, so that organisational change incurs costs.

The costs involved with the introduction of a new process have three parts; a search cost, a capital cost and an adjustment cost. The latter covers training of workers and any adjustment to the firm's structure. This cost and capital cost are incurred if the firm undertakes any reshaping of its use of various processes, including more intensive use of some process already in use within the firm.

Search costs are only incurred when processes not already in use within the firm are sought out. The more intensive and wide ranging is search, the greater its potential benefits, but the greater the costs. The main cost will be in terms of the human and physical resources used up in search activity. Penrose (1963) sees the management group as a fixed factor for the firm in each time period, since new personnel cannot easily be effectively initiated into the management team. One of the costs of search is therefore in terms of scarce management time. For our purposes however it will be more convenient to think of all search costs as equivalently being measured in pounds.

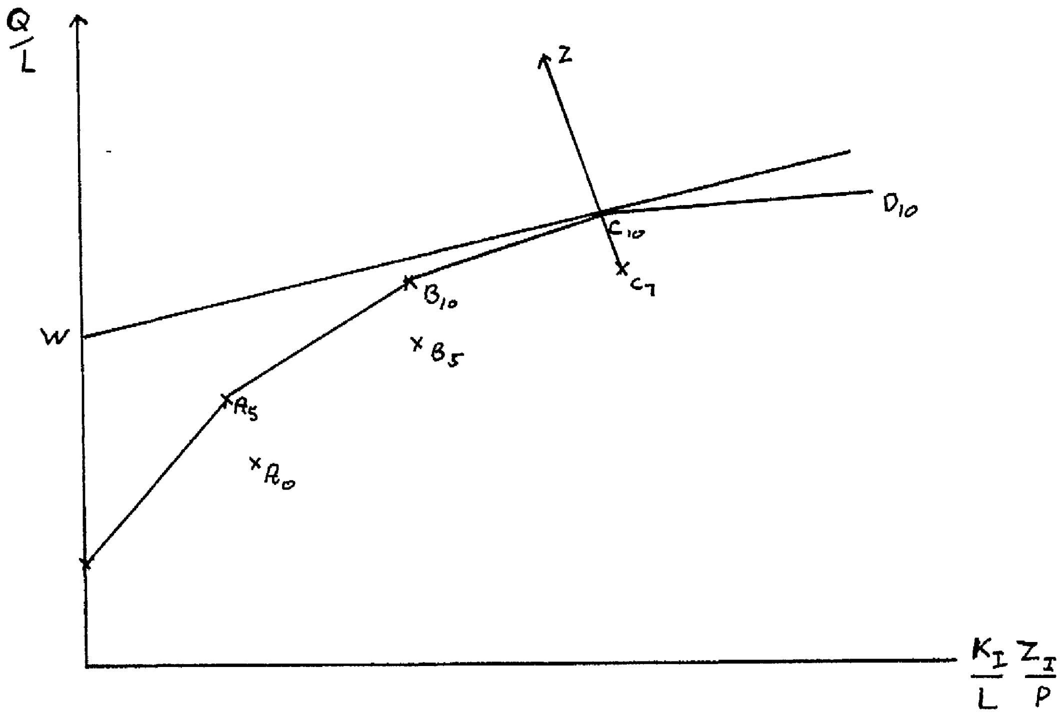
Decisions on research and investment in new capacity are inter-related. Both can be regarded as investment decisions and so profit seeking firms will carry out each until, within the limits of their rationality, expected marginal costs equal expected marginal revenue in each activity. The decisions are mutually dependent because search expenditures are a fixed cost which can be spread over all of the ensuing production. For expositional purposes however, we will treat these decisions as separate and we concentrate first on the search for new processes.

4.4 Knowledge and Search

Following Nelson (1982), we consider the firm's incorporation of a new technology as a two stage procedure. First, the firm will conduct a study of the technological options open to it, and second, there will be a design or development phase in which the new process is made operational within the firm. Both of these phases may be imagined as sampling from probability distributions. In the study phase the firm will look at the economic returns from a number of possible processes which are discovered, before initiating a single development programme. Search in this phase is thus parallel in nature. The process of design and development may be seen as a procedure of continued refinement until a design is working efficiently, so that here the search is sequential. We consider only sequential search in any detail.

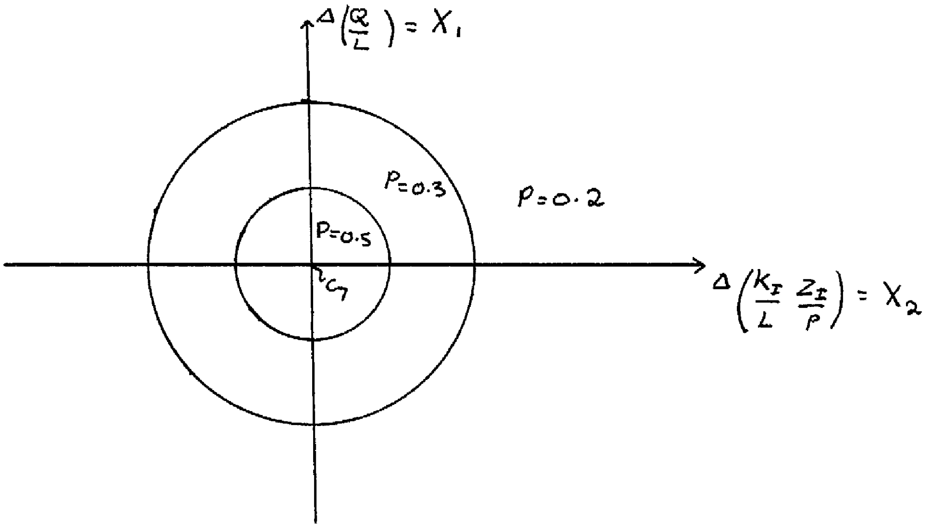
Depicting processes as we did in chapter 3, figure 4.1 illustrates a typical firm at t = 10, where P is output price, ZI an index of capital rents, KI an index of capital input, L labour input and Q output. Techniques A_5, B_{10}, C_{10}, D_{10} are the best in use in the industry for each basic process. The firm has capital equipment appropriate to A_0, B_5 and C_7. Technique A_0 is already obsolete, whilst process D is not yet in use within this firm.

Figure 4.1



The outcome of the firm's search for a new process will be dependent on three factors; the firm's environment, the firm's knowledge about its environment and the amount of search undertaken. When search is seen as a series of draws on a probability distribution, the outcome of which is a process of a given economic yield, then the firm's economic and technological environment determines the probability distribution and sample space. This is illustrated by figure 4.1, where the space illustrated would be a suitable sample space, and in which any point reflects both technological and economic considerations (given the role of prices on the horizontal axis).

Figure 4.2



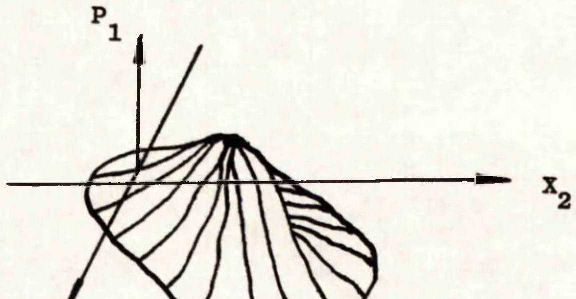
The firm's knowledge is described by Nelson (1982) as the ability to focus its study (search) of new processes. The firm already has working knowledge of the two processes currently in use, B_5 and C_7, and of its trend away from labour intensive processes given by the sequence A_0, B_5, C_7. On the basis of this information the firm chooses one of these three as the starting point for its study, and in this case we assume the firm chooses the most profitable current process, C_7. For example the firm selects people familiar with C_7 to join its R&D department. In the absence of any other knowledge, 'blind' search will begin from point C_7 of the economic yields of new processes. Such a search may be modelled as drawing from a probability distribution which gives circular iso-probability contours, as shown in figure 4.2, with centre at C_7. The outcome of the i'th draw on the distribution is $X_i = (X_{i1}, X_{i2})$, the distance from point C_7.

The outcome from search may be an incremental innovation, deriving from the current basic process, or it may be a fundamentally new way of working; a new basic process. To model discovery of a new basic process, we may consider it to be found if the firm is successful in achieving a sufficient distance from the current process in an appropriate direction.

The acquisition of more knowledge will improve on blind search. In the present context we can consider within the same framework both the acquisition of knowledge and the relative ease with which certain search directions may be pursued. The ability to direct research will mean that processes in the chosen search direction will have a higher probability attached to them than with blind search, for any given level of search activity. Some directions will be easier to pursue than others, perhaps because they lead towards processes which are widely used elsewhere in the industry (or economy), a factor akin to gravitational attraction in certain directions. These two possibilities may be incorporated into the model of blind search above by appropriate settings of the parameters of the probability density functions.

Considering the change in the probability density function, we can see that in the case of blind search the expected value of X, E(X) = (0,0). We could generate our circular iso-probability contours if X1 and X2 were normally distributed, uncorrelated and with the same mean and variance. By changing means and variances an iso-probability contour map such as Figure 4.3 may be generated. This shows a bivariate normal distribution, with iso-probability contours being ellipses.

Figure 4.3



4.5 A Model of Search

In this section we adopt a simpler search environment for the firm. We are thus able to develop a more detailed model of the search process. We begin by examining the search environment, moving on to look at the firm's decision process. The analysis is first conducted for the case of a given research budget. We consider capital using firms which undertake search to improve the input/output ratios of the plant they purchase. We then move on to consider the choice between investment in search and investment in new capacity within a given investment budget.

We define the era of any basic process by the particular extent of science used to develop it. At any time the current level of scientific knowledge determines the era of processes developed by the most advanced firms. An era will typically last for a number of time periods. We can make it a condition of advance for a firm using only equipment from an old era, that it uses (however briefly) equipment from all intervening eras before it can use the most modern techniques, ie. requiring a sort of learning experience.

We may determine the length of eras by preventing the discovery of a new basic process until some requirement is met, for example that x% of capacity is of the current era, or that the current era has lasted some minimum length of time. This would reflect the idea that ultimately new basic innovations depend on scientific advance, which is, in part, exogenous to the economic system.

We assume that the firm's starting point is that technique, of all those currently in use, which it considers will provide the maximum expected profit over the planning horizon. With stable prices this will be the current most profitable process. The outcome from search is uncertain. We assume that the firm can pursue a number of independent research programmes (search directions), each with the potential to increase or decrease usage of each of the inputs it uses. Such search is essentially seeking to achieve incremental changes in the coefficients of the starting process.

Binswanger (1974) allows each search direction to affect more than one input coefficient and this seems the most satisfactory approach, since it allows for search to substitute one input for another. Search in each direction is modelled by a series of draws on a probability distribution of search outcomes. Intensity of search is given by the number of draws. The environment is given by the exact form and parameters of the probability distributions, which determines the expected outcome from each draw. A larger mean or variance has the effect of making search easier.

As well as seeking incremental improvements, by engaging in search activities in areas where the firm has some quantified expectations about the nature of possible outcomes, the firm when engaging in search, also has the possibility of making a fundamental breakthrough to the next basic process. The firm perceives the ordinal nature of the probability density function for discovery of a new basic process; that more search increases the probability of success. Because of the greater uncertainty, it is not aware of the cardinal nature of the function. Thus the firm is assumed not to make precise calculations of the optimal amount to invest in the search for a new basic process. We may model this by summarising the potential for fundamental breakthroughs in a single number, the firm's degree of optimism, which the firm uses to multiply the variance of the incremental search probability function, when making its search decision. Thus an optimistic firm will engage in more search than a pessimistic firm.

Within a given distribution search will be local, in that new techniques 'close' to the starting process will have the highest probability of being found. Nelson, Winter and Schuette (1976) model distance in terms of the proportional change in input coefficients, rather than the absolute distance. Their approach has the advantage of allowing the same probability distributions to be used in modelling all circumstances. The disadvantage is that with proportional changes a particular input can never be completely discarded nor new inputs introduced. The proportionality approach seems best for a computer simulation given the evolution of the model over time and the problems of respecifying probability distributions for each firm each period if this is not assumed. By allowing a possible search outcome to be a jump to a new basic process, perhaps with very different input proportions to those currently in use, we can avoid the disadvantage mentioned.

The parameters of the probability distribution for a search direction will depend on the following:

(i) The pool of Scientific Knowledge Search allows the firm to develop a series of production techniques within each era (each advance being embodied in the new capital stock purchased). The particular scientific era within which the firm is searching determines the basic process whose input output coefficients are at the origins of the search probability distributions. Within successive periods of a given era it becomes cumulatively more difficult to find ever more profitable processes as invention possibilities are used up. A shift to a more modern era opens up a new set of opportunities for the firm. The technology of the new basic process may be made exogenous or endogenous in our model.

One way of modelling the endogenous case is at the start of an era, to take the firm's current most profitable technique as the new basic process. During the era it searches for proportional improvements in input coefficients on the basis of a given probability distribution, finding by the exogenously declared end of the era, a technique which becomes the starting point of the next era. This approach has the advantage of allowing some firms to get cumulatively ahead of, or behind, the others, but the disadvantage of blurring the distinctive character of any particular era.

An alternative is to define a specified starting point for any era, which can be found with a non-zero probability by a firm searching in the previous era. For example any new process found involving more than some minimum distance from the starting point shifts the firm to the start of the next era up to the most modern developed. If say, the new era were computer intensive, we might define the minimum distance in terms of proportional change in computer input discovered, thereby retaining an element of induced innovation. This approach has the advantage of allowing qualitatively new inputs to be introduced and others to be discarded. We will have occasion to use both of these approaches to the introduction of a new era.

(ii) The Ease of Imitation Some firms are innovators and are the first to enter a new era, whilst others are imitators. As the proportion of industry output produced by a given process increases, so we expect imitation to be easier for new users of the process due to the rising number of people with knowledge of the process in the economy. Equally within any era the more advances that are made, the easier it becomes for new entrants and less advanced firms to learn. Both of these effects can be modelled by increasing the variance of the probability distribution according to the proportion, z, of industry output produced using more profitable techniques than the best in use by the firm in question. If the standard variance is σ_s^2 then the variance for any firm can be given as

$\sigma_f^2 = (1+z)x\sigma_s^2$. Ease of imitation can then be set by the parameter x. This general form allows ease of imitation to increase as x increases. For x less than zero a 'technological gap' may be created which means that once firms get too far behind they become unable to catch up.

(iii) Learning by doing The longer and more extensively a firm has been using the techniques of a given era then the greater the loss from giving it up relative to the new basic process. This may be modelled either by changing the mean and/or variance of the distribution or by making this an adjustment cost.

Once the firm has knowledge of its economic and search environments, it is able to decide on the intensity of search in each possible direction. The firm's decisions on investment in new capacity and on search are interdependent. The knowledge gained from search will add to the profitability of all future new capacity, and may also make future search more productive. Thus the benefits from search will be appraised given plans for current and future investment. Since the benefits from search affect all new capacity, it is subject to increasing returns to scale. However the existence of rapidly rising adjustment costs or constraints on investment funds will guarantee that finite levels of search are chosen, as discussed below. A profit seeking firm will devote resources to search and new capacity until marginal expected returns are the same in all activities.

The elements of cost savings are the same whether we take a single period time horizon or many periods (Binswanger, op cit). For simplicity we simply consider search for new processes which create a profit stream in the next period only. Search directions are as shown in figure 4.4 and search in direction M (or N) is pursued with intensity I_m (I_n) at a price per draw P_m (P_n). The extra rate of profit expected to result from increasing search intensity from I_{m-1} to I_m is given by $D_{Im}(r)$. The benefit from search can be equally described either as an improved rate of profit or in terms of the reduction in input costs, and it will be useful to use both of these. For research intensity I_m the expected proportional reduction in input requirement is $E_{Im}(K^*)$, $E_{Im}(L^*)$ so that if the original input coefficients are K_0, L_0 with prices r_k, W the expected reduction in unit input costs is $r_k K_0 E_{Im}(K^*) + WL_0 E_{Im}(L^*)$

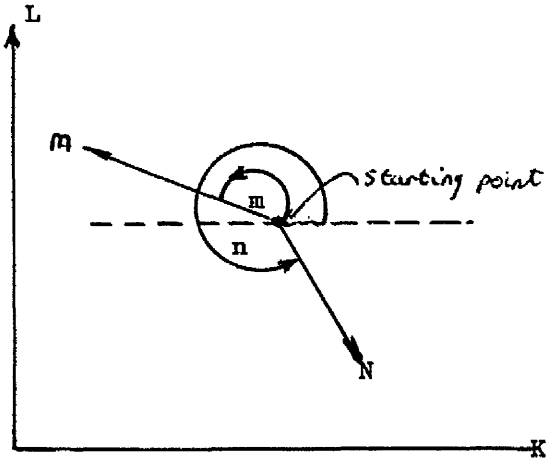
Because the different research projects are independent the benefits each generates can be simply added together to get the total saving.

If the total funds available for investment in capacity or search have already been determined as F and the price of new capital is P_k then the total cost savings generated by search are given by

$$S = \frac{(F - P_n I_n - P_m I_m)}{P_k} \left[r_k K_0 [E_{Im}(K^*) + E_{In}(K^*)] + WL_0 [E_{Im}(L^*) + E_{In}(L^*)] \right] \qquad 4.1$$

The greater the resources that are devoted to search in any direction, then the greater the number of draws on the distribution of search outcomes and the greater the expected improvement. For search direction M we define a single probability density function $f_m(X_m)$ with cumulative density function $F_m(X_m)$.

Figure 4.4



The proportionate changes in capital and labour coefficients are then given by $P(X_m)\cos(m)$ and $P(X_m)\sin(m)$ where m is the angle shown in fig 4.4 giving the search direction and P is a function with range 0 to 1 for positive X. For example $P(X) = X/(100 + X)$ for $X>0$ and 0 otherwise. This means that any small value of X is equivalent to approximately X% change whilst X is free to vary without limit.

The cumulative distribution function of X_m^*, the largest X_m found, is $F_m^{I_m}(X_m^*)$ for number of draws I_m,. In our computer simulation we assume that the sample space is continuous and that the density function f_m is given by an exponential distribution, and we examine that case here:

$$f_m(X_m) = A_m e^{-A_m(X_m - B_m)} \qquad 4.2$$

$$F_m(X_m) = 1 - e^{-A_m(X_m - B_m)} \qquad 4.3$$

$$F_m^{I_m}(X_m^*) = \left[1 - e^{-A_m(X_m^* - B_m)}\right]^{I_m} \qquad 4.4$$

The expected value and variance of X_m^* are

$$E_{I_m}(X_m^*) = B_m + \frac{1}{A_m^2} \sum_{i=1}^{I_m} \frac{1}{i} \qquad 4.5$$

$$Var_{I_m}(X_m^*) = \frac{1}{A_m^2} \sum_{i=1}^{I_m} \frac{1}{i^2} \qquad 4.6$$

Clearly the firm will only adopt processes which are an improvement on its starting point, ie. for which Xm* is greater than any previously found Xm. In successive time periods the firm searching within a given era will take as its starting point the best process found so far. Thus if $\hat{X}_m > 0$ is the best value of X_m found to date, the expected improvement in X_m is

$$E_{I_m}(\Delta X_m^*) = \int_{\hat{X}_m}^{\infty} \left[1 - F_{I_m}(X_m^*)\right] dX_m^* \qquad 4.7$$

For the exponential distribution the expected value and variance of ΔX_m^* are

$$E_{I_m}(\Delta X_m^*) = \sum_{i=1}^{I_m} \frac{1 - \left[1 - e^{-A_m(\hat{X}_m - B_m)}\right]^{i}}{A_m i} \qquad 4.8$$

$$Var_{I_m}(\Delta X_m^*) = \sum_{i=1}^{I_m} \frac{2E_{I_m}(\Delta X_m^*)}{A_m i} - E^2_{I_m}(\Delta X_m^*) \qquad 4.9$$

The contribution of one extra trial, $D(X_m^*)$ is positive and diminishing

$$D(X_m^*) = E_{I\,m}(\Delta X_m^*) - E_{I\,m-1}(\Delta X_m^*) = \frac{1 - \left[1 - e^{-A_m(\hat{X}_m - B_m)}\right]^{I_m}}{A_m I_m} \qquad 4.10$$

The case for search in any other direction is symmetrical and the analysis can be extended to include search in as many directions as desired. Binswanger (op cit) points out the implausibility of the independence of research projects, since the results from one may well contribute to advance in others. In our simulation we may incorporate this element by making success in finding a new basic process dependent on the aggregate achievement across all research directions taken together.

In deciding on its investment strategy, the firm must make a choice between search in any direction and investment in new capacity. We assume for the moment a fixed budget F. The firm will allocate funds to each activity until the marginal expected benefits are the same in each activity.

Considering the choice between search activity in direction M and investment. Increasing research intensity by 1 increases the expected value of X_m^* by $D(X_m^*)$ and input coefficients will therefore change, dependent also on the direction of search, by $K_0 P(D(X_m^*)\cos(m)$ and $L_0 P(D(X_m^*)\sin(m)$.

We can most usefully apply this by seeing the effect of this on the rate of profit, $D_{Im}(r^*)$.

$$D_{Im}(r^*) = \frac{K_0 P(D(X_m^*)\cos(m) + L_0 P(D(X_m^*)\sin(m)}{r_k K_0 + WL_0}$$

The effect of increasing search intensity by 1 is to increase the expected return on all future investment, but also to allow a lesser quantity of investment. At the optimum the marginal benefits of these two effects will be the same, and this will be true for all search directions. If P_o is the output price we obtain

$$D_{Im}(r^*)(F - P_m I_m - P_n I_n) \qquad 4.11(a)$$

$$= \frac{P_m}{P_k} \left[P_o - r_k K_0 (1 - E_{Im}(K^*)) - WL_0 (1 - E_{Im}(L^*)) \right] \qquad 4.11(b)$$

$$= D_{In}(r^*)(F - P_m I_m - P_n I_n) \qquad 4.11(c)$$

$$= \frac{P_n}{P_k} \left[P_o - r_k K_0 (1 - E_{In}(K^*)) - WL_0 (1 - E_{In}(L^*)) \right] \qquad 4.11(d)$$

In equations 4.11 the two terms (a) and (c) show the expected reduction in profits over all new capacity as research intensity is increased by 1 in either direction. Terms (b) and (d) show the profits lost from not investing the Pm and Pn thereby spent in new capacity. Including a longer time horizon in the planning decision will require D(r) to capture the effects of current search on future search and for terms (b) and (d) to cover the whole planning period (including the expected terminal value of the investment).

Having developed expression 4.11 we are now in a position to consider the comparative static properties of search and investment equilibrium in this model. In so doing we will seek to determine whether certain changes will lead to more or less search.

(i) Easier Search in any Direction Taking research in direction M (in figure 4.4), an increase in the mean or variance of the probability distribution will lead to $|E_{I_M}(K^*)|$, $|E_{I_M}(L^*)|$ increasing, and so given I_M a consequent reduction in expected unit costs. This increases term 4.11b. To restore equality with 4.11d, I_M will increase relative to I_M. The effect on the total quantity of search in each direction is also clear. The change in the distribution will increase or leave constant $D_{I_M}(r^*)$ according to whether the variance or the mean increased. Taking the latter case, expression 4.11b is increased relative to 4.11a,c which will lead to a lower research intensity. This is to be expected, since improving the expected returns from search makes each unit of new capacity, for any given level of research, more profitable.

The effect on the bias of technical progress is uncertain. Invention possibilities are more biased towards capital saving, and because research in any direction becomes ever more difficult, $\frac{d^2E(K^*)}{dI_M^2} < 0$, the effect of the shift in the distribution is likely to outweigh the relative rise in I_M and so result in capital saving bias in technical change.

(ii) Cheaper Search in any Direction If say P_m falls then intensity in direction M must increase leading to $E_{Im}(K^*)$ and $EI_m(L^*)$ increasing and so to greater cost reductions until equilibrium is restored. If M is predominantly capital saving this will lead to a more capital saving bias in technical change.

(iii) Increased Investment Budget As this increases, so terms 4.11a and 4.11c increase, leading to more search and increased expected cost reduction and faster technical progress. The effect on bias is undetermined.

(iv) Cheaper New Capital As P_k falls so the opportunity cost of resources used in search increases. A fall in P_k increases terms 4.11b and 4.11d and so leads to a reduction in research intensity. If there is no further effect on rental price of capital, the effect on bias is uncertain. However, in this context Binswanger (1978) notes that capital saving search has the additional benefit of allowing extra capacity to be created for any given investment budget. Thus the bias of search will be inherently capital saving even when invention possibilities are neutral. A fall in P_k will tend to make this effect less important.

(v) Cheaper Capital Rental As r_k falls, and with M as the predominantly capital saving search process, $E_{Im}(K^*)$ will be greater than $E_{In}(K^*)$ and so the value of the search outcomes will be such that term 4.11b is increased more than 4.11d.

This will lead to an increased intensity in direction N, an induced innovation effect, as the firm tries to reduce its use of the newly more expensive input. The effect on I_m is less clear. In the case shown in fig 4.4 where M leads to a larger labour coefficient, I_m will be reduced, however if in direction M both coefficients were reduced I_m may well rise. (In both cases this change is described before we take into account the effect of increased search on the overall investment budget).

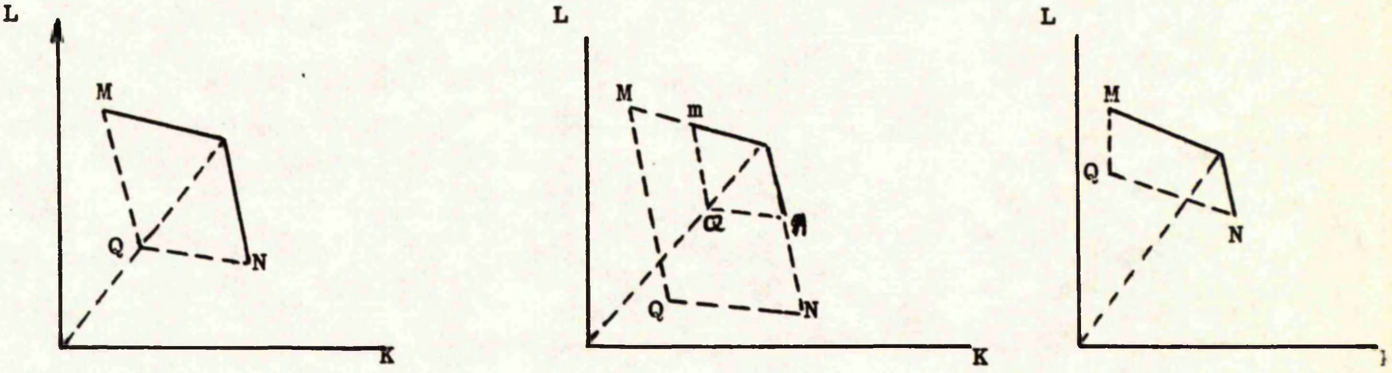
<u>(vi) Cheaper Labour</u> The effect is symmetrical to case (v).

<u>(vii) Increased Demand</u> This will lead to an increase in the price of output P_0 and thus to increased profits on each unit of capacity. The effect is therefore to reduce search intensity and increase capacity creation. The effect on bias is uncertain.

Finally in this section we consider the neutrality of invention possibilities. Bias of invention possibilities between two inputs is given by the difference in proportionate reductions in input coefficients which are expected to occur, either from one draw on each of the distributions, or from unit expenditure on research in each direction (eg. taking a fair $1 bet to win the price of one draw on the distribution), or that can be achieved with a positive probability. Of these the second seems most satisfactory as it includes ease of search, although Binswanger (1974) adopts the third.

These possibilities are shown in Figure 4.5 for the two factor case. We see that each search direction affects both coefficients, but that direction M is capital saving, labour using, whilst N is labour saving capital using. Assume that the cost of each draw is the same in both directions (ie. alternatives 1 and 2 are identical). The line MQN represents the limit of possibilities achievable, mqn is expected with one draw

Figure 4.5



(a) Neutral in Binswanger's sense.

(b) Neutral in my sense, labour saving in Binswanger's sense.

(c) Capital saving in Binswanger' sense.

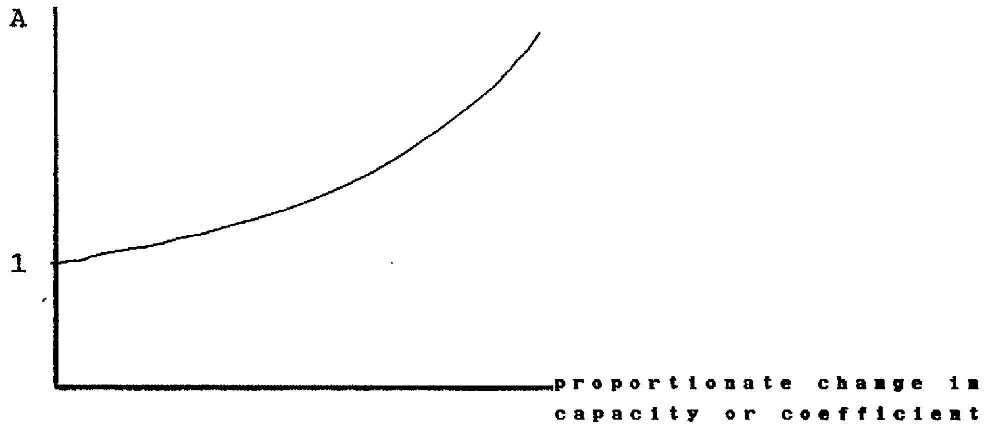
The diagrams are clearly illustrative of a particular firm, since each firm faces its own specific environment. These might be weighted and aggregated for an industry or economy wide bias (weighted perhaps by using the fraction of new investment funds going to each firm) though this does not appear very satisfactory. A better approach is to concentrate on changes in bias. A shift in scientific knowledge towards say easier labour saving search at the process level, will shift the bias of each firm and hence the industry and economy will become more biased in that direction also. The bias of invention possibilities will be one factor in determining the final (ex post) bias of technical change.

4.6 The Evolution of the Firm

Given its existing state and environment the firm must decide its current levels of production and investment. We consider two cases, first where the firm can borrow all it wishes at a given rate of interest and second where borrowing is constrained in some way.

In the first case the firm will operate units of capacity, according to its rules of thumb. Investment will take place until the marginal return to each activity is equal to the rate of return plus a risk premium. The existence of adjustment costs as illustrated in Figure 4.6 will limit expansion, ensuring that an equilibrium exists. Adjustment costs will affect both the expansion of capacity and the introduction of new technology. The justification for figure 4.6 was given above, in terms of the need to make organisational changes, disruption of routines, the need to seek out new markets etc. The further is the new state from the old then the greater the difficulty in incorporating it. This may be modelled as reducing the potential savings, S, as given in equation 4.1 by a factor A. We define A as a function of the proportional changes in coefficients and the proportion of the firms capacity that is being newly installed. Thus actual savings are S/A.

Figure 4.6



If the firm operates in a product market with any degree of monopoly, or if the firm believes its competitors will also expand or decline then it will need to take account of expected changes in the price of its output.

The second alternative is to include a limit on overall investment. As noted above, such a constraint may have an effect on the intrinsic bias of technical change so that the precise form of the constraint can have a crucial bearing on the results obtained from a model (Binswanger, 1978). Amongst the possibilities are:

(i) Overall investment is limited by previous profits (times some multiple if borrowing is allowed, and perhaps reduced by a dividend payment). This approach is used by Nelson, Winter and Schuette (1976). It has the advantage of introducing selection effects into the model, in that firms which can develop the most profitable production routines are best able to finance more search and new capacity per unit of output and so grow most quickly. If dividends are paid then investment funds may be negative for the worst firms, who must then sell off capital equipment. The more rapid growth of profitable firms may also speed up the diffusion of their processes if diffusion is related to the extent of current use as described above. Obviously this approach does not preclude inclusion of adjustment costs into the model.

(ii) All current activity is limited by previous profits, for example the working capital constraint used by Day et al (1974). This approach makes the firm's current production and investment into a joint strategy so that some currently profitable production may be foregone to finance investment (and vice versa). In this way we have an implicit treatment of adjustment costs, in that the firm can only organise activities in any period that can be financed by its working capital. This formulation seems to make most sense if the firm has a very short time horizon. This is problematic in a model of technological change, but may be justified on the grounds of uncertainty in a risk averse firm.

4.7 Application

We have described various approaches to modelling firm behaviour. In using our simulation model we incorporate particular versions of these approaches, appropriate to the task at hand. Before moving on to this element of our study we need to consider firm behaviour in an industry and economy wide context. This is the subject of the next chapter.

CHAPTER 5 THE INDUSTRY AND THE ECONOMY

5.1 Introduction

A model of firm behaviour is the main building block of an evolutionary model of economic growth. To understand the growth process its necessary also to consider how firms interact in an industry context, and how industries combine to generate overall economic performance. These issues are the subject of this chapter. Again we seek to describe various possible approaches and possibilities, prior to developing our own simulation models where the issues raised will be investigated further.

An industry comprises the firm or number of firms which produce products designed to satisfy essentially the same customer requirements. The industry and the market for its product is the environment in which the firm competes, whilst industry performance is determined by the performance of its component firms. So far as industry performance is concerned, we need to understand how technological variety comes about and how it is sustained, how different technologies are appraised, and how technological advantage is translated into increased market share. These topics are the subject of sections 5.2 to 5.4. In section 5.5 we discuss some problems of simple models of economic selection.

Technological progress within an industry, from either product or process innovation, will alter the pattern of consumer demand and so affect other industries. The pattern of demand will change according to both changing consumer demand and induced innovation as relative input prices change. In section 5.6 we examine the relationship between technical progress and economic evolution in the economy as a whole.

5.2 Firm Performance in an Industry Context

In this section we discuss how variety of performance between firms can come about and be sustained. Our model of firm behaviour emphasises the human, behavioural, aspects of decision taking. Firms contain individuals with knowledge of production processes, and have the capital equipment and organisational structure to use that knowledge in productive activity and accumulation. As Winter (1984) notes, capability is not the same as behaviour, and seemingly similar firms may perform very differently. Some firms will be efficient in their use of the resources they have others less so. All of these aspects of a firms state will be summarised in its 'revealed performance'. It is this which determines a firm's fortunes in the market.

In the previous chapter, a firm's state at any time was seen to be the legacy of previous decisions and their outcomes. In particular the firm would have decision rules pertaining to particular basic processes. In comparing firms' revealed performances it is useful to consider the boundaries between basic processes. Across an industry, firms may be using fundamentally different methods to produce the same good, for example natural power or nuclear fission to produce electricity. Metcalfe and Gibbons (1987) would see these as two technological regimes. Because of their knowledge base, firms using natural power are most unlikely to seek technological advance in the field of fission, and vice versa. This is partly because of lack of knowledge, but also because individuals learn to think in particular ways; they work within a single technological paradigm, in a self limited world (Dosi (1982)).

Within a regime there may be very different methods of producing the product, for example wind or wave power. Firms will tend to be committed to one of these, but could switch, with difficulty, if necessary, since both devolve from the same paradigm and contain similar elements (illustrated in our example by the use of small scale generators and transmission systems). Thus a technological regime will contain a number of essentially different conceptions, or 'design configurations', all of which share elements of the same knowledge base. Within a design configuration there will be scope for a series of basic processes (many small windmills widely dispersed, or 'fields' of huge windmills, to continue our example), and each of these will be the starting point for a range of incremental innovations. What distinguishes a regime from a configuration is the ease with which firms can switch between them. A firm will tend to become locked within one regime, less so within one configuration. Specialization creates barriers to change and inertia.

As firms differ in their array of skills, knowledge base, structure etc., so their revealed performances will differ. This generates technological variety within an industry. Given the human origin, we conclude that variety will be the norm, and uniformity the exception in any industry. It will be useful to follow Metcalfe and Gibbons (1986), in identifying three distinct dimensions of revealed performance: **efficiency**, determined by the firm's revealed technological performance, the unit costs of production and the quality of product; **fitness**, which determines the firm's ability to convert profit into growth; and **creativity**, which determines the firm's ability to develop its knowledge base into new products and processes, either by innovation or imitation.

These distinctions correspond to the different types of decisions the firm makes, as described in the previous chapter. Within each dimension, performance will be the outcome of a complex of individual decision rules. The three dimensions are not totally independent; creativity will tend to lead to greater efficiency; high efficiency funds growth and search. A degree of independence can mean, for example, that high fitness, aggressive, firms but with low efficiency may outgrow low fitness, high efficiency firms, or that high creativity low fitness firms are unable to take advantage of their innovations.

Differences in efficiency, fitness and creativity will tend to both create and diminish technological variety within an industry. Sources of inertia described in the previous chapter, and the existence of fixed capital (Salter (1969)) will tend to ensure that, once variety is generated, it persists for some time. This inertia, and consequent variety, plays an important role in the selection process (Matthews (1984)): By ensuring that firm behaviour is fairly consistent from one period to another, selecting currently successful firms for growth in preference to unsuccessful ones makes sense for the long term progress of the economy.

In describing industry performance therefore, it will be useful to consider frequency distributions of firms' revealed performance. We assume that the cost and quality aspects of revealed performance can be coalesced into a single index. Iwai (1984b) suggests that two distributions be considered; the cumulative frequency of firms with better than a given revealed performance, and the cumulative share of capacity with better than a given revealed performance. The distributions can be usefully summarised by their means and variances (and perhaps higher moments). The distributions at any time describe the industry's state, and so the environment within which the industry's firms compete. The outcome of that competition determines new distributions, redefining the selection environment. The time path of the frequency distributions describes an industry's evolution. In order to analyse this process we now consider the selection mechanisms in more detail.

5.3 Selection Processes With Given Technology

In this section we consider a situation in which no innovations are being made; the decision rules in existence in the industry form a closed technology set. Initially a variety of revealed performance is displayed. We examine the time path of the distribution of revealed performance. Consider first the case of selection of efficient rules arising from growth of existing users, with no imitation taking place.

Given the industry state and economic environment, decision rules will fall into the following categories: profitable, break even, loss making.[1] Profitable rules are able to expand, loss making ones contract, and break even ones keep constant capacity. There is an asymmetry between contraction, which is limited and enforced and expansion which need be neither. However so long as expansion is sufficiently limited, the selection process will take time.

Within a single firm, as discussed in the previous chapter, investment will tend to be in the best process available to it. Thus in time, without innovation, that process will come to dominate the firm. In the case of selection between firms,

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[1] Potential new entrants could also be added to this list (Winter (1971) for example).

Winter (1971) models the process as a Markov chain, in which profitable firms expand and loss making firms contract probabalistically. In the context of his model of a competitive market (and with loss makers engaging in search) he finds that this selection rule is adequate to ensure that a zero profit, competitive equilibrium will result.

Others have developed models in which growth rates are positively functionally related to profits. For example production and market price adjust so that, given demand, the least productive process in use just covers its operating costs, whilst all others in use earn a quasi rent, which is invested in each firm's best process. In this case, the industry is predicted to converge towards the most efficient decision rule, when technical inefficiency (as defined in chapter 2) is eliminated. (Iwai (1984b), Metcalfe (1984), Metcalfe and Gibbons (1986), Nelson and Winter (1982)). Each of these authors finds, in the context of their particular selection rules, that the speed of convergence, as measured by the change in the mean of revealed performance, is positively related to the variance of revealed performance at any time. This parallels Fisher's fundamental equation of natural selection, that "the rate of evolution is proportional to the genetic variance of the population" (Nelson and Winter, 1982 p243).

The speed of convergence will depend on firms' fitness. If the most efficient firms are also the fittest, convergence will be faster. If efficiency is completely uncorrelated with fitness, convergence will still occur, but otherwise need not do so; the evolution of average practice depends on the joint distribution of efficiency and fitness (Metcalfe and Gibbons (1986)). Clearly access to finance is a crucial feature. The Soete and Turner (1984) model, discussed in chapter 3, illustrates one way in which funds may be diverted towards expansion of the best processes.

If the best process is newly introduced into the industry, convergence, as measured by industry average revealed performance will tend to follow a sigmoid curve. Initially the weight of the new process is small, and so its impact on variance is small. As it accumulates capacity, so variance increases and the speed of improvement increases also. Eventually, as the worst processes diminish in share, as a result of lack of investment, depreciation and obsolescence, variance begins to fall, and with it the speed of improvement. The introduction of this new process clearly has a major impact on the other processes in the industry, whose decline is accelerated. In particular the process which is now second best, will see its final share of capacity drop from 100% to zero.

Metcalfe and Gibbons (op cit) show how the variance in revealed performance can be attributed to variance in the use of inputs. From this it is possible to explain the impact of changes in input prices on the process of convergence. If the various decision rules use inputs in different proportions then Nelson and Winter (op cit) show that, so long as more than one process is still in use, a change in relative input prices will begin convergence to a new process, using the now relatively cheaper input more intensively, in conformity with the standard, neoclassical, prediction.

In the above, each firm's growth rate was independent of its size, in accordance with Gibrat's 'law of proportionate effect' (Iwai, op cit). With no imitation, economic selection will ensure that the final size distribution of firms will be dependent on the initial distribution of technology. Only those firms with access to best practice will still exist; economic selection tends to concentrate share in the most efficient firm(s). Once imitation is allowed then all firms, except those who already have the best process, may switch to a superior process. This will increase the speed of convergence to best practice, though perhaps at the cost of some capacity if resources are devoted to search by imitating firms. Imitation tends to reduce industry concentration.

The ease of imitation can depend on many factors, as discussed in the previous chapter. The speed with which information is spread and the perceived risks are clearly important. Conventional models of diffusion suggest ways in which these may work.[2] The more firms are able to direct their imitative

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[2] For example Stoneman (1983), who discusses the merits of epidemic, profit versus risk, game theoretic and other approaches.

search, then the faster convergence will occur. Iwai (op cit) analyses the case in which ease of imitation is proportional to the share of total productive capacity of the imitated process. Another factor may be the technological gap between imitator and imitated. If this gap is across two technological regimes it may be too large to bridge in the time available to the imitator.

5.4 Selection Processes and Innovation

Creativity within firms can generate rule changes as a result of learning by doing or search. An additional source of rule change is chance mutation, for example changes of personnel. Search is the activity by which firms deliberately seek to change their decision rules. A satisficing firm, with a very short time horizon, may wait until its current rules are loss making before it begins to search (as in Winter (1971)). More realistically currently profitable firms, anticipating the erosion of their market share and existing quasi-rents as a result of competitive selection, may also engage in search. Thus, typically, a wide range of firms will be introducing new rules, with superior revealed performance, into the available technology set. We consider in this section the impact of innovation in general on the industry, before reintroducing our search model from chapter 4, to generate specific types of innovation.

A new innovation increases technological variety within the industry. With competitive selection, innovation will tend to increase the industry average rate of technical advance. Competition is now truly dynamic, and Schumpeterian in nature[3]. It is chronic disequilibrium as competitive selection changes firms' fortunes and the continued diversity of behaviour, as a result of innovation, that drives the process of economic growth.

To be improving its position in the long term a firm must advance its best practice at a faster rate than the industry average. This leads to a wide range of possibilities. If, as in chapter 4, search must be financed from current profit, and with substantial economies of scale in search, we might well expect to see the largest and/or most efficient firms making the most important innovations. If search is mainly local, innovators whose past expectations of current prices were the most accurate, will now have processes appropriate to those prices and are in the most advantageous position to conduct research in that environment. Imitating firms will try to adopt similar input combinations.

As an illustration of this, suppose that there are two leading firms in an industry and many lesser firms. In the early 1970's one of the leading firms correctly anticipates the fall in computer prices, so that by the 1980's it has already developed a computer intensive best practice technology. The firm is already best placed to develop new technology on the

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[3] Nelson and Winter (1982) discuss, in detail, the relationship between evolutionary theory and Schumpeter's work.

basis of current prices and to respond to further falls in computer prices. The computer using firm will be the most profitable and fastest growing. It will therefore become the target for imitating firms. Diffusion is part of the induced innovation process and competitive selection is seen to be working in a beneficial manner.

The existence of inertia, however, may mean that it is small, uncommitted, newcomers that are the most creative firms, making the major new innovations; discovery of new regimes or configurations. Such firms may well take longer to make an impact on variation, and may also be less efficient and fit. (Rothwell and Zegveld (1981)). One major innovation may be sufficient to make a firm prosperous in the short term. Lack of further creativity will surely see its position eroded in the long term. Clearly many possible outcomes are feasible, dependent on the relationships, in individual firms, between efficiency, fitness and creativity.

Iwai (op cit) develops a model in which technology is disembodied, and the unit cost of the next process to be discovered is declining at a constant, exogenous, rate. Every firm, in the competitive industry, has an equal chance of making the next innovating advance. Taking small intervals of time, the probability of any one firm being the innovator is quite small, and the occurrence of innovations in the industry as a whole is subject to a Poisson process. Successful innovation, with disembodied technology, immediately and dramatically transforms a typical firm's competitive position. (Additionally Iwai includes imitation as described above.) We might expect that the statistical regularity in innovation translates itself into a regularity in the variety displayed at any time within the industry. This is in fact what Iwai finds; that the distributions of revealed performance and firm size are independent of time, and a spectrum of production methods and diverse unit costs will forever exist in the industry, within a range of different sized firms. Iwai's results are clearly in part a consequence of the very special case he chooses to examine. We note that the continual existence of diversity is predicted, and consider this matter further in chapter 8.

5.5 Problems with Economic Selection

So far we have considered the selection and search processes as working in an essentially beneficial way. Only if efficient firms are too unfit would there be non-convergence to best practice within a given technology set. Profit directed search is seen to seek out new, more advantageous, processes. If creative firms are poor performers in other dimensions, the benefits of their innovations may be more slowly realised than otherwise. However there are additional factors which may prevent the most socially desired outcome from being attained.

5.5.1 We have been at pains to emphasise that behind revealed performance lie the whole behavioural characteristics of the firm, summarised in the totality of its decision rules. Decision rules are the economic analogue of genes in biological evolution. Ideally the evolutionary process will select the best genes. Firms are seen to be the analogue of organisms. Selection is at the level of the organism, not the gene. We have already considered the possibility of efficient firms being unfit. This notion may be extended. Efficiency, the basis of selection, is itself the outcome of many decision rules, only the total effect of which is pertinent to selection. Thus the most efficient firm may still contain, within it, inefficient rules. Equally low efficiency firms may contain very efficient rules, which clearly have some possibility of being lost altogether to the economy.

The cost of selecting out inefficient rules is likely to be very high. Either inefficient rules are allowed to persist in the medium term or the elimination, and scrapping, of low fitness firms is speeded up with a consequent loss of capacity. In biology this is known as Haldane's dilemma (Matthews op cit). We conclude that competitive selection may lead us to stable local optima, but not necessarily to global optima.

5.5.2 Externalities are a problem for both neoclassical and evolutionary theories. Externalities are tackled by the creation of appropriate institutions, for example enforcement of physical and intellectual property rights. Other institutions facilitate the finance of investment, trade and so on. Institutions are themselves human organisations, whose behaviour may be modelled as a set of rules. These rules will themselves be subject to evolutionary change. Clearly an institution can only come into existence if sufficient weight can be put into its creation, either from general consensus, government imposition or from some other means. Once in existence institutions may get stuck in local optima. No one feels it worthwhile to alter them; "an economic agent will not only have to overcome his own inertia but also will find himself swimming against the stream and upsetting other people's expectations" (Matthews op cit p111). Alternatively the government may be unwilling to allow change.

More problematically, since only one set of institutions is in force at any time within an economy, the variation necessary for natural selection is not present in fact (though alternatives may be postulated)). We note therefore that there is no reason to suppose that institutions are optimal, nor necessarily subject to beneficial selective pressure.

For our purposes, one externality and institutional response is worth particular consideration. We have already seen that knowledge is both valuable and possibly expensive to create. It is cheap to reproduce. Thus an effective method of allocating property rights to knowledge will be very important to economic growth. One institution designed to perform this function is patent rights. Nordhaus (1969) shows that a patent system can never be a first best system of encouraging technological change, since it involves a deadweight loss. The optimal system of production of knowledge has a price for information of zero, whereas a patent system ensures a nonzero price for the lifetime of the patent.

The longer the lifetime of a patent the greater the incentive to engage in search and so the faster will be technical progress. However the consequent monopoly of knowledge leads to a welfare loss. The optimal lifetime of a patent is where the these two forces balance out at the margin. Nordhaus discusses the optimal lifetime of a patent using this approach. He finds that determination of the optimal lifetime is extremely difficult, as it is very sensitive to parameter changes. However the changes in welfare loss as patent lifetime is changed are minimal for patent lifetimes over about 6 years, so that the problem of optimal time is not very important. More usefully he finds that the patent system is socially efficient (as compared to the first best outcome) for 'small' innovations, and for products with inelastic demand (because consumption is not reduced much as a result of the monopoly). As elasticity and the importance of the innovation increase so the efficiency of the patent system falls sharply. A patent system is a second best method of generating technical knowledge for small innovations. For major innovations a properly designed subsidy is preferred.

<u>5.5.3</u> One externality of particular importance is the 'locking in' to particular technologies. Arthur (1987)

reviews work on this subject. Consider some factors which may lead to the dominance of a particular technological regime or design configuration. There are nearly always several alternative ways of satisfying a demand for product characteristics. At the outset of an industry's development these 'compete' for adopters. An externality exists if technologies become more attractive to new adopters as they become more widely used; increasing returns set in. Reasons for this include: learning by using; network externalities (a user base develops for example); economies of scale in production; informational increasing returns (the technological paradigm becomes better understood). In this case the eventual final outcome may depend on chance factors as to which of several competing technologies is adopted by early users; the outcome is path dependent and not predictable at the outset. An additional possibility is that a technology which offers high final productivity, once fully adopted, but low initial productivity may never be developed. The technology offering the best return to early adopters is developed instead. Indeed the early adoption of the (ultimately) inferior technology widens the gap for the marginal adopter, and reinforces the locking in. Technological monopoly is certain if the increasing returns to the selected technology are unbounded, merely possible otherwise (Arthur, op cit).

Locking in results in attainment of a local rather than a global maximum. Eventually the selected technology, given its revealed performance, will fill its niche within the whole economic system. It will persist until a sufficiently radical innovation is able to invade that niche. Given the existence of search and Schumpeterian competition, the possibility of an uninvadable technological monopoly can probably be discounted in the long run. The main point is that the economy can devote considerable resources to developing inferior technologies.

5.6 Economic Evolution

In this section we consider the relationship between innovation and economic development. We examine factors which determine the nature of technical progress in an industry and in the economy as a whole. A number of possible evolutionary scenarios are described, which are further investigated in chapter 9.

The previous chapter described how firms search is determined. We first return to this issue, but now focussing more on the interactions of firms, and how these affect the direction of technical progress. Second we consider how an industry develops, focussing especially on the roles of innovation and competitive selection. Finally we examine the economy as a whole. We consider various possible evolutionary scenarios of the structure of industries, of relative prices and their feedback to the pattern of future innovation.

5.6.1 Technological Trajectories In the literature on the determinants of innovation, there have been two schools of thought: demand pull and technology push. It will prove useful to briefly consider this categorisation.[4] In the demand pull approach, the principal causal agent of technical progress is a recognition of customer 'needs' by firms, either existing firms or new entrants. Needs, in this context, are derived from utility seeking consumers. They are not just for specific product characteristics, but also for particular groups of characteristics; actual products. As real incomes rise, as a result of past technical innovations, so the pattern of demand changes. New or improved products, which offer more of the most desired characteristics, now have sufficient demand to make them profitable. This demand is perceived by the innovator, who engages in search to provide the requisite product. In this extreme form of the theory, we clearly assume that sufficient search can discover any sufficiently profitable product, and that this is the sole determinant of innovation. A similar rationale would explain the development of new capital goods.

Technology push theories have developments in science as the progenitor, via innovation, of new types of product. Over the lifecycle of a new product technological opportunities will diminish, for both process and quality improvements. Growth in output will eventually slow as a consequence of the reduced

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[4] We do not seek to enter the debate over the validity of either approach. Dosi (1982), Rothwell and Zegveld (1985) and Gort and Wall (1986) review this.

rate of technical progress, perhaps due to a reduced rate of price reduction. The design configuration gradually approaches obsolescence as newer technologies emerge.

Our profit seeking model of search and innovation, encompasses both of these approaches. The object of a firm's search is expected profit. This depends, over the firm's time horizon, on total investment, the prices of inputs, outputs and search and the expected potential advance for a given search effort in any direction. In the context of competitive selection, our search model is revealed as a Schumpeterian theory of innovation (Nelson and Winter (1977)): (transient) rewards to innovation are the spur to creative firms or entrepreneurs. This leads directly to some conjectures about the way in which technology in an industry and the economy will evolve.

Consider first innovation by an existing firm. The search decision will be critically dependent on the firm's perception of viable technological opportunities. If the firm operates within a given technological paradigm, the outcome from search is likely also to be within that paradigm; a 'technological trajectory' develops (Dosi (1982)). Of the large set of potential search directions, current behavioural rules will preselect a subset. For a number of reasons, imitation and 'locking in' being two, firms are likely to develop along the same technological trajectory; it gains a momentum of its own, and becomes a 'natural trajectory' (Nelson and Winter (1977)). The boundaries of such a natural trajectory may be narrow, confined to a single industry, or wide, perhaps pervasive across the whole economy.

Selection will play a part in this process. Major new innovations are most likely to be introduced by a subset of firms; from the analysis of chapter 4, those firms already familiar with the current, most advanced, scientific era. Evidence cited by Stoneman (1983) suggests that major innovations are most likely to be made by large firms. These firms are already located within a trajectory, and have the economic weight to make important signals to imitating firms (as in the Iwai model already described). Thus imitators will tend to swarm around a successful and major innovator, reinforcing the natural trajectory by creation of more inertia.

Once on a trajectory, the limits of the firms' perceptions will tend to reinforce it. This is not to say that innovation will be unresponsive to economic forces. For process innovations, a narrower range of input changes will be sought for any given change in relative input prices. For product innovations, the nature of the innovation will respect current thinking. In the agricultural chemicals industry, for example, the response to strains of insect pest resistant to existing treatments is a new insecticide. (Their customers probably expect and want this too).

The potential for new design configurations, or even technological regimes, always exists so long as there are creative firms. There is extensive debate over whether large firms or small firms are most likely to make such breakthroughs, corresponding to the two Schumpeter models of innovation.[5] Once such a breakthrough has been made, it may be sufficient to generate an economy wide technological trajectory. This may be the spur for a period of rapid and productive innovation across the economy. In this way surges of economic development may come about. We briefly discuss the possibility of this generating 'long waves' of economic development in section 5.6.3.

5.6.2 Innovation and Industry Development

Above we considered the role of competitive selection in the evolution of an industry's technology. We now put this into the context of evolutionary growth. We begin by considering a major new product innovation. This is a product for which substantial demand will ultimately exist, given current technology throughout the economy. The starting point is obviously the single innovating firm, large or small. (Winter (1984) generates useful computer simulation results for both cases.) The firm also finds an initial demand for its product.

Initially capacity is small, but demand is also well short of its final level. Potential customers will have already

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[5] We need not go into this here. Freeman (1974), Freeman, Clark and Soete (1982), Rothwell and Zegveld (1985) all debate the issues.

established patterns of expenditure. They may also need to learn of the products existence or of its usefulness.[6] Initial demand is high enough to allow a price mark up over costs, generating profit, which in turn allows capacity creation. The industry is growing.

We assume that demand will follow a sigmoid path up to market saturation. The finance of new capacity may come from internally generated profit or from external sources, as discussed above. The higher the rate of profit the greater is finance from both sources. Clearly demand has the potential to outstrip supply, and price will adjust to clear the market (perhaps with some lag as firms respond to falling stocks). In such a situation capacity will follow a sigmoid diffusion path. Metcalfe (1984) shows that the time path of price will be gradually to fall, until it ultimately equals costs plus normal mark up. The time path of the rate of profit is continually declining, whilst total profit will first increase, during the period of rapid capacity creation, and ultimately decline, until it is sufficient to keep the industry capacity at the final level, given depreciation etc.

We have so far described a single major product innovation. Typically such a basic innovation will be the starting point

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[6] Pasinetti (1981) discusses the role of Engels law, and emphasises learning. Metcalfe (1984) models the joint growths of demand and capacity. Gort and Wall (1986), in their analysis of innovation, model demand as dependent on exogenous factors (reflecting demand pull effects on innovation) and the level of technology (reflecting technology push).

for incremental search, for superior processes and products. Search may be carried out by existing firms, who are best placed to exploit dynamic economies of scale. Alternatively new entrants may introduce improvements as they seek to secure a share of the market. Gort and Wall (1986) investigate the time profile of search activity. Whilst their model seeks to determine the optimal search levels, given perfect foresight, the essence of their results is likely to be still applicable to our behavioural approach. The profit maximising firm is first considered as a monopolist. Demand grows exogenously, following a sigmoid diffusion path, and may thus exert a demand pull effect on technology. Demand can be further increased as a result of technical progress, which can improve product or reduce cost. They assume that incremental innovations become progressively more difficult to make, as technological opportunities gradually get used up.

The marginal conditions they find are very similar in principle to those described in equations 4.11. Various possible optimal time paths of search effort are possible, according to the relative importance and phasing of the two influences on demand. One possibility is that search investment is initially increasing, but then ultimately declines. Search will be increasing in the early phase of the industry, even though the current return to search investment is low, anticipating the growth in demand. However this result is derived from a model in which there is no constraint on investment. If the firm must finance both search and capacity creation from current profits, search is likely to be delayed if high current profits are to be made given existing technology (as in section 4.5.vii). This conclusion is supported by evidence that the ratio of investment for expansion to investment for rationalisation declines over an industry's lifetime (Rothwell and Zegveld (1981)).

The rate of technical change is found to be decelerating at the peak point of the search effort. Other possibilities are multiple peaks in the time path of search investment, if the incremental innovations are sufficiently large, or even continually increasing search effort if demand continues to increase indefinitely. Gort and Wall cannot incorporate competition into their analytical model. They suggest two conflicting effects: duplication and imitation may result in more search effort than the monopoly case; the creation of expensive knowledge which becomes freely available to competitors decreases search effort.

As well as the level of innovation, the type of innovation will also typically vary over an industries lifetime. In the early phase, search will be directed towards product improvement, partly from new entrants and partly because early designs can generally be improved upon with comparatively little effort. As the industry matures, demand becomes stable and the rate of profit falls, so the type of competition and the emphasis of search change. Firms which are creative, but lack fitness and efficiency will be taken over or fail, and the industry will become more concentrated. By now the basic technology is well known. Firms seek to increase their profitability by cost reducing process innovations.

In this section we have examined a single industry, within a given environment. A nascent industry expands to fill a 'niche' in the economic system. The size of that niche depends on the level of demand, and hence on prices, incomes and tastes. Price in the long term is predicted to fall to near the level of costs, and this is the endogenous factor determining the size of the niche. Technical progress can reduce cost and increase quality, thereby increasing the size of the niche. From our discussion of competitive selection, the best process within that industry will be destined to fill the niche. Continuing basic advances in fulfilling the same product characteristics, and to satisfy new ones, continually work to make this a moving target. Over time relative prices and incomes will be changing, and with them the long term niche for an industry.

<u>5.6.3 The Economy as a Whole</u> An economy consists of many industries, which are interdependent in many ways; competing for customers, competing for inputs, users of each others products, imitators of each others technology being amongst the most important. We consider each of these in turn.

Real incomes and relative prices are the endogenous determinants of consumer expenditure. We have examined how a new product will expand to fill a niche in the pattern of consumer spending. During that diffusion process the income elasticity of demand for the product will be changing (Pasinetti (1981)). At its birth, the product will typically be providing a desirable and hitherto unavailable group of product characteristics. It will tend to have a high income elasticity of demand. As the product matures, so the market becomes saturated and other new products become available; income elasticity of demand tends to fall. As the economy as whole grows so real incomes rise. Demand for new products is increasing more quickly than the economy as a whole. Demand for the products of mature industries grows less quickly than the economy as a whole. For some industries income elasticity will be negative as newly available products replace them in the consumers expenditure pattern. Industries in decline, relatively or absolutely, may respond with price cuts. However high income also tends to have the effect of making goods less price elastic (Freeman et al (1982)). Products have a natural lifetime, the product cycle, through birth, youth, maturity to final crisis and death.

As economic growth takes place we see a constantly changing pattern of demand. At any time we expect to see industries at different phases of their lifetimes. As an industry moves from birth to crisis it will also affect the rest of the economy. First, the new industry creates a demand for capital goods and this will have a multiplier effect. This effect will be most marked in the rapid diffusion phase of the innovation. If capacity in the capital goods industries is limited, the price of capital may rise. The new industry will also compete for labour, again possibly hastening a rise in real wages. If capital markets function with any degree of efficiency, the high profits in the new industries will divert investment funds away from mature industries.

Second the new innovation may allow new innovations to take place in other industries, both in the development of new products and from process innovations. Induced innovation is a major feature of economic evolution. Induced innovation leads to the development of new techniques which are more intensive in the products which are now relatively cheaper. Technical change in any sector influences the research and development in all sectors as well as the viability of existing techniques.

There are thus two causes of changing production coefficients; substitution of inputs given current technology, and induced innovation in future technologies. Binswanger (1978) has devised a test to distinguish these two cases, although Frenger (1978) finds that the substitution effect is very weak. Consequently this need not be a problem and we shall consider all such changes as being part of technical change. Carter (1970b) refers to all such changes as adaptive structural change and does not distinguish them.

The mechanism of induced change begins with the search process. If a major new innovation occurs in a particular sector, then once the innovation begins to diffuse through that sector, it will be reflected in lower output prices. For other sectors, search for techniques using this product as an input will become more fruitful (and the more intensive the use the greater the benefit). The probability of finding a profitable technique using this product will increase for any given level of search. Such price changes may also allow reappraisal of techniques previously researched and discarded, triggering off new directions of advance which in the past had been scientifically possible but economically unviable (Fujimoto (1983)) as discussed in chapter 3.

Changing prices and new techniques affect the structure of investment. In industries where advance is rapid, new investment will be needed both to meet the increased demand resulting from falling price and to replace capacity which is now obsolete. Whitley and Wilson (1981) have found that this extra investment is a major factor in increasing aggregate demand to take up the labour saved by technological advance in the case of microelectronics. If investment is dependent on existing profits, then these effects will be reinforced, since the firms in the best position to take advantage of new techniques are those already earning the highest profit rate from being early users of them.

From the above, it is clear that a very major innovation, generating a new technological regime, can cause fundamental changes in the structure of the economy; spawning new design configurations across many industries, dramatically increasing productivity and thereby causing an acceleration in economic growth. In other cases it may be that a group of important innovations occur together can jointly have such an impact. In either case, if the acceleration in economic growth eventually fades away, perhaps because opportunities for new innovations within the new regime become used up, a cycle of economic activity will have been observed. Freeman (1984) describes the necessary conditions for a technological revolution: a drastic reduction in the costs of many goods, which creates widespread investment opportunities; a dramatic improvement in the technical characteristics of many products; pervasive effects throughout the economic system; social, political and environmental acceptability.

Some statisticians, for example Kondratiev (1935)), claim to have observed such cycles as occurring every 50 to 60 years. Such waves are thus called economic long waves. A key question for the debate over economic long waves is whether there are mechanisms within the economic system which can cause the bunching of major innovations, and thus generate the waves. Mensch (1979) provides one explanation. He assumes that the flow of inventions is fairly steady through time, but the profitability of turning these into innovations varies through the wave. His argument follows from our discussion of profits over the product cycle. In the upswing of the wave funds are directed towards incremental search within the new technology and to capacity creation. As profits diminish and markets stagnate, firms begin to develop new innovations based on the cumulative inventions of the preceding period, and a new wave is generated.

Freeman et al. (1982) criticise Mensch's theory on a number of grounds, of which we consider two. First, it is difficult to see why unrelated products, such as plastics and computers, should act in concert to form a long wave. Second, it is not innovations per se, but rather their diffusion, which generates waves and needs to be explained. They argue that natural trajectories create a coherence between innovations, leading to new technology systems which generate waves as they are successively exploited. The development of new trajectories will be partly as a result of economic forces, but will also require social and organisational changes; inertia must be overcome.

Our explanation of long waves has so far emphasised supply factors. The Systems Dynamics Group (Sterman (1985)) focus on the demand for capital goods and the multiplier effects this generates. During the upturn of the wave firms have a high demand for capital due to high profits. This also encourages manufacturers of capital to invest. Eventually overexpansion of the capital stock results, due to poor information, lags in the supply of capital and bounded rationality. Capital investment falls off and the downturn begins. Eventually due to similar reasons, shortages of capital result in the start of the upswing. The Systems Dynamics computer simulations, reported by Sterman, found the final source of the cycles to be the investment requirements of firms producing capital goods.

Freeman et al (op cit) are at pains to point out that the creation of waves is incidental to the important phenomenon of creation of new natural trajectories. Thus there is little purpose to detailed debates about the existence and exact turning points of the cycles. We agree with this view. The important conclusion is that we expect the economy to undergo continuous evolutionary change. The effect of cycles will be to compress the period for adjustment.

5.7 Application

In this chapter and the previous one we have seen how the behavioural theory of the firm, and the evolutionary theory of economic development can together provide models which are capable of realistically describing the micro foundations of the long term development of capitalist economies. This was a task we identified in chapter 1, as necessary for the furthering our understanding of the growth process over that provided by the neoclassical model.

A number of possible models and scenarios have been presented as descriptions of firm behaviour, competitive selection, industry development and so on. We have also seen how these various elements fit together to give us a micro based, dynamic and nonequilibrium description of the process of economic evolution.

We have not sought to give detailed empirical support for the various ideas discussed. The literature cited provides sufficient evidence to convince us that they are, at least, plausible descriptions of real world occurrences. We believe that the models developed in these last two chapters are worthy of further investigation: to see in more detail how the various component elements; production rules, search, competitive selection, patents, long waves and so on fit together in the whole evolutionary process. To this end we develop a computer simulation model and use it to more fully describe than was possible here, the evolution of a simple economic system.

CHAPTER 6 THE SIMULATION APPROACH

6.1 Introduction

Our objective is to further understanding of how technical change comes about and how its effects manifest themselves. To this end we have seen that it is necessary to understand the fundamental mechanisms which drive the process of economic evolution; innovation, diffusion and selection. Creativity and disequilibrium are seen to be hallmarks of an economy undergoing technical change, and as such the process of change is fundamentally unpredictable. In seeking our explanation we identify various levels of aggregation, from aggregate output, down through individual markets, to individual firms and consumers, to individuals within firms.

Scientific practice is generally to seek explanation at a lower level than the explanandum. Ultimately to understand the growth process it is therefore necessary to have a microeconomic based study, in which the structure of interrelated firms and industries is apparent. Such an approach will be, by its very nature, complex. In this type of situation analytical results may be impossible to achieve, and it is here that the simulation approach comes into its own. In this chapter we first briefly discuss what an understanding of growth and technical change will require, and the methods economists may use in that task. We then examine what the simulation approach is and how it may be used to further our understanding. Finally we consider how simulation studies should be carried out and, by means of selective examples from the literature, what constitutes good practice.

6.2 Explaining Technical Change

Elster (1983) identifies three fundamental modes of scientific explanation; causal, functional and intentional, though the distinctions between them are not absolute. Each of these may be used to generate explanatory models. It is not our purpose to examine in detail the methodological foundations of simulation modelling and we therefore deal with these issues very briefly, to inform us as to the alternatives.

In a causal explanation all events have a cause and a mechanism by which the cause acts directly to bring about the subsequent event. Causal explanations relate these by causal laws, describing the relevant mechanisms by which actions and outcomes are linked. Causal explanation is the dominant mode in the physical sciences, but is also applied to the social sciences. To understand a causative mechanism it is generally necessary to examine the system in a steady state, so that the effects of all exogenous factors have been fully accommodated and the net effect of any causal mechanism on the whole is apparent.

This is the intended methodology of neoclassical explanations of economic growth and technical progress: economic agents take optimal decisions on the basis of given constraints, resulting in a harmonious equilibrium at all levels of aggregation. Comparative static or dynamic analysis then uncovers the causal mechanisms. This is not very appropriate to the study of technical change since by definition the terrain over which the firm searches is unknown and to some extent endogenous to the economic system as a whole. Thus there is too much uncertainty for rational choice to be well defined given the strategic nature of the firm's decision. Additionally the very essence of technical change is disequilibrium, so that a fuller understanding will be gained by supplementing neoclassical analysis with alternative explanations.

Functional explanation sees actions as being non-intentionally directed by each component of an 'organism' towards the benefit of the organism as a whole, given the environment. To qualify as a functional explanation, an action X is explained by its function Y for group Z if and only if the following five conditions hold true: (i) that Y is an effect of X; (ii) Y is beneficial for Z; (iii)) Y is unintended by actors producing X; (iv) Y is unrecognized by the actors; (v) Y maintains X by a causal feedback loop passing through Z (Elster, op cit).

In the context of technical change we might take the 'organism' to be the economy as a whole. The current state of each firm has been shaped by the history of all. Small random mutations in productive techniques occur and are selected if they enhance the firm's attainment of its goals. Such selections also benefit the economy, with a feedback through the most profitable firms also being the most productive and growing most quickly. With a given level of scientific knowledge, the whole system will evolve until it reaches a position of general optimality in which the relative position of firms is constant given the exogenous environment. The advance of the economy is explained by the independent pursuit of profit by firms.

The problems with functional explanation are many, particularly in the social sciences. In particular it excludes human intentions which allow a more active role for economic agents. For example a purely functional explanation sees technical changes as arising from random mutations of existing processes. It also focuses on optimal adjustments, in which disequilibrium is transitory. Thus whilst functionalism may indicate some useful modes of explanation, of itself it will not be appropriate to explaining technical change.

Intentionality is behaviour conducted to bring about some goal, ie. that the actor believes the action will bring about that goal. We can therefore explain an action when we can specify the future state it is designed to bring about. The question as to whether or not beliefs can themselves be explained is not pursued here, since all that we require is that decisions be made for a reason. An implication of this is that it allows indirect strategies such as two steps forward one step back to be explained. An important feature of intentionality is to recognize the consequences of actions on others and vice versa, such as to have intentional interaction between intentional beings.

Whilst functional explanation is looking back to explain the present, intentional explanation can also look at the present to explain the future, since goals only have to be imagined not attained. Intentional explanation allows us to fully explain the evolution of macro states in terms of macro states at time t (and previously) influencing intentional decisions at time t at the micro level which in turn bring about the macro state at time t+1.

Intentional adaptation is a modified version of functionalism, allowing for the intentionality of human behaviour and the insights it affords into the potential of possible innovations. Here the market is analogous to natural selection in nature, where profitable production processes are actively sought out by both innovators and imitators. The market selects so that ex post the best production processes expand most quickly. The current state is determined by the legacy of past investment decisions, but current actions are forward looking, as in the behavioural and evolutionary models described in chapters 4 and 5.

6.3 Methods of Analysis

In seeking causal explanations the method of neoclassical economics is to build models, generally of a mathematical nature, which are then used to generate falsifiable predictions. These are subject to empirical testing. This positivist approach is termed 'modernist' (McCloskey, 1986). Modernism is the notion that "we know only what we cannot doubt and cannot really know what we can merely assent to. It is the attitude that the only real knowledge is, in common parlance, "scientific", that is knowledge tested by certain kinds of rigourous scepticism" (McCloskey, op cit p5).

In conventional science, theories may be accepted or rejected according to whether they explain the world more satisfactorily than competing approaches. Theory may advance by a refutationist approach. Ideas based on a mode of explanation lead via logical analysis to expectations about real world behaviour. These may be either factual or counter factual, but they contain universal statements and are thus open to refutation by a single exception. The more ideas are corroborated the more strongly we come to believe them, though no truth can be certain nor any knowledge absolute.

Prediction is seen, by the modernist, to be the point of economic science. The veracity of predictions, demonstrated by objective empirical tests, is the means by which theories are judged and accepted. Whilst introspection, belief, aesthetics and the like may figure in the formulation of an hypothesis they cannot play any part in its acceptance. Prediction matters, whilst realism does not.

McCloskey (op cit) argues persuasively that modernism is not, in fact, a cogent method, and that it is in any case not adhered to. Prediction is not possible in economics, which is in any case more concerned with understanding the past. If prediction were possible the nature of futures markets would be very different. The very essence of falsificationism is the crucial test, but in economics, in the absence of controlled experimentation, such tests cannot be devised. In fact data is more generally used to discover facts which conform to a theory, or paradigm, which the scientist does not doubt. Econometricians redefine the specifications of their models until statistically significant results are obtained. If modernism were strictly adhered to then new theories, not yet demonstrably true would never gain acceptance: "the road from scientific law to scientific measurement can rarely be travelled in the reverse direction" (Kuhn, 1977 p219, quoted in McCloskey, op cit p19).

By ostensibly adhering to the modernist method, economics does itself a disservice. By defining rules for correct reasoning, which cannot in any case be kept, it also excludes potentially useful modes of inquiry. McCloskey argues that a more pragmatic approach as to what is considered as good science is required. Good science is a real contribution to a conversation between scientists: "As civilised human beings, we are the inheritors, neither of an inquiry about ourselves and the world, nor of an accumulating body of information, but of a conversation begun in the primeval forest and extended and made more articulate in the course of centuries" (Oakeshott 1933 pp198-199, quoted in McCloskey, op cit p27).

Rhetoric, the art of probing what to believe, of finding good reasons to arrive at plausible conclusions which a reasonable person will accept, is the means by which contributions to the conversation are made.

Rhetoric does not replace careful analysis, mathematical models and rationality; it requires them as the foundation of plausible argument. By rejecting modernism we open ourselves up to a wider range of acceptable analysis; to introspection, thought experiments, literary arguments, metaphor and so on. The task is to develop persuasive ideas. To do this we do not need to know that arguments are also true. McCloskey (op cit) argues that in fact contemporary economics, neoclassical included, does in fact use these alternative methods. Authors convince by means of comparative static and dynamic analysis, but generally of very simple models seen as metaphors of the real economy, supported by appeals to authority, analogy and other rhetorical tools. Literary style, elegant mathematics and sophisticated mathematics can all play their part in a convincing argument.

6.4 The Use of Simulation

It is in the context of seeking to contribute to the 'conversation' of economists that the positive role of simulation studies may be seen. Simulation is an operating model of a real system. It is taken to mean use of a process to model a process. The real world complexities of relationships between agents can be explicitly modelled, allowing more complex and realistic patterns of behaviour than can generally be incorporated into conventional analytic models. In simulation we consider an initial state and the means by which this devolves into successive states. Simulation is thus a model of the process of transition between initial and final states. It is appropriate to so called "middle level" problems, that is problems too complex to be handled by traditional methods but not so global as to defy analysis.

Simulation is essentially a thought experiment, trying out arguments to see if they are sufficiently plausible and powerful. "Simulation is affirmative, not falsifying, asking whether we can make a case for such and such, not whether one can prove it wrong. It tests systems, not isolated hypotheses, and affirms a framework in which to test them. It tests the reasonableness of affirmation, not the possibility of doubt" (McCloskey, op cit p14). Given the impossibility of falsification in economics, the qualitative understanding which simulation can give has the potential to be just as persuasive in the rhetoric of economists as regression analysis. This is particularly so in the field of technical change and economic evolution, where we have seen advantages in analysing the system as a whole. By allowing for random factors and path determined actions, simulation may be contrasted with the deterministic nature of traditional mathematical models of economic systems. Simulation is a complement to analytical models.

A model seeks to elucidate structural relationships among elements of the real system, whilst omitting those elements not of interest. A useful distinction can be made between a model and a theory. Models seek to represent the real world, theories to explain it. Theories need not exhibit the structure they seek to explain. Models will in general embody theory, but they may be used to predict without actually explaining.

In order to be an effective tool it is necessary to derive an appropriate method for the use of a simulation model. In conventional economics, falsifiable prediction is the main method by which economists try to present their analysis. As we shall argue below, simulation is not necessarily well suited to this task, it aims for a more qualitative understanding.

Simulation experiments allow a degree of control otherwise unavailable to the social scientist. As the simulation is run we hope to gain more knowledge of the implications of the model's structure and thus of the real world. To this extent Bunge (1967) asserts that simulation modelling may be seen as a hypothetico-deductive method. The ability to use simulation in this way clearly depends on the validity of the model. Schulz and Sullivan (1972) discuss the idea that simulation may aid the sorting out of cause and effect by the falsification of theory, ruling out certain possibilities. A related idea is the so called postulational approach in which simulation can aid the refinement of theory by producing results in conformity with the real world but missing out variables previously considered to be important. In a similar vein we may consider the work of Nelson, Winter and Schuette (1976) who reproduced all of Solow's (1957) results without using the neoclassical concepts he relied upon.

The principal advantage of simulation modelling is the way it tries to imitate explicitly the processes going on in the real system, including chance factors. In computer simulations we have complete control over the whole model and can thus design experiments to exact specifications. Using computers we can build more complex models than is feasible with traditional techniques, enabling the modeler to understand in their entirety systems previously only examined in component form. In particular the time element and interactive processes can be examined in detail.

Our computer simulation, described in the next chapter, may be considered as the analogue to a piece of apparatus in a physical science. We use it to conduct our thought experiments, and intend to convince the reader of the plausibility of the theories and systems which are embodied in its rules. The fact that such models are being increasingly used is indicative of two factors. First, recognition of the validity of this approach, in line with the arguments presented here. Second, as computers have become cheaper and easier to use, such studies have become more practical: a case of induced innovation in the production of economic research.

Models can help to develop theory and understanding by raising questions, showing important and unimportant relationships and perhaps by allowing different theories to be compared. Holland (1972) makes this point strongly. He also suggests that in an analysis of policy, simulation allows a clear separation of analytical and policy issues since no welfare function (or whatever) need be specified before policy issues are analysed, and because all individual utility functions are clearly specified in the model. Just the building of the model itself may enhance understanding since a complete specification of all elements will be necessary. The credibility of the hypotheses used in the building of the model, and in particular the theories explaining the behaviour of the component parts of the model, may be enhanced by demonstration of the additional power to explain total system behaviour.

Taking simulation to be an analogue of the laboratory experiment in the physical sciences, we need to consider the design of experiments carefully if the meaning of results is to be understood. Two types of experiment may be conducted. Static experiments compare different simulation runs at various stages through the runs. Dynamic experiments involve extending the period over which the simulation extends or perhaps changing the time unit. The first stage in designing an experiment is a clear statement of the objectives of the study. These will take the form of: questions to be asked, and so specifying what will constitute a suitable answer; hypotheses to be tested, and thus criteria for acceptance or rejection will be required; and finally effects to be estimated, in which case confidence limits will need to be set.

The nature of simulation also brings with it clear disadvantages. The greater the fidelity of the model to the modelled system then in general the less is the degree of abstraction and the less general we may presume results to be. Ultimately computer simulations are numerical rather than analytical models. To an extent this problem may be overcome by the design of experiments conducted with the model and by ensuring that the component parts of the model are as securely grounded in accepted theory as is possible. That is we try to ensure the maximum validity of the model for the purposes to which it is put.

The usefulness and validity of a model are related but not synonymous concepts. The validity of a model is not an end in itself but a means of enhancing the utility of the model, which in turn depends on its purpose. A model valid for one use may not be so for another. Cyert (1966) suggests that inordinate emphasis on validity may inhibit usefulness. Validity is the ultimate test of a theory, whilst the test of a model is utility. In a simulation many parameters may have to be set. Thus a close correspondence with the real system may just be fortuitous, so that good predictive power cannot be taken as indicative of an accurate model. Thus an added danger of simulations is the possibility of forgetting the limitations of the model and in particular in seeing empirical details as important and valid. We may need to limit our understanding to a qualitative appraisal of system behaviour.

6.5 Developing the Model

The first stage of model building is a set of postulates about the real system. These postulates will be selected a priori from the infinity of possibilities, based on the modeler's general knowledge of the system. The postulates will concern the specification of components and the selection of variables as well as the form of functional relationships. The validity of these postulates is the subject of the study. There is little purpose in simulation for simulations sake.

The world may be seen as a set of interacting agents, together forming a system. Feedback mechanisms result in the coordination of the agents activities and the development of the system over time. Many models may be constructed of the real system. The "law" of requisite variety in cybernetics, asserts that every conception of a system sets an absolute limit to the variety of situations permitted by and comprehended in this conception (Ashby (1956)). The organisation of the system into the whole places constraints on individual behaviour and thus reduces variation, making comprehensive model building easier. Thus in modelling technical change firm behaviour need only conform to the subset of possible actions expected to be profitable.

The second stage in the design of an experiment is the formulation of a mathematical model. The endogenous variables to be included in the model are generally easy to specify, given the purpose of the simulation. The problems arise in the specification of exogenous variables and behavioural relationships. Naylor (1972) asserts that too few exogenous variables can lead to invalid models, whilst too many leads to problems of complexity and high computing and programming costs. Complexity is also a problem in the design of the model system. In general we seek to develop models that yield adequate description with minimum complexity.

One approach to model construction is to make use of one of the of the shelf simulation languages, of which the most widely used by economists is the DYNAMO language developed by the Systems Dynamics group at MIT[1]. The use of such a language allows the modeler to easily develop a working programme, however this is at the cost of being forced into the structure imposed by the language. In the case of DYNAMO this is a system of feedback loops in continuous time. This may well not be appropriate to the problem at hand. In the simulation of an evolutionary economic system it will be desirable to have a greater degree of independence between agents than DYNAMO allows.

A computer program deals with events in a sequential manner, whereas in the real world events happen in parallel. The structure of simulation models may be made hierarchical allowing events at one level to be dealt with before moving on to the next, so that the program acts in a quasi-sequential manner.

Once a basic model has been constructed it is necessary to test it. Testing assesses the extent to which the model performs the tasks it was designed to do. Thus testing is one aspect of the validation procedure. If empirical testing of the model or parts of it is possible then this may form part of the test procedure, (though, as noted above this is not a guarantee of validity). The alternative is to aim for a qualitative appraisal of the state histories the model provides as compared to the real world. This is particularly

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[1] Properties of this language are discussed in Randers (1980)

relevant to the testing of the feedback and other mechanisms of the model. Clearly the extent to which the behaviour of the individual components of the model conforms to current theoretical understanding will also be a part of this assessment.

Assessment of a simulation model will thus involve the following stages:

(1) The checking of the logical consistency of the model processes and behaviour of agents.

(2) Careful description and analysis of the individual components of the model so that the system behaviour can be understood as the outcome of individual actions and motives.

(3) Understanding of the stochastic properties of the model so that individual simulation runs may be put in a general context.

Having finally developed a satisfactory model, the design of specific experiments to run on it must be considered. In the literature of experimental design, the two most important concepts are factor and response. A factor in our computer simulation will be an exogenous variable and a response an endogenous variable. In our simulation model all factors are capable of being controlled by the user. The role of uncontrolled factors is taken by the stochastic nature of the model. Some factors will have been included because they are of basic interest, others to increase the precision of the simulation. A factor is quantitative if its levels are numbers that have a meaningful relationship with the response, otherwise it is qualitative. An example of a qualitative factor is the stipulation that firms will search for new production processes when profitable search opportunities exist (rather than, say, only when current processes are no longer satisfactory).

In the design of simulation experiments a number of problems arise, of which we describe two. First, the problem of stochastic convergence, which follows from the central limit theorem. To reduce the variance of outcomes may require unacceptably large computing costs. In this case error reduction using Monte Carlo techniques may be employed. This will not be a problem in our analysis. Second, the problem of size. The use of regression techniques to establish links between factors and responses will be appropriate if the variables are quantitative, and this may mean that size is not a problem. If the factors are qualitative and we need to analyse all permutations of controllable factors at various values for each factor, then size may well be a problem. Limiting experiment to some fraction of the full factorial may mean that certain main effects are confounded with various interaction effects. Again, in our simulations this will not prove to be a problem.

6.6 Simulations of Economic Systems

In this section we consider how simulation studies in economics should be carried out. By means of selective examples from the literature we discuss what constitutes good practice. Two different types of study have been termed as simulation in the economics literature. First, there have been deterministic models such as the econometric models used to predict short run behaviour of the U.K. economy. The methodology behind such models is clearly that of traditional analysis, differing only in the use of computers to carry the burden of calculation. This type of model does not accord with the now conventional definition of simulation given above. Of the second type of simulation, in accord with our definition, studies may be put into two categories, those that try to model complete economies based on individual behaviour and those that focus only on a single aspect of the economic system. The examples described below focus on the former as most relevant to our own study.

One problem with analysing such simulations is that authors tend to focus very much on the results obtained, comparing various simulation runs, rather than on the interpretation of those results in the light of the model's construction. Many of the modelers seem to have fallen into the trap of over emphasising the detail of their results. In what follows we describe individually a number of simulations.

E.P. Holland, (1972) 'Simulation of an Economy with Development and Trade Problems' This study is loosely based on the Indian economy, and the model is used to identify an optimal technically feasible development plan. This helps to identify key constraints in policy options and to work towards an optimal policy strategy. The reasons for using simulation were basically those identified above, and Holland is careful to point out that the structure of the model is more important than numerical accuracy in tracing the dynamic effects of policy alternatives.

The model was constructed with the prime objective of making the main endogenous variables behave realistically in a dynamic context, thus focusing primarily on adjustment mechanisms rather than equilibrium relationships. The model includes six domestic production sectors, with varying shapes of supply curve, determined according to prior information. Two sectors, agriculture and supply of personal services, undertake no investment. The other four sectors are continuously making such decisions. At the same time old capital is depreciating and thus the net capital stock is changed. The foreign sector allows import of products and demand for exports. Demand for each sector's products is endogenous, with aggregate disposable incomes the principle determinant of consumer demand, together with prices. Prices are set endogenously to clear the markets.

In each simulation run parameters and policy variables are set. In the case of a developing economy the government may have special roles to play in initiating investment, even in the non-nationalised sectors, and particularly in agriculture. This is explicitly incorporated into the model. Holland describes a number of sample 'histories' of the model economy, each covering a simulated 20 year period. Problems which occur in one run, such as inflation or BoP deficits can be addressed in subsequent runs as the modeler tries to discover the ideal policy mix. With sufficient time and effort this should eventually be found. Given the impossibility of empirical accuracy in the models predictions, the usefulness of the results is in learning about possible outcomes and how to cope with them. The model can be used to generate long term projections to inform current policy makers focussing essentially on the short run.

R.L. Bennett and B.R. Bergmann, (1980) 'Policy Explorations with the Transactions Model of the U.S. Economy' This model tries to simulate the macro performance of the U.S. economy, built up from the actions of individual economic agents. The model aims for empirical accuracy as a scale model of the U.S. economy at the start of each simulation run. The primary purpose for which the model was designed was the analysis of alternative policy regimes.

The model economy has 12 firms each representing a complete sector of the economy. The sizes of firms are given by the appropriate real world counterpart. Firms set prices each period on the basis of costs plus a mark up. The population is also modelled on the demographic characteristics of the U.S., both in the type of labour supplied and in the pattern of consumption. Consumers purchase goods on the basis of demand functions corresponding to a linear expenditure system. In addition firms may invest, accumulate inventories, borrow from the banking system, hire or fire labour, and all the rest of the activities which constitute their role in the economy, according to a set of decision rules built into the model, based on the behavioural theory of the firm. The complete sequence of events in the economy is termed a round, and in the model a quarter of a year calender time corresponds to 12 rounds. Thus in generating 'quarterly' data the model allows actors to react more than once to the actions of others within the same period. This recursive feature is seen by the authors as a distinct advance on traditional quarterly models.

Having constructed the basic model, parameter values were set so that the model provided a best fit simulation of certain macro series for the period 1973-75. This was done basically by a process of trial and error. Having done this the model is used to discover the effects of various policy changes such as tax cuts or wage subsidy for the long term unemployed, with the results reported as a series of tables of the macro performance.

A discussion of the paper by D.A.Nichols and R.P.Strauss (1980) contains a number of useful criticisms. Principally these concern the uses to which the model is put. The model was fitted for a specific historical period and we are not told how the model predicts for other periods. This limits any validity attached to the experimental results reported. Nichols and Strauss would in this respect attach more weight to predictions from a traditional econometric model. More importantly they are concerned that the model has been used to perform tasks which are more satisfactorily performed by econometric models, ie. the generation of simulated macro data, rather than the investigation of the micro responses to policy changes which are uniquely the province of micro based simulations. They feel that a description of adjustment processes in response to policy changes, and an examination of the various distributions behind the macro aggregates would have been more worthwhile. This is in accord with the point made above that the strength of simulation is the behavioural realism rather than empirical accuracy and applications need to reflect this.

<u>G.Eliasson, (1980) 'Experiments With Fiscal Policy Parameters on a Micro to Macro Model of the Swedish Economy'</u> Eliasson's model is conceived with similar purposes to Holland's, but additionally the opportunity to study the micro adjustment of the economy is also recognised. At the heart of the model is a dynamic Leontief production model with four sectors. Each of these sectors contains, as the decision units, satisficing firms modelled in size and technology to be representative of the Swedish economy. Firms decide production and investment on the basis of expected prices. Technical progress is

incorporated via investment, with firms searching for new technology to improve their profits, (the exact nature of this search is not specified in the paper cited). Around this are other sectors comprising households, government, services, banks etc. In each market the price is determined by a series of iterations in which firms offer their products for sale at specified prices and then assess demand. After a fixed number of iterations prices are set, with any differences between current production and demand being accommodated by changing inventories.

Whilst the model is able to simulate the behaviour of the Swedish economy, the performance is very dependent on the chosen structure. Changing the profit targets of firms, or the way inventories feed back into production decisions can result in radically different macro behaviour. This suggests once again that simulation is not best suited to problems where empirical realism is crucial. Despite this Eliasson reports a series of macro predictions for the model economy under various fiscal regimes. He also describes in a general way how the structure of industries and the economy is affected over time by such changes. Eliasson asserts that whilst he would not be confident in the model's ability to catch short term (quarterly) fluctuations it does predict well long term (5-20 year) growth trends and the accompanying structural change[2].

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[2] Similar results are also found in Eliasson (1986).

This model does have some advantages for the type of study we are to carry out. However in trying to simulate an actual economy, the model incorporates much institutional detail which causes problems. It encourages experiments which focus on the empirical rather than the systems features of the model.

Evolutionary Models Nelson and Winter have developed a series of models based on intentional adaptation (summarised in Nelson and Winter, 1982). They describe satisficing firms in an evolutionary economy, and their models are able to depict evolution as essentially non-equilibrium and often non-steady state transitions over time, in which the environment changes too rapidly for it to be fully adjusted to at any instant. This can make it difficult to understand the status of the mechanisms involved. They develop their analyses in two main ways. Firstly by searching for steady state properties, such as industrial concentration, even when the performance of each individual firm is not constant, and then causally explaining that pattern in terms of the exogenous variables. Such steady states as exist may be identified analytically or by a series of computer simulations. If no steady state exists the second approach is to allow the transition effects of parameter changes to be analysed over many simulations of the model, looking especially at the later stages of the simulations when the effects of the changes are most fully worked out.[3]

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[3] This still leaves open the possibility of cyclical behaviour and thus an area of doubt.

Their models seek to describe the changing structure of the economy over time. The relative performance of firms and industries will be constantly changing as firms which discover the most profitable lines of production displace the others. Thus the modelling of such systems is ideally carried out by computer simulation. The most relevant of their models to our purpose is R.Nelson, S.Winter and H.Schuette, (1976) 'Technical Change in an Evolutionary Model'. This simulation model starts with a fundamentally different purpose to those described so far. It is primarily concerned with understanding the economic mechanisms embodied within it and only secondarily with empirical realism. It is one of a family of models each embodying the same philosophy but directed towards specific tasks. The purpose of this model is to understand the evolving industrial structure during a period of technical progress. Computer simulation is used because the detail of the dynamic processes is not readily susceptible to mathematical analysis.

The model consists of a single production sector in which there are a number of firms. There is a finite number of production techniques available. Each firm uses only one process at any time and this together with its capacity defines the firm's state. Firms keep the same process until their rate of profit falls below a satisfactory value, when they begin to search for a superior one. Technical progress is disembodied and is incorporated into all new and existing capital. Firms only interact in the labour market, where they compete for scarce labour. The numeraire is the price of the product, and thus the wage set is the real wage. Firms operate all capital that covers its wage costs, and their net investment is equal to net profit minus depreciation. In essence the model is the evolutionary analogue to the one sector neo-classical model. This is in accord with its purpose, which is to challenge the neoclassical orthodoxy.

Having set up the structure of the model Nelson Winter and Schuette calibrate it so that the average input output coefficients conform to those of Solow (1956). The first use to which the model is put is to reproduce the Solow data and results but without the necessity of the strong assumptions he needed. Thus, just the construction and execution of the model has served a worthwhile purpose. Having developed the simulation the authors are able to extensively investigate the dynamic properties of their model economy and undertake a series of experiments involving changes of various parameters. In all they changed four parameters with two levels for each factor, generating sixteen combinations, allowing all interactive effects to be investigated. The bulk of the paper is a reporting of these results and their interpretation.

This study seems to be a more constructive use of simulation playing to its strengths, and using it to complement analytic models. By clearly defining objectives at the outset, by limiting the scope of the model and especially its pretence to empirical accuracy they seem able to generate valid and useful conclusions in their area of interest.

G.Dosi, L.Orsenigo and G.Silverberg, (1986) 'Innovation, Diversity and Diffusion: A Self Organisation Model' This model presents an evolutionary perspective of a single market (as a precursor to developing a more complete model at a later stage). The principal purpose of the model is to investigate how different diffusion paths for innovations can be generated, depending on the nature of the new technology and the state of the firms. Two properties of new technology are identified; it may be universal and thus freely appropriable by all firms, or it may be local and firm specific. Firms differ in their ability to innovate, imitate, in their cost structures, in the nature of the technology they use and in their behavioural rules. An industry is made up of a number of such diverse firms, and market selection determines which firms and technologies succeed. This leads to two basic modes of diffusion, one based on selection and 'creative destruction' and one based on cumulative accumulation of technological knowledge within firms.

Given the desire to investigate diffusion paths and given the need to investigate the coexistence of weak and successful firms, the industry is suitably modelled by taking the evolutionary approach and by using computer simulation. A self organisation model allows all agents to actively pursue their own objectives, but given feedback from the aggregate behaviour, generates relatively ordered paths of change. Because of the nature of the feedbacks Dosi et al argue that it is not possible to generate game theoretic descriptions of the progress of the industry.

Each firm is modelled by certain rules of thumb (in this case mainly relating to feedback, somewhat as in Systems Dynamics), which generate its decisions and by its key characteristics of capacity, competitiveness and market share. The firm faces an exogenous market demand, and sets its prices (and thus competitiveness) as cost-plus but with a concession to prevailing market prices. Firms decide current production and net investment according to how they fare in this competitive market situation. The essence of the model is that market share increases for low cost firms. As the degree of appropriability of new innovations or the local nature of production technologies are changed and as the search behaviour of firms is changed so different patterns of diffusion are generated. Various results from simulation results are discussed in the paper, with the emphasis on describing the relative performance of the individual firms over time, details of which need not concern us here. The detailed rules built into the model were chosen for reasons of realism but also because they generate robust behaviour. Whilst rigid mechanisms for feedback seem somewhat unrealistic they do lead to tractable models.

<u>Systems Dynamics Studies</u> The Systems Dynamics approach has been used to simulate both complete economies and partial systems. The simulations are based on a common set of principles of systems behaviour. The system is pictured as a series of levels, which represent accumulation, and rates, which represent flows of what has been accumulated. Decision rules control rates, and policy describes how available information is used to generate decisions. Feedback loops are the basic building blocks of the system. These are closed paths which link levels, decisions and the environment (Randers, 1980). A Systems Dynamics model will consist of multiple feedback loops, both positive and negative. The DYNAMO language allows easy implementation of models using this approach. The approach itself has been subject to much criticism, particularly concerning the mechanistic nature of the feedback. A new advance is Probabalistic Systems Dynamics which allows variables within the model to affect event probabilities[4].

Among micro to macro models of economies developed using the Systems Dynamics method, probably the most well known are the global models such as 'World Dynamics' (Forrester 1971) and the 'Limits to Growth' (Meadows et al 1972). Of more interest to the present study is the 'National Model of the U.S. Economy', of which one application has been the investigation of economic long waves (Sterman, 1985). Like the models

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[4] Morecroft (1983) discusses advances in Systems Dynamics.

described above this has as its basis a set of satisficing firms, in this case making decisions on the basis of rules of thumb, given the information available to them. Being a systems dynamics model this information is a series of feedback loops, by which firms adjust their production, inventory and investment decisions. The model also adds a random noise to the feedback to simulate chance events and non-included factors. The model is calibrated to simulate the major trends in the macro economic behaviour of the U.S. economy over long periods (1800-1984), (in contrast to the very short period analysis of Bennett and Bergmann op cit).

Having developed a model which displays the observed trends in the real system, Sterman uses it to investigate the sources of those trends. His conclusions are worth quoting. "The long wave is characterised by successive waves of overexpansion and collapse of the economy, particularly the capital-producing sector.......The explanation can be divided into two parts. First the internal structure and policies of individual firms tend to amplify changes in demand, creating the potential for oscillation in the adjustment of capacity to the desired level. Second, a wide range of self reinforcing processes significantly amplify the response of individual firms to changes in demand, increasing the amplitude and lengthening the period of fluctuations generated by each firm. Through the process of entrainment the fluctuations generated by individual firms become coherent and mutually reinforce one another" (Sterman, op cit pp110-111).

Without describing the detailed structure of the model we can see in this explanation of the long wave many of the characteristics of the Systems Dynamics method. Having constructed a model by which firms decide to change levels on the basis of past and current performance it is not surprising that this feedback should be the source of fluctuations. Equally the "self-reinforcing processes" seem an effect of the construction of the model. Thus the validity of Sterman's conclusions relies on the close correlation of the model to real world events. However as described above the choice of parameters is so complex that such correlation cannot be sufficient for validity. This again demonstrates the dangers of reading much into the empirical behaviour of simulations rather than focussing on behavioural aspects, though in this case this latter is somewhat constrained by the nature of Systems Dynamics itself. Perhaps Sterman's paper would be better titled 'A Description of the Economic Long Wave'.

6.7 Conclusion

We have seen that simulation models have a distinct role to play in the analysis of social systems, complementary to that of analytical models. It is most appropriate to those problems where we need to describe the situation of individual agents and what determines their particular decisions. In this way we can understand more intimately the workings of complete systems, such as an economy. Whilst simulation does have the advantage of generating complete information about what goes on in any simulation run, understanding the significance of the results is problematic. We have discussed the problems of validity and observed that this was to an extent dependant upon the use to which the model is put. In particular we note that use of simulation to generate empirically detailed predictions of real performance under various scenarios is fraught with danger. Simulation models are more reliable in enabling us to understand the qualitative nature of behavioural and system relationships.

These observations have not always been considered in the application of simulation models to economic problems. The attraction of a working model of the real system has proved very strong, leading some analysts to utilise their models for tasks which may be better tackled by more conventional means. Of the studies cited the more successful seem to be those which have attempted to further the understanding of disequilibrium systems, playing to the strengths of simulation.

In using simulation it seems that a careful description of the workings of the model, developing stage by stage through the hierarchical structure of the model, is the first step. Thus in developing our simulation model we must describe the behaviour of firms, then industries and then the economy as a whole. In this way we hope to understand the nature of the relationships within the model and thus the real system. At this stage we may begin to construct experiments, both static and dynamic, in order to gain some greater understanding of the behaviour of the system as a whole and perhaps the quantitative significance of various factors. These are the tasks for the next three chapters.

CHAPTER 7 THE SIMULATION MODEL

7.1 Introduction

Chapters 4 and 5 describe how firms and industries may be modelled in ways appropriate to our task of investigating technical change in an evolutionary economy. A wide range of possible features were mentioned. Our simulation model is based on that description, incorporating all of the essential elements, but not all of the possibilities mentioned there. In this chapter we describe the model and in chapters 8 and 9 we use it to investigate the process of technical change. A number of alternative versions of the simulation program are used in those chapters, and details of particular settings for each run are described there. Here we seek to describe the basic model. We begin with a detailed description of the behaviour of firms, industries and the economy as a whole. Finally we discuss, in section 7.5, an alternative structure for the model, to consider reasons why it proved not to be a fruitful approach. We refer to two appendices in this chapter. In an appendix to the chapter (page 228), we present a mathematical description of the model and of some of its properties, which complements the discussion in this chapter. Equations in that appendix are numbered A.* The computer simulation program is an appendix to the thesis as a whole.

7.2 The Structure of the Model

The simulated economy comprises three industries, each of which contains 10 firms. There is one consumption good and two capital goods. Homogeneous labour is in perfectly elastic supply at a fixed wage. All firms use homogeneous labour and capital of various types as their only inputs. The model uses discrete time periods within each of which a complete round of production, sales and investment takes place.

The principal objective of firms is to grow. The first decision the firm must make is to set its price. The firm's price helps determine two variables, its market share, which decreases as price increases, and profits, which, in the current period, increase as price increases. Firms make two decisions concerning output and capacity. First their current level of production, which is decided by rules of thumb, and second the level of investment, in either search or new capacity, which is equal to the maximum that can be purchased from current profits, supplemented by borrowing based on the firms relative rate of return. Thus in seeking to attain its objective the firm sets its price such as to increase market share as fast as possible, commensurate with acquiring sufficient capacity to satisfy demand. We now look at prices, market shares and demand/production in more detail.

<u>Prices</u> Two types of price are used within the model. We assume that each market is organised by a central marketing board. This board sells to all customers at a single ruling

market price (MP)[1], and it determines each firm's market share. Each firm within the industry determines for itself the price (FP) at which it will sell to the marketing board, based on a weighted average of a mark up of its costs and the current ruling market price. The weighting in this calculation reflects the degree of consumer loyalty/monopoly power we give the firm. The price mark up is determined by the extent to which the firm has adapted its capacity to its demand and to its plans for growth.

The market price is calculated as a share weighted average of the firm prices, so that the marketing board operates for nothing. This arrangement does introduce a number of undesirable elements of unreality into the simulation (eg. firms buying back their own output for more than they sold it for), but the alternative is to give each firm specific customers, adding complexity without enhancing our understanding of technical change.

<u>Market Shares</u> These are determined by the share in the previous period and the firms price relative to market price. Adjustment costs, as described in chapter 4, are the reasons for not allowing share to increase very rapidly for advancing firms. Firms are limited in their ability to absorb new capacity, and new processes.

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[1] Notation is given in section A1 of the appendix to this chapter.

Demand and Production At the start of each production period, each industry faces a known demand function for its product. Since prices are already set at the start of the period the total demand for the industry is also known. Each firm within the industry has also already been allocated a share of the demand. Thus the demand for each firm's product is already specified at the start of the period.

In making its production decisions, the firm operates a percentage of its capacity predetermined by its rules of thumb. The firm then meets its demand from current output with any difference met by an adjustment of stocks. Justification for this behaviour may be found by supposing various communication and organisational difficulties within the firm and in particular between the marketing and production departments.

Thus in this model prices and output are set prior to the start of each period, and it is stocks which adjust to match supply to demand. In particular stocks enable the firm to smooth the response to changing patterns of demand.[2]

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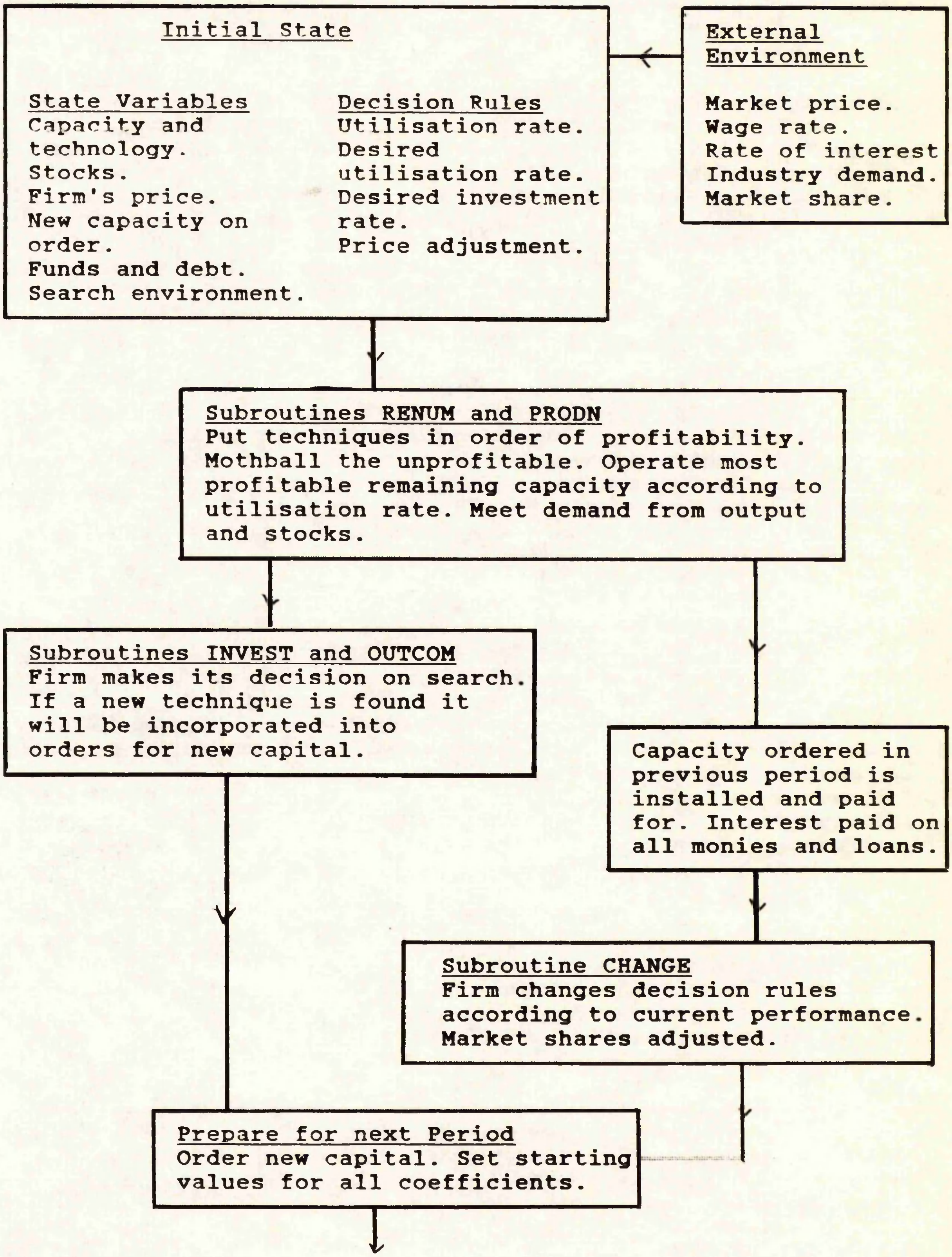
[2] Given the structure of the model, it would be possible to build in a recalculation of prices, and hence demands, if there were to be shortage of capacity in the industry overall. However in the simulation runs described later this feature was not needed and so was not developed.

Figure 7.1 Flow Chart of a Firm's Activities



Initial State

State Variables
Capacity and technology.
Stocks.
Firm's price.
New capacity on order.
Funds and debt.
Search environment.

Decision Rules
Utilisation rate.
Desired utilisation rate.
Desired investment rate.
Price adjustment.

External Environment

Market price.
Wage rate.
Rate of interest
Industry demand.
Market share.

Subroutines RENUM and PRODN
Put techniques in order of profitability. Mothball the unprofitable. Operate most profitable remaining capacity according to utilisation rate. Meet demand from output and stocks.

Subroutines INVEST and OUTCOM
Firm makes its decision on search. If a new technique is found it will be incorporated into orders for new capital.

Capacity ordered in previous period is installed and paid for. Interest paid on all monies and loans.

Subroutine CHANGE
Firm changes decision rules according to current performance. Market shares adjusted.

Prepare for next Period
Order new capital. Set starting values for all coefficients.

7.3 The Firm

The model of the firm used is based around two major decision processes. First, decisions about current output, investment and pricing. Second, changing specific decision rules from period to period according to given feedback mechanisms.

We distinguish a long period (a year) and 10 subperiods (months). The economy at the outset of each simulation run is set to grow at 5 percent per year. This can create problems for the smoothness of adjustments unless production and parameter changes are taken more slowly. The production cycle and investment in capacity take place each month, whilst search is limited to only one month per year. This allows the firm (ie. the program) to consolidate changes and to more smoothly carry out the development of the model economy. All activities begun in any month are also completed within that month.

The firm's initial state each month is governed by three main groups of variables as Figure 7.1 shows[3]. First, the external environment gives the ruling market prices, wage rate and demand facing the firm (contingent upon overall industry demand and the firm's share of it). Second, the economic and physical state of the firm is given by the quantity of, and technology embodied in, existing capital stock, the stocks of finished product and the funds the firm has available for

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[3] Subroutines are sections of the computer program in the final appendix.

investment. Third, the firm's current decision rules, determined by the firm's previous experiences, for deciding the percentage of capacity to be used, and hence output, the desired price mark up and the extent to which it is committed to following market prices, as distinct from strict mark up pricing.

At the start of the month for firm i in industry j, the first decision is to operate a given percentage of its capacity. The computer program first puts the N_{ij} processes available to the firm in rank order, from worst, (1), to best, (N_{ij}). The firm then mothballs, at zero cost, all capital which will not break even at current prices. The capital remaining now constitutes current capacity and it is upon this quantity that output decisions are based.

The output decision rules depend on two parameters. The firm's desired level of capacity utilisation (DU_{ij}), which it aims for in the long term, and the current level of utilisation (U_{ij}). The program uses only the latter in the actual production decision, the desired rate affecting changes in U_{ij} as described below. The desired rate is initially set at 90 percent utilisation in any year, the idea being that the firm cannot efficiently use its capital at 100 percent utilisation since this leaves no margin for breakdowns, unexpected surges of demand or whatever. Output in any month from a machine is at most 10% of its yearly capacity.

As shown in equation A.1, firm i,j's actual output is equal to its current utilisation rate (U_{ij}) times current capacity (C_{ij}). In the actual simulation the firm will use its most productive capital at 100% of capacity and may use less productive capital not at all, U_{ij} being the average across all current capacity. Additionally the firm produces some extra output to accumulate stocks appropriate to any increase in its capacity. It is able to do this even if utilisation is 100%. The production for stock accumulation is not reflected in the utilisation rate solely to simplify the feedback mechanisms in the program.

Having determined its output, the firm fulfills the demand for its products, given current market demand (D_j) and its market share (S_{ij}), with any shortfall from output being made up from stocks. The firm's initial level of stocks is set at 10% of yearly capacity.

If the firm cannot meet its demand without its stocks becoming negative the unmet demand is allocated pro rata with market shares to the other firms in the industry. The firm is then penalised by having its market share reduced by 10%, and shares for all firms are increased to compensate. Partly this is an artificial construct to enable the program to function, and partly it reflects two real world phenomena. First, given an unanticipated rush of orders, a firm may find that to meet contractual obligations it is forced to subcontract, or in this case buy up stocks from competitors. Second, in such an eventuality the firm's customers may well lose confidence, resulting in lost market share.[4] The level of destocking (DS_{ij}) perceived by the firm encompasses only any depletion of stocks to meet demand, and not any changes in stocks required to match any increase in capacity (equation A.3). The level of destocking will eventually feed back into utilisation rate and price markup.

The next stage of the program, but conceptually simultaneous with production, is the firm's search for new processes. The search process is very much as described in chapter 4 section 4.5 and there is some duplication of that description here, in order to avoid excessive cross referencing.

Firms engage in search activity in order to discover new, superior, production processes and techniques, which will allow them to increase profits and grow faster. We distinguish two types of search activity; basic research to discover a fundamentally new 'basic' production process and incremental research to make improvements to existing techniques, (based on an existing basic process). The simulation program explicitly models only incremental search. However, the outcome of that search may be a new basic process if the firm 'strikes it lucky'.

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[4] If the industry as a whole cannot meet the demand then the program stops (see note 2).

Figure 7.2 Basic and Incremental Innovations

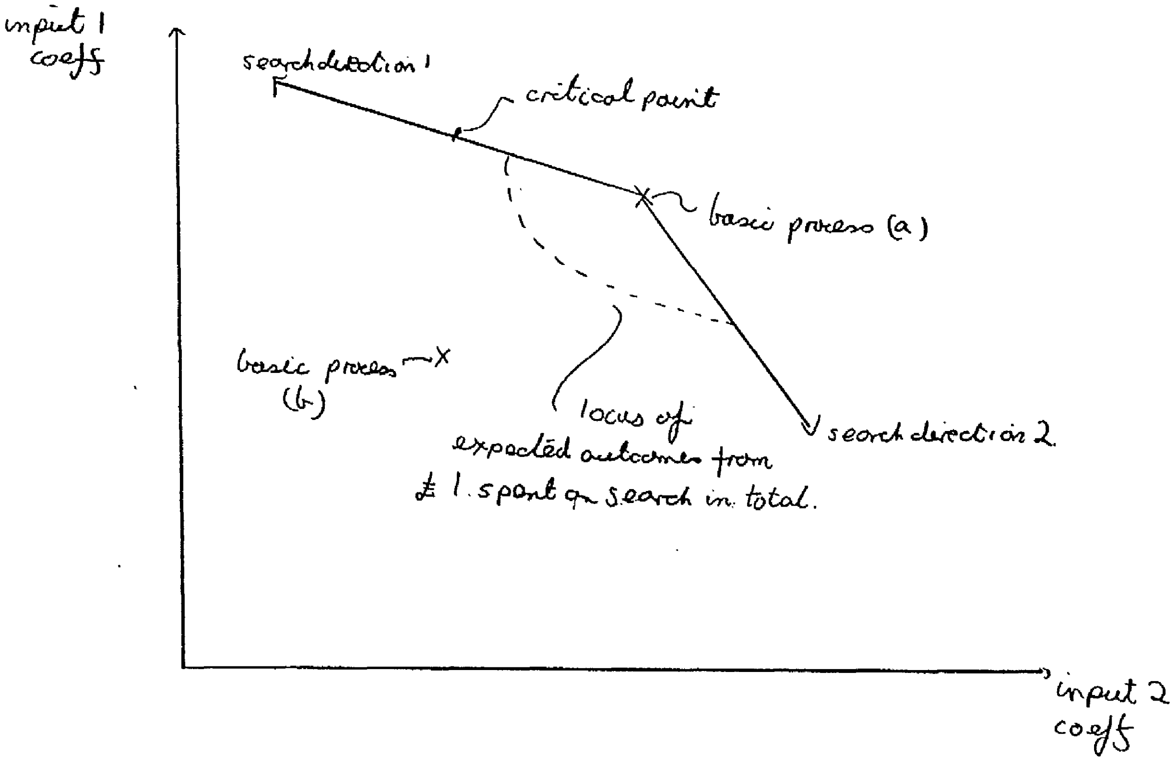
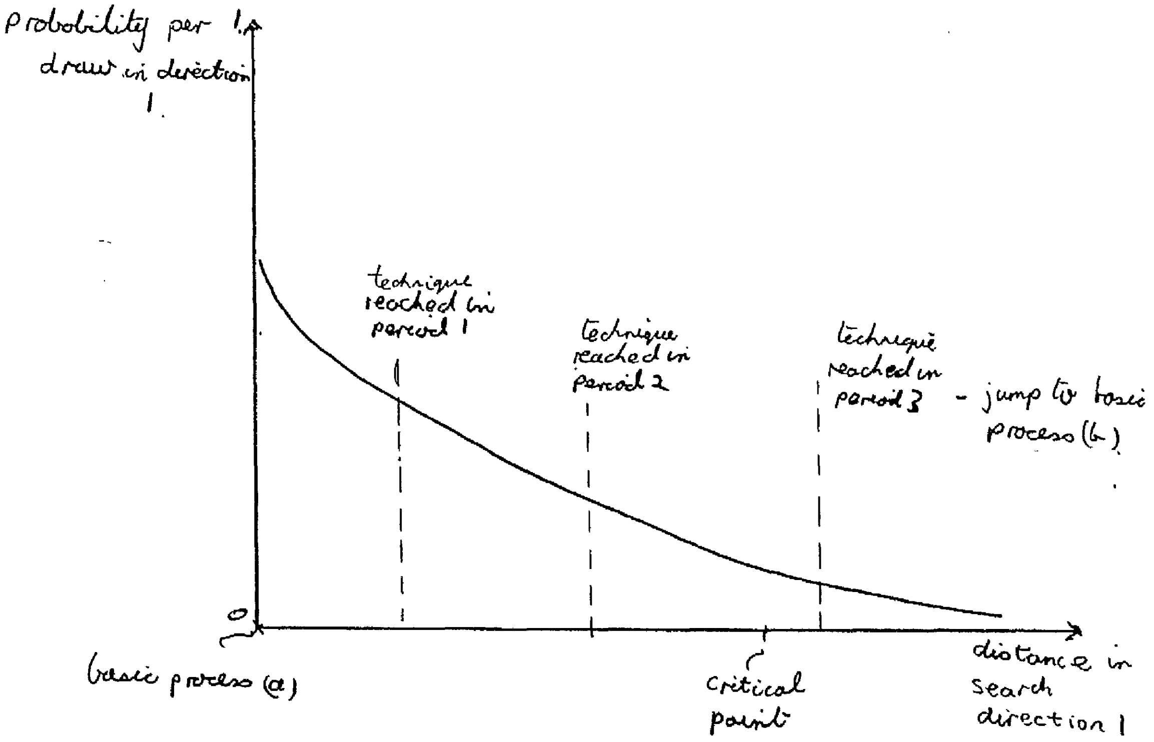


Figure 7.3 Cross Section of Figure 7.2: Incremental Search in Direction 1



Referring to figure 7.2, the firm is currently using basic process (a). It has available to it a number of lines of possible research, of which figure 7.2 shows two. The firm chooses the intensity of search in each of the possible directions on the basis of the search environment faced and expected prices and output over its time horizon. (The full range of search directions is described below).

The outcome of search is determined according to an exponential distribution, as illustrated by figure 7.3. In each period the origin of the probability distribution is the most productive basic process currently in use by the firm, in this case (a). The intensity of search in each period is modelled as the number of draws on the probability distribution, with the search outcome being the best technique reached. The firm pays a fixed amount per draw, determined by the type of technology it is investigating. In the program, search price increases as the technology in use by the firm advances.

As the firm engages in search over successive periods it will gradually achieve incremental improvements. The expected incremental improvement over the previous period gets less per draw as such improvements are attained. At any time all of a firm's new investment will be in its best currently available technique. In making its search calculations the firm will need to form expectations about the future course of prices. It would be possible to use one of the familiar expectations forming models from economic theory, such as rational or adaptive expectations. Our model uses the simplest of all approaches; that current market prices are expected to rule over the firm's planning horizon. This is adequate given the rates of change of prices which occur in the model and the length of the planning period (20 years). These features can be seen in equation A.6.

As well as seeking incremental improvements, by engaging in search activities in areas where the firm has some quantified expectations about the nature of possible outcomes, the firm when engaging in incremental search, also has the possibility of making a fundamental breakthrough. The firm perceives the ordinal nature of the probability density function for discovery of a new basic process, that more search increases the probability of success, but is not aware of the cardinal nature of the function. Thus the firm cannot make precise calculations of the optimal amount to invest in search taking this possibility into account. We model this by summarising the potential for fundamental breakthroughs in a single number, the firm's degree of optimism, which the firm uses to multiply the variance of the incremental search probability function, when making its search decision. Thus an optimistic firm will engage in more search than a pessimistic firm.

The firm is deemed to have attained a fundamental breakthrough if it reaches a predetermined distance along one (or more if desired) of the search directions. This distance is set by the parameter $PASS_{ij}$. On reaching such a critical point it then jumps to the next basic process, which it begins to invest in immediately. There is no need for the new basic process to have similar factor proportions to those sought by the firm. In figure 7.2, the firm pursuing search direction 1 seeks to substitute input 1 for input 2, but on discovering process (b) finds that it has managed to reduce both inputs.

Having reached such a point the firm is able to engage in further incremental research, starting with a clean slate from a new origin: the production coefficients of the new basic process. The mean and variance of search probability functions are set to be the same whatever basic process the firm is using. This can be changed however. One possibility is to reduce the mean and/or variance of the search probability function as new basic processes are discovered, to reflect the increased difficulty of research as technology becomes more complex. In the program the degree of difficulty in attaining a new basic process, $PASS_{ij}$, is increased with each successive basic process discovered.

An important area of policy in the field of research and innovation, is the use of a system of patents. Whilst our model does not incorporate any other policy tools, since analysis of policy is not our purpose, a system of patent rights is included in some simulation runs. Patent rights are awarded to the first firm to find any particular basic process. The holder of a patent receives, for a fixed period following its inception, a royalty per unit of capacity from each subsequent user of that basic process. The royalty is set each period as a fixed percentage of that period's market price.

The patent system has three important features. First, firms at the current forefront of technology now have the potential of earning royalties, and this encourages them to devote more resources to search. This is modelled by increasing the firm's degree of optimism when making its search decision. Second, the existence of the patent encourages the holder to disseminate the knowledge it contains, speeding the diffusion of the innovation through the industry. This is modelled by increasing the effective search variance for those firms not yet using the patent. This means that the diffusion process still takes time, and some firms may still not discover the patented process. Third, it redistributes funds to patent holders from the other firms in the industry. Since there are economies of scale in search activity, this will tend to increase industry concentration.

Turning now to the sequence of calculations made in the computer program. Each firm first makes a decision as to what fraction of its investment funds it will devote to new capacity and what fraction it will devote to search. To do this the expected outcome from an extra draw in each search direction is first calculated. There are six search directions as follows:

DIRECTION	INCREASED	DECREASED
1	K1	K2
2	K2	K1
3	K1	L
4	L	K1
5	K2	L
6	L	K2

For illustrative purposes we describe here only direction 1 in detail. Equation A.4 describes the expected outcome of an additional draw, whilst equations A.5 give the expected new coefficients. The parameter ϕ_1 determines the relative weight of changes in each of K1 and K2, and in common with the other search directions, was set at either 45 or 30 degrees as specified in chapters 8 and 9. Having calculated expected coefficients, the expected profit over the planning period is calculated for each search direction, as in equation A.6. If the best of these exceeds the current best expected profit, then the number of draws in that direction, for this period, is increased by one, funds for new capacity are reduced by the extra search cost and the sequence of calculations A.4 to A.6 is repeated. Once no additional draws are found to be profitable, the decision on search intensity is complete.

The next stage is to find the actual outcome from search. This involves drawing randomly the chosen number of times, on the appropriate probability distribution, a section of the program which uses routines from the National Algorithms Group Fortran library. The sequence of results may be found using either quasi-random numbers, specifying a chosen starting point in the sequence, or pure random numbers. For each search direction, the search outcome is the maximum value found from the current sequence of draws (equation A.7). If this exceeds the value already found by the firm in previous periods, in one or more search directions, then the firm is deemed to have found a new technique (equations A.8, A.9). On the basis of the search outcomes the program next determines whether or not a new basic process has been discovered. Equation A.11 shows this being achieved if the aggregate search result across all six search directions, is greater than the predetermined value $PASS_{ij}$.

Finally the new production coefficients are calculated. If only an incremental innovation has been made the method is the same as in equation A.5, using the actual search outcomes (equations A.10)). If a new basic process is discovered, then its coefficients may be given exogenously, or endogenously as those of the best technique found so far, using equations A.10 as before.

The process of search uses up resources, and these must be accounted for in the simulated economy. A firm expends its investment funds either on search or on new capacity. In the program both activities use the same combination of inputs. In effect search consists of building new plant and testing it to destruction. This may not be very realistic but it is as good a guess as any other as to the resource requirements of research projects. Thus the effect of search is to reduce the amount of new capacity actually installed by a fraction equal to the fraction of current investment funds devoted to search.

In the program the firm invests its available funds each month, and installs new capacity accordingly. However it engages in search only at the start of every year. This limits it to investing only 1/10 of all its investment funds in search, if problems of allocating funding from month to month , or of installing negative capacity in some months, are to be avoided. This constraint can be overcome if desired by allowing the firm to engage in search in two or more months. In engaging in search the firm has a time horizon over which it expects to reap the benefits of search. By changing the number of months in which search may occur, by changing the time horizon and by setting the mean and variance of search probability distributions it is possible to have firms spend widely varying fractions of their investment funds on research, allowing a wide range of experiments to be conducted.

The purpose of introducing the idea of a basic process has so far been presented as helping to allow the firm to experience the unforseen. The idea has a second benefit, in allowing learning to be introduced in a fairly uncomplicated way into the simulation. By learning we mean firms acquiring knowledge from others.

Learning may take two forms. First, learning by doing; the firm becomes more efficient the more it produces with a given process. This is most easily modelled by associating learning with use of a basic process. Output per unit of capital increases as total output from that process increases. The simulation program does not include this, since it would involve the creation of too many different levels of production process, making some of the arrays of coefficients too large to be easily handled with the computing facilities available to the author.

In the simulation learning occurs only from other firms, as new basic processes are discovered. This is supposed to be indicative of how far the firm is behind its competitors. The effect of learning is felt on both types of search, by increasing the variance of the search probability distributions. As in some other models of learning, the size of the learning effect for a firm, LR_{ij}, is positively related to the fraction, B_{ij}, of industry output produced using a superior basic process to those in use by the firm. Thus, where TCH is a parameter setting the size of the learning effect we have:

$$LR_{ij} = TCH*B_{ij} + 1$$

$$\text{effective variance} = \text{original variance}*LR_{ij}$$

The firm's investment in new capacity is a two stage process, which takes place before and after the assessment of current performance. At the end of the production phase, the firm takes delivery of capital ordered at the end of the previous period. The quantity of new capital ordered is equal to investment funds, plus interest (which is earned on all monies carried over from period to period), minus search expenditure and divided by the cost of each unit of capacity (equations A.19 and A.20 show this).

Once the new capacity is installed the firm moves on to monitor its current position. It can change its production and pricing rules. Equation A.2 shows the firm's price determined by a mark up of its production cost, ie. wages plus rental on capital, plus also a reflection of the prevailing market price. The production costs are a capacity weighted average of the costs of operating all current capacity. On the basis of its current performance a firm will assess, and may change, its decision rules. Current performance is assessed in two ways; by the extent to which it is running down stocks and the change in its market share.

Taking first the effect of stock changes, this is the analogue of responding to delivery lags in a continuous time model. The two adjustment mechanisms for output and price are shown in equations A.14 and A.15 respectively. Both utilisation and price markup adjust according to the current period's level of destocking (DS_{ij}). This arrangement, and the values of parameters yy and mm, are the result of experimentation, seeking stable, rapid adjustment paths. If the firm accumulating stocks were to meet demand conditions in accord with its long run investment plans, then the price markup π_{ij} will return to zero eventually. Sufficient rate of return to cover 'normal' investment for a growth rate of r is included as a cost. The rate of interest is described below.

The simulation model functions adequately with only the single feedback mechanism of destocking. The addition of a second feedback, the change in market share, increases the rate at which technical progress can be absorbed into the simulated economy, thereby increasing the range of simulation experiments that the program can carry out. The feedback from the change in market share works in two ways. A short run effect to improve the stability of the adjustment process, and a long run effect to make firms take more account of their growth prospects, particularly if they are expecting to increase their market share; higher growth requiring more planning than faster decline.

Acting on changes in market share makes a firm more responsive to its external environment, and is also more forward looking than attention to stock changes. Consider first the short term objective. A firm with a changing market share may feel it is likely to face a similar change in the future. Thus changes in capacity utilisation as a result of changing stocks may need to be reinforced according to the extent of the change in market share. The program incorporates this effect by increasing the parameter which adjusts capacity utilisation in response to stock changes, by an amount proportional to the change in market share. These adjustments are implemented via the parameter y3 in equation A.14.

The changes to plan for faster growth over the longer term affect only those firms whose market share has increased in the current period. At the start of each simulation run each firm has a desired rate of utilisation for its capacity of 90%. Faced with the expectation of being able to grow more quickly than its industry average, a firm feels able to take the risk of increasing its desired rate of capacity utilisation, even though this leaves it more open to failing to fulfill an unexpected surge in demand. Changes in a firm's market share are determined by the industry marketing board. The firm does not need to know all the details of the board's decision process, only that its market share depends on the price of its product, which in turn depends on production costs. Thus in the simulation the change in desired capital utilisation depends only on the fact that market share is rising.

The change in the desired utilisation rate is dependent on the ratio of market price to the firms current production costs (equation A.16). Costs are preferred to the firm's selling price here, since the latter may include a price markup, caused, say, by a temporary loss of stocks, whilst we are interested in the long term prospects which ultimately depend on underlying costs. The influence of the increase in desired capacity utilisation is felt in both output and pricing. The actual level of capacity utilisation is increased if it is currently less than the desired rate, (equation A.17). The effect on prices is to reduce the price markup if actual capacity utilisation is less than the desired rate (equation A.18). This will lead to greater profit and hence investment so long as the firms demand is price elastic, which it is given the parameter settings.

It would be easy to build into the model a stochastic element to determine the parameters governing firms' decision rules. This would be in line with the arguments for variety in behaviour discussed in chapters 4 and 5. This additional feature however, would make the interpretation of results much harder, and would add little to our understanding, and so is not included.

The final act of each month is to prepare for the start of the next. Capital ordered at the start of the month is installed. If desired, existing capital used during the current month may be reduced by some depreciation factor. Exponential depreciation is incorporated in some of the simulation runs. Reduced efficiency of capital as a consequence of use is much harder to include in the model, because this would lead to many more different qualities of machine in operation at any time which, necessitating a substantial increase in the amount of computing power required, probably beyond that readily available to the author.

The firm's price for the coming period is calculated (equation A.28 gives the price vector for the industry). The starting values of the various production coefficients are set equal to the end coefficients from the current period.

At the end of every year each firm is monitored to measure its productivity. Two measures are used, Total Factor Productivity and rate of return.

Firm's total factor productivity The approach taken is to measure total factor productivity for a firm in the first instance. The program can also look at a single technique within a firm if required. The two capital inputs to the firm are treated as separate machines whose efficiency is unchanged through the simulation run. The level of productivity of the firm is measured in period 1 as the ratio of the total value of output to the total value of inputs.

We recall that in the simulation there is a distinction between the price the firm sells at and the market price, which rules for customers. In measuring output value, the market price is used so that varying degrees of efficiency are reflected in the value of firms' total factor productivity. To produce its output the firm will not only use capital and labour, it may also have some capital in reserve, and it will also hold stocks, all of which need to be included in the calculation of the firms costs. Thus the formula for calculation of capital costs is that used in the calculation of costs for pricing purposes. In period 1 the firm's price is equal to its costs, and thus total factor productivity is calculated to be the ratio of market to firm price (equation A.23).

In all subsequent time periods, the program calculates the improvement in the firm's productivity and adds this to the existing level of total factor productivity. The change in productivity is calculated as the difference between the proportional change in output and the Divisia weighted changes in the quantities of inputs (equation A.24). The weights are given by the fraction of total input costs going to each input (equations A.22). The input quantities used in the calculation of the weights are the average of those used in the current and previous periods, and the prices used are those ruling at the start of the period (equations A.21), as suggested by Usher (1980).

Rate of return The rate of return is calculated first for each technique, as the market price minus the unit labour cost divided by the value of capital stocks used to produce unit output (equation A.27). The technique rates of return are weighted by the techniques' shares in the firm's total capital value to calculate the average rate of return for the firm.

The prices used in this calculation may be the current prices if the result is to be used for monitoring the firm's current performance, or those ruling at the start of the simulation to monitor the effects of technical progress (equation A.27).

7.4 The Industry and the Economy

An industry is characterised by three variables, the current market price, the total demand for its products and the vector of market shares for the constituent firms. The nominal control of industry wide activities is in the hands of a marketing board. No formal marketing organisation is included within the model, but its actions in setting prices, redistributing stocks, allocating market shares, making payments to firms and receiving customer payments are included at various stages throughout the simulation.

The industry demand function is given by either equation A.30 (consumer good) or A.31 (capital good). For the consumer good, demand depends on the total wages carried over from the previous period, and the current market price. In this case the market elasticity of demand is -1. For each capital good industry, demand depends on the total profits carried over and the prices of both capital goods. The individual industry elasticity of demand is thus inelastic, the degree depending on the proportion of capital spending which the industry accounts for.

The market price is a weighted average of the firms' prices (equations A.28, A.29). The shares used to calculate the next period's market price are those of the current period. (Once market shares for the next period have been calculated it would then be possible to recalculate the market price, to take account of new capacity installed, although our program does not do this). The extent to which market price reflects current production costs is determined by the monopoly power of each firm (and thus the extent to which firm prices can differ from market price). The simulation starts with each firm being allocated a given share of industry demand. At the end of the period each firm's performance is assessed for its efficiency, measured solely by the firm's price. The market share of firms is adjusted according to their changing relative prices (equation A.32). As noted above the firm's market share is also adjusted if it cannot meet its demand.

The adjustment mechanisms described above mean that the time path of prices is a second order difference equation, as described by equation A.33. There is no equation for aggregate industry demand, but equation A.34 gives the vector of industry outputs over time. The time paths of output and prices are interdependent, which contributes to the economic realism of the model.

The final phase of industry activity is to monitor performance.

Industry Total Factor Productivity In each period the industry level of total factor productivity is calculated as the weighted average of each firms' productivity, the weights being the market share of each firm during the current period (equation A.35).

Rate of Return The industry rate of return is the weighted average of firm rates (equation A.36). The weights used in this calculation are the firms' shares of the total value of capital used in the industry, as suggested by Soete and Turner (1984).

There are only two variables of economy wide significance, the wage rate and the rate of interest. Both the wage rate and rate of interest are given during any period. Each may be held constant throughout a simulation run, as is usually the case in the results reported below, or it may be allowed to increase according to some rule, for example in line with productivity or economic growth. The economy can also be monitored for the overall economic performance, as measured by total factor productivity and rate of return. Economy wide total factor productivity is calculated as the average of the industry levels, weighted by their shares of Gross Domestic Product. The economy wide rate of return is calculated as the industry levels weighted by their shares of the total value of the capital stock in the economy.

7.5 An Alternative Structure for the Simulation Model

Two fundamentally different possibilities for the structure of our model were considered. In that described above prices and outputs are set by firms on the basis of feedback from current performance. The feedback introduces a strong element of stability into the model, since the extent of fluctuations in output and price are strictly limited. There is much evidence to show that firms do operate in this way in the real world, so that this approach does not suffer from lack of realism in this respect. The consumers then make their decisions on the basis of the ruling price, with stocks adjusting to clear the market each period.

An alternative approach is to model markets as reaching an equilibrium each period. Firms make supply decisions on the basis of expected prices, and then put all their supply on to the market. Consumers and investing firms come to the market with their funds available to spend. The market price then adjusts to clear the market. A three sector simulation model, (two capital, one consumption good), based on this system was developed as part of this study. In an extremely stylised scenario, in which each industry had 10 identical firms, with no technical progress, and with all starting capacities, demands and prices set to appropriate levels, it did prove possible to set the model economy along a sustained path of balanced growth. However any slight deviation from the balanced growth path resulted in complete instability with prices going to zero or infinity within a very few periods. Experimentation determined that the source of the problem was the existence of two capital goods, consumed in fixed proportions by each investing firm. There was no problem with a one capital good model. The theoretical underpinning of the problem would seem to be related to the dual instability problems in dynamic input output models (Jorgenson (1961), Woods (1978)). The lesson for the simulation of evolutionary change is to ensure that the potential for violent change within the model is strictly limited.

APPENDIX TO CHAPTER 7: A MATHEMATICAL DESCRIPTION OF THE MODEL

In this appendix we first give a mathematical description of the basic features of the simulation model. This is intended to clarify the text of Chapter 7, and so covers only the key features of the model. We next analyse some basic properties of the model complementing the discussion of chapters 4 and 5.

A7.1 Notation

(i) General Points

n refers to a process throughout

i refers to a firm throughout

j refers to an industry throughout

For convenience the same letter(s) may refer to elements, vectors or matrices, the number of subscripts indicating which is meant. The maximum number of subscripts which may be assigned to any letter(s) is given below. All vectors are defined as columns. ^ indicates a diagonal matrix.

(ii) Roman Notation

A_{ijs} = variance of search distribution

B_{ijs} = mean of search distribution

$BASIC_{ij}$ = number of basic processes found

C_{nij} = capacity of a process

C_{ij} = capacity of firm

C_j = $10*N_{max}$ matrix of process capacities

dd = adjustment parameter for utilisation rate

D_j = industry demand

DR_{ijs} = number of draws in search direction s

DS_{ij} = current destocking

DU_{ij} = desired rate of capacity utilisation

e = unit vector

FP_{ij} = firm's price for its product

GTD_{ijs} = total draws so far (with current basic process)

H_{ij} = degree of optimism (hope) for basic discovery

HOR = time horizon

IF_{ij} = investment funds

$K1_{nij}$ = coefficient for capital good 1 for a process

$K1_{Nj}$ = vector of capital good 1 coefficients of the best processes available to firms

$K1_E$ = value of K1 expected given current search level

$K2_{nij}$ = coefficient for capital good 2 for a process

$K2_{Nj}$ = vector of capital good 2 coefficients of the best processes available to firms

$K2_E$ = value of K2 expected given current search level

L_{nij} = labour coefficient of a process

L_{Nj} = vector of labour coefficients of the best processes available to firms

L_E = value of L expected given current level of search

LR_{ij} = learning factor

mm = adjustment parameter for price markup

$m3$ = adjustment parameter for price markup

$m4$ = adjustment parameter for price markup

MP_j = market price

N_{ij} = number of processes in use by a firm

N_{max} = maximum of all N_{ij} (used to size matrices, eg. see C_j above)

$PASS_{ij}$ = parameter for the difficulty of basic discovery

PE_s = profit over the planning period for search direction s

Q_{ij} = current output

r = rate of interest

R_{ij} = firm rate of return

R_j = industry rate of return

S_{ij} = change in market share

$SCST_{ij}$ = current search cost

ST_{ij} = stock of final product

ss = adjustment parameter for market shares

TC_{ij} = total capacity

TFP_{ij} = firm total factor productivity

TFP_j = industry total factor productivity

$TK1_{ij}$ = total use of K1

$TK2_{ij}$ = total use of K2

TL_{ij} = total use of L

U_{ij} = utilisation rate

V1,V2, VL = Divisia weights

W = wage rate

X_{sd} = outcome of draw d in search direction s

X_s = final attainment in search direction s

yy = adjustment parameter for utilisation rate

y3 = adjustment parameter for utilisation rate

ZZ_{ij} = firm's original price markup, on the basis that it will require profits to expand capacity at a constant desired rate

Z1,Z2 = rental prices for capital

(iii) Greek Notation

α_j = weighting of MP_j in calculation of FP_{ij}, $0 \leq \alpha \leq 1$

β = weighting in the calculation of DU_{ij}, $0 \leq \beta \leq 1$

δ_{ij} = Kroneker delta

δ = vector of Kroneker deltas

π_{ij} = price markup over and above ZZ_{ij}

ϕ_{ijs} = direction of search

A7.2 Description of a Typical Firm, i, in Industry, j

(i) Initial decisions and outcomes

$$Q^t_{ij} = U^t_{ij} C^t_{ij} \qquad \text{A.1}$$

$$FP^t_{ij} = \alpha_j MP^{t-1}_j + (1 - \alpha_j)(1 + \pi^t_{ij}) \left[\sum_{n=1}^{N_{ij}} [W.L_n + \frac{r}{ZZ_{ij}} \{MP^t_1 K1_n + MP_2 K2_n\}] \frac{C^t_n}{TC^t_{ij}} \right] \qquad \text{A.2}$$

$$DS^t_{ij} = Q^t_{ij} - S^t_{ij} D^t_j \qquad \text{A.3}$$

(ii) Marginal Search in Direction 1

We omit the i and j subscripts in this section for clarity.

$$E(\Delta X_1) = B_1 + \left[\sum_{v=1}^{GTD+1} \frac{1}{V} \right] A_1 H.LR - X^{t-1}_1 \qquad \text{A.4}$$

$$E_1(K1) = (1 + \sin(\phi_1)) \left[\frac{E(\Delta X_1)}{X_1 + 100} + 1 \right] K1_E \qquad \text{A.5a}$$

$$E_1(K2) = (1 - \cos(\phi_1)) \left[\frac{E(\Delta X_1)}{X_1 + 100} + 1 \right] K2_E \qquad \text{A.5b}$$

$$E_1(L) = L_E \qquad \text{A.5c}$$

$$E(PS_1) = \left[\frac{FP^t - r[MP_1^t E_1(K1) + MP_2^t E_1(K2)] - WE_1(L)}{MP_1^t E_1(K1) + MP_2^t E_1(K2)} \right] * \left[IF.HOR - SCS \right] \qquad A.6$$

(iii) Search outcomes

We continue to omit the i and j subscripts, except where there is possible ambiguity.

$$X_s^t = \max\{X_s^{t-1}, x_s 1 \ldots\ldots x_{sDRS}\} \qquad s = 1\ldots6 \qquad A.7$$

$$P(X_s) = \max \left[0, \frac{X_s^t - X_s^{t-1}}{X_s^{t-1} + 100} \right] \qquad s = 1\ldots6 \qquad A.8$$

$$\text{Iff} \quad \sum_{s=1}^{6} P(X_s^t) > 0 \quad \text{then implement equations A.10} \qquad A.9$$

$$N_{ij}^{t+1} = N_{ij}^{t} + 1 \qquad A.10a$$

$$K1_{Nij}^{t+1} = K1_{Nij}^{t} \left[1 + P(X_1)\sin(\phi_1) - P(X_2)\cos(\phi_2) + P(X_3)\sin(\phi_3) - P(X_4)\cos(\phi_4) \right] \qquad A.10b$$

$$K2_{Nij}^{t+1} = K2_{Nij}^{t} \left[1 - P(X_1^t)\cos(\phi_1) + P(X_2^t)\sin(\phi_2) + P(X_5^t)\sin(\phi_5) - P(X_6^t)\cos(\phi_6) \right] \qquad A.10c$$

$$L_{Nij}^{t+1} = L_{Nij}^{t} \left[1 - P(X_3^t)\cos(\phi_3) + P(X_4^t)\sin(\phi_4) - P(X_5^t)\cos(\phi_5) + P(X_6^t)\sin(\phi_6) \right] \qquad A.10d$$

$$\text{Iff} \quad \sum_{s=1}^{6} X_s^t > PASS_{ij} \quad \text{then implement equations A.12} \qquad A.11$$

$$X_s^t = 0 \qquad s = 1\ldots6 \qquad A.12a$$

$$BASIC_{ij}^{t+1} = BASIC_{ij}^{t} + 1 \qquad A.12b$$

$$GTD_{ijs} = 0 \qquad s = 1\ldots6 \qquad A.12c$$

(iv) Parameter changes applying to all firms

$$\Delta S_{ij}^{t} = S_{ij}^{t+1} - S_{ij}^{t} \qquad \text{A.13}$$

$$U_{ij}^{t+1} = U_{ij}^{t} - yy(1 + y3\,|\Delta S_{ij}^{t}|)\frac{DS_{ij}^{t}}{TC_{ij}^{t}} \qquad \text{A.14}$$

$$\Pi_{ij}^{t+1} = \Pi_{ij}^{t} - \frac{mmDS_{ij}^{t}}{TC_{ij}^{t}} + m4\left(0.2 - \frac{ST_{ij}^{t}}{TC_{ij}^{t}}\right) \qquad \text{A.15}$$

$$DU_{ij} = 0.09\left[\frac{\beta FP_{ij}}{(1 + \Pi_{ij}^{t+1})\ MP_{j}^{t+1}} + (1 - \beta)\right] \qquad \text{A.16}$$

(v) Parameter changes applying only to firms for which both $\Delta S_{ij}^{t} > 0$ and $DU_{ij}^{t+1} > U_{ij}^{t+1}$ are true

$$U_{ij}^{t+1} \Longleftarrow U_{ij}^{t+1} + dd(DU_{ij}^{t+1} - U_{ij}^{t+1}) \qquad \text{A.17}$$

$$\Pi_{ij}^{t+1} \Longleftarrow \Pi_{ij}^{t+1} - m3\,|\Pi_{ij}^{t+1}|\left(\frac{DU_{ij}^{t+1}}{U_{ij}^{t+1}} - 1\right) \qquad \text{A.18}$$

(vi) Final capacity

$$IF_{ij}^{t+1} = (1 + r)\left[FP_{ij}^{t}Q_{ij}^{t} - \sum_{n=1}^{N_{ij}} U_{ij}^{t}W.L_{n}^{t}C_{nij}^{t}\right] \qquad \text{A.19}$$

$$C_{ij}^{t+1} = C_{ij}^{t} + \frac{(1 + r)\left[FP_{ij}^{t-1}\ Q_{ij}^{t-1} - \sum_{n=1}^{N_{ij}} U_{ij}^{t-1}\ W.L_{n}^{t-1}\ C_{n}^{t-1}\right]}{MP^{t+1}\ K1_{Nij} + MP_{2}^{t+1}\ K2_{Nij}} \qquad \text{A.20}$$

(vii) Monitoring performance

$$Z1^{t} = \frac{rMP_{1}^{t}}{ZZ_{ij}} \qquad Z2^{t} = \frac{rMP_{2}^{t}}{ZZ_{ij}} \qquad \text{A.21}$$

$$V1^{t} = \frac{TK1_{ij}^{t-1}\ Z1^{t}}{TK1_{ij}^{t-1}\ Z1^{t} + TK2_{ij}^{t-1}\ Z2^{t} + TL_{ij}^{t-1}\ W} \qquad \text{A.22a}$$

$$V2^{t} = \frac{TK2_{ij}^{t-1}\, Z2^{t}}{TK1_{ij}^{t-1}\, Z1^{t} + TK2_{ij}^{t-1}\, Z2^{t} + TL_{ij}^{t-1}\, W} \qquad A.22b$$

$$VL^{t} = \frac{TL_{ij}^{t-1}\, Z1^{t}}{TK1_{ij}^{t-1} Z1^{t} + TK2_{ij}^{t-1} Z2^{t} + TL_{ij}^{t-1}\, W} \qquad A.22c$$

$$TFP_{ij}^{1} = \frac{MP_{j}^{1} U_{ij}^{1} C_{ij}^{1}}{TK1_{ij}^{1} Z1^{1} + TK2_{ij}^{1} Z2^{1} + TL_{ij}^{1}\, W} \qquad A.23$$

$$\triangle TFP_{ij}^{t} = \frac{U_{ij}^{t} C_{ij}^{t} - U_{ij}^{t-1}\, C_{ij}^{t-1}}{0.5(U_{ij}^{t} C_{ij}^{t} + U_{ij}^{t-1}\, C_{ij}^{t-1})} - \frac{V1(TK1_{ij}^{t} - TK1_{ij}^{t-1})}{0.5(TK1_{ij}^{t} + TK1_{ij}^{t-1})}$$

$$- \frac{V2(TK2_{ij}^{t} - TK2_{ij}^{t-1})}{0.5(TK2_{ij}^{t} + TK2_{ij}^{t-1})} - \frac{VL(TL_{ij}^{t} - TL_{ij}^{t-1})}{0.5(TL_{ij}^{t} + TL_{ij}^{t-1})} \qquad A.24$$

$$TFP_{ij}^{t} = \triangle TFP_{ij}^{t} + TFP_{ij}^{t-1} \qquad A.25$$

$$R_{nij}^{t} = \frac{MP_{j}^{1} - WL_{nij}^{t}}{MP_{1}^{1} K1_{nij}^{t} + MP_{2}^{1} K2_{nij}^{t}} \qquad A.26$$

$$R_{ij}^{t} = \sum_{n=1}^{N_{ij}} \frac{R_{nij}^{t} (MP_{1}^{1} K1_{nij}^{t} + MP_{2}^{1} K2_{nij}^{t}) C_{nij}^{t}}{\sum_{n} (MP_{1}^{1} K1_{nij}^{t} + MP_{2}^{1} K2_{nij}^{t}) C_{nij}^{t}} \qquad A.27$$

A7.3 Description of a Typical Industry, j

(i) Initial state

$$FP_{j}^{t} = \alpha_{j} eMP_{j}^{t-1} + (1 - \alpha_{j}) \Big[\delta [W.L_{j} + rZ_{j} (MP_{1}^{t-1}\, K1_{j} +$$

$$MP_{2}^{t-1}\, K2_{j}) C_{j}^{t}\,'] (e + \pi_{j}^{t}) \Big] \qquad A.28$$

$$MP_{j}^{t} = S_{j}^{t-1}\,'\, FP_{j}^{t} \qquad A.29$$

$$D_{0}^{t} = \sum_{j=0}^{2} (1 + r) W.U_{j} \Big[\delta (L_{j} C_{j}\,')^{t-1} e \Big] \frac{1}{MP_{0}^{t}} \qquad A.30$$

$$D_{a}^{t} \underset{a=1,2}{} = \sum_{j=0}^{2} (1 + r)\left[FP_j^{t-1}\ \hat{Q}_j^{t-1} - \delta W\ U_j^{t-1}{}'(L_j C_j^{t-1}{}')\right] \left[MP_1^t K1_{Nj} \overset{\wedge}{+} MP_2^t K2_{Nj}\right]^{-1} Ka_{Nj} \qquad \text{A.31}$$

(ii) Time paths

$$S_j^t{}' = S_j^{t-1}{}'\left[I + \frac{ss(e\overset{\wedge}{MP}{}_j^t - FP_j^t)}{MP_j^t}\right] \qquad \text{A.32}$$

$$MP_j^{t+1} = S_j^t{}'\left[\alpha_j e.MP_j^t + (1 - \alpha_j)[\delta(W.L_j + r.\hat{ZZ}_j^{-1}(MP_1^t K1_j + MP_2^t K2_j)C_j^t{}')]TC_j^{t-1}(e + \pi_j^t)\right] \qquad \text{A.33}$$

$$Q_j^{t+1} = \left[C_j^t{}' + (1 + r)[FP_j^{t-1}{}'\ \hat{Q}_j^{t-1} - W\delta U_j^{t-1}{}'(L_j C_j)^{t-1}]\ [MP_1^t K1_{Nj} \overset{\wedge}{+} MP_2^t K2_{Nj}]^{-1}\right]\left[U_j^t - yy\widehat{TC}_j^{t-1} DS_j^t\right] \qquad \text{A.34}$$

(iii) Industry Productivity

$$TFP_j^t = \sum_i TFP_{ij}^t S_{ij} \qquad \text{A.35}$$

$$R_j^t = \frac{\sum_i R_{ij}^t \sum_n (MP_1^i K1_{nij} + MP_2^i K2_{nij})C_{nij}}{\sum_i \sum_n (MP_1^i K1_{nij} + MP_2^i K2_{nij})C_{nij}} \qquad \text{A.36}$$

A7.4 Properties of the Simulation Model

Our model is designed to include realistic firm behaviour, chance and disequilibrium. As such, it is not really designed to yield insight from a full mathematical description of its properties. However, in order to enhance our understanding of our simulation results, and to place the model more clearly in the context of the literature considered in chapters 1 to 5, in this section we describe more fully some simplified special cases of the model. Results for the most simple cases are fully worked out. As we introduce more complexity, the intractability of our behaviourally realistic assumptions quickly becomes a problem. We then indicate the direction in which further mathematical description would go, preferring to describe the full model using simulation runs.

(i) Time Paths of Output and Prices Throughout this section we assume:

a) all firms operate a single output decision rule, $U = 1$. In this case we can ignore stocks completely;
b) perfect knowledge;
c) price markup always adjusts to clear the market;
d) all firms in an industry operate the same technology which is unchanging.

Thus all firms in an industry charge the same price, and market shares are constant. We can treat the industry as a single firm, and need examine output and prices at the industry level only.

Variable names are as given in A.1 except:

(a) $FP = MP = P$;

(b) x is a vector pertaining to capital goods

X is a matrix pertaining to capital goods

x_0 is a scaler pertaining to the consumption good

X_0 is a vector pertaining to the consumption good.

Consider first demand for capital goods. This comes from the capital goods sectors themselves, and from the consumption goods sector. The latter, from equations A.30, A.31, A.34, equals in value the wage payments paid in the previous period in the capital goods sector. Because prices adjust to clear the markets, we can eliminate the prices of capital goods themselves from equation A.34, to give:

$$q(t) = K(q(t+1)-q(t)) + (q_0(t+1) - q_0(t))K_0 \tag{A.37}$$

$$q(t+1) = K(q(t+2)-q(t+1)) + \frac{(1+r)wl'q(t)K_0}{p'K_0} \tag{A.38}$$

Consider first the case of balanced growth at rate g.

$$(1+g)q(t) = K\{(1+g)^2 q(t) - (1+g)q(t)\} + \frac{(1+r)wl'q(t)K_0}{p'K_0}$$

and so

$$(1+g)\{I - gK\}q(t) = \frac{(1+r)wl'q(t)K_0}{p'K_0} \tag{A.39}$$

This represents balanced growth within the capital goods sector. If the consumption goods sector grows at the same rate then from A.37

$$\{I - gK\}q(t) = gK_0 q_0(t) \tag{A.40}$$

That is the capital goods demanded by the consumption goods sector, to maintain its growth rate, are exactly those available after the capital goods sectors own investment programme. Finally

$$q(t) = \{I - gK\}^{-1} gK_0 q_0(t)$$

$$q(t) = [\{I - gK\}^{-1} gK_0]^t q_0(0) \tag{A.41}$$

The balanced growth path is determined by the total direct and indirect capital requirements of the consumption sector.

Turning to prices, the dual of equation A.37 is

$$p(t+1)' = rp(t)'K - (p(t+1) - p(t))'K + wl' \qquad A.42$$

$$p(t+1)' = p(t)'(1+r)K\{I + K\}^{-1} + wl'K\{I + K\}^{-1} \qquad A.43$$

For the consumption good

$$p_0(t+1) = rp'(t)K_0 - (p(t+1) - p(t))'K_0 + wl_0 \qquad A.44$$

Along a balanced growth path prices will be constant for a given numeraire.

$p(t+1) = p(t)$ and $p_0(t+1) = p_0(t)$

Hence in this case

$$p' = wl'(I - rK)^{-1} \qquad A.45$$

$$p_0 = rp'K_0 + wl_0 \qquad A.46$$

Equation A.46 means profits per unit of output of $rp'K_0$, and hence demand for capital goods of rK_0 per unit of output in A.40 and thus for balanced growth with constant prices, $r = g$. In the open dynamic input output model, as discussed in chapter 2, the growth rate is determined by the growth in final demand. In our model, growth rate on a balanced growth path is determined by the rate of interest.

In the non-balanced growth case, the time paths of output and prices for the capital goods sector are given by the simultaneous system of A.38 and A.42. This system exhibits instability, as described in chapter 7 section 7.5, if the assumptions made in this section hold. Our simulation model functions because firms exhibit inertia in both pricing and output, with stock changes allowing production to differ from demand in any period.

<u>(ii) Competitive Selection</u> Throughout this section we consider a single industry. We assume:

a) all firms operate a single output decision rule, $U = 1$. In this case we can ignore stocks completely;

b) perfect knowledge;

c) price markup always adjusts to clear the market;

d) market demand grows at a constant rate g^*. Firm i's capacity grows at rate g_i.

MP = market price of the product

FP_i = firm i's price

p = vector of capital goods prices

K_i = capital coefficients for firm i

x^a = share weighted industry average of x

Δx = change in x

<u>Each firm uses only a single technology</u> The first case we consider is when each firm has a single process, which it cannot change. This corresponds to the no imitation, no

innovation case discussed in chapter 5. Selection means the most productive firms increase market share.

Consider first the case when the adjustment parameter for change in market share, ss, is infinite, ie. perfect competition exists.

$$g_i = (MP - wl_i)/P'K_i \qquad \text{A.47}$$

$$MP = g^* P'K^a + wl^a \qquad \text{A.48}$$

$$\sum S_i g_i = g^* \qquad \text{A.49}$$

$$g_i = (MP - wl_i)/P'K_i = (g^* P'K^a + wl^a - wl_i)/P'K_i \qquad \text{A.50}$$

From A.50 we see that the firm's growth rate will differ from the industry average, according to the difference in its costs from average. Thus

$$g_i = g^* + \Delta S_i/S_i \qquad \text{A.51}$$

$$\Delta S_i = S_i \{g_i - g^*\} \qquad \text{A.52a}$$

$$S_i = 0 \text{ if } MP < wl_i \qquad \text{A.52b}$$

From A.50 and A.52 we find for viable processes

$$\Delta S_i = \frac{S_i}{p'K_i}[(g^* p'(K^a - K_i) + w(l^a - l_i)] \qquad \text{A.53}$$

That is the proportionate change in market share equals the proportionate difference in costs. We next examine the effect of selection on industry average costs (MP).

$$MP = \sum S_i (g^* p'K_i + wl_i) \qquad A.54$$

For a firm only share changes given our assumptions. We find

$$\Delta MP = \sum \Delta S_i (g^* P'K_i + wl_i) \qquad A.55$$

Substituting in from A.53

$$\Delta MP = \sum \frac{S_i}{p'K_i} [(g^* P'(K^a - K_i) + w(l^a - l_i)](g^* P'K_i + wl_i) \qquad A.56$$

$$\Delta MP = \sum \frac{S_i}{p'K_i} [MP - (g^* P'K_i + wl_i)](g^* P'K_i + wl_i) \qquad A.57$$

That is $\Delta MP = -\sum \frac{S_i}{p'K_i}$ x variance of costs. Thus equation A.57 corresponds to the fundamental equation of evolution described in chapter 5. $1/P'K_i$ is the cost of a unit of capital equipment and is thus the propensity to grow per unit of profit. From A.57, MP is falling so long as the variance in industry costs is non zero. In this case eventually all but the most productive process will become obsolete.

We can relax our assumptions in a number of ways.

<u>Imitation</u> In this illustration of the impact of imitation, we consider the growth of processes rather than of firms in the first instance. However firms still invest in the best process they have available, as in the full simulation model. We do not consider our search model directly. For simplicity we assume that the probability that a process will be in use by a firm, increases as the share of total industry capacity devoted to that process increases.

Processes available are ordered from 1 (best) to n (worst). S_j is the share of capacity using process j or better.

Thus

$$g_n = (1 - S_n)(MP - wl_n)/p'K_n \qquad A.58$$

$$g_j \leq (1 - S_j)(MP - wl_j)/p'K_j \qquad A.59$$

Strict equality will hold in A.59 only if all firms investing in process j have it as their only process. If not they will be earning profits from inferior processes, and g_j will be consequently reduced. Treating A.59 as an equation, tantamount to assuming disembodied technical progress, and substituting into equation A.47, we see that imitation speeds up the selection process, without fundamentally altering it.

<u>ii)Less than perfect competition</u> In this case firm price may differ from market price. We assume that the firm adjusts its price to keep capacity equal to its demand. The growth in capacity equals the growth in demand. We have therefore from equations A.32, A.47, A.48 and A.51

$$g_i = \frac{(FP_i - wl_i)}{p'K_i} = g^* + \frac{\Delta S_i}{S_i}/S_i \qquad A.60$$

$$g_i = g^* + ss\frac{(MP - FP_i)}{MP} = \frac{(MP - wl^a)}{p'K^a} + ss\frac{(MP-FP_i)}{MP} \qquad A.61$$

We saw in equation A.50 that with perfect competition the increase in share is dependent on its proportional cost advantage. In the case of each firm having complete customer loyalty, effectively being a monopolist, share is constant and FP differs from MP in the same proportion as the firm differs from average production costs, and selection does not operate. In the intermediate case, $0 < ss < \infty$, the selection process operates, but is slower than in perfect competition.

CHAPTER 8 THE BEHAVIOUR OF THE MODEL

8.1 Introduction

In this chapter we describe the outcomes from various simulation runs. The purpose is to understand how our model functions and thereby to begin our description of the course of economic evolution. This will enhance our understanding of technical change in two ways, as discussed in chapter 6. First, we will see that our model does give plausible results, so that it, and the theoretical understanding it is based on, gain in plausibility; simulation is affirmative. Second, we will have a fuller understanding of the relationships within the model, and thus to some extent the real system, in that our simulation will suggest one possible way in which economies develop.

The dividing line between the subject matter of this chapter and the next is a fine one. Essentially in this chapter we seek to describe separate elements of the model, with relatively tightly controlled experiments, involving technical change in only one firm or industry at a time. We focus on the individual firm and its interactions with the others in its industry. In the next chapter we allow the evolutionary process to unfold without such constraints, and describe its progress.

Our description will focus on the key features of the model. A full factorial description, demonstrating the effects, say, of allowing, separately and jointly, more borrowing, faster learning, different degrees of competition etc., would be very lengthy and would add little to what is intended to be an essentially qualitative understanding of the process of technical change. Only the comparative dynamic properties of the model thought to be of particular interest are investigated. Our results are presented in the form of graphs. For ease of reference, these are collected at the end of the relevant chapter (section 8.6 begins on page 274). In each section we draw specific conclusions from observations of our model economy, whilst in chapter 10 we make overall conclusions.

8.2 The Basic Scenario

To generate results a number of alternative scenarios are developed, each designed to illustrate some particular aspect of the working of the model. They all derive from a basic simulation of balanced growth, as described in the appendix to chapter 7. Only one process is used in each industry, with no search for new ones. All firms within each industry are identical. At the start of the simulation run all capacities, prices and all other settings are those appropriate for a balanced growth of 5% minus the rate of depreciation per yearly period. In this case the economy merely replicates itself, except in the levels of output, each period. No results for this basic case are reported.

The main settings for the balanced growth path are:

INDUSTRY	0	1	2
K1 coeff	5	4	5
K2 coeff	4	2	2
L coeff	4	3	2
Price	6.0	4.4	3.6
Capacity	1111	519	343

In conducting experiments in this chapter we confine ourselves to technical change within one industry, industry 2. In order to keep conditions otherwise as close as possible to the simple balanced growth scenario, there is a zero rate of depreciation and demand for the two capital goods industries is set to grow at a constant rate of 5% per yearly period throughout each simulation run (except those described in section 8.5). The absence of technical change in the other two industries helps to keep their prices constant.

8.3 A Single Firm

8.3.1 Output and Pricing In order to generate results in a controlled way a very simple setting for technical change within an industry was devised. The economy is basically as described in section 8.2. The only change is that firm 1 in industry 2 is given a 25% cost advantage over the other firms in that industry, with all the firms in the industry identical in all other respects at the outset of the simulation. This is equivalent to an unanticipated and disembodied improvement in productivity for the selected firm, a situation it should be able to exploit. There is no search and the only source of technical progress is from the relative growth of the advantaged firm. This scenario corresponds to the very simplest case of economic selection discussed in chapter 5. The industry performance for this scenario is described in section 8.4.

Figures 8.1 and 8.2 show the advantaged firm, in the immediate period after its 'discovery' of a superior process. The horizontal axis measures time in model 'years', (the same is true for all the graphs presented in this and the next chapter unless otherwise stated). Behaviour is typical of a firm growing rapidly and expanding its market share. Given that the firm has the same initial capacity, price and outputs as the other nine firms in the industry, the sudden change in its productivity requires it to make some changes in its decision rules. The accommodation to the new circumstances is not immediate, but the firm is able to adjust fairly quickly.[1]

The first effect is for the firm's price to drop, and thus for market share to increase and consequently for stocks to be run down. Almost immediately however the firm increases its price markup, and by the end of the first year price is only just below that ruling at the start of the simulation. Similarly the run down of stocks triggers off an increase in capacity

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[1] Partly the ease of adjustment reflects the very stable environment in which the firm is operating, with essentially balanced growth and stable prices. Figures 9.2,9.3, 9.5,9.6, 9.8,9.9 show behaviour and performance in a more unstable situati

utilisation. The adjustments in price markup[2] and capacity utilisation are seen to work in unison, slightly preceding changes in the change in market share, as one would expect since market share responds only to price. The firm is managing its pricing and output rules to keep its growth of market share in line with growth of output and capacity.

Figure 8.4 shows that the trend in the firm's market share is strongly upward. In the early phase of the simulation, before the firm has accommodated itself to its advantageous situation, the firm does in fact need to reduce its share in some periods and raises its price markup in order to do so. From about year 3 onwards market share is continuously increasing. The firm is clearly successfully operating its utilisation and pricing rules to adapt to the exogenous shock. The response takes some short time to settle down, but given the scale of the shock, not excessively so, and by year 5 the firm is firmly on its long term course.

Figures 8.3 and 8.4 show the advantaged firm, firm 1, in comparison with one of the other nine identical firms which make up the rest of the industry, over a 100 year period. Figure 8.3 shows that the adjustment problems for the single advantaged firm are much greater than for the other nine, as one would expect. In fact it is the need to keep the

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[2] Recall that price markup here is that in excess of 'normal' markup (see the definition of $_{ij}$ in the appendix to chapter 7, page 231)

behaviour of advantaged firms stable that limits their expansion and hence the rate of technical change in our model.

The dominant feature of figures 8.3 and 8.4 is the growth in market share for firm 1. From figure 8.3 we see its growth in share gradually rises (after the initial period of instability), as its size increases relative to its competitors. After about period 40, when the advantaged firm has about 50% of the market, the growth in share decreases, and obviously eventually approaches zero as complete monopoly is approached.[3] By the end of the simulation run firm 1 has about 95% of the market.

The rate of increase in firm 1's market share is limited by the ability to acquire new capacity. The need to limit the increase in market share is reflected in the price markup being consistently around 20%, and which thus gives the firm only a very small price advantage over its competitors, who are forced to run at negative price markups, covering their operating costs, but unable to fund much new capacity. This also gives firm 1 a higher profit margin and consequently both more borrowing and faster growth. The other firms in the industry are forced to lend their limited investment funds to the advantaged firm, thus further slowing their growth rate. The growth rate of capacity does not follow a similar pattern to growth in market share, and is in fact fairly continuously

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[3] Whether this actually reaches zero depends on the rules on firm closure built into the model.

decreasing, as the advantaged firm becomes more and more limited by the growth of the market. The growth rate of the firm is independent of its initial size, and the final size distribution of firms is determined solely by access to the superior technology, as described in chapter 5.

Firm 1's success is also seen in its capacity utilisation rate which is consistently above 90%.[4] This reflects the current profitability of production, which encourages the firm to set a price low enough to increase market share. Conversely the other firms in the industry are discouraged from production, and their utilisation rate is low. To produce more they would have to lower their price, which they cannot afford to do.

Figures 8.5 and 8.6 show the effects on the advantaged firm of changing some parameters. The 'Base Run' is that used to generate figures 8.1 - 8.4. Figure 8.5 shows what happens if the firm no longer recognises that it is consistently increasing its market share, and so takes no action to increase its utilisation rate accordingly (as described on page 219). In this case it is solely changes in the level of stocks which govern output and pricing. Initially stocks are depleted, and utilisation and price increase to compensate. Fairly quickly however the firm reduces its utilisation rate to 90%. Since output is lower than in the base run, it is necessary to keep price higher, in order to match market share

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[4] It is in fact at the desired rate, calculated on the basis of its changing market share, which thus explains the downward trend (see chapter 7).

and demand to output. Thus we see that the firm's long run planning rule has a beneficial effect in allowing the advantaged firm to grow more quickly, and thus to pass on the benefits of its technology.

The low utilisation rate later in the simulation run reflects the nature of the demand for capital goods in this model, and firms' lack of awareness about the market demand function for their product. Stocks are very high, and the advantaged firm needs to cut its price and increase output in order to make more use of its capacity. However the total market demand for new capacity is a joint demand. For the market to grow the firms in industry 1 would also have to expand their capacity, with an increase in price to effect this. What is required is a change in the relative prices of the two capital goods in order to keep the joint capacities in step (this point is raised again in section 8.5). In our model firms do not acquire such information, rather, when the full model is operating, in the longer term induced innovation allows an appropriate response to the problem.

Figure 8.6 shows the effect of not allowing borrowing. The major effect is to slow the domination of the market by the advantaged firm. Additionally, in order to finance its new capacity, the firm is forced to charge a higher price than for the base run. Borrowing is clearly beneficial, and will also help to alleviate the problem described in the previous paragraph.

In this section we have seen that our simulation model produces results in accordance with the behaviour of firms discussed in chapter 4. The very simple pricing and output rules do enable firms to operate successfully and, together with the rules of the marketing board, to coordinate firm behaviour within the industry. The model firms and industry work better with more sophisticated rules, as one would expect.

Our results show that the dominant factor in firm behaviour is the need to keep demand and capacity in line. Thus if the advantaged firm cannot borrow it raises its price markup instead. If through poor management capacity is not utilised as intensively as it might be then price markup is higher so as to limit the growth in demand. Although not shown here, if it is made easier to increase market share the firm would increase its price markup to compensate. Firm behaviour, in terms of its growth in market share, is fairly stable as borrowing or competition or other aspects of the environment are changed[5]. The firm accommodates such changes quite easily.

<u>8.3.2 Search</u> In this section we describe how the firm searches and the impact of search on technology. The scenario used to generate the description of search is that of section

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[5] Providing that the changes are not too dramatic. The introduction of a perfect financial or product market would be too much for the model to cope with for example.

8.2, but additionally search occurs in one industry (industry 2). All firms in the selected industry search for incremental innovations, and on achieving these are able to implement them immediately. The conditions for achieving a new basic discovery were made so stringent that no firm was able to achieve this during the simulation run, since this additional element would only serve to complicate. The graphs show the results for a typical firm in the chosen industry during a single simulation run.

The angle for each search direction was set at 45° (see figure 4.4 p121), so that for any pair of search directions (see p213), only one will be used in any period. In the simulation described only three directions are used throughout, (since prices change very little), these were directions 2,3 and 5. We recall that:

direction 2 decreases K1 and increases K2;
direction 3 decreases L and increases K1;
direction 5 decreases L and increases K2.

Thus the firm seeks to substitute capital for labour as perhaps its principal priority, with substitution of K2 for K1 as a second objective.

Figure 8.7 shows the intensity of the firm's search in two ways. The top graph shows the percentage of investment funds devoted to search in each period, whilst the other three graphs show the total number of draws each period. The results presented in figure 8.7 show an early emphasis on search activity, as easy progress can be made. Search then stops for some 20 years, as incremental innovations are now hard to achieve. Towards the end of the simulation run the intensity of search increases for short periods, despite the fact that the expected return per draw is by now quite small. Search continues because by then the firm is much larger and so the cost of each draw becomes an ever smaller fraction of each period's investment budget and also because the capacity into which an improvement can be incorporated is much larger than early in the simulation run.

Figure 8.8 shows the results of the firm's search activity. The top graph shows the total distance achieved so far in all search directions taken together. This, we recall, may be used to govern the discovery of a new basic process. The other three graphs show the attainment in each search direction used. We see that in the initial few periods substantial advances are made. This is particularly so for direction 2, where good fortune resulted in major advance within the first 10 periods for only a small search effort. This probably also explains why when search in direction 2 is resumed in period 60, a large number of draws (25) are made. We also see that the explanation for temporary cessation of search, and the peaks in figure 8.7, is a successful innovation.

The impact of search on the production coefficients is shown in figure 8.9. The labour coefficient declines by about 30%, whilst the K2 input increases by around 50%. The time path of the K1 input is less uniform in direction. In the early periods it declines as the impact of search direction 2 presumably dominates that of direction 3. The plateau between periods 25 to 70 can be related to the successes achieved in direction 3 (period 25) and direction 2 (period 70) as shown in figure 8.8. The final increase can similarly be explained by reference to figure 8.8. Seven techniques are discovered by the firm in the first 15 periods as it is able to exploit the relatively easy improvements to be made in the original basic process. The extent of the improvements is shown by the total factor productivity of the best process so far discovered, which increases by about 11% over that period. Over the next 85 periods another 8 processes are discovered and together these increase best practice productivity by about 7%, as innovation possibilities become exhausted.

From our theoretical discussion of economic evolution in previous chapters, we expect that induced innovation effects will be a major force in directing the course of economic development. We now seek to confirm the conclusions drawn in chapter 4 about the effects on search of changes in the firm's economic and search environment, and the consequent impact on innovations produced. The impact of search on induced innovation within the economy as a whole is discussed in the next chapter.

Figures 8.10 to 8.17 show four comparative dynamic studies. To generate these graphs a different approach to that used so far was adopted. Since the outcome of search is a random event, to understand the impact of a change in an exogenous variable on search outcomes it is necessary to use data from a series of simulation runs for each scenario, from which the sample mean outcomes can be compared. The graphs show the search outcomes averaged over the 10 firms in the industry over 5 simulation runs, an effective sample size of 50. In generating the graphs the base run is that used to generate figures 8.6 to 8.9.

Figure 8.10 shows the effect on the search effort of making search easier, whilst figure 8.11 shows the consequent impact on the innovations produced. The new scenario is the same as for the base run except that the variance of the search probability distributions is increased from 4 to 5. Figure 8.10 shows that the search effort is on average about 1.5% of investment funds once the initial intense search effort is over, and showing a slight downward trend over time. Easier search results in some increase in the search intensity, as one would expect, particularly in the later periods of the simulation. However the increase is modest, since the effect of easier search is subsequently to make production more profitable, which, as we show in figure 8.15 reduces search intensity.

The main impact of easier search is seen in figure 8.11. Compared to the base run[6], we see that the firm has been much more successful in achieving its search objectives, and in increasing productivity. Thus we see that it is technical restraint on search possibilities, rather than economic factors, which ultimately limit search in our growing economy. Eventually economies of scale will make it worth while to investigate all possibilities within a static search environment.

Figure 8.12 shows the effect on the search effort of a change in factor price, whilst figure 8.13 shows the consequent impact on the innovations produced. The new scenario is the same as for the base run except that the expected price of capital good 1, used in the calculation of search intensities, is increased by 30%. Figure 8.12 shows that in the later periods of the simulation, there is a definite reduction in search in direction 3 (which increases K1) and increase in direction 2 (which reduces K2). There is perhaps a very marginal increase in the overall intensity of the search effort, as we predicted in chapter 4 (p126), although the effect on best practice total factor productivity is marginal.

The clearest effect of the increase in P1 is that the K1 coefficient is reduced from early on in the simulation run in comparison to the base run, whilst use of the other capital

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[6] We also notice that as compared to the path of K1 in figure 8.9, averaged over many runs the trend is clearly to reduce K1 in the base run scenario.

input is marginally increased. There is seemingly no effect on the labour coefficient, presumably because the firm still has as its main priority the reduction of its labour coefficient, as witnessed by the continued pursuit of search direction 3. Additionally our conclusion from figure 8.11, that the search environment is a crucial determinant of what is found, would seem relevant here; the firm is still searching with the same probability distributions. This would also explain why the size of the induced change in the coefficients is quite small in relation to the extent of the price change.

Figures 8.14 and 8.15 reinforce the conclusion that reduction in labour input is the firm's main search objective. Here the new scenario is of an expected increase in the wage rate of 30%. We see a clear increase in search intensity, both overall and in the labour reducing directions. The marginal increase in direction 2 is probably because production is seen as less profitable and the opportunity cost of search is reduced. The effect on the production coefficients is more marked than in the previous example, but still limited, as figure 8.15 shows. The seemingly large impact on the K1 coefficient is a consequence of the increased effort in direction 3, but also of the large scale of the graph. Clearly however the changes are in the expected directions.

We have already referred to the effect of output price on search activity. Figures 8.16 and 8.17 show the effect of the firm expecting its output price to rise by 30%. We see clearly that the search effort is reduced, as predicted in chapter 4 (p127). Direction 3 is particularly reduced, and this results in the K1 coefficient being somewhat lower than in the previous examples (the scale of that particular graph is changed here to accommodate this). The effect on the total number of processes discovered and on productivity is as expected. Eventually however, even in this new scenario, the available search possibilities would be investigated, if we were to allow the simulation to run on long enough.

We have seen that our search model does perform as it was designed to do, generating induced innovation effects in accord with neo-classical theory, but without its perfect decision making requirements. A perhaps surprising conclusion from our description is the importance of technical factors over economic ones. This occurs because the search environment was constant, and no new basic processes were uncovered. Clearly basic research is vital in allowing new search environments to be opened up. The technology of new basic processes may or may not be determined by economic factors, but in either event (particularly the former) they allow new scope for induced innovation effects.

The other major features of our description were the importance of economies of scale and the profitability of production in determining the search effort. These factors indicate that monopoly or cartels will speed technological advance, whilst a market protected from dynamic competition and having high profits will slow it. To investigate these issues further we now turn to examine the performance of the industry as a whole.

8.4 The Industry as a Whole

In this section we first follow up the discussion of chapter 5 on selection processes. We investigate versions of the three scenarios analysed by Iwai (1984b): selection with no imitation and no search, and with these two elements sequentially introduced. We then move on to examine how different environments affect industry performance.

8.4.1 Imitation Only The no imitation case has already been discussed in section 8.3.1, where a single firm was allowed to discover, at the outset of the simulation, a new process with a 25% cost advantage, with no successful imitation or search allowed to the other firms in the industry. Figure 8.4 shows how the single advantaged firm eventually gains dominance. That scenario, with one small difference[7], is shown in figure 8.18 as the Base Run. It is shown in comparison to the same situation except that now the other firms engage in search in order to imitate the new process. The firms engage in incremental search, but the results of incremental search are not implemented. Once a firm has achieved sufficient

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[7] The advantaged firm has its initial capacity in the same process as the other firms. Only investment undertaken during the simulation is in the new process. This means that the graph of diffusion begins at the origin.

research performance, measured by the aggregate distance achieved across all search directions, then it is deemed to have 'discovered' the new basic process, and is a successful imitator. Thus only the two basic processes are ever in use.

The bottom two graphs of figure 8.18 show the means of the two distributions suggested by Iwai as indicators of performance; the proportion of firms and the proportion of capacity with better than a given level of revealed performance (in this case using the second basic process). For the imitation allowed scenario, we see that in the early periods of the simulation a firm discovers the new process every few periods and that by period 15 five firms are using the second process. Recalling figure 8.3, this is fortunate for those firms, since if the initially advantaged firm is allowed to gain too much ground it will force down the profit margins of the other firms and borrow their investment funds. This explains why the rate of inter-firm diffusion slows after period 15, and we notice that only 8 of the firms actually succeed in imitating the innovator by the end of the simulation run.

The rate at which the second process comes into use, as shown by its percentage of total industry capacity, is clearly speeded by the introduction of imitation. The graphs show sigmoid diffusion paths such as those typically found in empirical studies of diffusion. A similar pattern is seen in the average cost of production in the industry. As well as mean performance we may also examine the variance. The second graph in figure 8.18 shows the variance in average production cost plotted against time. We see that the imitation case succeeds in achieving its more rapid change with a lesser level of variance than the non-imitation case. This is because the zero rate of interfirm diffusion in the base run means that more investment takes place in the inferior process, thus increasing variance. Also, by virtue of their ability to borrow, high profit firms also have high fitness (in the terminology of chapter 5), in that they are adept at converting profit into growth.

Fitness also explains the shapes of the third graphs, which show the change in average cost plotted against variance; the relationship described by the Fisher equation. We see that the graphs are downward sloping as expected. We also see that in the imitation allowed case, any given degree of variance causes a much more rapid level of cost reduction. That differential levels of fitness is the explanation seems to be supported by the loop shapes in those graphs. The level of cost reduction is less for any level of variance once variance has passed its peak in both the runs shown, that is when 50% of capacity is in the second process. The dominant firms are by then reducing their prices and their profits, as figures 8.3 and 8.19 show, hence reducing their fitness.

The impact of diffusion on individual firms is seen in figure 8.19. The firms are identified according to their final market share. Discovery of the second process quickly turns a firm from a lender into a borrower, and dramatically increases its growth rate, from below that of the industry as a whole to at least equal to it. Similarly the firm's loss of market share is quickly halted.

Compared with the reduction in average cost shown in figure 8.18, the firms' prices fall more quickly. In the early periods of the simulation the firms shown are forced to run negative price markups in order to compete with the innovating firm. For the sixth firm, quite a period elapses before the dominance of the second process is sufficient to allow its price markup to rise to that of the second firm. However once the diffusion process is complete, markups are approximately zero, and prices become more equal to production costs (as defined in chapter 7).

Our description of the two simulation runs shows that the process of dynamic competition described in chapter 5 is certainly at work in our model industry. Success in the market is seen to be absolutely dependent on discovering the second process. Thus in the no imitation case the advantaged firm dominates the market. When imitation is allowed a firm's relative performance is solely determined by whether it has yet found the new process. Nothing the firm can do can compensate it for non-discovery of the new process.

8.4.2 Search and Imitation To investigate the effects of search, a scenario similar to that used in the previous section was devised. The only differences are that there are now three new basic processes to be discovered, each representing an increase in efficiency of 25% over its predecessor, and no firm is given an initial advantage.

Figure 8.20 shows the spread of the new processes as before; by the number of firms using them and the proportion of industry capacity which they account for. We see that the rate of diffusion in terms of capacity, production costs and TFP increases as we discover ever more advanced technology, but that the converse is true for the number of firms. This is attributable to the large market share of the early users of process 3 and then process 4, as illustrated by figure 8.21. The graphs show that the best firm, as defined by its market share at the end of the simulation, is the first to discover process 3 and the first to discover 4 also, whilst the worst firm is the last to find process 2 and gets no further. We observe also in figure 8.21 the surge in growth rate and borrowing as the best firm discovers its new processes, and how these are reduced as imitators come in, reinforcing the picture of dynamic competition described in figure 8.19. Clearly continued success for a firm depends on a stream of innovations or imitation. Failure to keep up with current best practice will ultimately cause a firm to be eliminated from the market.

Turning again to figure 8.20, we see that each new innovation creates an upswing in variance, but which eventually begins to die out. Only in the case analysed by Iwai (op cit), of a constant exogenous rate of technical advance in best practice, would we expect to see variance constant over time, and then only if firms all have an equal chance of being innovators. In our example, where innovators are increasingly monopolistic, an accelerating level of technical advance in best practice would be required for constant variance.

8.4.3 The Environment and Industry Performance

In this section we consider the industry in two cases of a changing environment, one economic the other technical. In the first case, described by figures 8.22 and 8.23, we show the result of increasing the level of 'static' competition. The parameter ss[8], which governs the rate at which firms lose market share within each period, was increased. A value of 0 for ss would indicate complete consumer loyalty, whilst a value of infinity would be akin to perfect competition. The Base Run shows the situation used to generate figure 8.20 with ss set equal to 0.15, whilst the competition increased scenario has ss increased to 1.5.

Figures 8.22 and 8.23 represent the mean outcomes from 10 simulation runs of each scenario. Figure 8.22 shows that the difference in competition only begins to make a major impact on performance in the later periods of the simulation run. However this is the culmination of less evident changes in earlier periods. Disadvantaged firms find they must match the

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[8] See the appendix to chapter 7.

price of more productive firms that much more closely if they are to maintain their markets. This of course means cutting their price markups, reducing both their growth and search. Figure 8.23 shows that prices are marginally higher as a result of these tensions. As figure 8.23 shows search is marginally higher when 'static' competition is increased, reflecting the high propensity to search of the larger, advantaged, firm(s). These two effects jointly mean that the fourth process is discovered somewhat earlier when 'static' competition is increased, but by a smaller number of firms. Ultimately of course the industry will be dominated by the fourth process in both scenarios, unless further new processes come onto the scene.

Within the confines of our model, increased 'static' competition, paradoxically, tends to increase the concentration within the industry, through allowing advantaged firms to increase their dominance of search. If the economies of scale within the model are realistic this result will apply to the real world also. However we may also note that increased competition in the sense of decreased consumer loyalty would allow the speedier market penetration of new firms into the industry, and hence perhaps a reduced degree of concentration over time, a feature not incorporated into our model.

Our second case of changed environment is harder search, in this case a reduced variance of the search probability distributions. Figures 8.24 and 8.25 were generated in the same way as 8.22. As expected harder search increases the percentage of industry investment funds devoted to search. TFP is reduced and average costs increased, as compared to the base run, during the period of the simulation.

One consequence of harder search is that discovery of a new basic process gives a firm that much greater advantage over its competitors. This results by period 30 in more concentration within the harder search scenario, as compared to the base run. Again we see a paradoxical result of this in the earlier introduction of the third process. Industry variance is much higher in the harder search scenario, at this stage of the simulation, reflecting the slower inter-firm diffusion rate. This is also clearly reflected in both prices and costs.

The harder search means that early discoverers of process 3 are unable to press home their advantage with an early discovery of process 4. Larger size and learning effects together result in other firms being able to imitate the third process before the fourth process is found, and hence market concentration is reduced below that of the base run. The final consequence of this is a later introduction of process 4. Ultimately if new innovations came to a halt, the harder search outcome will be the same as that of the base run, except for slightly lower capacity.

Both our examples of changed environment show that, as with the behaviour of individual firms described in section 8.3, what is important is the interaction of the various influences on industry performance. More competition results in disadvantaged firms being worse off, and hence ultimately in increased concentration within the industry. Harder search means that discovery of a new process is that much more of an advantage, possibly increasing concentration and consequently, through economies of scale, actually speeding technical progress.

8.4.4 The Effect of Patents

Our final study of industry performance considers the effect of a simple system of patent rights, as described in the previous chapter, in which patent holders receive a royalty for each unit of capacity installed for a period of 25 years following registration of the patent. Once patented, a process is more easily acquired by imitating firms than in the non-patent situation. The possibility of a patent also increases firms' optimism when searching. Figures 8.26 and 8.27 show industry performance and were generated in the same way as figure 8.22, whilst figure 8.28 shows two firms from a single simulation of the patent system in operation.

Comparing the bottom graphs of figures 8.28 and 8.20 we see that, in the case of the two runs shown at least, the effect of the patent system is to speed the diffusion of new innovations. This is confirmed by the bottom graph of figure

8.26, which shows more rapid diffusion of process 3, and the middle graph which shows that the patent system achieves diffusion with a much lower level of variance.

The graphs illustrate an interesting paradox of the patent system. Above we saw that increasing 'static' competitiveness in fact lead to a greater degree of market concentration. Here we see that a policy designed to advantage a particular firm results in a lower level of industry concentration, both in the share of the top firm and of the top 3 firms. This lesser degree of concentration is the reason why, towards the end of the simulation run, productivity is lower in the patent on scenario; economies of scale in search are being less easily exploited with patents in operation because firms tend to remain more equal in size. Clearly this conclusion would not apply if the patent holder refused to licence its discovery. Figure 8.4 illustrates that within a 25 year period the single advantaged firm attained a 40% market share.

Finally we refer again to figure 8.28. Firm 6 holds the patent for processes 2 and 4, whilst firm 1 is an early imitator of process 3[9]. We see that the rapid diffusion of process 2 results in royalty payments eventually adding 40% to firm 6's investment funds, with a consequent impact on its

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[9] The initial intention was to show the patent holder of process 3, but the firm was misidentified, and the error only noticed once all the duplicate copies of figure 8.28 were ready. Figure 8.28 shows all the main features and so was not redrawn.

growth rate.[10] However the dominant factor is the very rapid diffusion rate. Whilst the patent holder is able to increase its market share during the patent's lifetime, the other firms maintain a higher growth rate than in the case of figure 8.4. Once the patent expires, firm 6's market share remains virtually static.

The discovery of the third process sees both our firms increase their growth rate, only for it to fall back as diffusion proceeds. The diffusion is slower and less complete than in the case of the second process. Both firms pay royalties, but because firm 6 fairly quickly discovers process 4, it also begins to receive them too. Discovery of process 4, sees our two firms once again begin to increase market share. With every patent taken out, one or two firms get left behind, and industry concentration increases. Obviously new entrants would counteract this trend in the real world, providing that they can overcome the economies of scale in search in the first instance.

8.5 The Economy as a Whole

This section considers the implications of technical progress in just one sector for the relative performance of industries and for the macro economy. As such it provides an initial view of the evolution of industrial structure, to be developed

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[10] This royalty does not affect the rate of profit used in calculation of lending. To some extent royalties replace funds which otherwise non-imitating firms would have had to lend anyway.

more fully in the next chapter. The scenario considered is similar to that used to generate figure 8.20, with the same three new processes to be discovered in industry 2. For all of the graphs described so far in this chapter the growth of demand for capital goods has been set exogenously at 5% per year. To examine the relative performance of industries we relax this condition.

The first point to note is the fact, mentioned in section 8.3, that the two capital goods are jointly demanded, whilst industry 0 is free from all such restraints. Figure 8.29 illustrates this point. Industry 2 is a net borrower, acquiring about 6% of its investment funds from this source. The cycles in borrowing coincide with the discovery and diffusion of the new basic processes. The growth of industry 0 is basically constant, except that it increases when funds lost through lending are reduced. The growth of output of industries 1 and 2 are seen to be linked. The fluctuations in output growth for industries 1 and 2 are clearly seen to be in phase with one another, and with the price markup, with the turning points for industry 1 just preceding those of industry 2.

The firms in each industry accumulate stocks as growth slows, leading them to increase their price, accelerating growth. Competition within industry 1 stops its firms increasing their price to enable the industry as a whole to coordinate its pricing strategy to expand its growth rate. Since in this scenario there is almost no scope for input substitution, rapid growth of industry 2, as a result of technical progress increasing profitability and decreasing capital costs is eventually be stopped by lack of capacity in industry 1.

Figure 8.30 shows the performance of the economy as a whole. The fluctuations in growth of GDP clearly mirror those of industry growth from figure 8.29. The fact that the cycles of employment growth are slightly out of phase with output growth reflects the fact that in industry 2, as growth accelerates firms begin to use their least productive capital, which is more labour intensive. The share of wages is declining, with the fluctuations reflecting our previous point.

Whilst not clearly seen in figure 8.29, the share of GDP accounted for by industry 2 is in fact falling slowly. This is explained by the fall in the market price of its product together with the limit on the growth of output described above. The productivity increases in industry 2 result in our two measures of economy wide productivity both showing an increase. Whilst not shown, TFP for industry 2 increases by about 14% during the simulation run, whilst economy wide TFP rises by about 4%. Since industry 2 accounts for only about 12% of GDP, we see that the increase in economy wide productivity is a little higher than the share weighted increase of industry 2, for reasons discussed in chapter 2.

The results from the next chapter give us a rather better picture of the dynamics of inter-industry behaviour. Figures 8.29 and 8.30 show that our model is being asked to perform a task for which it is not well suited; this scenario really requires firms to have more knowledge about the relative performance of their industry. In the next chapter we allow firms more freedom by allowing induced innovation in all firms.

8.6 Simulation Results for Chapter 8

FIGURE 8.1 THE ADVANTAGED FIRM IN THE SHORT RUN

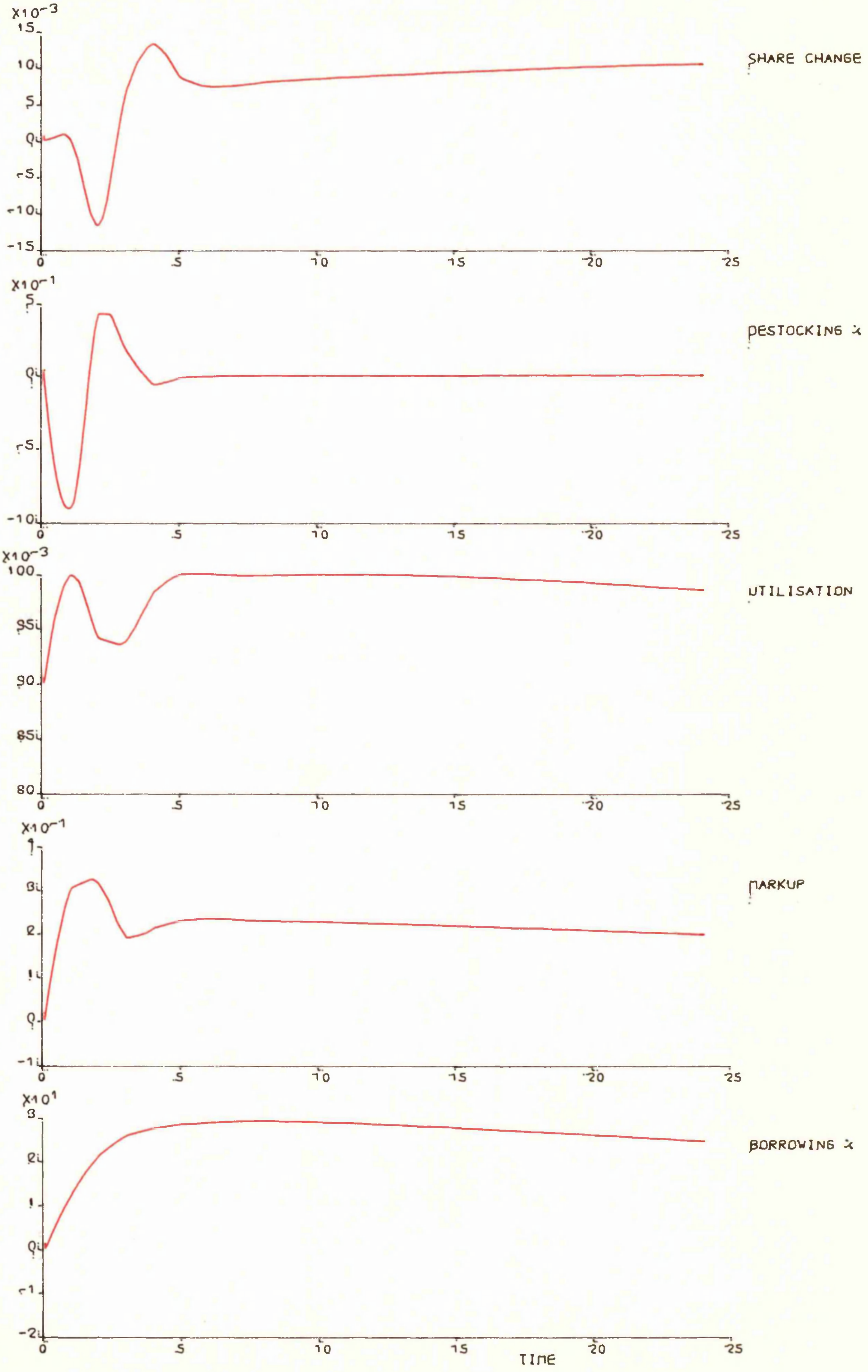


FIGURE 8.2 SHORT RUN PERFORMANCE OF THE ADVANTAGED FIRM

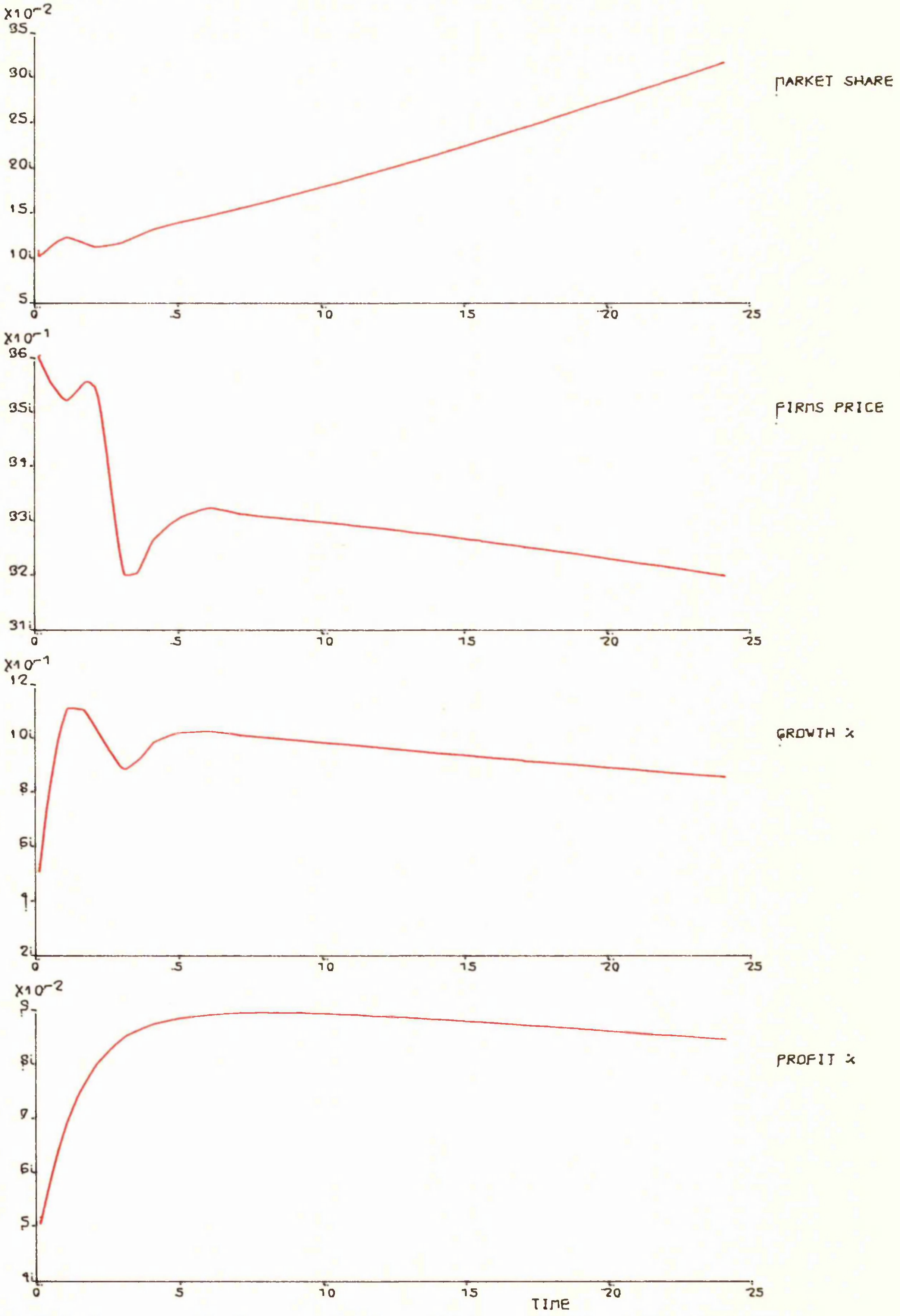


FIGURE 8·3 FIRMS LONG RUN BEHAVIOUR

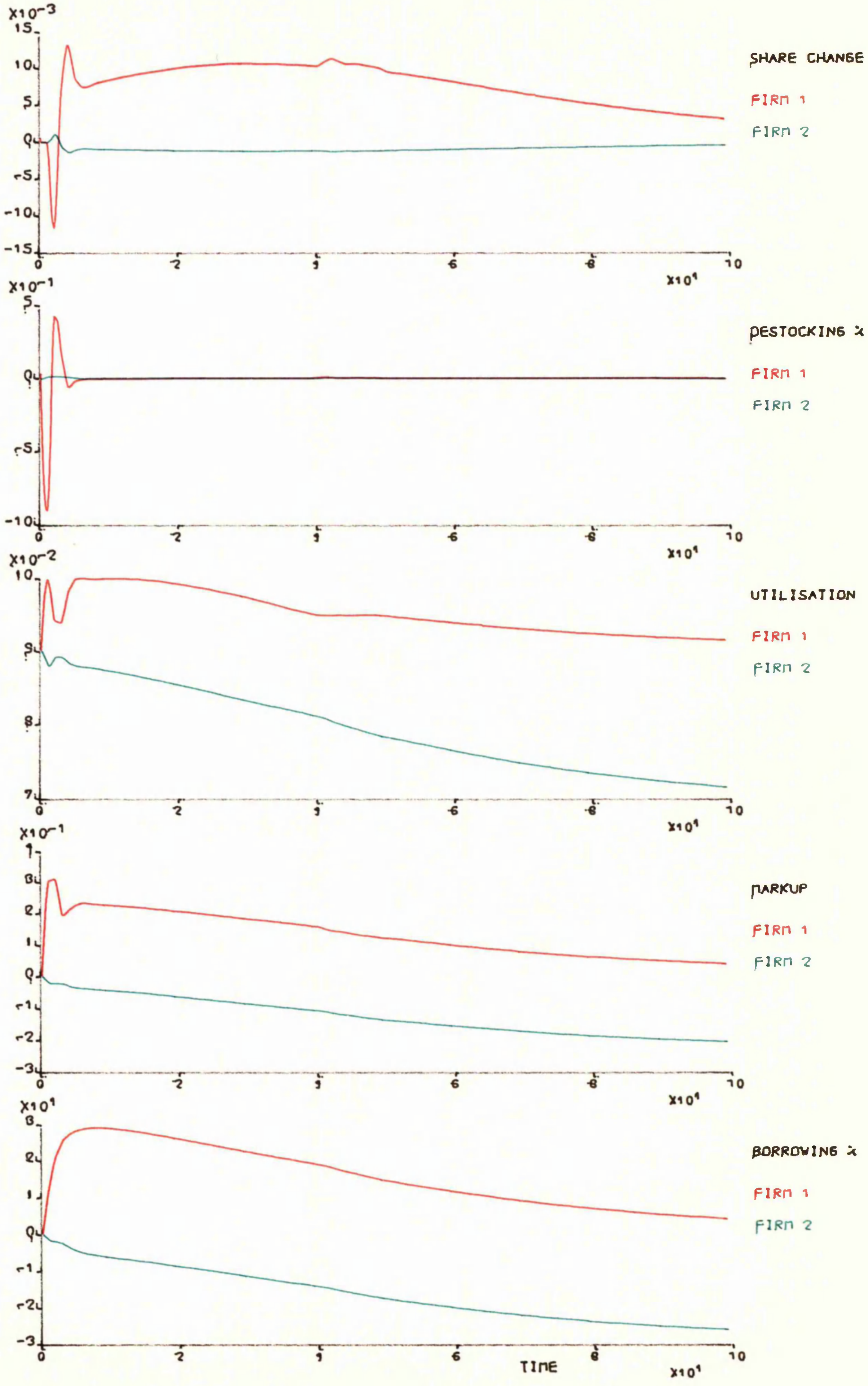


FIGURE 8.4 FIRMS LONG RUN PERFORMANCE

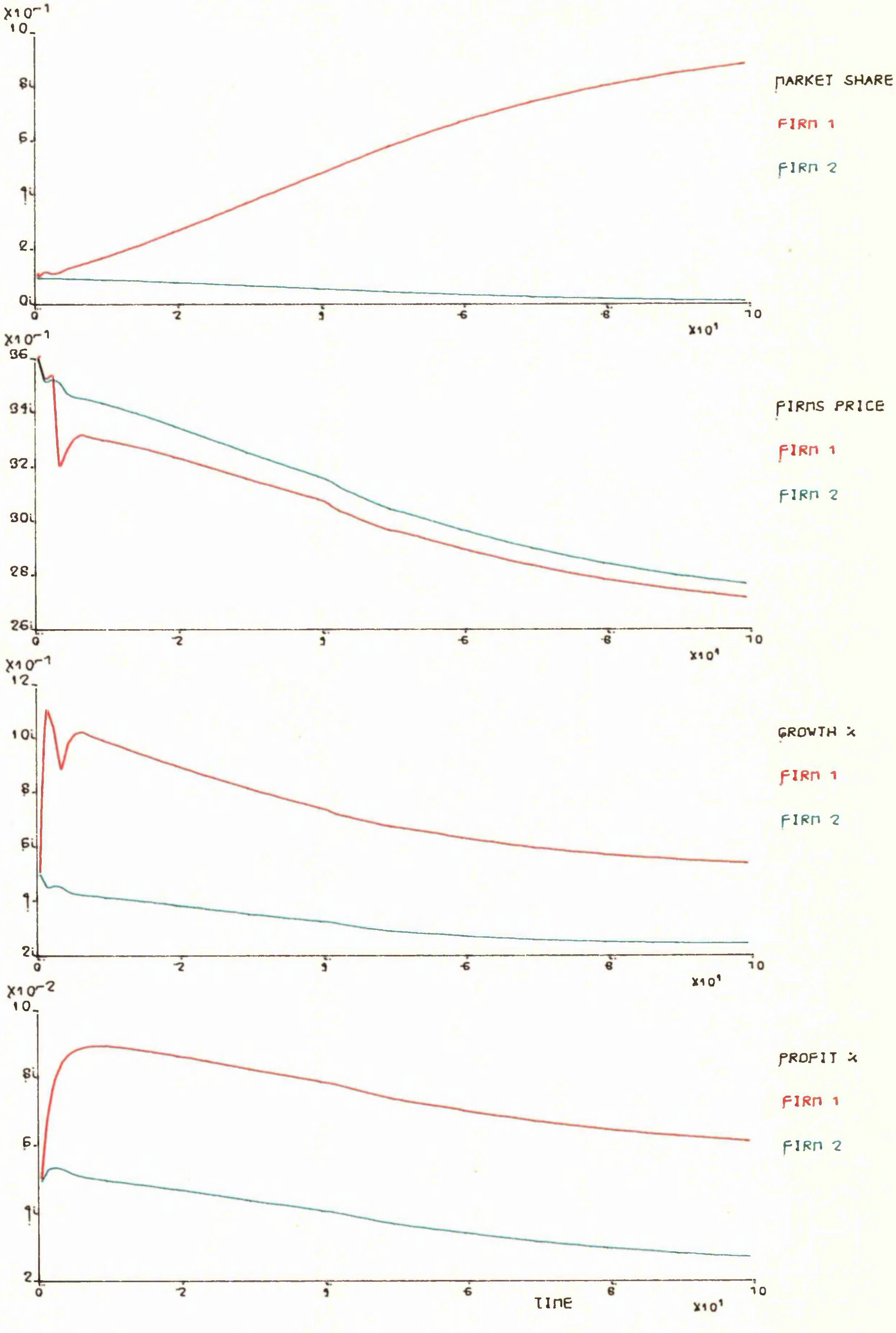


FIGURE 8.5 EFFECT OF NO LONG PLANNING ON THE FIRM

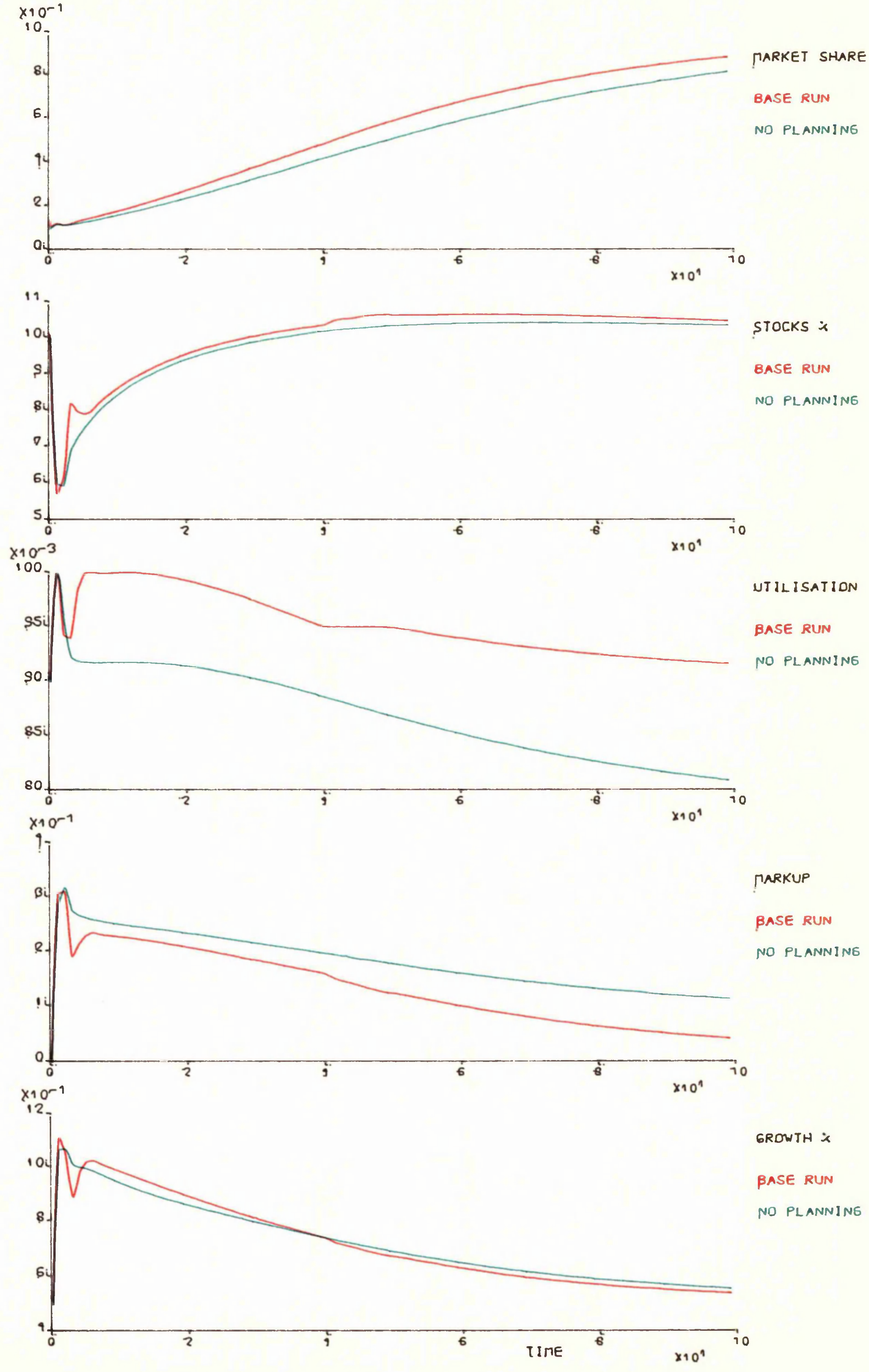


FIGURE 8.6 EFFECT OF NO BORROWING ON THE FIRM

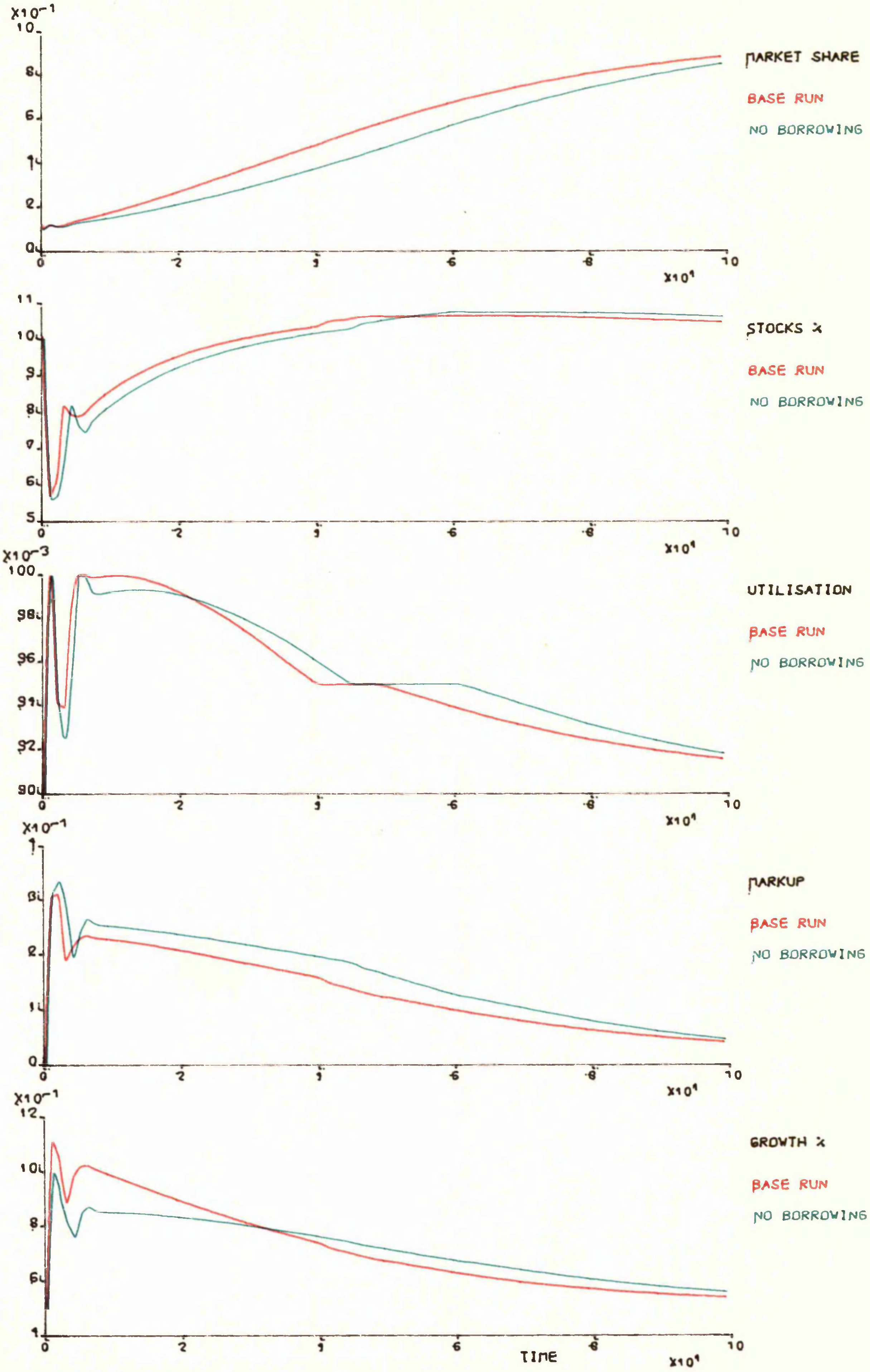


FIGURE 8.7 THE INTENSITY OF SEARCH ACTIVITY

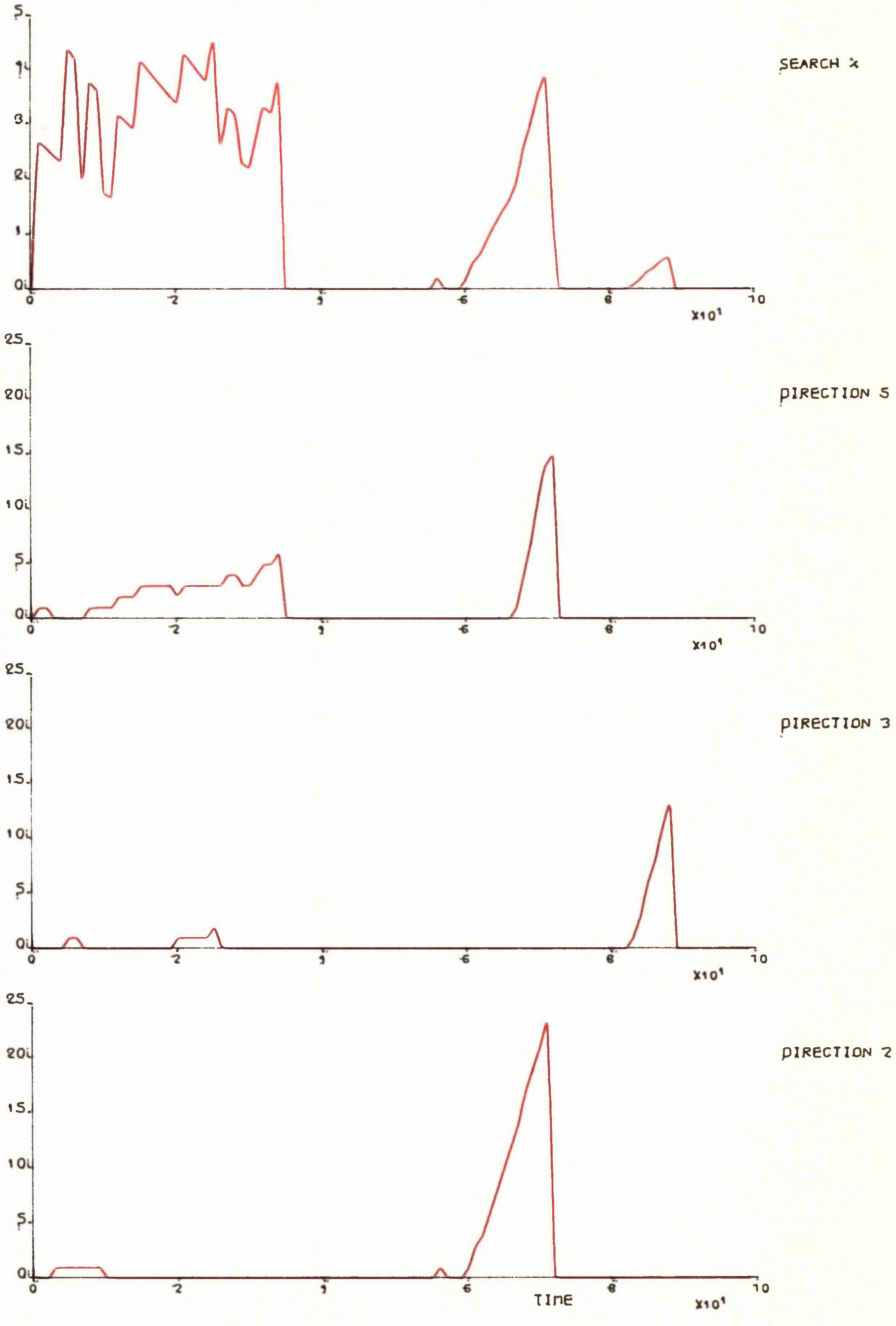


FIGURE 8.8 THE OUTCOME OF SEARCH ACTIVITY

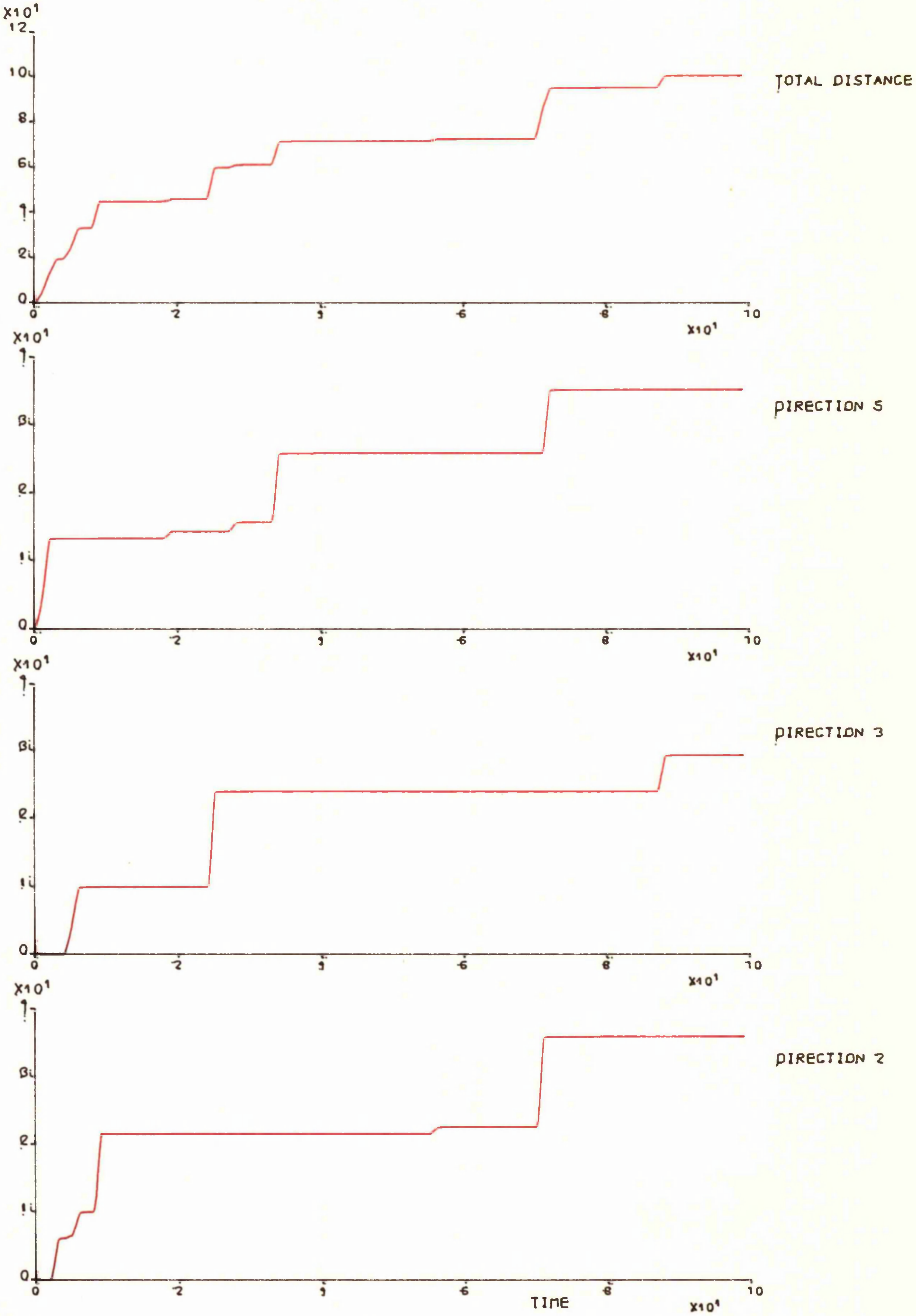


FIGURE 8.9 THE EFFECT OF SEARCH

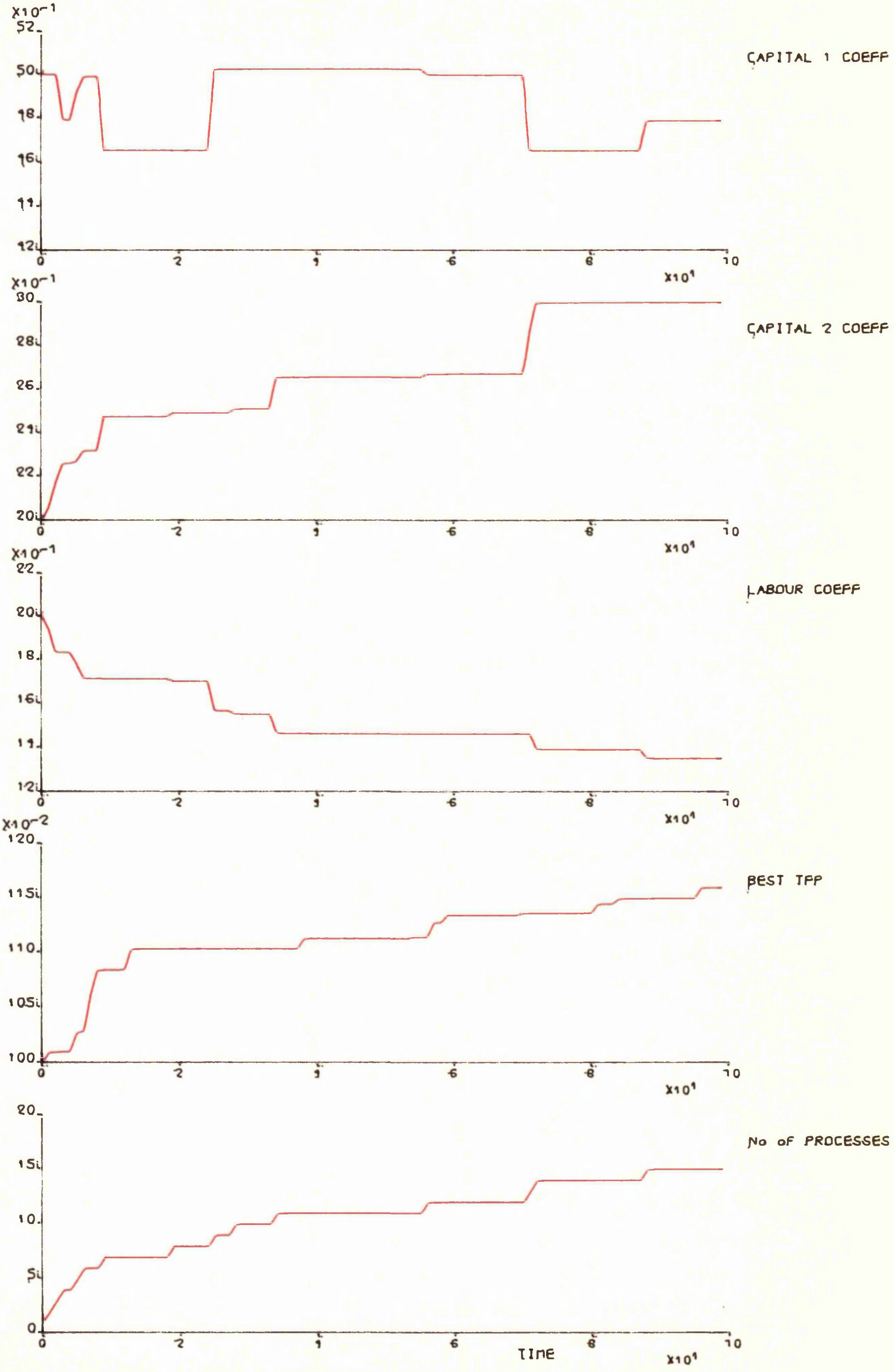


FIGURE 8.10 EFFECT OF EASIER SEARCH ON SEARCH EFFORT

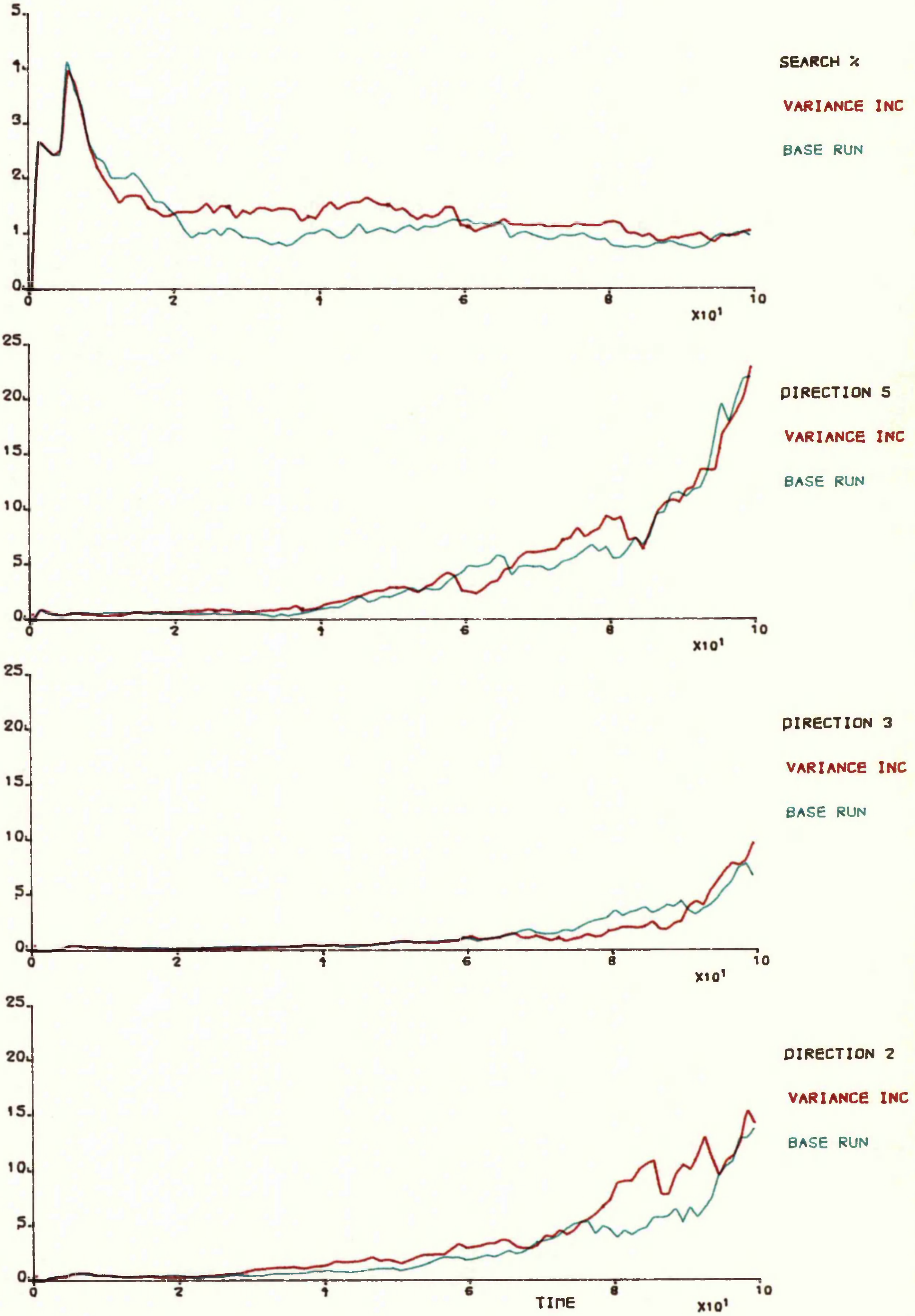


FIGURE 8.11 EFFECT OF EASIER SEARCH ON SEARCH RESULT

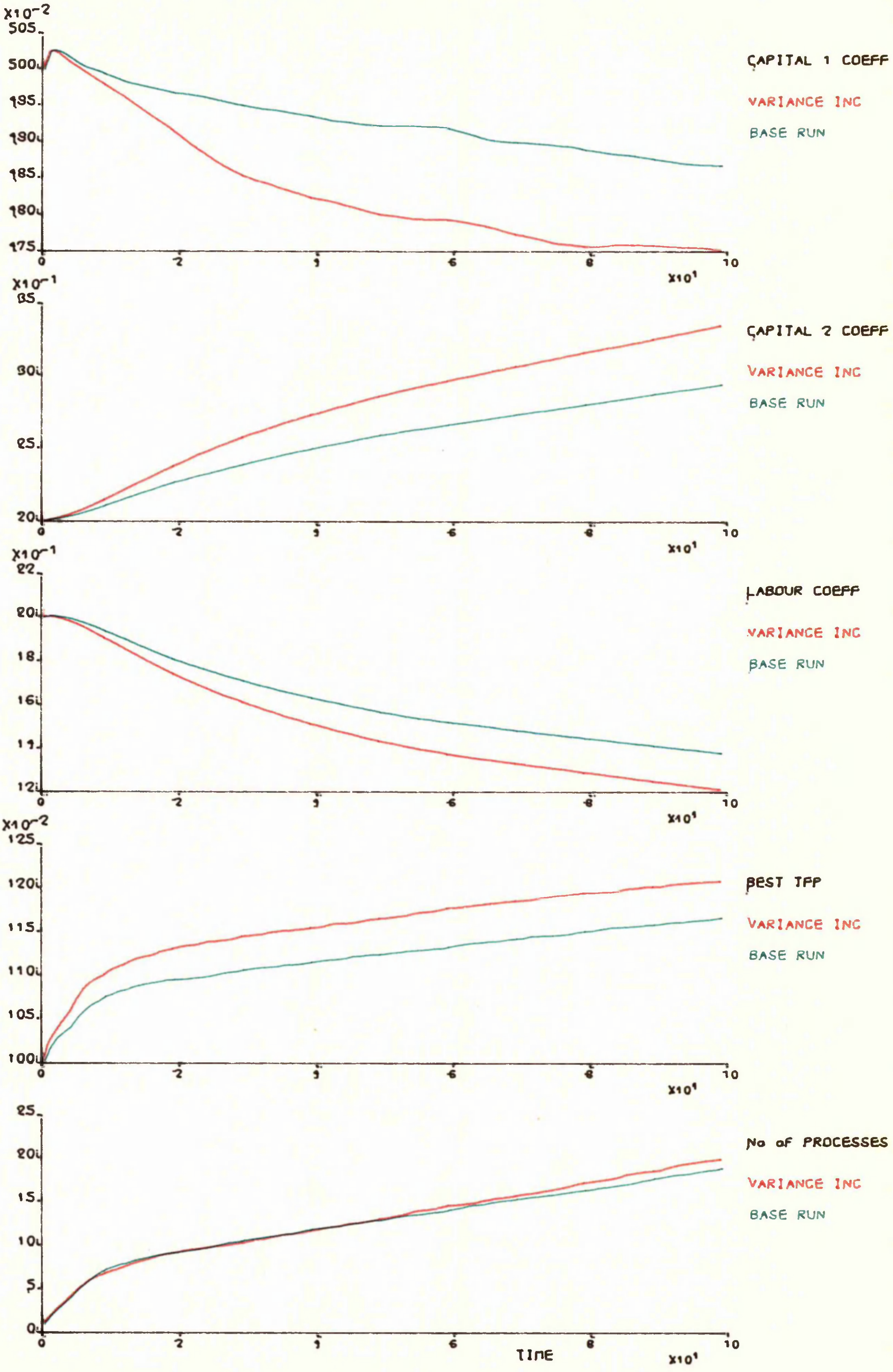


FIGURE 8.12 EFFECT OF CAPITAL PRICE ON SEARCH EFFORT

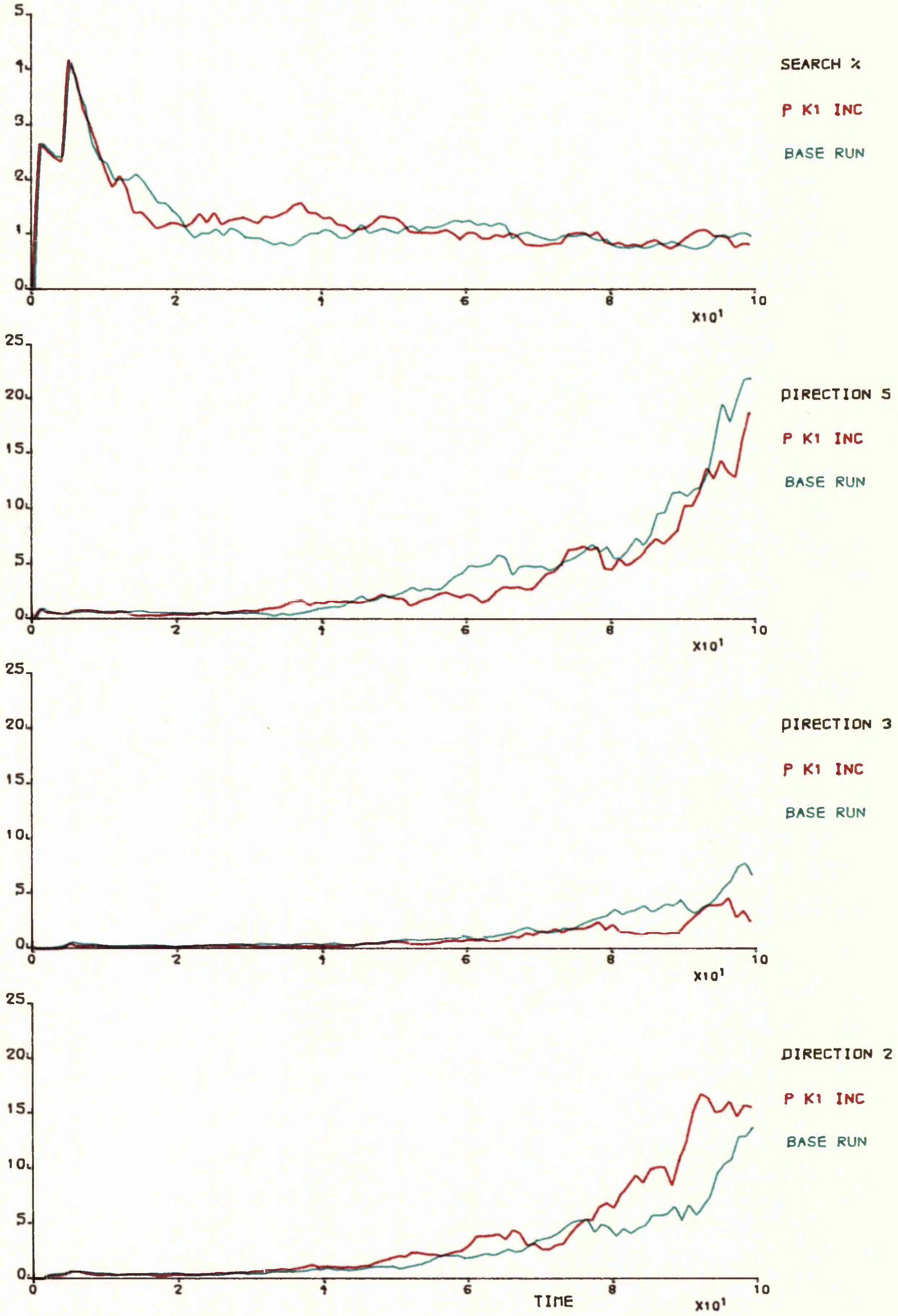


FIGURE 8.13 EFFECT OF CAPITAL PRICE ON SEARCH RESULT

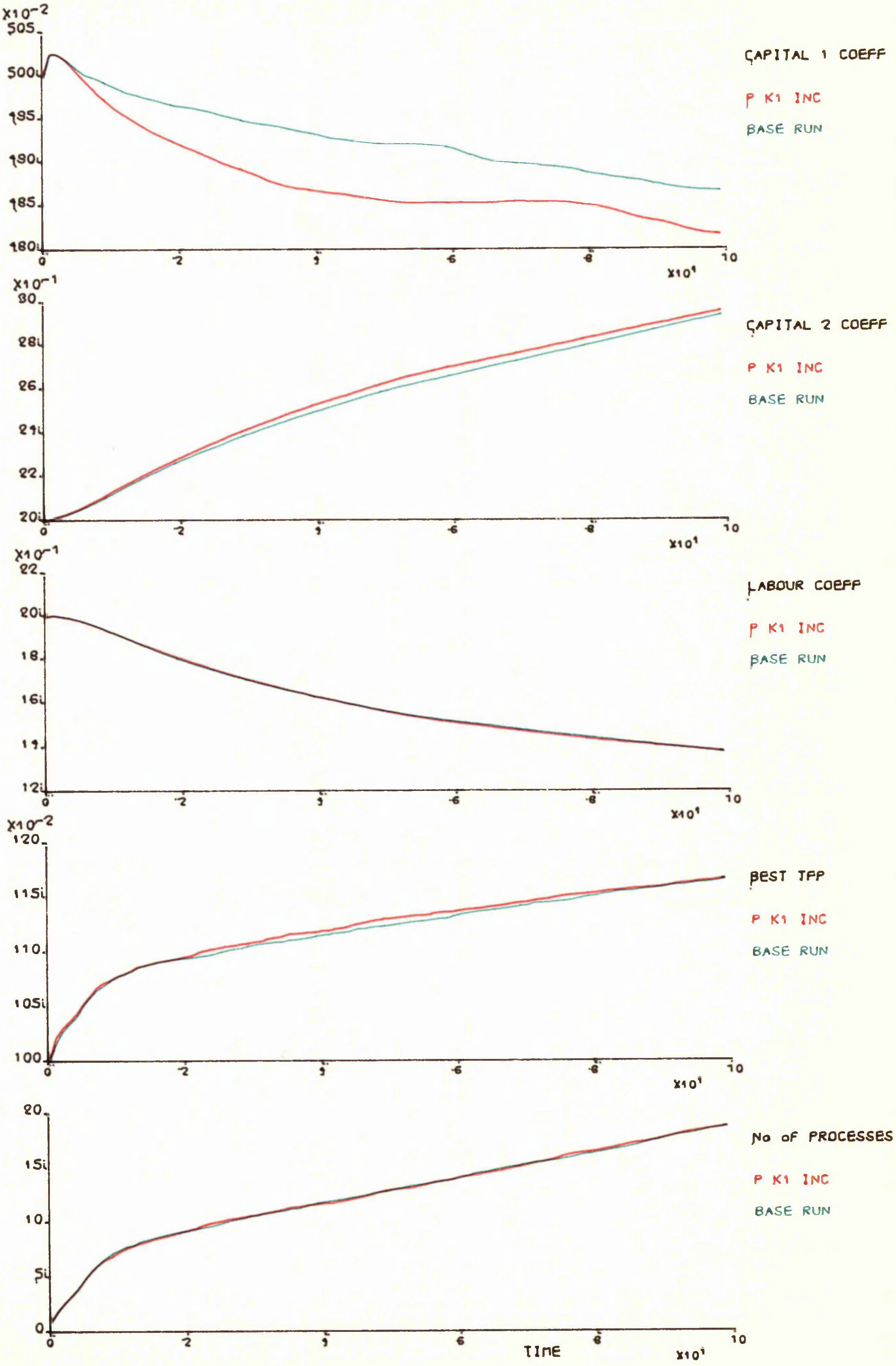


FIGURE 8.14 EFFECT OF WAGE RATE ON SEARCH EFFORT

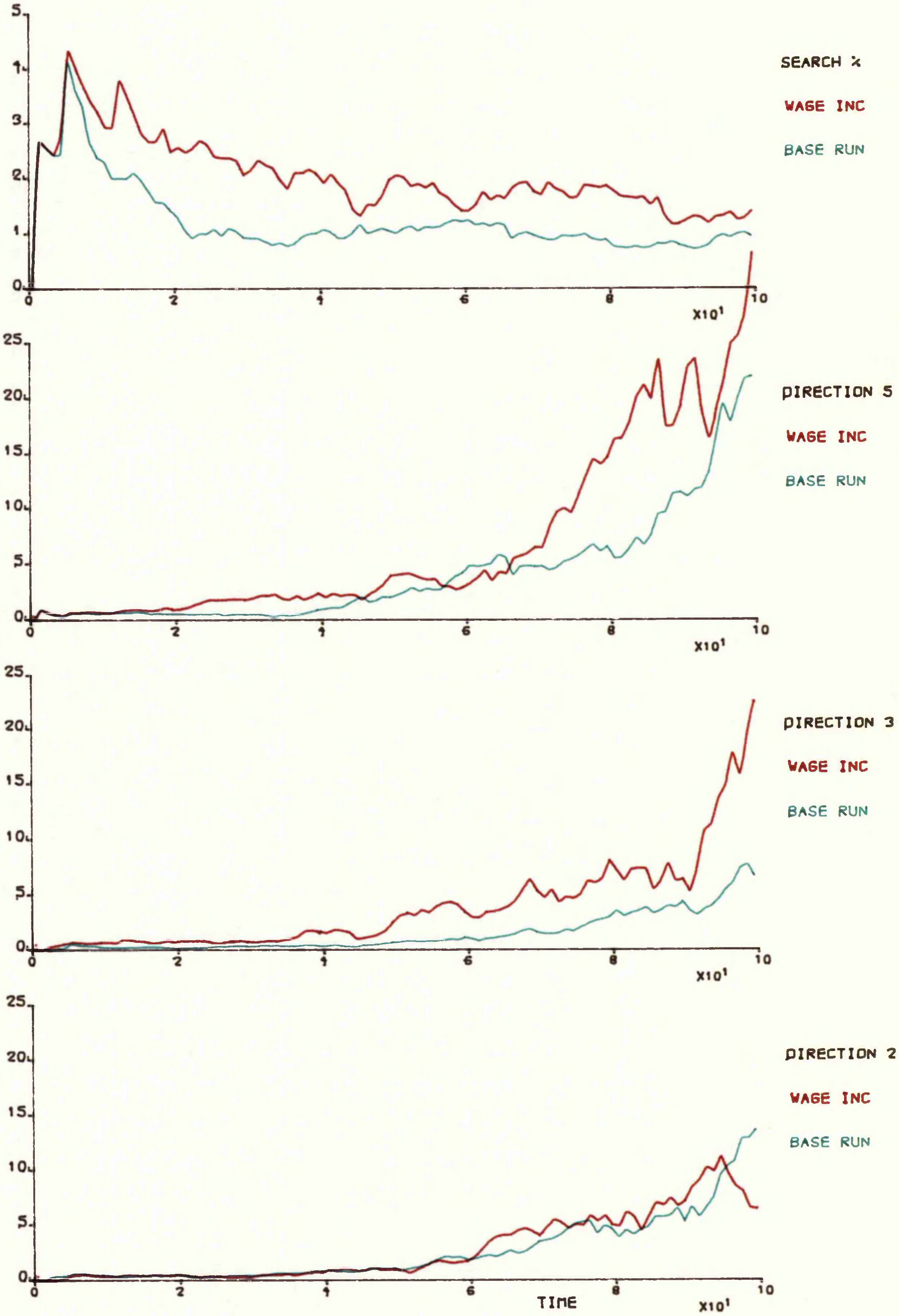


FIGURE 8.15 EFFECT OF WAGE RATE ON SEARCH RESULT

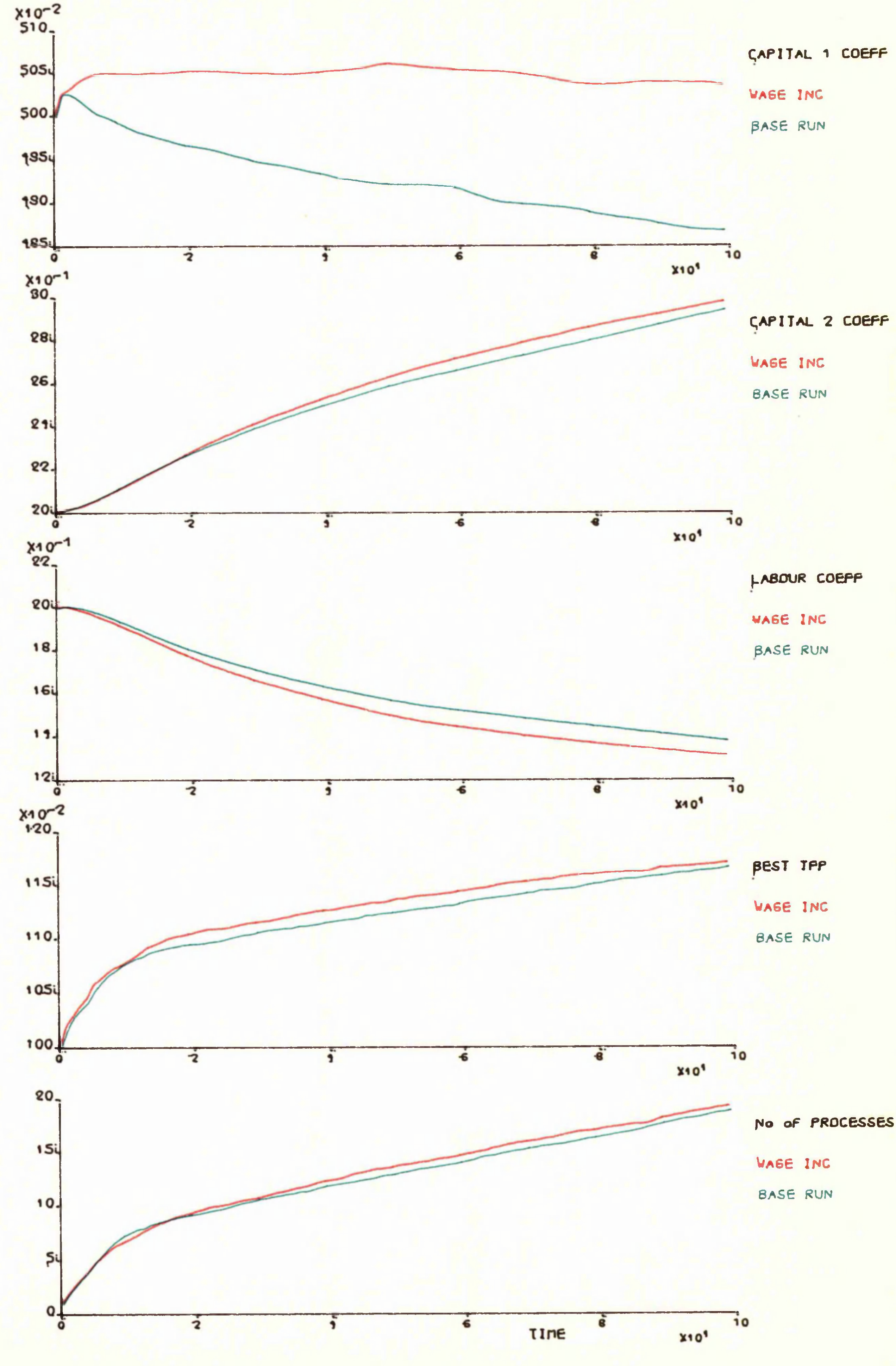


FIGURE 8.16 EFFECT OF OUTPUT PRICE ON SEARCH EFFORT

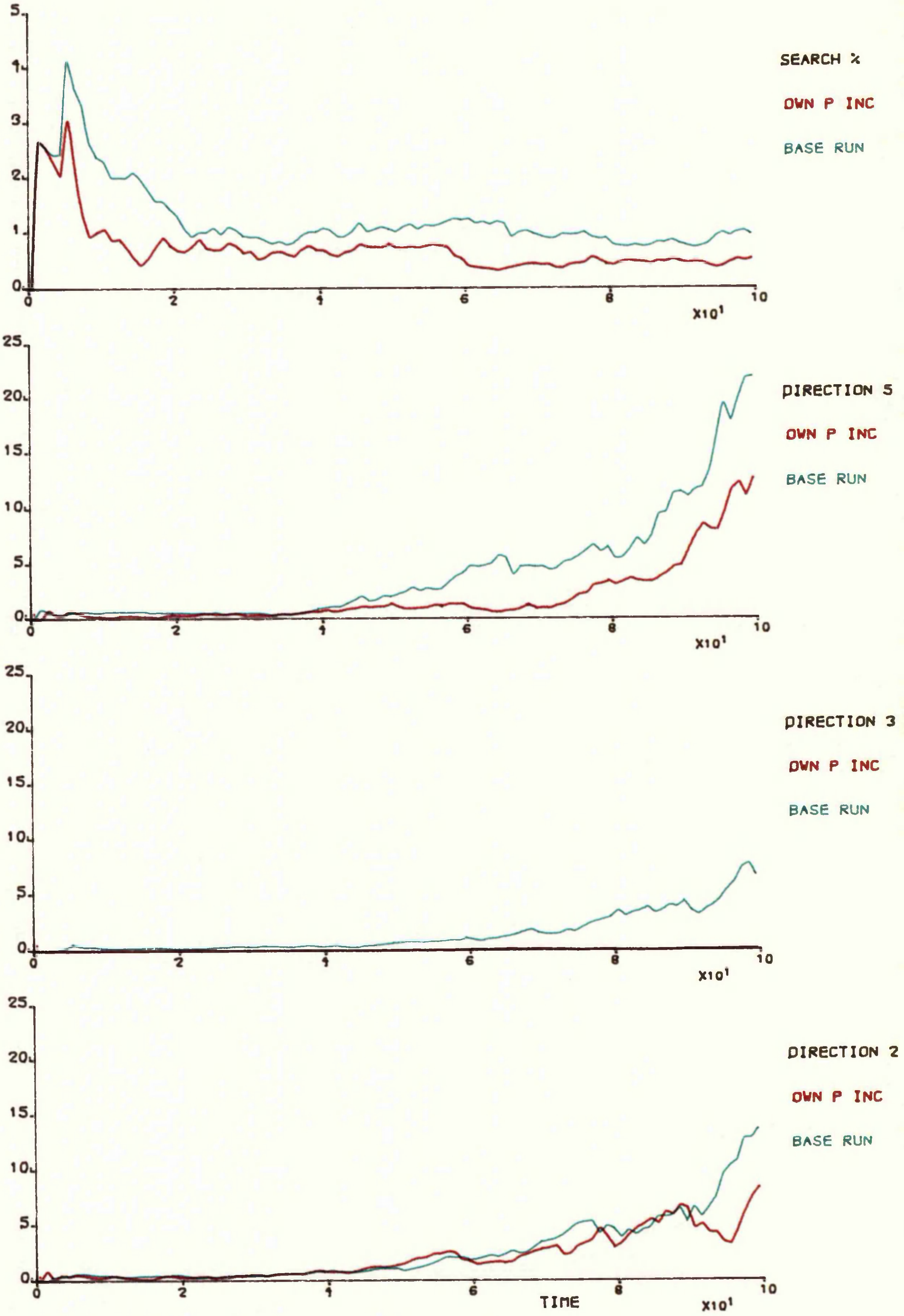


FIGURE 8.17 EFFECT OF OUTPUT PRICE ON SEARCH RESULT

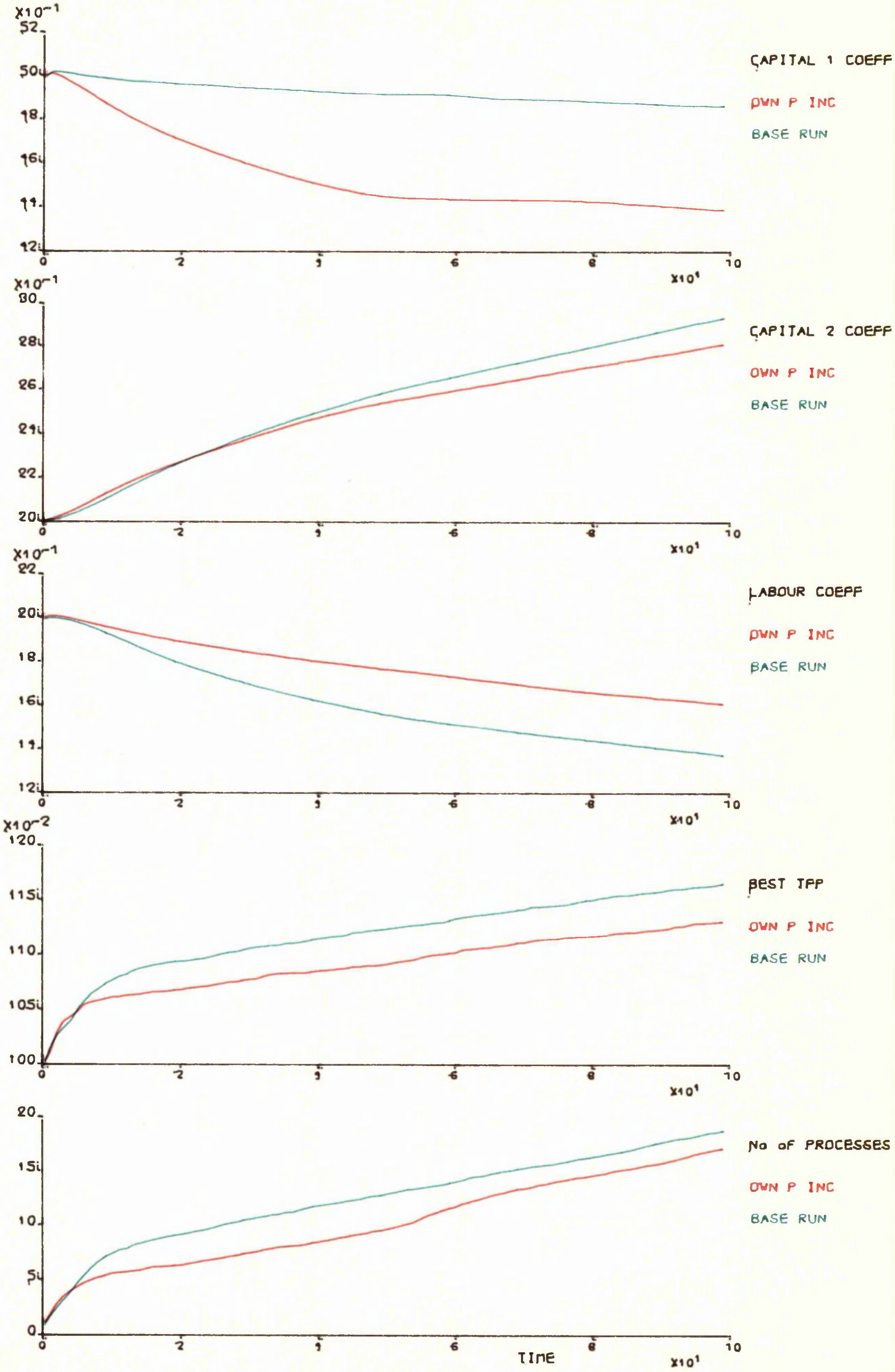


FIGURE 8.18 INDUSTRY PERFORMANCE AND IMITATION

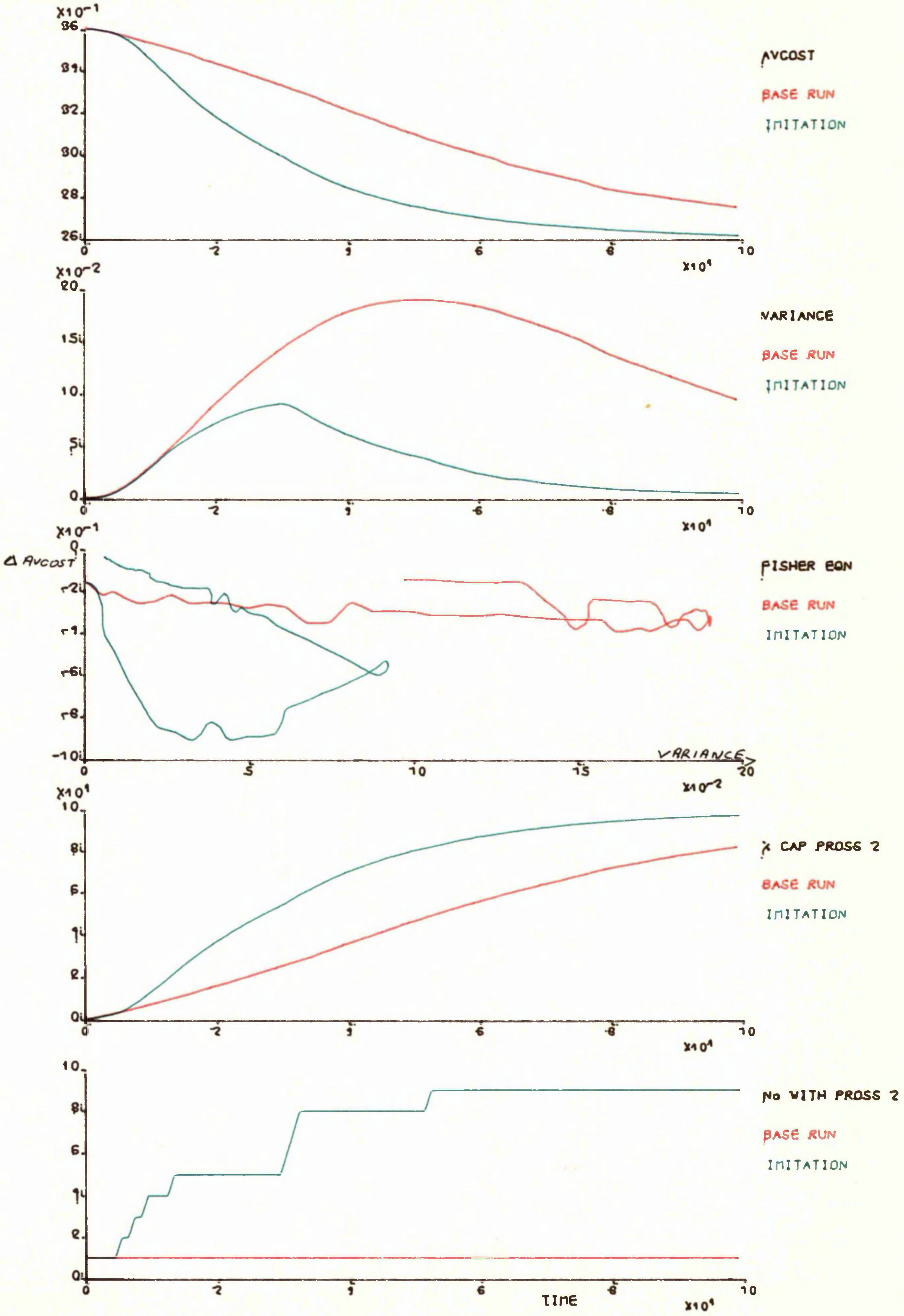


FIGURE 8.19 IMITATION CASE: SECOND AND SIXTH BEST FIRMS

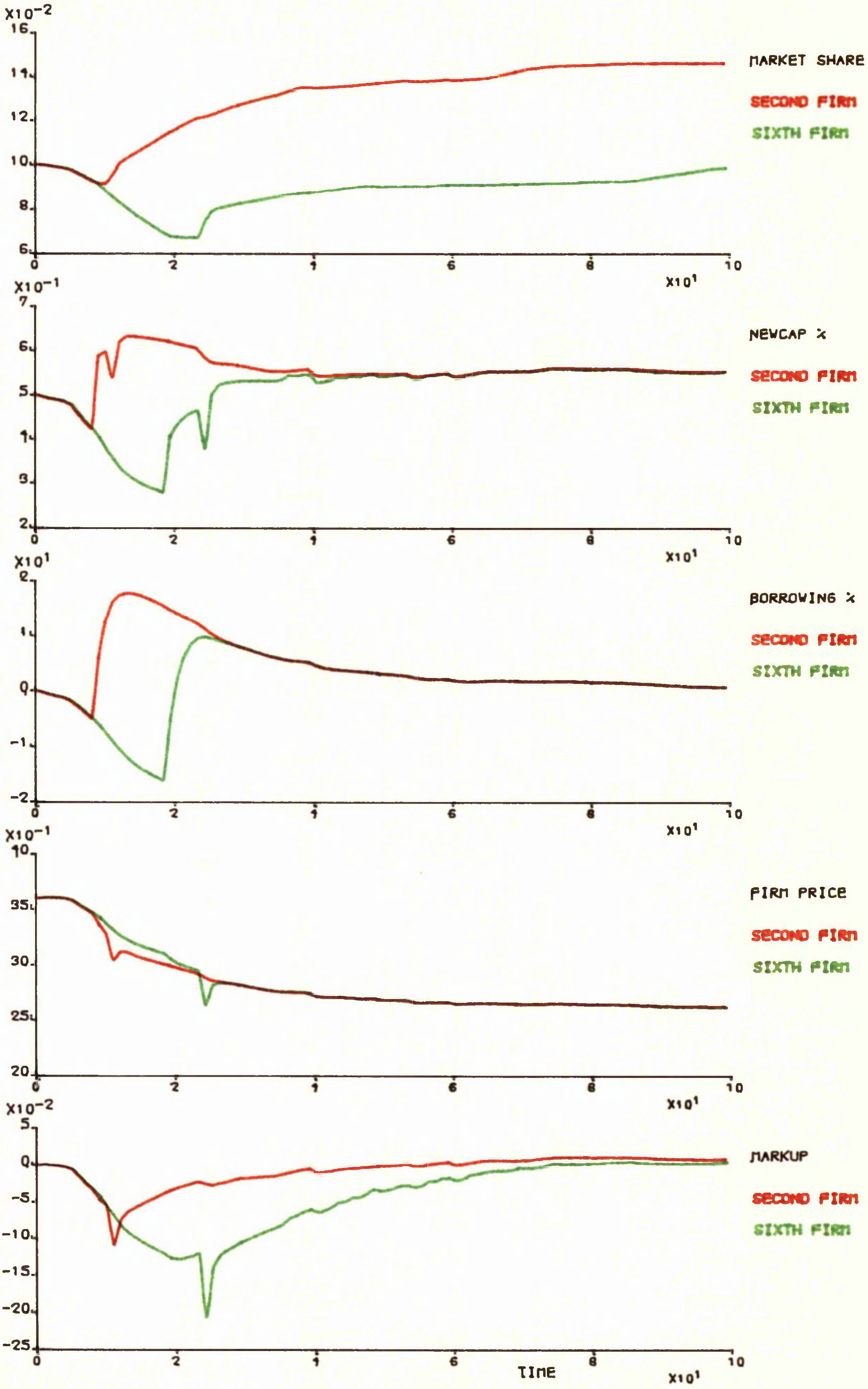


FIGURE 8.20 INDUSTRY PERFORMANCE: SEARCH AND VARIATION

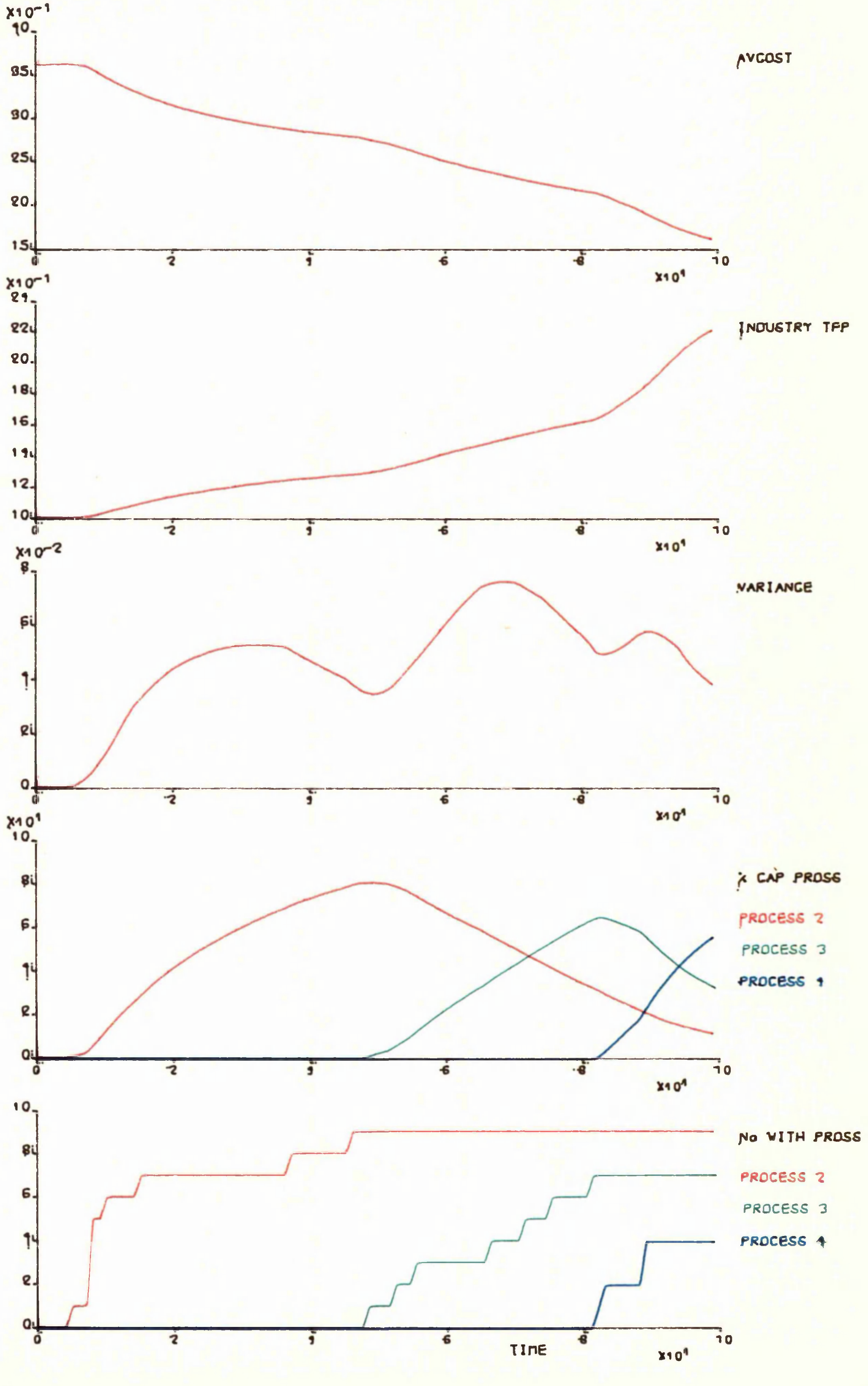


FIGURE 8.21 BEST AND WORST FIRMS

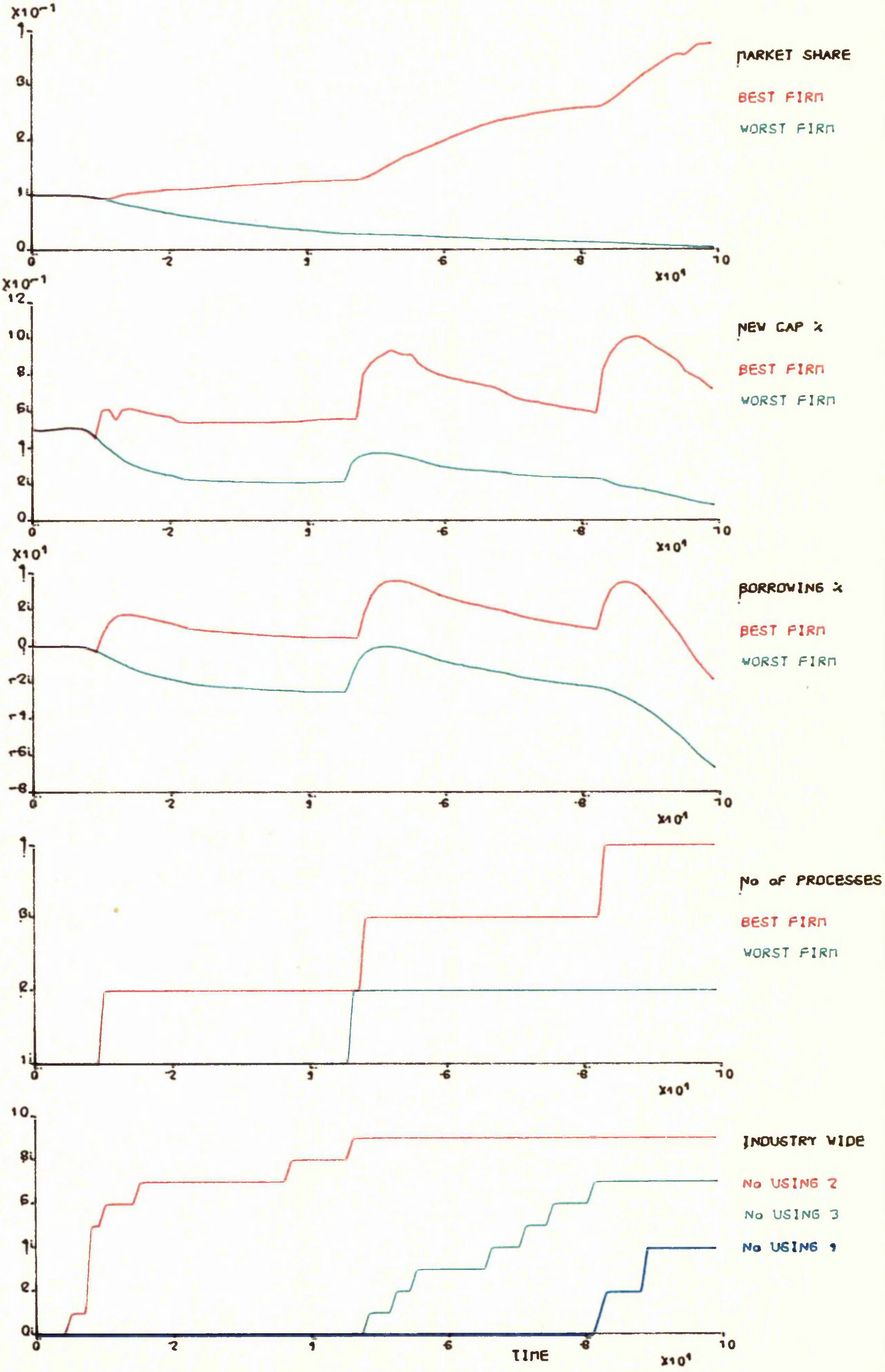


FIGURE 8.22 INDUSTRY PERFORMANCE AND COMPETITION

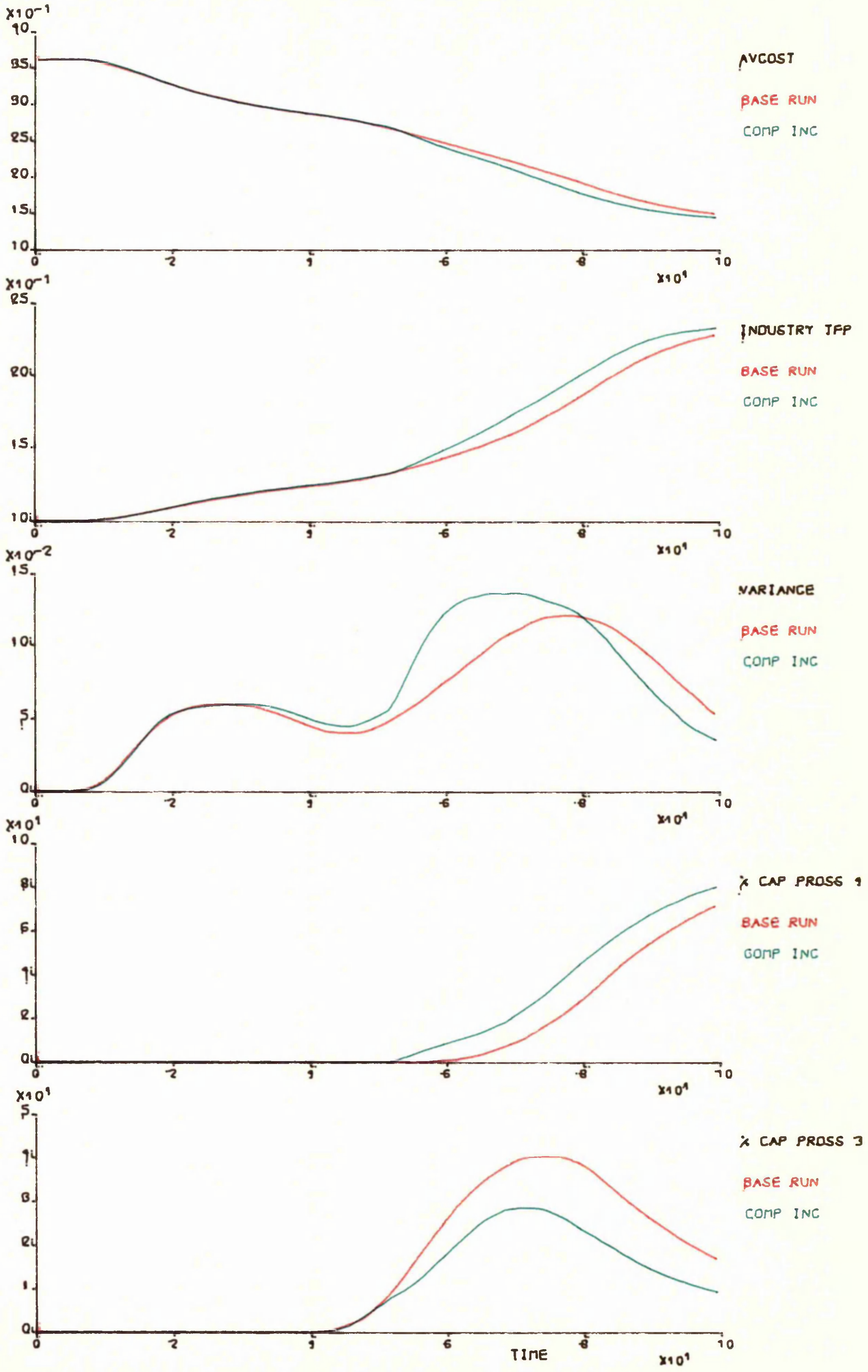


FIGURE 8.23 INDUSTRY PERFORMANCE AND COMPETITION 2

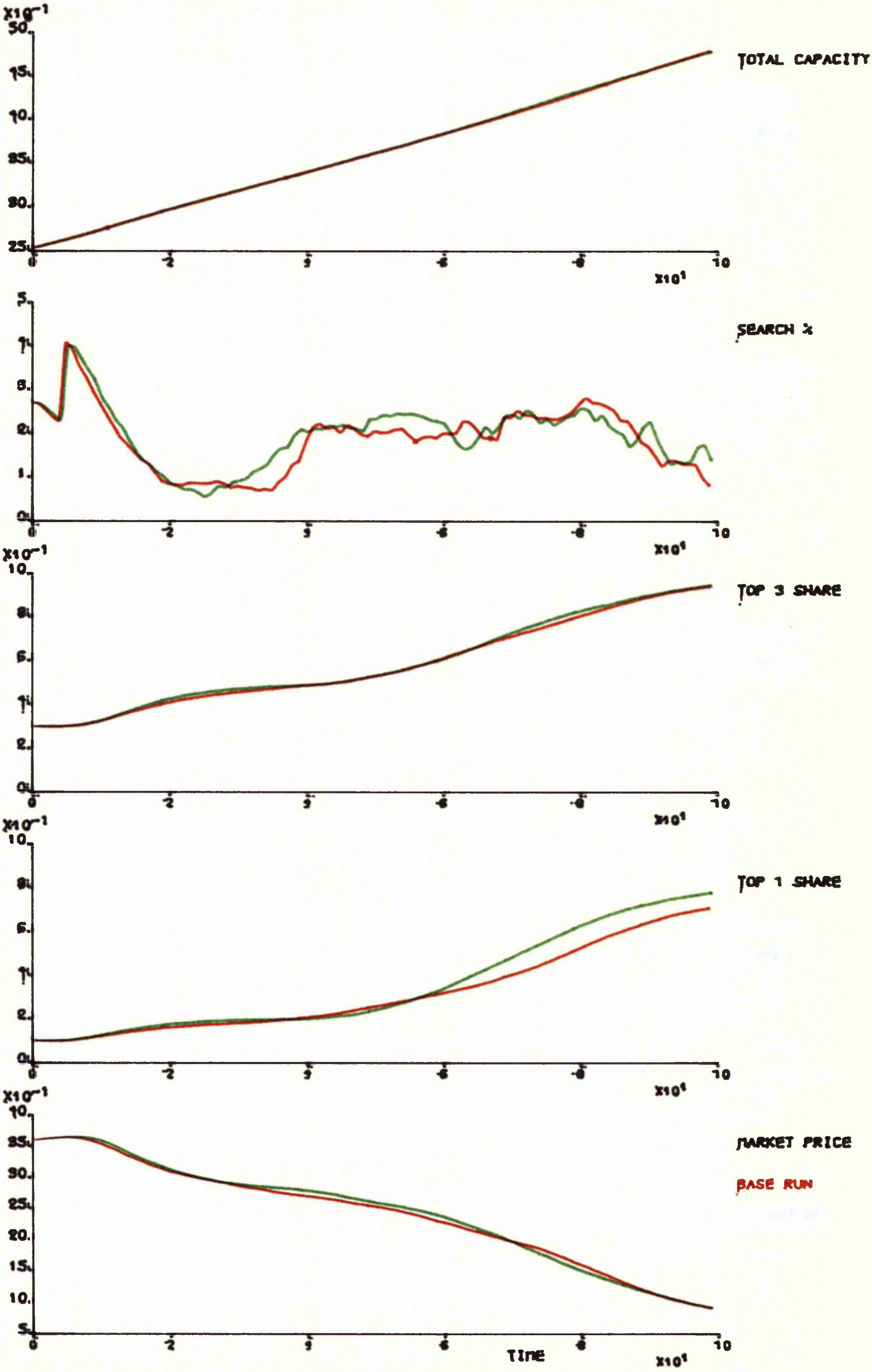


FIGURE 8.24 INDUSTRY PERFORMANCE AND HARDER SEARCH

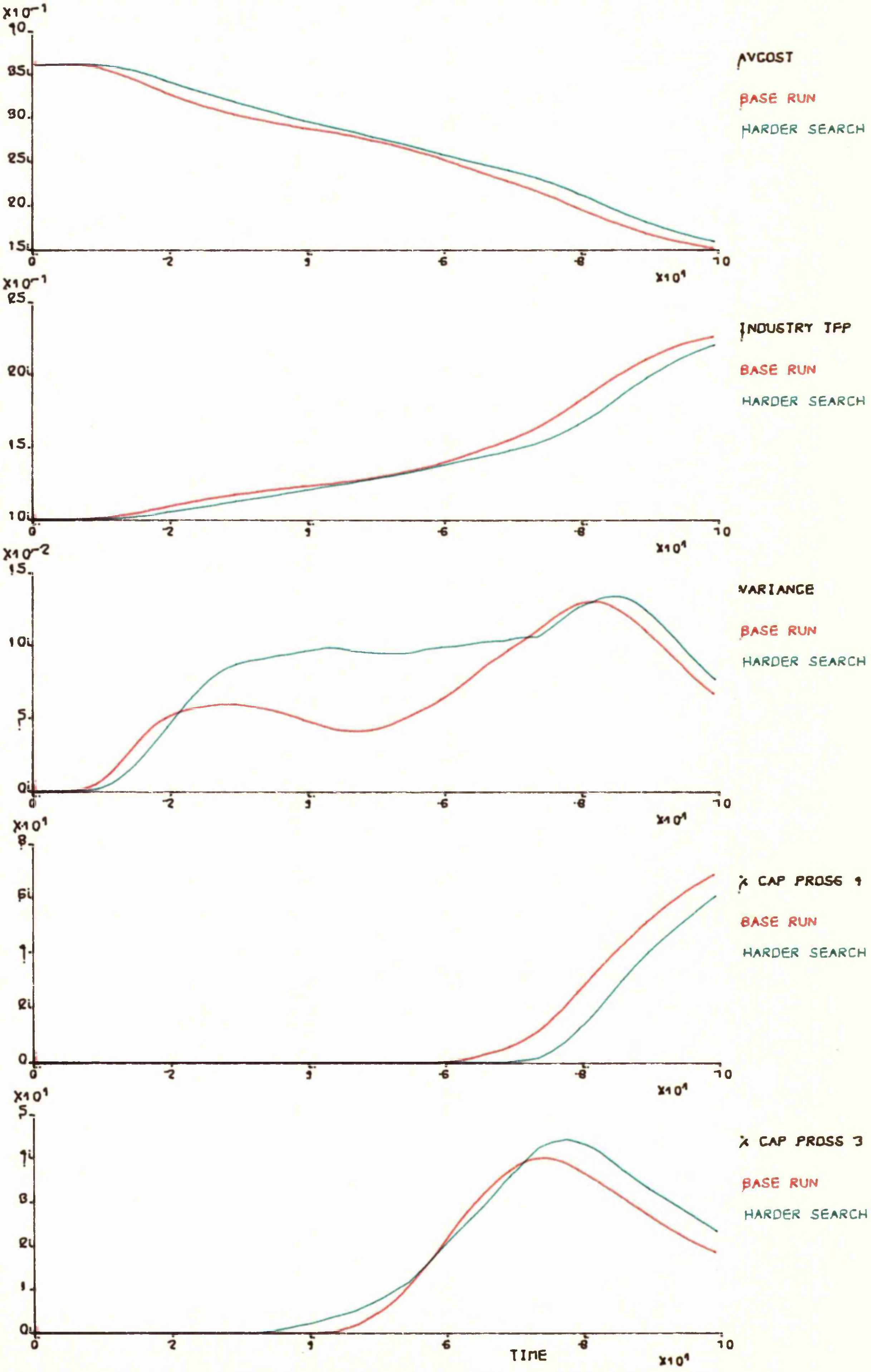


FIGURE 8.25 INDUSTRY PERFORMANCE AND HARDER SEARCH 2

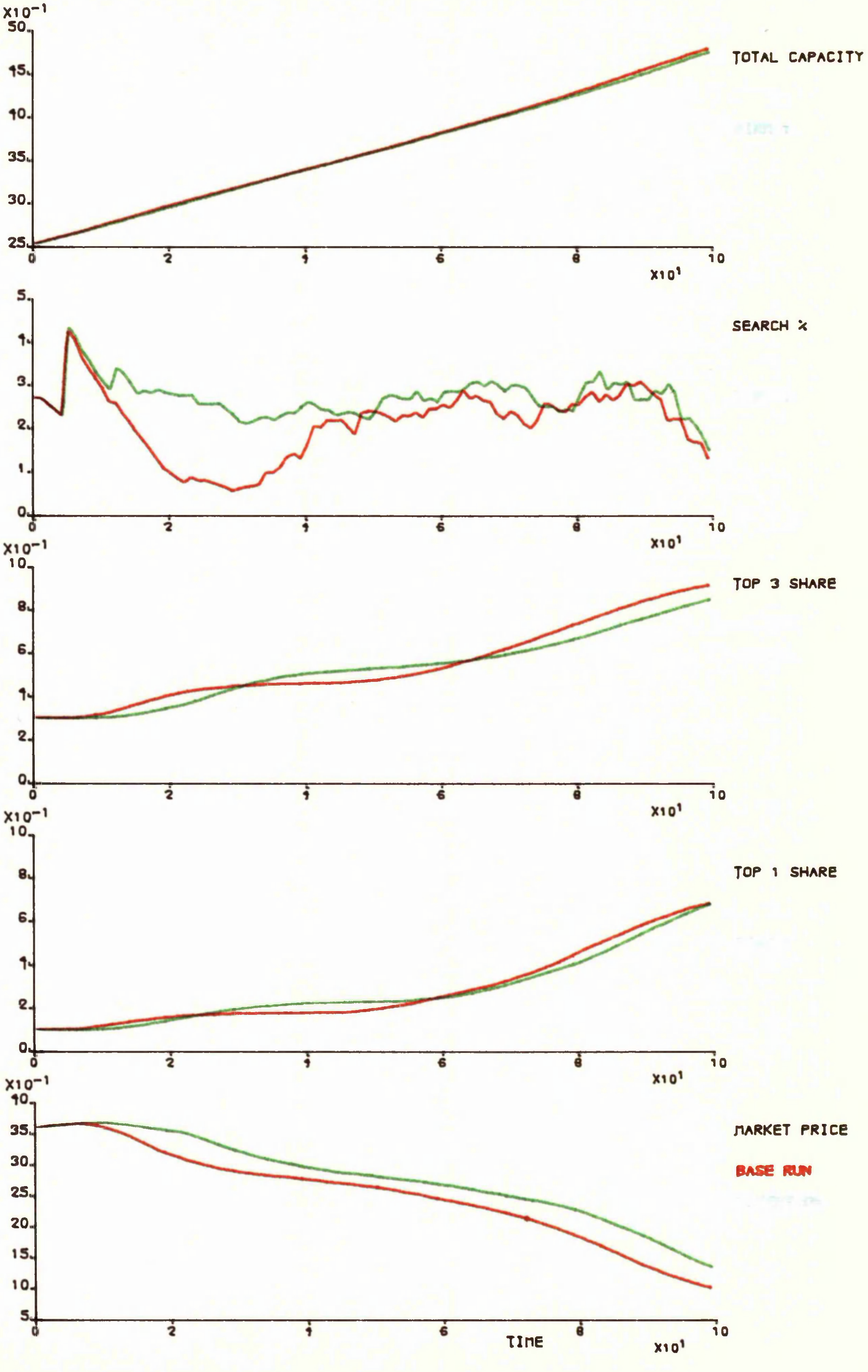


FIGURE 8.26 INDUSTRY PERFORMANCE 1: EFFECT OF PATENTS

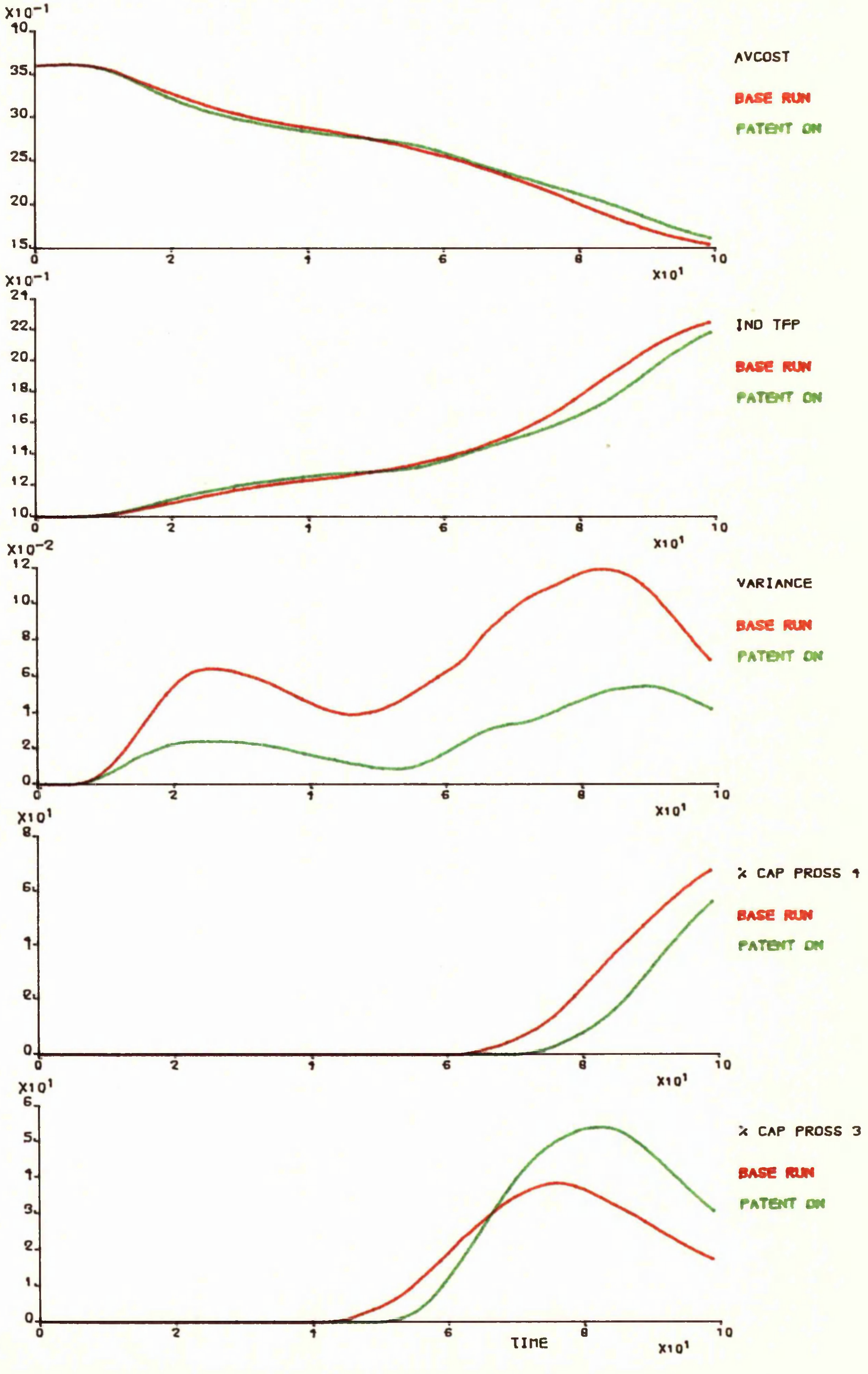


FIGURE 8.27 INDUSTRY PERFORMANCE 2, EFFECT OF PATENTS

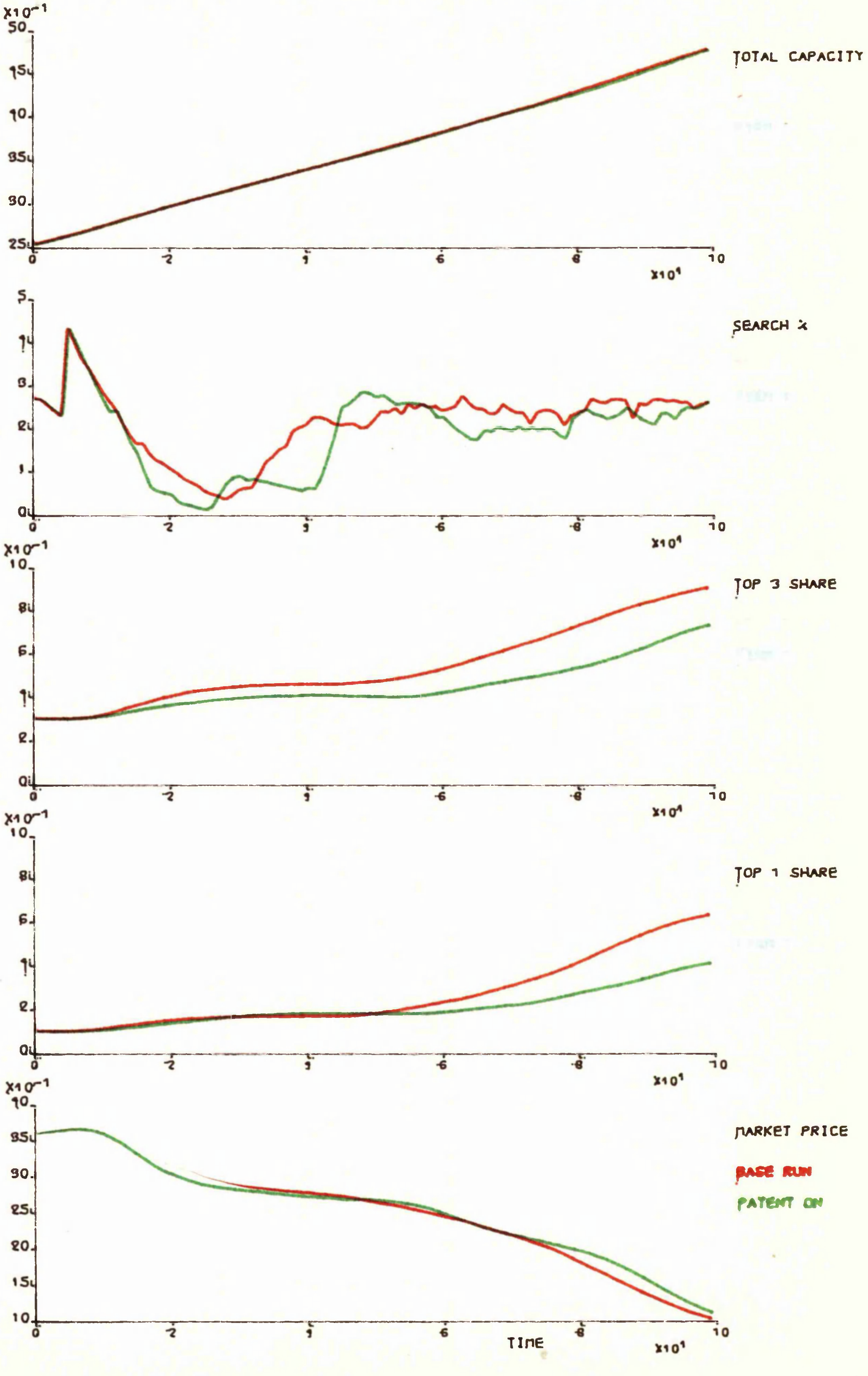


FIGURE 8.28 FIRM PERFORMANCE: EFFECT OF PATENTS

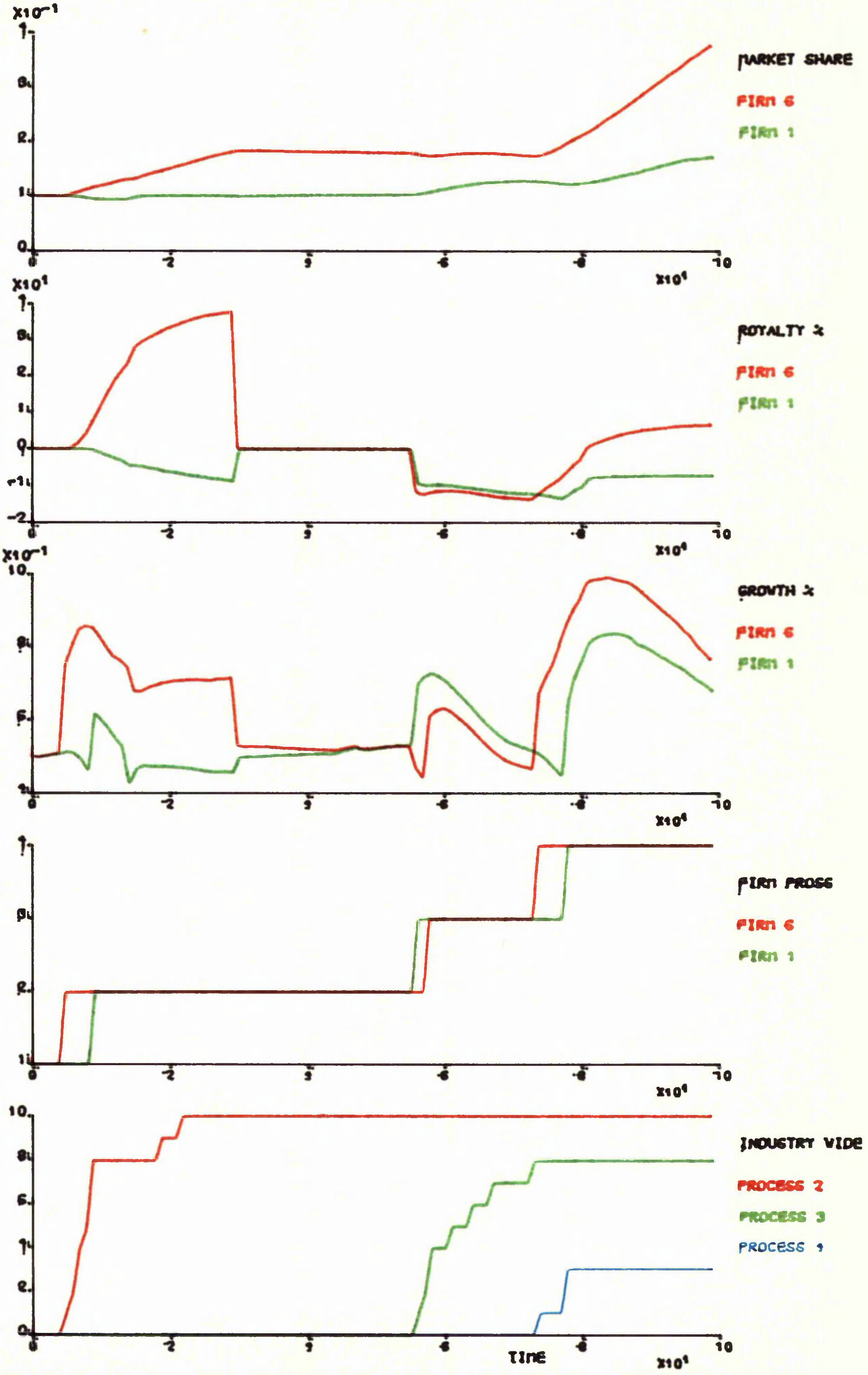


FIGURE 8.29 RELATIVE PERFORMANCE OF INDUSTRIES

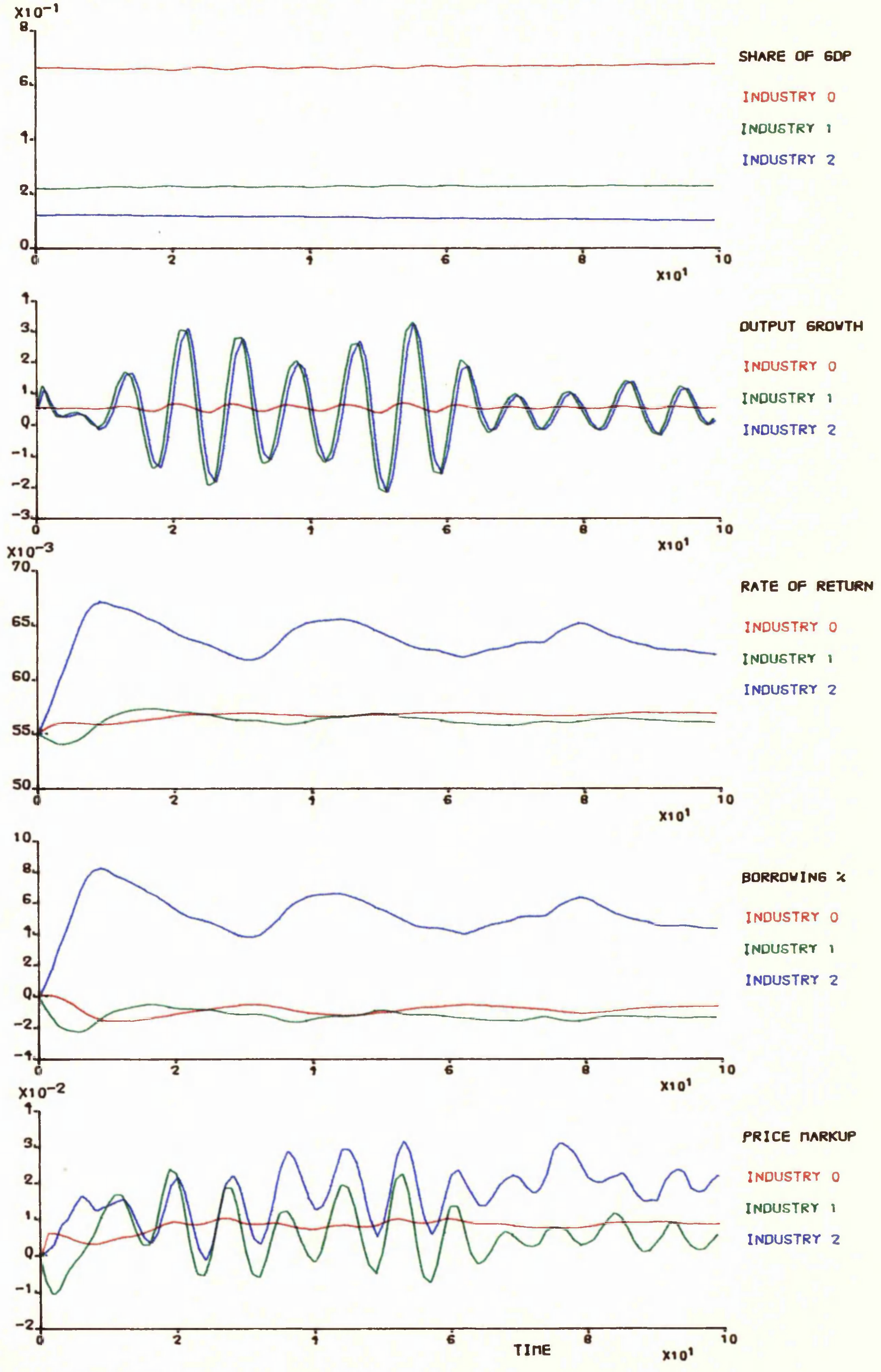
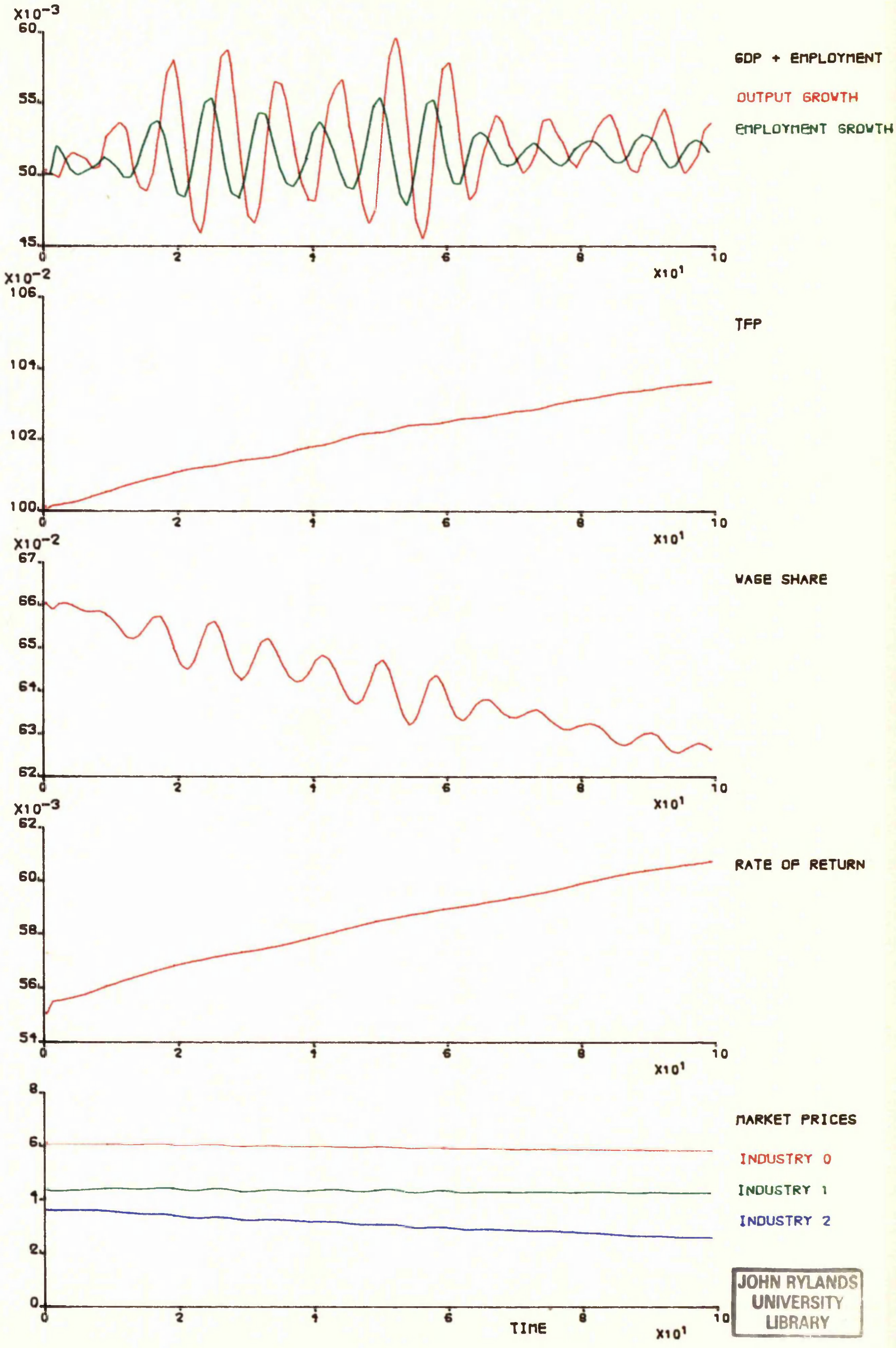


FIGURE 8.30 PERFORMANCE OF THE ECONOMY



CHAPTER 9 THE COURSE OF ECONOMIC EVOLUTION

9.1 Introduction

In this chapter we complete our description of the results from our simulation study. We allow all elements of the model as described in chapter 7 to operate[1]. In particular all firms now engage in search, both incremental and basic. We are consequently able to examine the contribution of induced innovation to economic development. We first consider the case of pure induced innovation, in which no exogenously determined processes are introduced. We then consider the effect of changing some parameter settings and finally we examine the impact on the economy of major innovations, whose production coefficients are given exogenously. Again the simulation results are collected at the end of the chapter, beginning on page 321.

9.2 Induced Innovation and Economic Development

9.2.1 Setting the Scene

The scenario for this section is that all firms engage in incremental search, the outcome of which is immediately incorporated in all new capital purchased by the firm. If and when the firm achieves a certain total distance, summed across all search directions, it is deemed to have discovered a new basic process. The coefficients of the new basic process are those of the best technique so far in use by the firm, which

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[1] Except the patent system, which is seen as outside of the evolutionary framework.

becomes the origin of the search probability functions (as in figure 7.2, p208). Thus discovery of a new basic process allows the firm to search for a new set of techniques, based upon what it has found so far; the technological development of the economy is endogenous, given the search environment.

In this chapter the angle for each search direction was set at 30°. The effect of this is that for each search direction the firm reduces one coefficient by an amount proportional to cos(30) (0.866), and increases another coefficient by an amount proportional to sin(30) (0.5). Thus the firm is seen to be in substantial control of the direction its technology develops in.

As firms move from one basic process to the next, the search probability distributions are not changed, but the difficulty of search is increased in two ways. First, the cost of each draw on the probability distribution is increased and second the difficulty of finding a new basic process is increased. The appendix shows the computer program as set up to generate figures 9.1 to 9.11 with the changing search environment shown in the subroutine OUTCOM. To reduce the impact of economies of scale, the 'annual' rate of depreciation of capital was set at 2%.

Figures 9.1 to 9.9 show the development of the three industries. Before describing our results we first consider a problem in setting up the model; rapid inter-firm diffusion of new basic processes. Figures 9.1 and 9.2 show the diffusion of six basic processes, B1 to B6 in industry 0, according to the percentage of industry capacity they account for and the number of firms using them respectively. The rapid diffusion pattern seen in figure 9.2[2] reflects decisions made to expedite the production of results.

The random nature of search and the growth in the economy as a result of technical progress make it difficult to prejudge a search environment to allow a gradual diffusion of new basic processes, particularly late on in a simulation run. Thus many simulation runs may be required to produce a desired set of diffusion patterns across all three industries. An additional problem is that towards the end of the diffusion period for any basic process, as the economy becomes larger, the number of draws on the search probability distributions can increase dramatically (as illustrated by figure 8.10). This has the effect of greatly slowing down the execution of the program.

The problem of rapid diffusion is exacerbated if, in setting the search environment for each new basic processes, the difficulty required for a new basic process is increased rather than the search price. Experimentation with the model

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[2] The impression of this from the graph is exaggerated by the change in horizontal scale from the previous chapter, as the simulation run was allowed to carry on until period 150. The other two industries show similar diffusion patterns.

has shown that slow patterns of diffusion can be attained by a low search cost and difficult conditions for making a basic discovery, but with the program taking much longer to run[3].

The effects of diffusion on industry structure have been examined in chapter 8, and here we are more interested in induced innovation. It was therefore decided to allow most of the adjustment in search environment to be by increasing the search cost, rather than increasing the difficulty of search, at the expense of rather too rapid diffusion paths for large inter-firm differences to develop.

9.2.2 Industry Performances

We now turn to the results themselves. Figures 9.1, 9.4 and 9.7 illustrate the best practice technology in each of the three industries. The production coefficients shown are the share weighted average of the best technique in use by each firm in the industry. All industries show a tendency to substitute capital good 2 for labour, with a lesser tendency to substitute capital good 2 for good 1.

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[3] The alternative option of making search less worthwhile by reducing the mean or variance of the search probability distributions was rejected since this would lessen firms effectiveness in developing new technology. The run time (central processor time) to produce figures 9.1 to 9.11 was 15 minutes. It is easy to generate run times of over 60 minutes by increasing the parameter PASS with each new basic process discovered. Long run times are problematic because many runs may be required to set up all the parameters, and because multiple runs are also used to generate comparative results, as in figures 9.12 and 9.13 below.

The eventual increase in average productivity is between 45 percent (industry 2) and 70 percent (industry 1), as six new basic processes are introduced in each industry. Given the rapid domination of each new process, as illustrated by the percentage of total capacity each accounts for, the average productivity is very close to best practice productivity (not shown).

The increase in productivity reflects the major changes in the actual coefficients. The best practice labour coefficient falls by over 50% in all three industries, whilst the capital good 2, K2, coefficient increases by between 25 percent in industry 0 and 50 percent for the other two industries. The most labour intensive industry, industry 0, concentrates on reducing its labour input, with no reduction in capital inputs. The other two industries, with less labour intensive production, are able to also direct resources to reducing the K1 input. These results show how, given their different factor proportions but the same search probability distributions, each firm, and hence industry, chooses to develop its technology according to its own input structure; induced innovation in practice.

We now examine each industry in more detail. As just noted, figure 9.1 shows that firms in industry 0 concentrate in the main on reducing labour input, and in so doing substitute K2 for labour, using, presumably, search direction 5. The fluctuations in the time paths of the coefficients occur because it is possible that with the search angle set at 30°, a firm will find all six search directions profitable at some stage during the simulation. Each search direction operates to effect a proportionate change in production coefficients. Thus from figure 9.1, the early search effort is to substitute K2 for labour. As the K2 coefficient increases, it then becomes worthwhile to devote resources to reducing it, for example between periods 80 to 100. This type of effect can be seen throughout the simulation run for all industries and inputs.

Behind the industry average performance there is the dynamic competition between firms. Figures 9.2 and 9.3 show the performance and behaviour of the best and worst firms, classified according to their final market share. Figure 9.2 shows that by the end of the simulation the best firm is approximately twice the size of the worst. After 150 periods, this is quite a small difference, except when seen in the light of the rapid diffusion paths. The gap between the two firms in discovering the third, fourth, fifth and sixth basic processes is only about 3 to 5 yearly periods in each case.

As in the previous chapter, early discovery of a new basic process allows a firm access to finance from both profits and borrowing. The differences between firm prices cannot really be seen from figure 9.2, where the scale of the graph is too small to show them. In figure 9.3 we see that from period 40 onwards, soon after it gets ahead, the best firm is consistently able to have a higher price markup, whilst at the same time maintaining an increasing market share. Both firms are net lenders to other industries, but the best firm is rather less so. Thus the best firm's success is seen to stem from the slightly superior average productivity which it is able to maintain throughout the simulation run, which has a big impact on the financing of new capital. Dynamic competition and economic selection are operating here as they did in the previous chapter. We defer consideration of the growth rate and prices until section 9.2.3.

Figures 9.4 to 9.6 illustrate industry 1. In terms of technological development, we see much the same story as for industry 0. The main point of difference is that industry 1 uses labour rather less intensively than industry 0, and so devotes more resources to reducing its use of K1. The other notable feature is that after period 100 the firms switch their search strategies, and try to substitute K1 for K2.

The comparison between the best and worst firms is rather more marked for industry 1, with the best firm being seen, in figure 9.5, to be about 5 times the size of the worst by the end of the run. The explanation for this is clearly seen in the technology used by each firm. The worst firm is the last to acquire the second basic process, and never really recovers from this and at one stage the best firm is two processes ahead of it. This is clearly reflected in the price markup and borrowing. Whilst figure 9.10 shows industry 1 as a net borrower, the worst firm is a net lender.

For the best firm, we see some interesting behaviour between periods 25 to 50. Although it is the first firm to discover basic process B2, it is one of the last to discover process B3. One reason for this may be the high profitability of its current production, which encourages it to devote investment funds to new capacity rather than search, as discussed in the previous chapter. Bad luck is clearly also a factor. During the period in which it lags behind the other firms it loses market share, and is forced to reduce its price markup and utilisation rate. However its larger than average size enables it to reap economies of scale in search, so that it is able to recover its position. It becomes the first firm to discover processes 4 and 6 and is the second firm to find process 5. The lesson is clearly that a failing industrial giant has some breathing space, during which it can stage a come back based on its remaining economies of scale.

Finally in this section we turn to figures 9.7 to 9.9 which illustrate industry 2. We have already made the main points regarding induced innovation. We note one more case here. Industry 2 uses the two capital inputs in rather different proportions to industry 1, being a less intensive user of K2[4], and it also uses less labour. As a result firms in industry 2

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[4] The capital coefficients per unit of output are given on page 246.

devote more resources to increasing K2 during the early stages of the simulation. The illustrations of best and worst behaviour show little difference from those of the other two industries. Figure 9.9 shows one additional feature. The worst firm begins to lose market share rapidly between periods 50 to 65. As a consequence it reduces its price markup slightly, and also its utilisation rate. From the graphs, most of the change seems to fall on the utilisation rate, which is able to effect a much more speedy response to increasing stocks. The firm is also limited in its ability to cut its price by the need not to lose too high a percentage of its funds through lending.

9.2.3 Performance of the Economy

In this section we examine the relative performance of industries and the macro-economy. We begin by considering the growth in output. Figures 9.2, 9.5 and 9.8 show that growth for firms in all sectors increases rapidly within the first few periods to about 8% per period, from which level it rises more slowly. Figure 9.11 show similar performance for the economy as a whole[5]. These growth rates should be compared to the 3% that the economy is set up to grow at in the absence of technical progress.

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[5] There is also some instability in industries 1 and 2 as the simulation gets going (figure 9.10). In figure 9.11 the initial growth rate should be 3%, not 5% as shown (the value is set 'manually', and incorrectly in this case).

The initial cause of this high growth is firms optimism as they increase productivity during the first few periods of the simulation. Each firm acts in isolation, translating its productivity increase into a higher utilisation rate and price markup, as in the previous chapter (figure 8.3 for example). This optimism is reinforced as the whole economy behaves in this way.

The rapid growth represents 'actual' plant (within the model), as the firm and industry growth rates record 'actual' outputs, not weighted by prices. The extra growth comes from the very high utilisation rates seen, even for the worst firms in each industry. An additional source of growth is the diversion of funds from the consumption good industry to the capital goods industries, seen in figure 9.10, increasing the capacity across all industries. One possible source of accelerating growth, falling capital coefficients, was shown in the previous section not to apply in this scenario.

Perhaps the most notable feature of figure 9.10 is the very high price markups. The effect is that market prices actually increase despite the technical progress. The high price markups are possible because there is no mechanism to slow growth in our model: the economy is closed; there is no monetary constraint; competition is mainly within industries, not between them. Experimentation with the model failed to produce runs with both rapid technical progress and low price markups. The high price markups are an accident of the construction of the model.

The price markups do not really affect our story of economic evolution, except in so far as additional induced innovation effects, as a result of endogenously generated input price changes, do not occur. They also affect the competition for resources within the model economy. This may be relevant to some real world situations as described below. It also illustrates once again that simulation models are tools to be used with some care; in our case we need to concentrate on the real production system, which the model was designed to simulate. The important point is that the average markup for industry 2 is the highest, reflecting the bias of technical progress towards using K2, whilst the markup of industry 0 is lowest reflecting the bias away from labour.

The high absolute level of the price markups does have one interesting effect. We have already seen that technical progress in our model is directed towards reducing the labour input. Thus the growth of employment is seen to be rather below that of GDP, even during the period when prices are falling[6]. Figure 9.10 shows that the share of GDP accounted for by industry 0 falls from 68% to 30% during the simulation, in line with the reduction in labour coefficients.

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[6] GDP is measured in current prices, so that real growth exceeds GDP growth.

Even though the demand for labour is growing more slowly than the economy as a whole, high price markups in the consumption good sector are needed to stop it losing investment funds to the other sectors. This has the effect of reducing the real wage and demand for the consumption good grows less quickly than it otherwise would. The effect of the high price markups is essentially to reduce real wages and divert funds to the accumulation of capacity in the capital goods sectors. Such a scenario may be pertinent to the debate over the price of capital equipment and manufactures to the third world from the developed world.

9.2.4 Alternative Scenarios

In this section we examine the effects on the economy, at the industry and macro levels, of changes in two key parameters of the model: the wage rate, reflecting the power of labour to increase its share of income; and the ease of borrowing, reflecting the efficiency of capital markets. The base run used as the basis for comparison below is that used to generate figures 9.1 to 9.11. The comparative graphs show results averaged over five simulation runs for each scenario. The simulations run for 100 yearly periods in each case.

(i) Wages Increase

Figures 9.12 and 9.13 show the effect of increasing money wages in line with previous increases in total factor productivity for the economy[7]. Figure 9.12 shows clearly that this has the consequence of increasing the share of wages and reducing the rate of return. Price markups have not been increased to compensate, as can be seen by examination of figures 9.10 and 9.13. Total factor productivity is slightly reduced by the end of the simulation period. The growth rate shows a more marked reduction. This confirms our observation in the previous section that the principal consequence of the high price markups was to divert resources towards capital accumulation and away from consumption. The effect of the increase in wages is to increase the share of GDP accounted for by the consumption good. Whilst in principle this can be seen from a comparison of figures 9.10 and 9.13, the effect is not clearly seen, except towards the very end of the 'wage increased' simulation (around periods 80 to 100). The same comment applies to the reduced lending of industry 0 to the other sectors.

(ii) No Borrowing

Figure 9.14 illustrates the effect of eliminating the only financial market within our simulation model, so that no borrowing takes place. This will increase inefficiency within the economy in two ways. First, within each industry more funds will be invested in techniques below best practice than would otherwise be the case; technical inefficiency is increased. Second, there will be no transfer of funds between

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[7] After year 10, the wage rate equals the level of TFP reached 10 years previously (see line 113 of the program).

industries, so that the capacity of a declining, low profit, industry will not fall as fast as would otherwise be the case; akin to the concept of increased adaptive inefficiency described in chapter 2.

Figure 9.14 shows a slight reduction in TFP, growth, employment and rate of return as a result of no borrowing being allowed. We have seen above that lending and borrowing can substantially affect the fortunes of individual firms. However, since in our model the firms uncover essentially the same technologies, and with a rapid rate of diffusion, the impact on economy wide performance is limited. The reduced performance shown if figure 9.14 arises from the extent to which some firms uncover marginally less productive technologies than others, and because of the lags in diffusion which do occur. The potential effect of capital markets is seen in our results even if their importance is probably understated.

9.3 Impact of Major Innovations

In this section we examine two scenarios in which major exogenously determined innovations occur. In the first case the technology of all industries is affected, in the second just one. The base run used as the basis for comparison is that used to generate figures 9.1 to 9.11. The comparative graphs show results averaged over five simulation runs for each scenario. The simulations run for 100 yearly periods in each case.

9.3.1 An Economy Wide Innovation The coefficients of the third basic process for each firm are set at 70% of the coefficients of the best technique so far in use by the firm[8]. Thus the new innovation is also to some extent endogenously determined. We might suppose that the third basic process is a superior mode of production, such as production line technology, which is, in our example, equally applicable in all industries.

Figure 9.15 shows the effects of the technological revolution. Up until period 25 the two scenarios run very much together. Once the first firms find their third basic process, the growth rate begins to accelerate. The key point from figure 9.15 is that the increase in growth rate is not once and for all. The major innovation generates a continuing acceleration in growth rate. The extra growth which stems from innovations, is supplemented by the reduction in capital required to install a unit of capacity. An additional factor generating growth is the reduction in the share of wages. Together these effects create a surge in growth, which continues.

The potential for a major innovation to generate the upswing of an economic long wave is evident in figure 9.15, which therefore suggests an alternative explanation of such waves to that of Sterman (1985). However within our model there is

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[8] See subroutine OUTCOM in the simulation program.

nothing to generate the downswing of the wave since, as described above, their are no constraints on growth.

9.3.2 Innovation in Industry 2 The new scenario is that the coefficients of the second and third basic processes for each firm in industry 2 are set at 75% of the coefficients of the best technique so far in use by the firm. Thus the new innovations are also to some extent endogenously determined. Figure 9.16 shows the impact on the economy of these innovations. We see that the first major innovation in industry 2 generates a comparatively small increase in the growth rate. Only when the cumulative effect of the two innovations is available does the economy begin the sort of acceleration in performance that we saw in section 9.3.1.

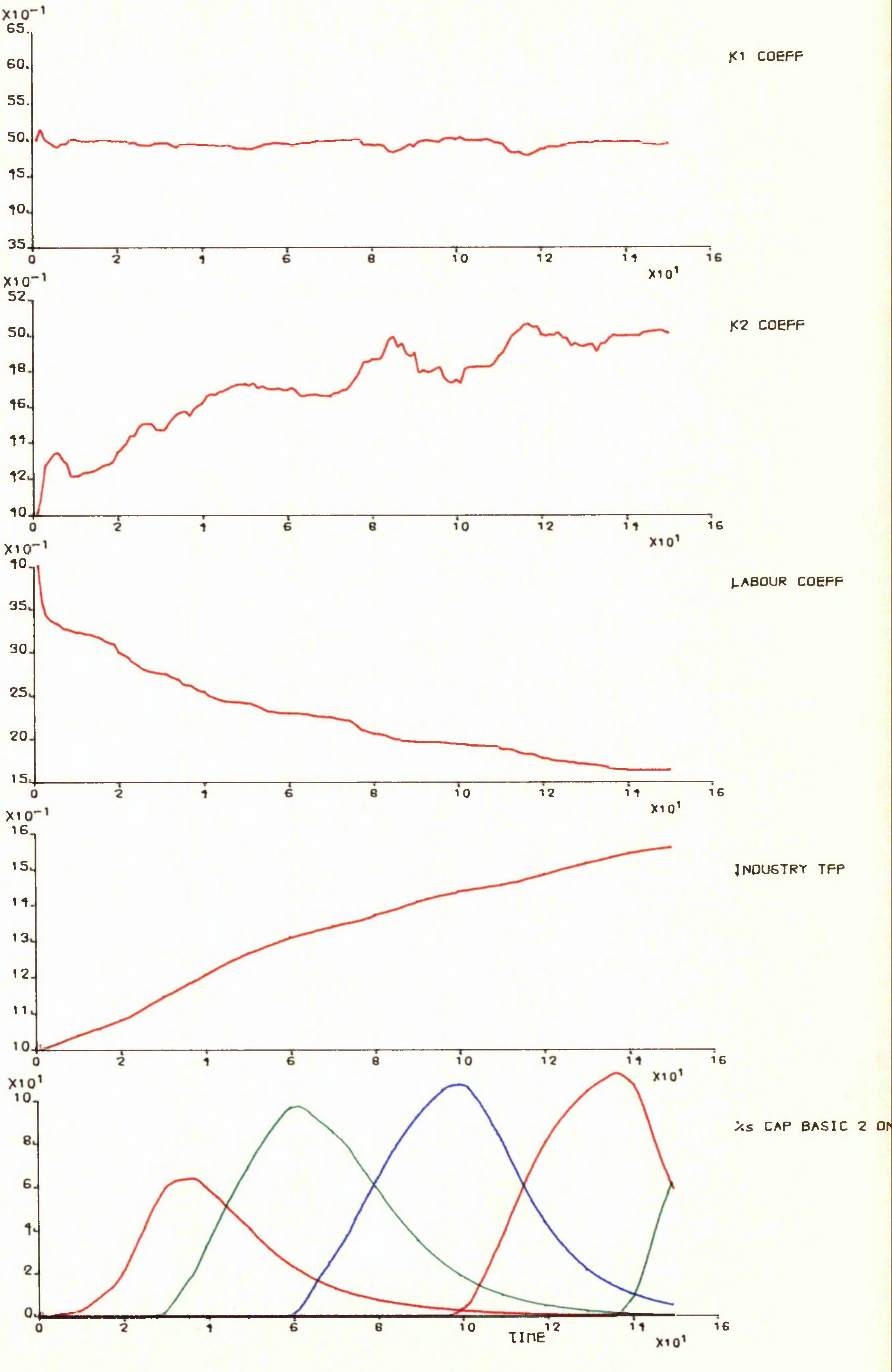
Figure 9.17 shows performance at the industry level for one of the simulation runs, which may be compared to figure 9.10. The principal effect of the major innovations is on the share of GDP attributed to industry 2, which is much reduced in the new scenario as compared to the base run. Another change is in the level of price markups, which rise steeply at about period 60 in figure 9.17. By the end of the simulation they are about double those seen in figure 9.10. This rise in the price markups helps to explain the reduced share of wages, and the acceleration of growth that allows.

Finally we compare figures 9.16 and 9.17 with results obtained in the previous chapter. Figures 8.29 and 8.30, we recall, represent three new processes being discovered in industry 2, each 25% more efficient than its predecessor. There was no innovation elsewhere in the economy.

The instability that is evident in figure 8.30, is not present in figure 9.16, despite the fact that figure 9.16 represents a much higher increase in productivity and growth. The flexibility in technology, and hence demand for capital, which induced innovation has allowed can in part explain the increase in stability. Another factor is diversity of behaviour, which means that all firms in the industry no longer behave in unison. Inertia at the firm level is a stabilising influence on the industry and economy as a whole.

9.5 Simulation Results for Chapter 9

FIGURE 9.1 INDUSTRY 0 TECHNOLOGY



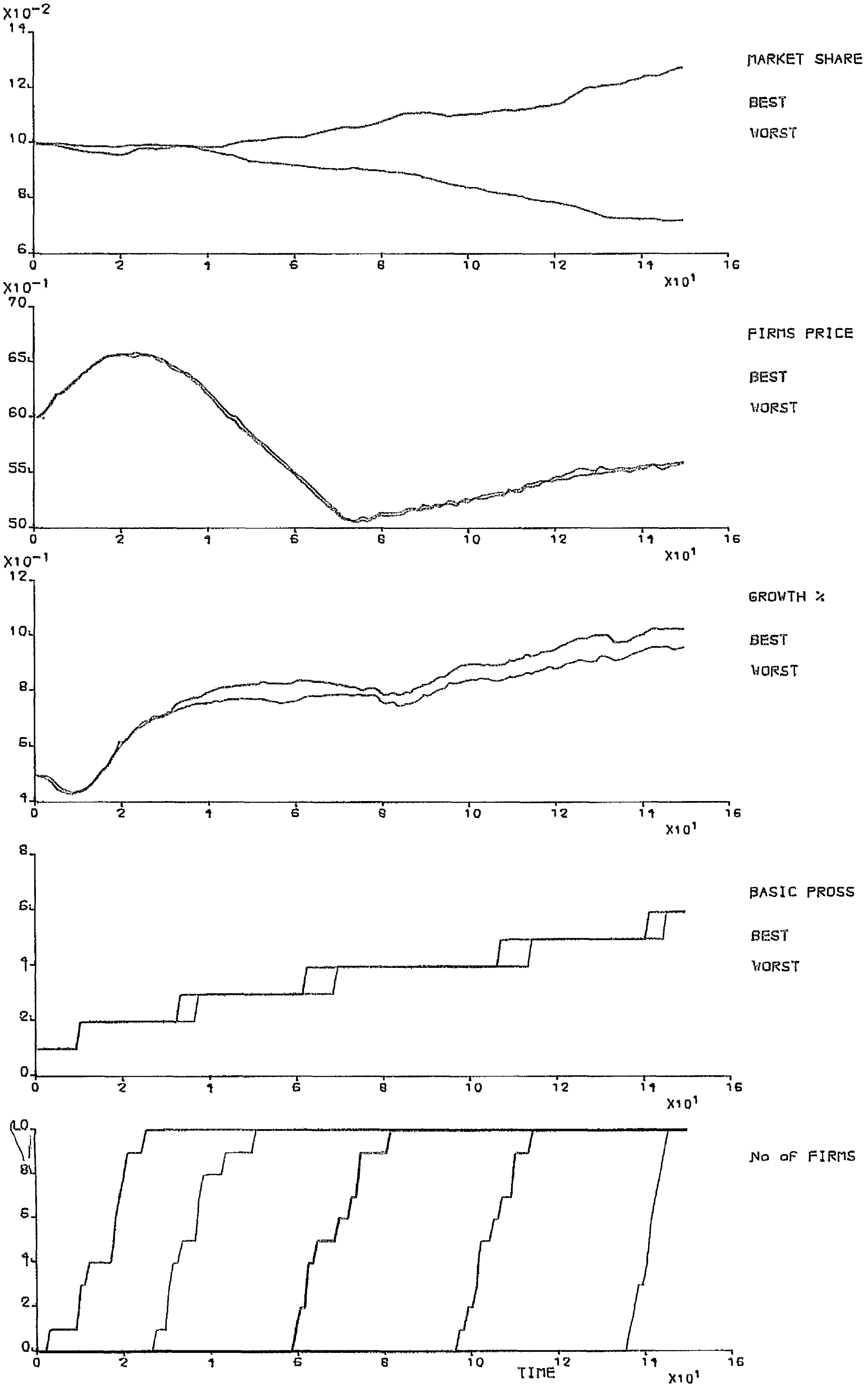


FIGURE 9.2 BEST AND WORST PERFORMANCE: INDUSTRY 0

FIGURE 9.3 BEST AND WORST BEHAVIOUR: INDUSTRY 0

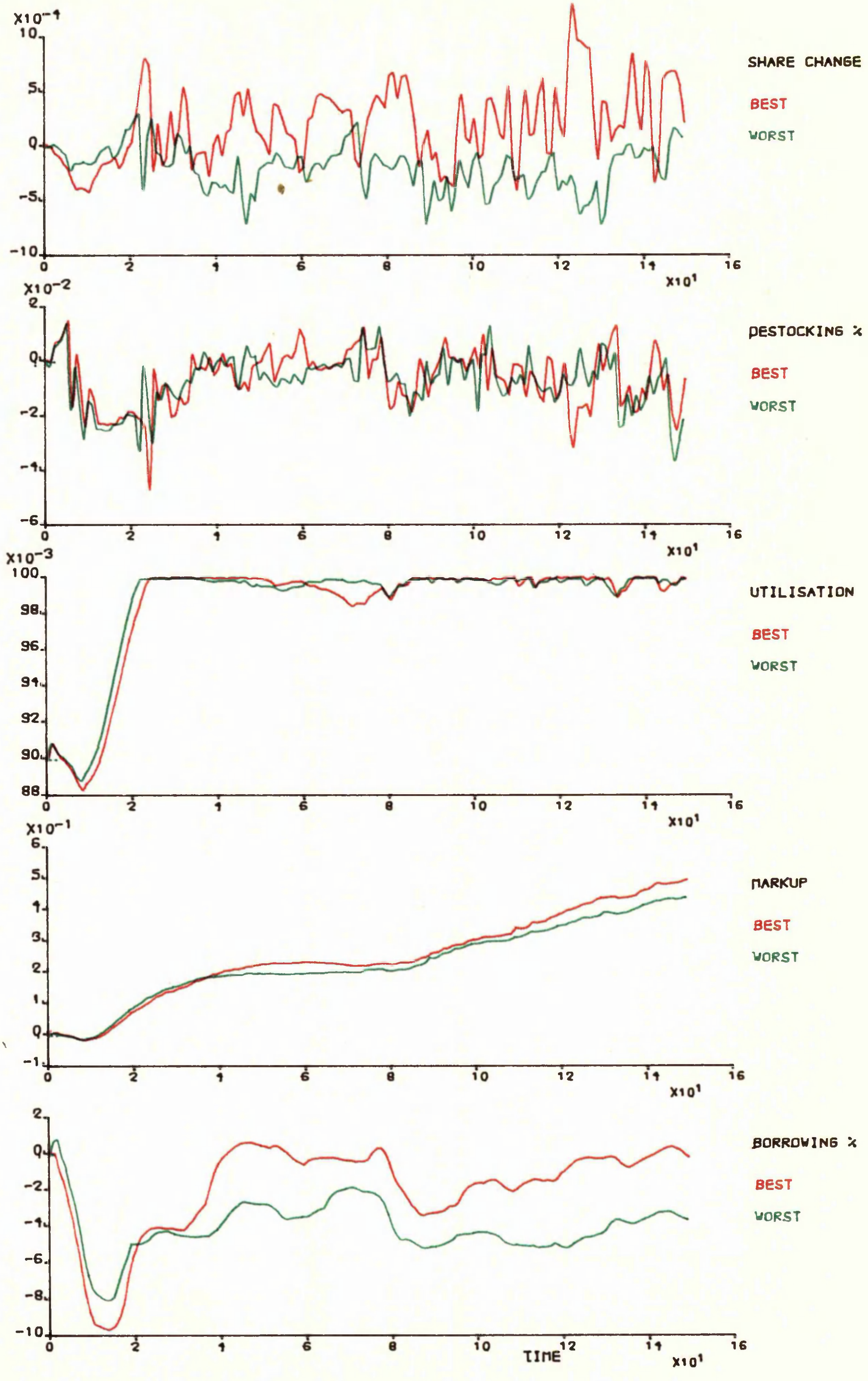


FIGURE 9.4 INDUSTRY 1 TECHNOLOGY

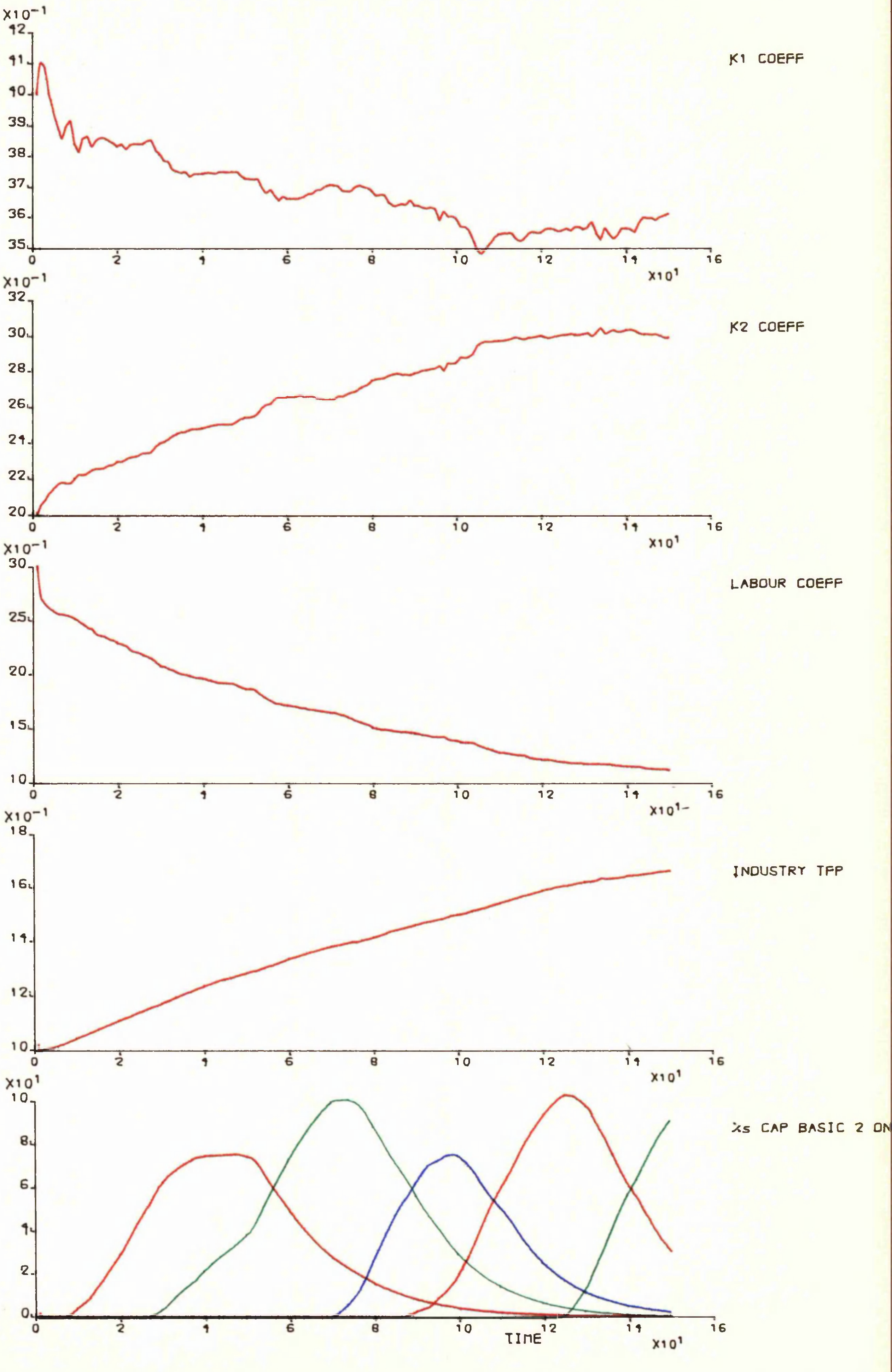


FIGURE 9.5 BEST AND WORST PERFORMANCE: INDUSTRY 1

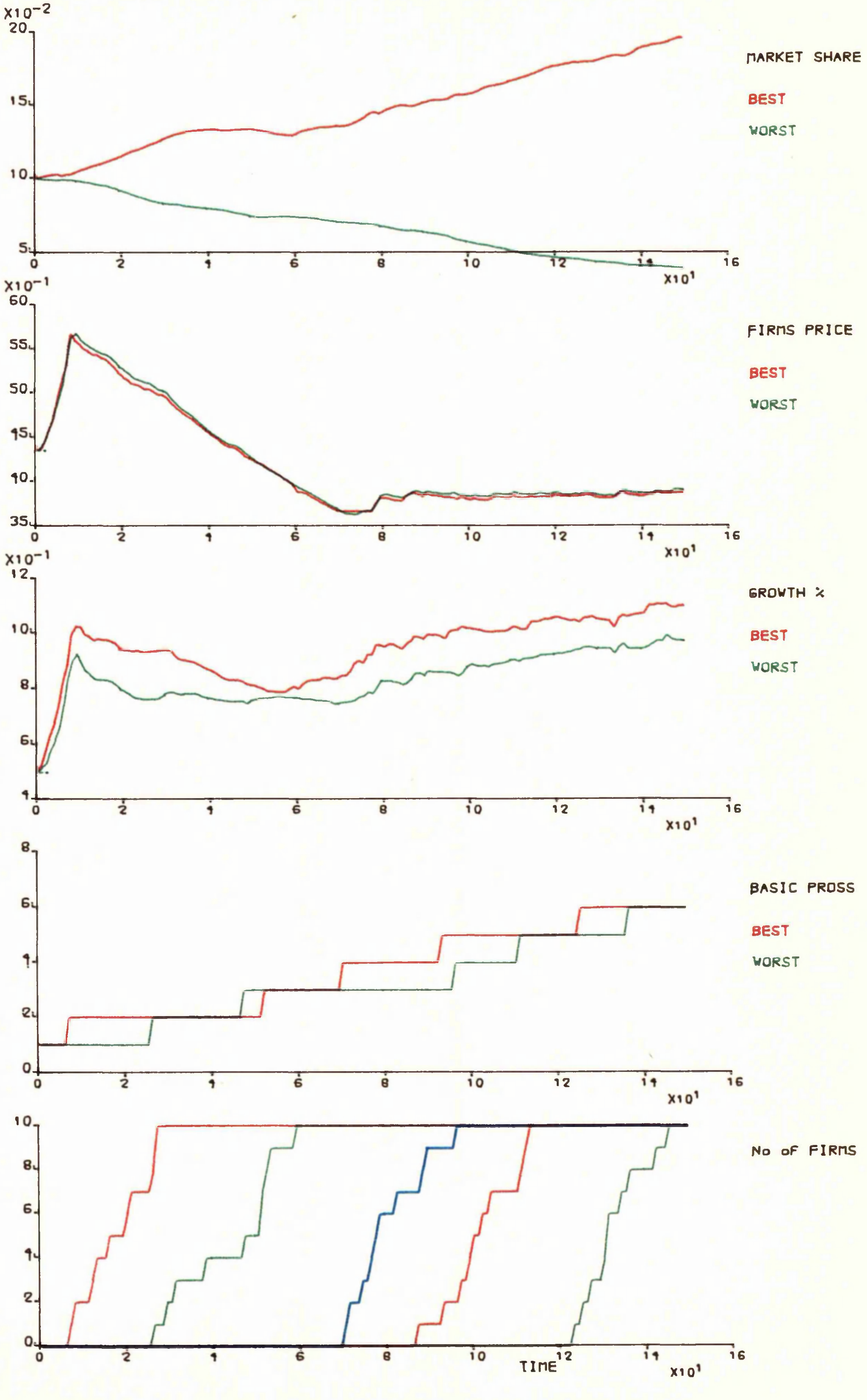


FIGURE 9.6 BEST AND WORST BEHAVIOUR: INDUSTRY 1

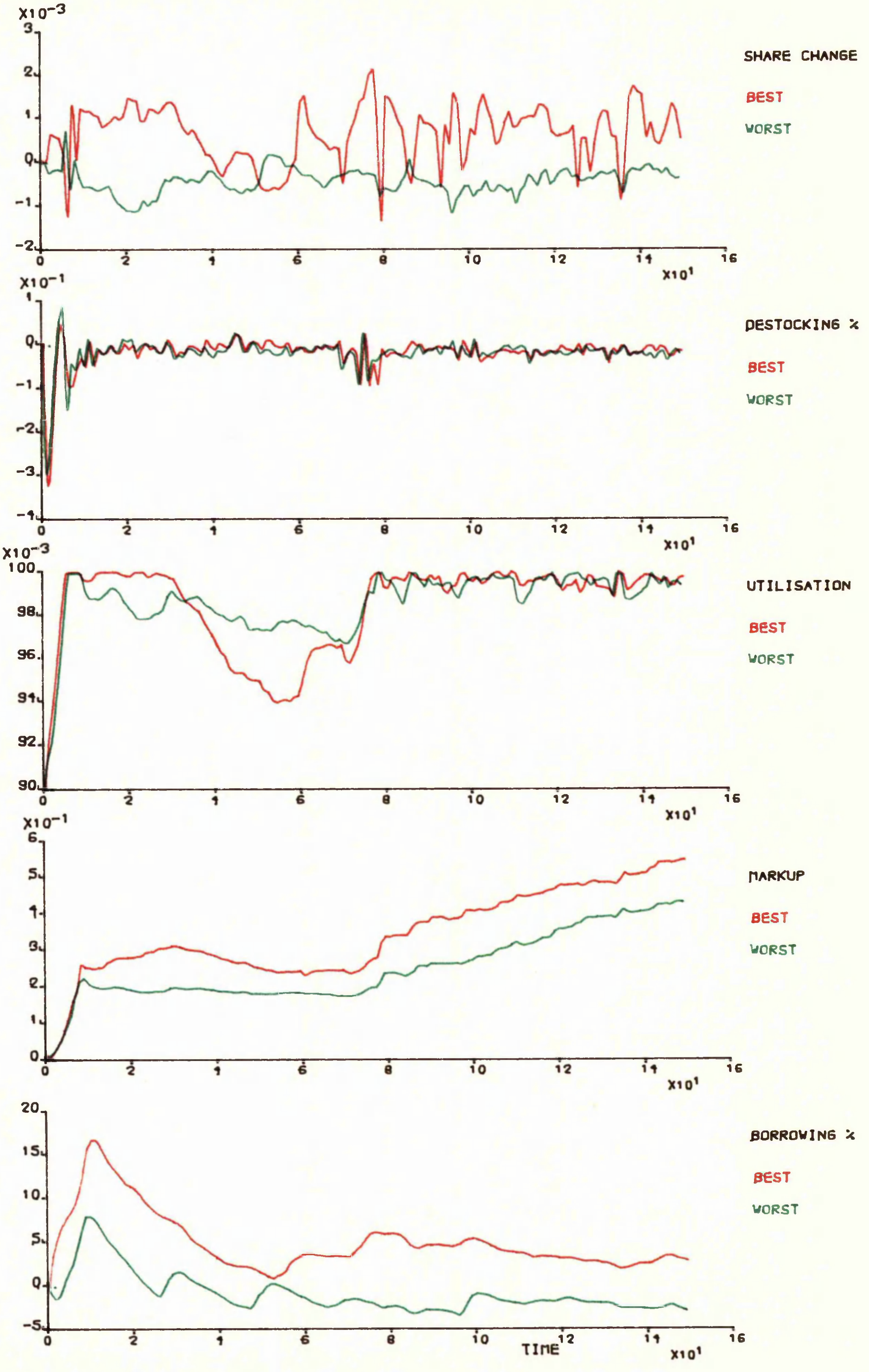


FIGURE 9.7 INDUSTRY 2 TECHNOLOGY

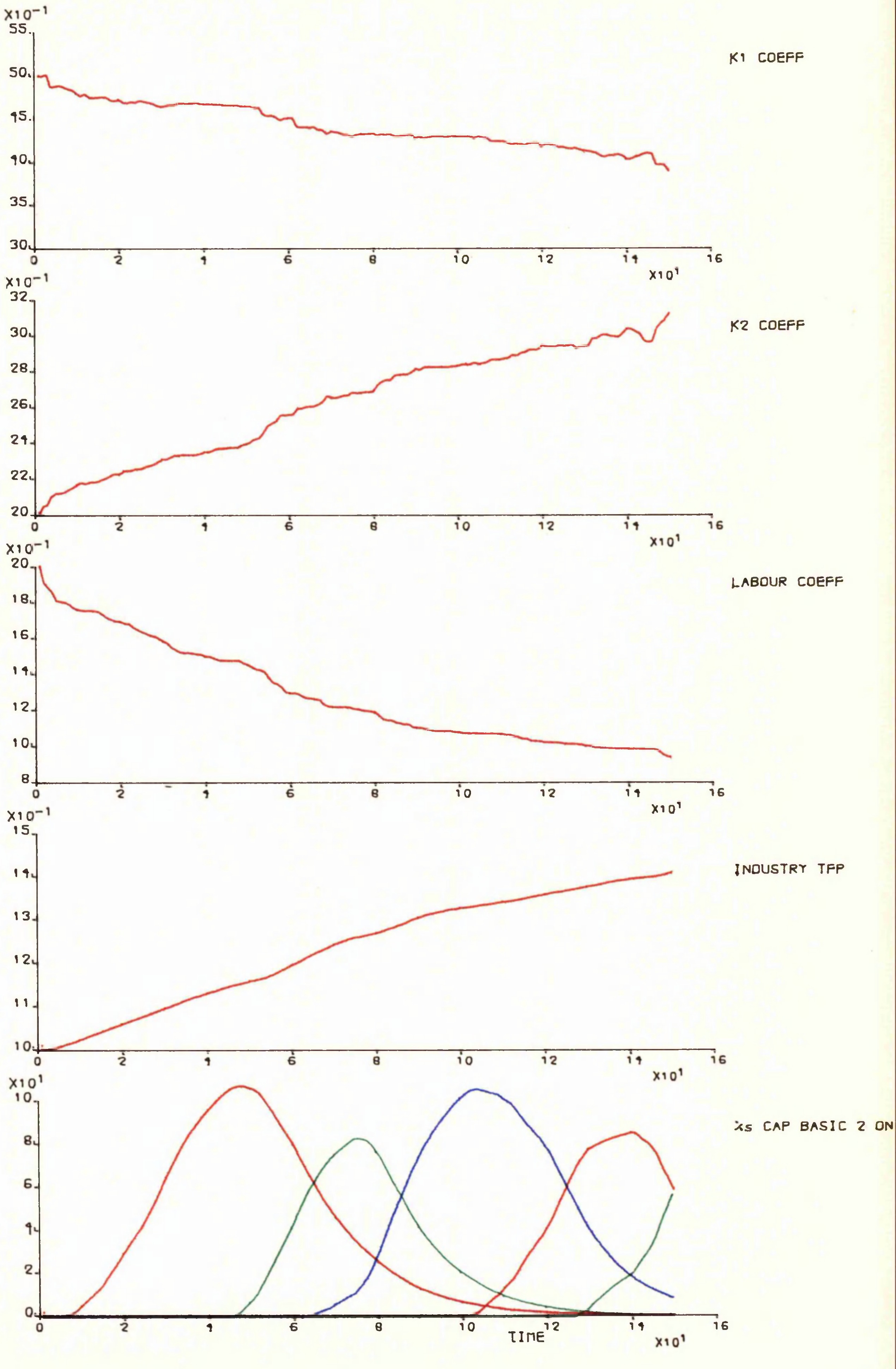


FIGURE 9.8 BEST AND WORST PERFORMANCE: INDUSTRY 2

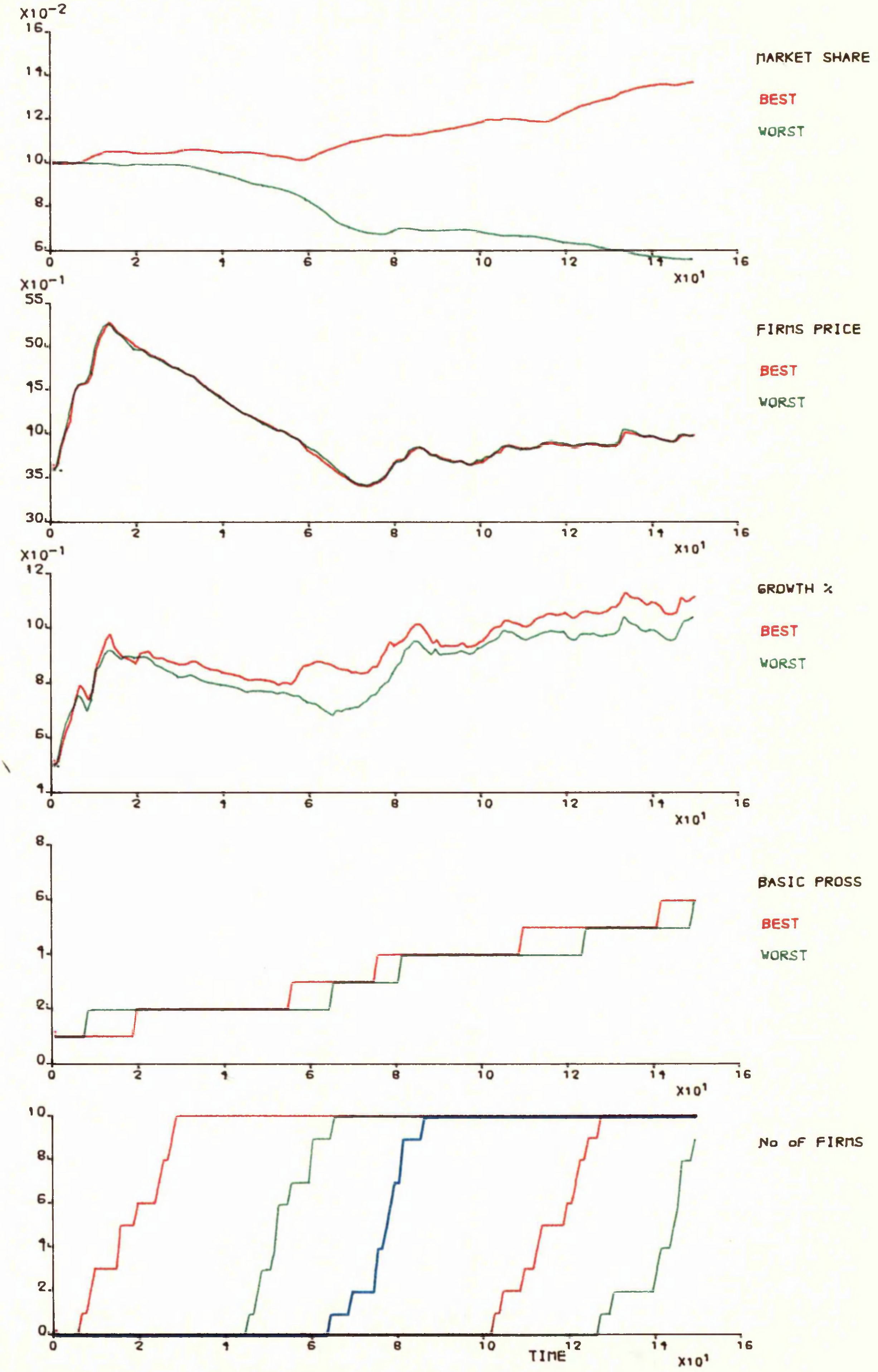


FIGURE 9.9 BEST AND WORST BEHAVIOUR, INDUSTRY 2

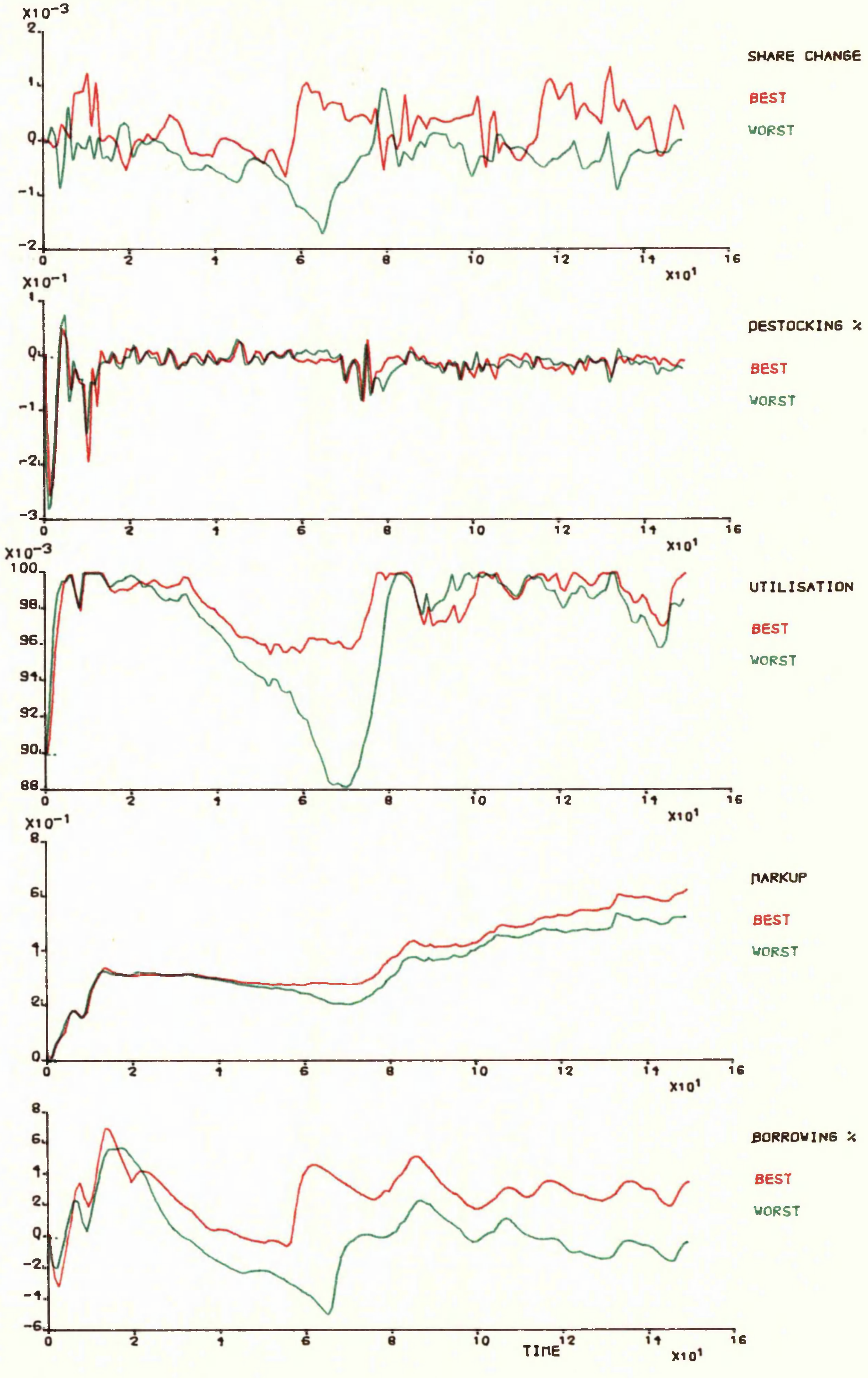


FIGURE 9.10 RELATIVE PERFORMANCE OF INDUSTRIES

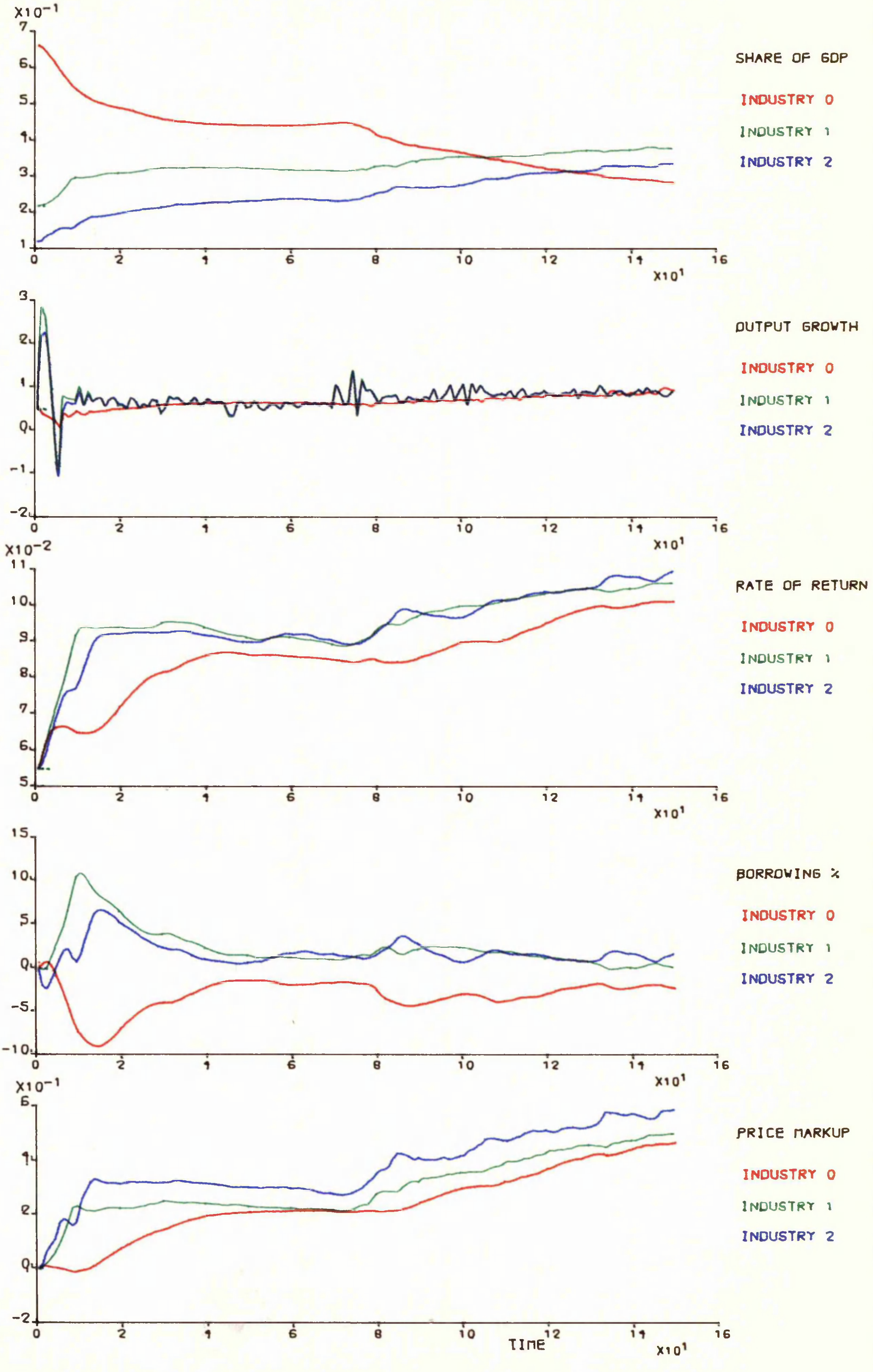


FIGURE 9.11 PERFORMANCE OF THE ECONOMY

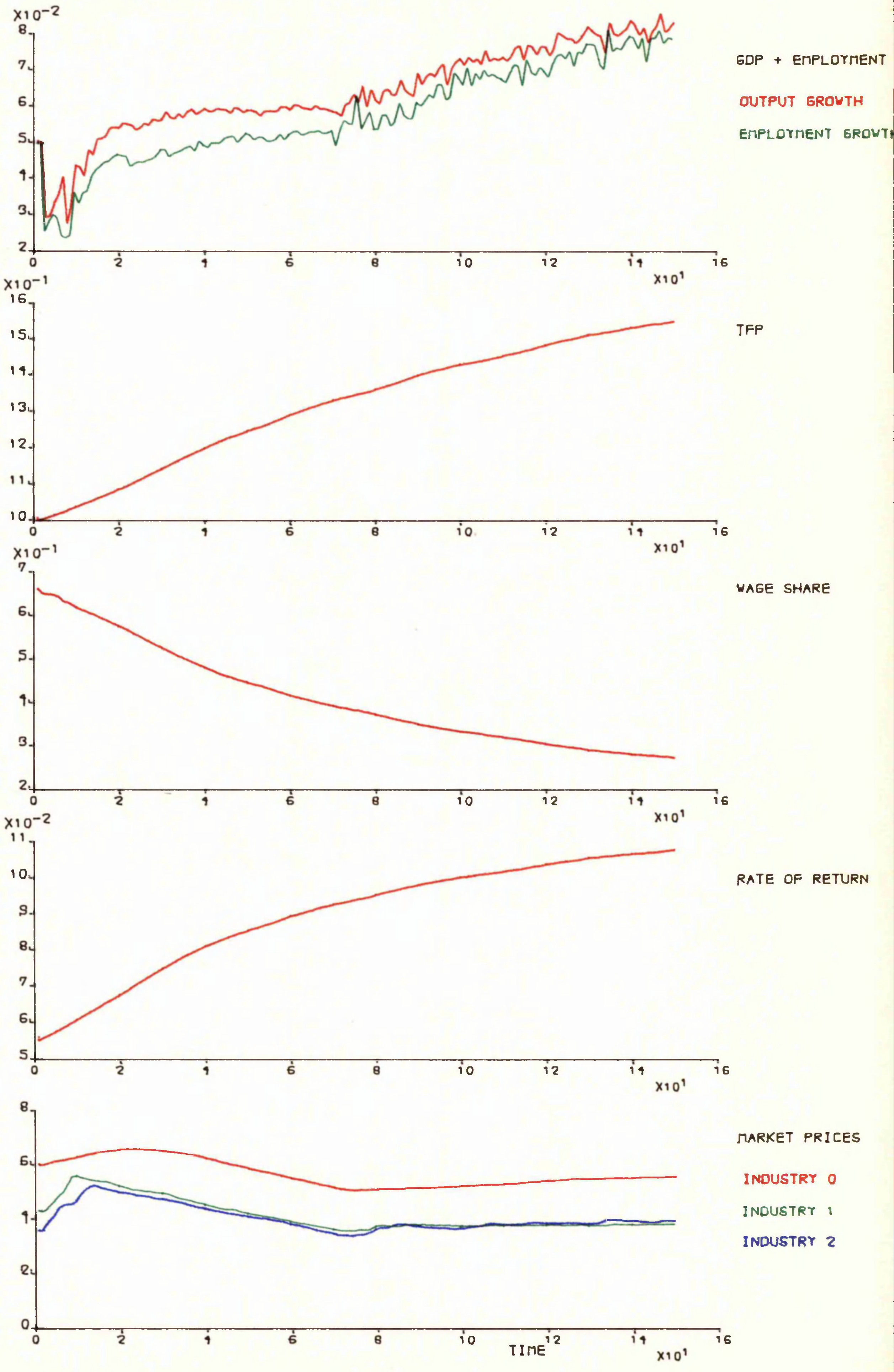


FIGURE 9.12 PERFORMANCE OF THE ECONOMY: WAGES INC

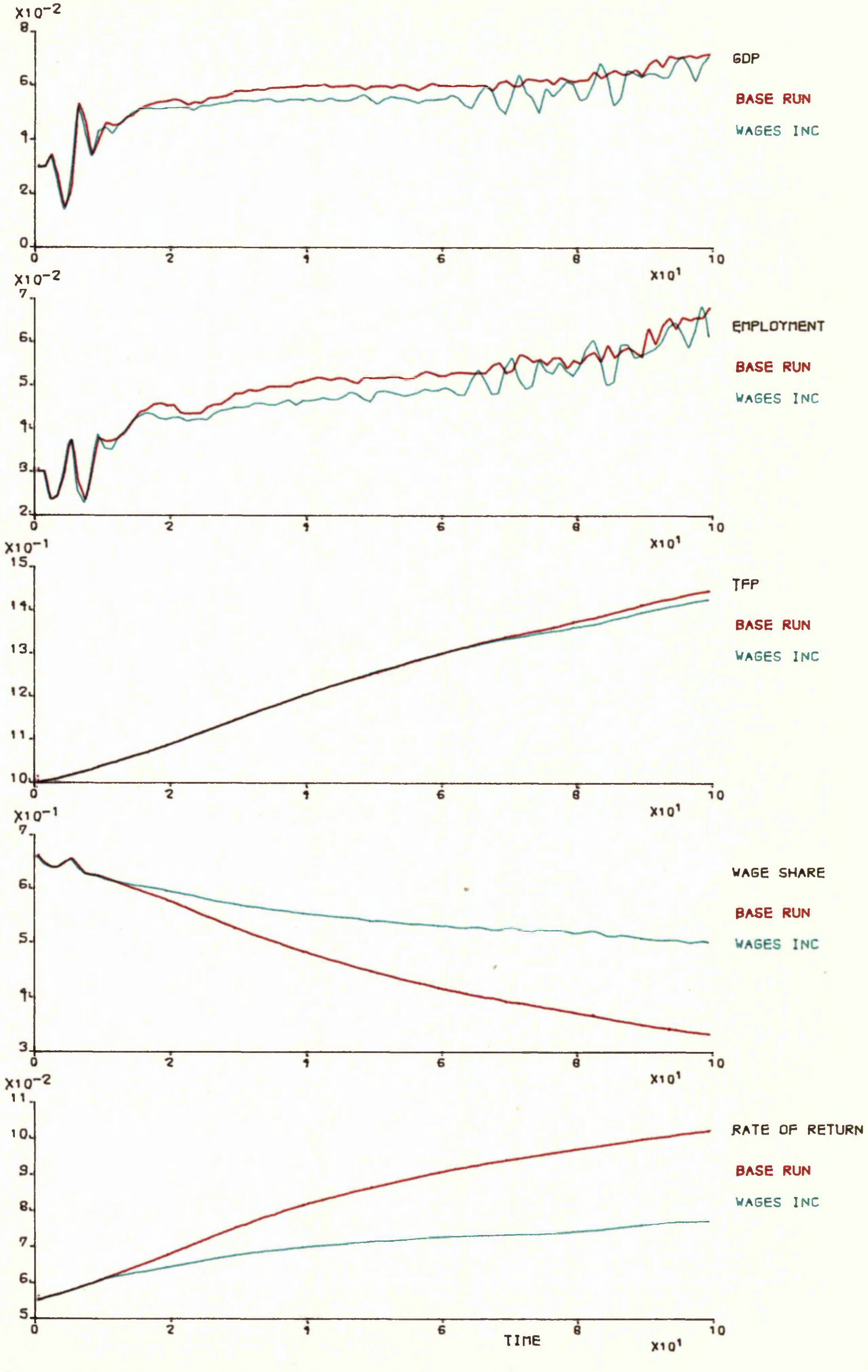


FIGURE 9.13 RELATIVE PERFORMANCE OF INDUSTRIES: WAGE INC

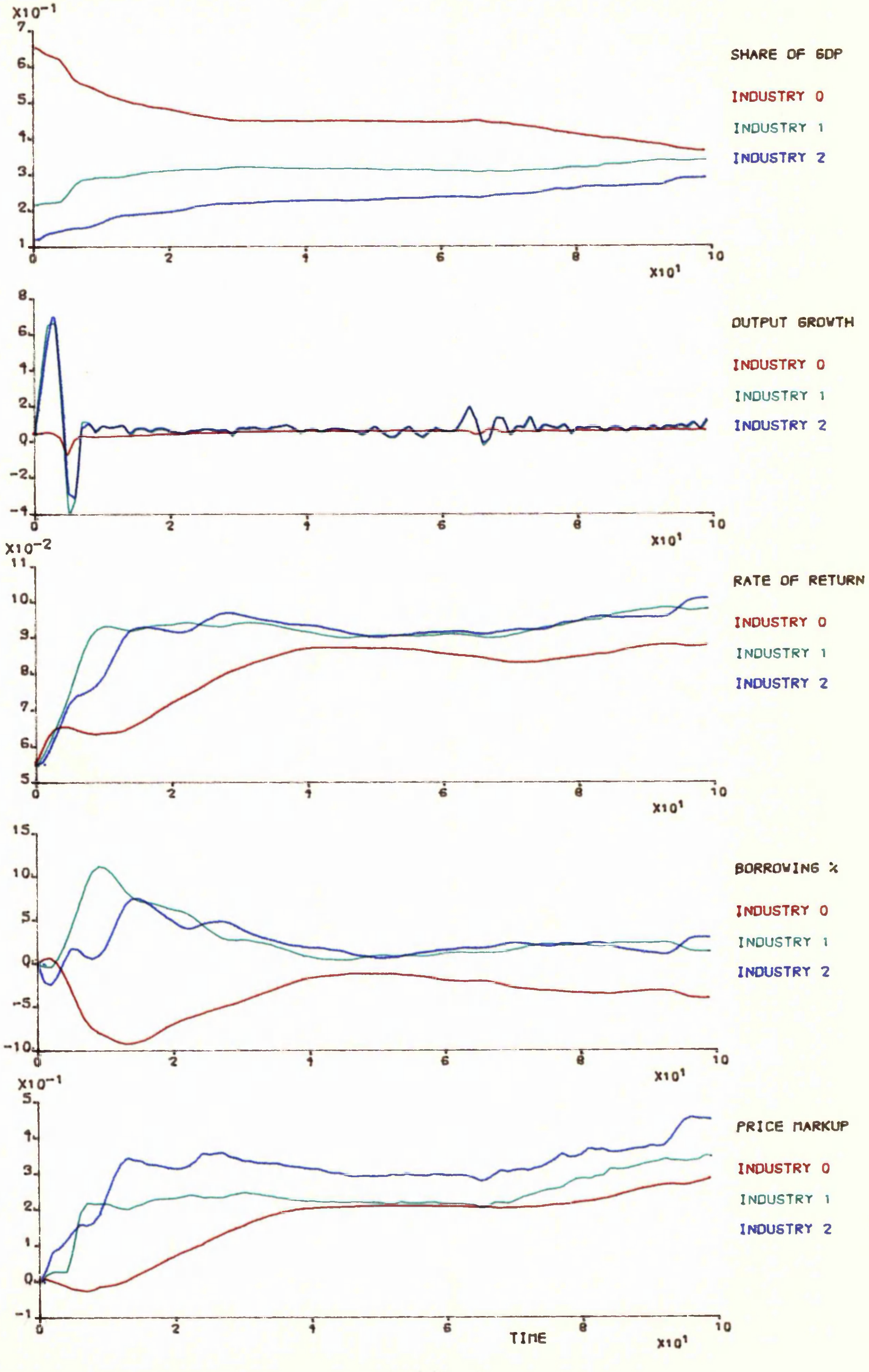


FIGURE 9.14 PERFORMANCE OF THE ECONOMY: NO LOANS

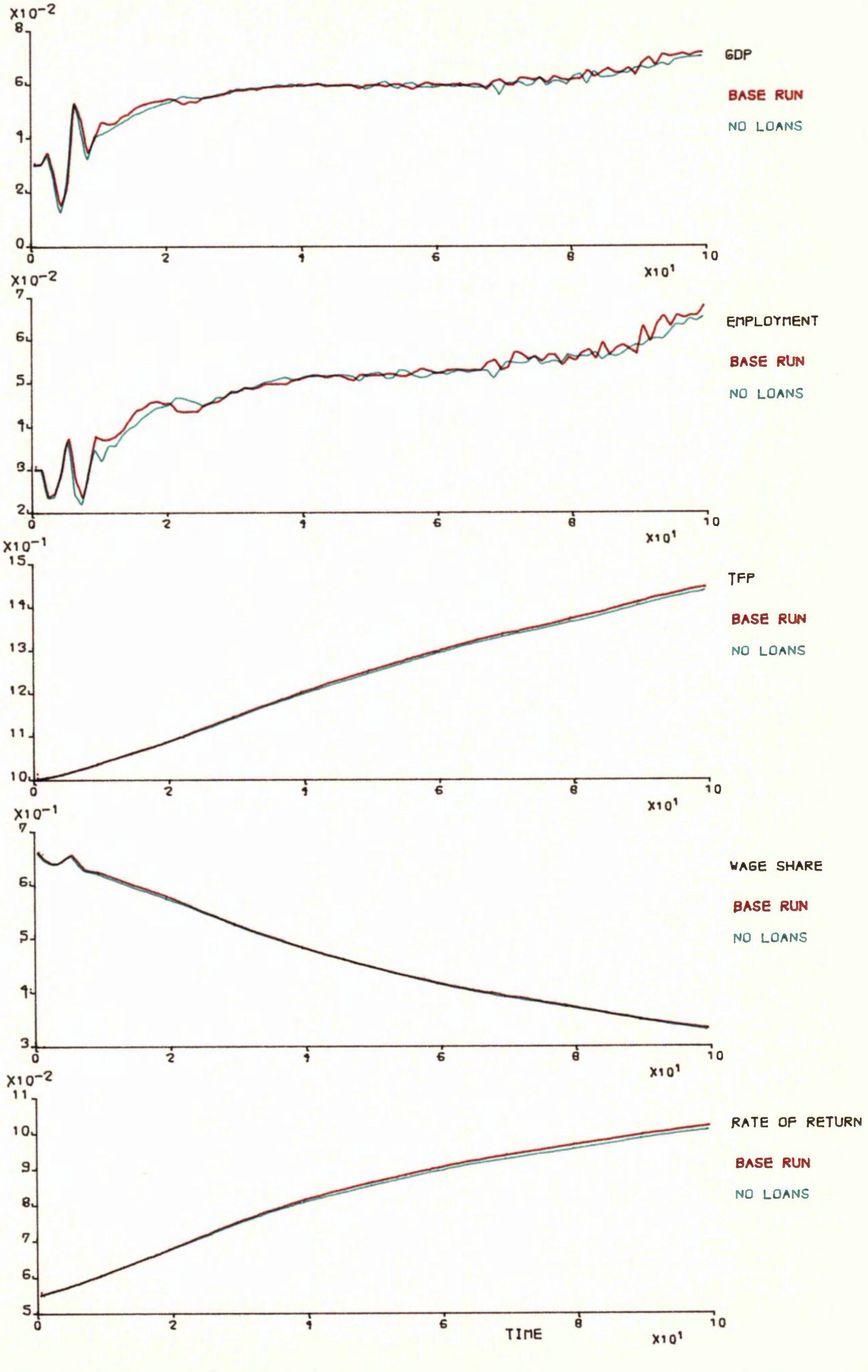


FIGURE 9.15 PERFORMANCE OF THE ECONOMY: LONG WAVE

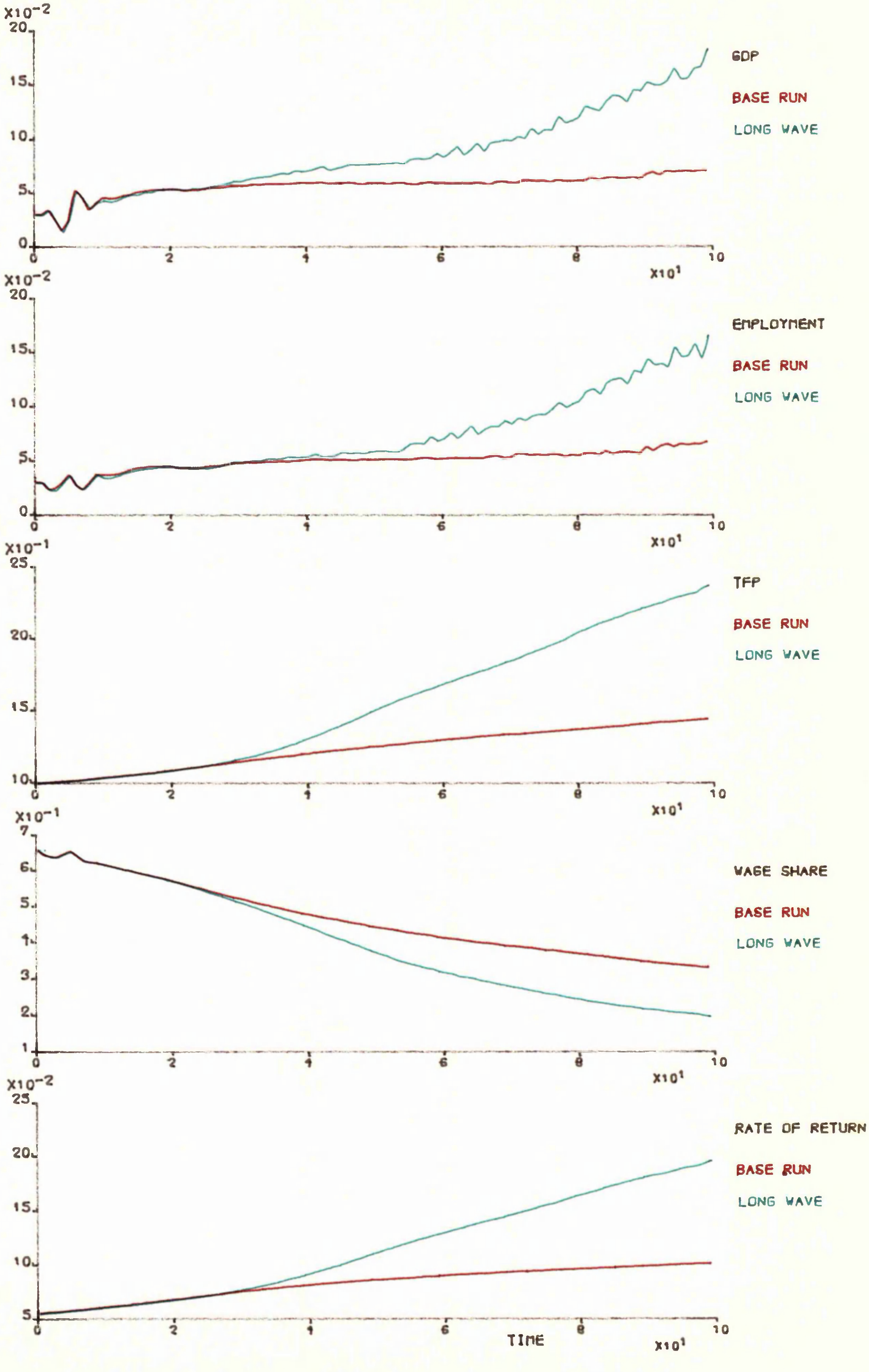


FIGURE 9.16 PERFORMANCE OF THE ECONOMY: IND 2 ADVANCES

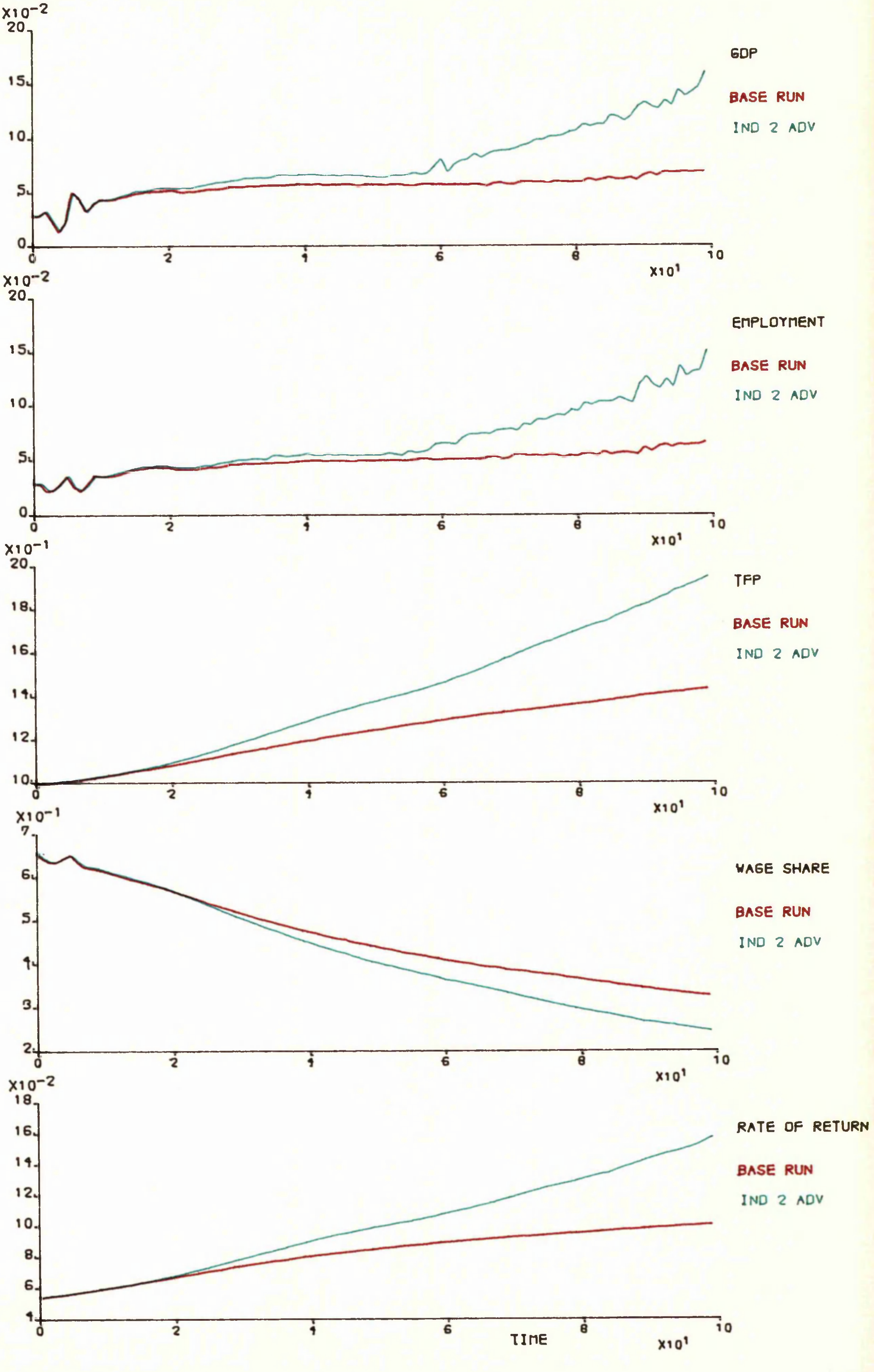
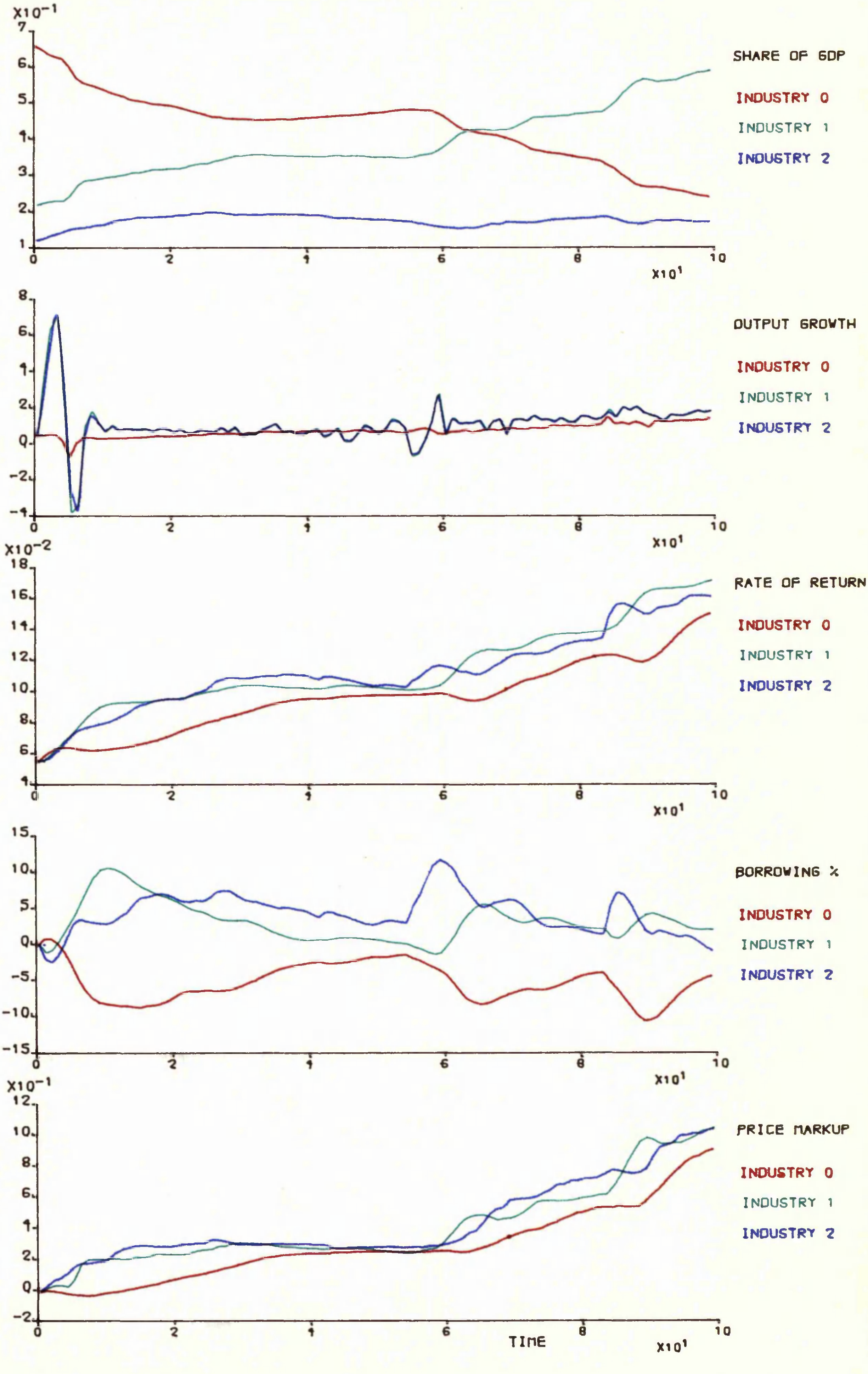


FIGURE 9.17 RELATIVE PERFORMANCE OF INDUSTRIES: IND 2 ADVANCES



CHAPTER 10 SUMMARY AND CONCLUSION

10.1 Introduction

In this chapter we appraise our analysis of technical progress and economic evolution. To this end we first review the aims of our study. We then consider the approach taken in this thesis: the theoretical background; the use of simulation; the development of the simulation model and description of the results generated from it. This provides a summary of the main arguments and events described in the previous chapters. We then move on to the conclusions which we seek to draw from our simulation study. First, in the support it gives to particular explanations of economic evolution and second, the features of the economic system which are identified in the simulations as being key determinants of the way in which the economic system behaves.

10.2 Review of Aims

Chapter 1 begins with the assertions that economic growth is one of the most notable features of industrial economies and that technical progress is a major factor in generating that growth. Our general aim was identified as increasing understanding of the micro foundations of economic growth, in particular that part of growth attributable to technical progress.

In seeking to develop such an understanding we would wish to relax the assumptions of the neoclassical approach, with its concomitant emphasis on optimality and equilibrium at all levels from firm to economy. We argued in chapter 1 and elsewhere, that such a relaxation was essential to understanding technical progress, particularly at the micro level. Our intention was to use a behaviourally realistic model of firm behaviour, and to adopt the evolutionary, non-equilibrium, approach to the questions at hand. In this way the resulting technical progress at an aggregate level was to be traced back to individual decisions within firms. We argued that a simulation model would allow us to achieve our aims.

10.3 The Background to the Simulation Model

Having set our aims, the first task was to identify what aspects of technical progress were to be explained. This was the function of chapter 2. We considered what technical progress is, how it is incorporated into production and the benefits this confers on society as the new techniques become absorbed into the industrial fabric.

In order to identify how the benefits of technical progress come about, and how this source of economic growth can be differentiated from other sources, we considered in some detail how technical progress may be measured, both in terms of its rate and its bias. A key conclusion from this discussion was that only in a multisectoral model of economic growth would it be possible to satisfactorily identify the contribution of technical progress. It was necessary to understand the interdependence and hierarchy of industries in order to identify the origins of overall improvements in performance. This was certainly in accord with our aim of developing a micro based simulation model, which was now seen to require this multisectoral and hierarchical structure.

In chapter 3 we considered how multisectoral models of economic growth may be structured. We did not consider the neoclassical model explicitly as the discussion was also to provide a basis for the construction of the simulation model. Thus we confined ourselves to models in which technology was given by fixed production coefficients. The wage curve proved to be a useful analytical device to show behaviour in an industry faced with alternative techniques of production, and thus to allow some discussion of factor proportions. In other respects the models discussed in chapter 3 embody key features of the neoclassical model, with their emphasis on market equilibrium and balanced growth. These were the focus of the criticisms, identified in chapter 1, of traditional analysis of dynamic processes

Whilst the models described in chapter 3 certainly provide insight into the nature of economic growth, they presented difficulties when we considered how technical progress could be incorporated into them. By focussing on equilibrium situations, they do not readily lend themselves to analysing the period of transition as new technology is gradually incorporated into an industry[1]. Since such periods of

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[1] With the exception of the Bensusan-Butt model.

transition are the norm, an alternative approach incorporating this feature would clearly provide a useful additional tool. The models of chapter 3 provided us with an understanding of the interdependence of industries during economic growth, and thus a structure of industries for our simulation model, but they also served to demonstrate the role for a non-equilibrium approach to modelling technical progress.

Having identified a useful function for such a model in complementing existing general equilibrium models of economic growth, we moved in chapters 4 and 5 to further consider the how the model may be constructed. In chapter 4 we considered the decision processes of firms, arguing that firms were usefully considered as complex organisations, run by human beings with limited capabilities. In order to function they need to develop relatively simple rules of operation, based on limited and readily accessible information. Day to day decisions are made according to such rules of thumb, rather than from a profit maximising calculation.

Firms contain a degree of inertia, which makes them respond less than instantaneously to a changing environment. So long as they perform satisfactorily, they will be reluctant to change their decision rules. Winter (1971), identified an important exception to this. In instigating a research and development programme, a firm is making a determined effort to change the way it operates. In a world of continuous technological advance, the firm must form judgments on the type of technology it seeks to develop. In its research and development programme the firm makes a conscious attempt to consider the profit implications of its decisions.

In chapter 4 we described various possibilities for rules of thumb, and research decision making processes which could be incorporated into a model of firm behaviour. Any one model would, necessarily, be unable to incorporate all of the possibilities raised in the discussion of chapter 4, but our computer model would contain the essence of them.

Chapter 5 moved the discussion on to consider the firm within the wider context of the industry, and the industry within the economy as a whole. We focussed on the evolutionary approach to the issues. A firm's success, relative to the others in its industry, was seen to be dependent on its revealed performance. The impact of imitation and innovation on the selection process were described. The relative success of firms in the market could be expected to vary widely, according to their success in acquiring new technology. The key features of the market, which determined the rate of advance, were inertia and the consequent variation in firms performance. Competition was seen to be a truly dynamic process, vindicating the evolutionary perspective of industry development; with widely varying levels of firm performance, it makes sense to investigate technical progress in terms of those differences.

Our discussion also allowed us to identify various ways in which economic selection would not necessarily lead to socially desired outcomes. Patents were identified as one possible remedy for externalities. Patents are the only element of policy introduced into our discussion, which otherwise is devoted to a purely laissez faire industrial economy.

Finally in chapter 5 we considered the relative performance of industries. Industries, or at least technologies, were seen to have a finite lifetime. Our evolutionary approach lead us to expect a constantly changing industrial structure. Within industries different technologies would come to dominate temporarily, altering relative prices and profitability. A major technological advance in an industry would see rapid growth in that industry. Additionally perhaps, if it supplied other sectors, growth would accelerate throughout the economy, generating an economic long wave.

Chapter 5 describes various possibilities for competitive selection and industrial development which could be incorporated into a model of economic evolution. As was noted above in relation to chapter 4, any one model would, necessarily, be unable to incorporate all of the possibilities raised in our theoretical discussion, but our computer model would contain the essence of them.

Our discussion in chapters 4 and 5 illustrated the potential for investigating technical progress at the micro level. Far from being in harmonious equilibrium, firms could be seen to be in a continuous struggle, first for existence and second to develop. They need to acquire, through research and development, efficient rules which result in good revealed performance, relative to their competitors. As such developments take place throughout the economy so firms and industries thrive or whither. Chapters 4 and 5 jointly illustrate the need to understand these processes, and their interactions, and at the same time suggest how the various elements may fit together.

10.4 The Merits of Simulation

To fulfill the aim of tracing macro performance back to individual decisions within firms in a non-equilibrium system was clearly an ambitious task. Having set such an aim, it was necessary to develop our method of investigation. Due to the degree of complexity in the situations which we would be analysing, the aim was delimited to be the development of a computer simulation of an evolutionary economy undergoing technical progress. This of itself added an additional element to the thesis. Computer simulation is a fairly new, but increasingly used, approach to the discussion of economic questions; a response to the increased availability, power and sophistication of computers. Given the generally limited experience with simulation by economists, some discussion of its virtues and methods was felt necessary.

Our simulation study would explain technical change in terms of the intentional actions of decision takers within firms. Firms respond to their environment by making output and pricing decisions and by choosing levels of research and development. The understanding of technical change would not come from falsifiable predictions, but rather in terms of affirming our prior beliefs, as embodied in the simulation model, and subsequently through description of the workings of the model.

We accepted the arguments of McCloskey (1986), that the way economic analysis progressed was by contributions to a 'conversation' between economists. The criterion of advance is to present good reasons to arrive at plausible conclusions which a reasonable person will accept. By this criterion simulation has a positive role in affirming qualitative beliefs about the system as a whole, as well its component parts. It enables us to better understand the interdependencies between the decision making units. Simulation is seen as a complement to analytical models.

10.5 Conclusions from the Simulation Study

We seek to draw conclusions in two areas. First what our study tells us about particular explanations of technical progress and economic evolution. Second what understanding it imparts about the behaviour of industrial economies.

10.5.1 Explaining Economic Development

Throughout this thesis we have developed the argument that the evolutionary approach to understanding economic development is to be preferred to that of equilibrium type models. The key elements of the evolutionary system are diversity of behaviour and economic selection on the basis of revealed performance. Firms operate using simple rules for decision making. Competitive selection and a stream of new innovations create a constantly changing economic structure, in which processes, firms and industries thrive or wither.

At the same time our evolutionary approach must be able to generate the elements of economic behaviour explained by alternative models. The diversity of behaviour at the micro level must generate a functioning market economy, in which the transition of states at the macro level is relatively smooth and orderly.

The results from our simulation model demonstrate both of these features. In the simulation described most fully in chapter 9 (figures 9.1 - 9.11), the economy undergoes a technological development which increases productivity by 60 percent. Performance at the economy level, as illustrated by figure 9.11, shows some degree of fluctuation in the growth rate, but otherwise demonstrates a continuously growing and stable macro economy. Figures 9.10 and 9.11 show how industries vary in their relative performance but that pricing and output strategies by individual firms produce stable prices, and the gradual erosion of the importance of the consumer goods industry.

Yet behind this appearance of harmonious development of the market economy, we see, at the micro economic level, the forces of dynamic competition at work. Our illustrations of firms' behaviour show that simple decision rules, involving very limited calculations of profitability, allow firms to function effectively in the market place. Whilst it will eventually be eliminated, poor revealed performance can persist over long periods. The forces of competitive selection result in the dominance of successive technologies, together with the firms that can make best use of them.

The results from our model affirm our belief in the evolutionary approach. They demonstrate one way in which behaviourally realistic firm behaviour, can be translated, through the process of competitive selection, into an acceptable description of industry and economy performance. The model can produce all the behaviour explained by equilibrium models, but additionally it allows the diversity of performance at the micro level which is so evidently a part of the reality of economic life. To that extent, our simulation have increased our qualitative understanding of the processes of technical progress and economic evolution.

Recognition of the individuality of the firm is the cornerstone of understanding technological development. The inertia embodied in the organisational structure of firms means that they will not readily and quickly respond to 'market signals', if such signals indicate a restructuring of their behaviour. The more so the more radical is the restructuring. The results from our simulations illustrate instances of the need for understanding to be at the level of the individual firm, for example to understand the dynamic nature of competition, or the persistence of technical inefficiency. Clearly the much greater diversity of behaviour in real world firms makes such understanding all the more relevant. Recognition of these ideas may lead to a new appraisal of industrial policy, emphasising the organisational rather than the profit seeking side of industrial development, although these are not issues we seek to develop here.

10.5.2 The Behaviour of Industrial Economies

We have seen that behaviour at both the firm and industry level in our simulated economy conforms, in major respects, to what we expect both from the theory of evolutionary economics and from empirical observation. To this extent the simulation model provides an acceptable description of real processes, though obviously the results still have a strong element of artificiality.

(a) Technological Determinism Perhaps the principal conclusion to be drawn from our simulation is the primacy of technological considerations over all other factors in determining the fate of firms, and ultimately the economy.

Since our simulation is designed to demonstrate the effects of technical progress, to some extent this conclusion may be thought to be built in to the model. However firms do have alternative courses of action within our model, in that they may try to operate old technology with low profit margins. In the real world firms clearly have many more alternative strategies to improve their revealed performance, including more aggressive marketing to compensate for poor technological performance. The inexorable force for superior technology to dominate within our model suggests that it is improbable that such alternative strategies can be other than a stop gap. This conclusion applies to a firm within an industry or to the development of a domestic industry in the international economy, and is so strong we term it 'technological determinism'.

Such a conclusion clearly has important implications for managing the long term technological and structural changes which we have seen are a natural part of economic development. The observation made in chapter 9 (p311), that a failing industrial giant has some breathing space, during which it may recover its fortunes by innovation, is also pertinent here. For an advanced economy, the inevitable decline of particular processes and industries is a nettle to be grasped early on, when profits are still high and available to finance the restructuring. Supply side industrial policy is a necessity to enable firms to overcome their inertia and develop new technologies at a sufficiently early stage.

(b) Technical Progress as a Source of Growth The yearly growth rate in our simulation, in the absence of technical progress, was set at 5% minus the rate of depreciation. Technical progress, in the form of new technologies discovered through directed search, results in dramatic increases in that rate. This would seem to indicate that technical progress has great power as a source of economic growth. Some studies, such as those of Jorgenson and Grilliches (1967), assert that growth can be mainly attributed to factors of production. Our study militates against this conclusion.

Rather we would suggest that one of the most cost effective ways of generating economic growth is to have a major research and development programme. Rapid diffusion of innovations is also clearly a part of this conclusion, requiring a high absorptive capacity for new technology in the economy. The additional benefits which accrue to early innovators in our model, adds weight to this argument. The need to recognise and exploit dynamic economies of scale is seen to be overwhelming. This is illustrated in our results by the continued acceleration of growth after major innovations, for example figure 9.15. The role of the state in this regard is not evident in our results, since our model has homogeneous labour and no constraints on growth.

Our analysis of the technologies which are ultimately developed, shows how in the absence of new basic processes, eventually all the possibilities for incremental innovations will be used up (for example our discussion of figure 8.11, p257). The extra growth which comes from basic innovations is illustrated throughout our results in chapter 9. Together these examples show the crucial importance of developing the new basic processes.

One conclusion from our search model was that the search effort would be less when current production is more profitable, as illustrated by figures 8.16 and 8.17. To this extent there is a contradiction within the economic system which is inimical to its ultimate development. Additionally our model illustrates the crucial importance of economies of scale in search. This enhances the case for state intervention to increase the amount of research and development over that which would otherwise be chosen.

(c) Induced Innovation Induced innovation effects determine the direction of economic advance. This in turn affects the relative performance of the industries and eventually the whole structure of the economy. The original technology, described in section 8.2, was chosen arbitrarily. The induced innovation observed in our results is thus a response to this exogenous starting point. Sectors whose products are in declining demand as a result of induced innovation see their share of GDP reduced, as they are replaced by new industries.

The speed with which the necessary transitions can be accomplished is important for the structural efficiency of the economy. Our simulation results showing the effect of borrowing on economy wide productivity (figure 9.14) illustrate benefits to be derived from efficient capital markets. Early recognition of the direction of advance will help speed the changes, which technological determinism suggests are inevitable.

(d) The Importance of Dynamic Considerations Our results in chapter 8 illustrate a number of instances in which the long term consequence of a parameter change in the model was the opposite of its immediate impact. Thus increased competition within a market resulted in more monopoly. The sale of patent rights resulted in less. The way to ensure the continuation of competition is through regimes which quickly allow interfirm diffusion of technologies. Whether this will result in more or less economic activity will depend on the extent to which this is combined with cooperation in search to exploit the economies of scale.

New entrants to an industry were not allowed in our model, and so the conditions under which such entrants are successful were not investigated. However the growth of monopolies and the large economies of scale in search in our model together illustrate the importance of recognising the importance of the dynamics of competition and market structure in policy making.

10.6 Future Research

This thesis is presented at the end of a period of study, as a completed piece of research. By confining ourselves to economic evolution in a simplified economic setting we have, it is asserted, attained the aims identified in chapter 1. However, any lengthy research project will inevitably point to future avenues of enquiry. As a means of rounding off this study we briefly raise areas for such work.

This thesis has two major constituents: description of the economic models and methodology which underpin the simulation model and the model itself, together with description of the results. Future research will seek to extend the simulation model to examine new issues. Such extensions would continue to explore the qualitative features of economic evolution, rather than aim for empirical realism.

The areas in which the model may be usefully extended have, in the main, already been mentioned in earlier chapters, where our investigation was curtailed by its limitations. Of these the following are seen as important:

(i) to allow new entrants into an industry. This would add an important area of new competition, and allow investigation of the constraints on the growth of such firms;

(ii) to introduce another, nascent, industry into the model in order to better investigate the product cycle;

(iii) to allow a range of basic processes to be developed at each stage. This would create more technological variety and allow investigation of issues discussed in chapter 5 such as locking in and technological trajectories;

(iv) to introduce more organisational and behavioural complexity into firm behaviour, in order to better investigate inertia and the different components of revealed performance such as creativity and efficiency.

In making these suggestions we must bear in mind the already complex nature of the computer program. An additional area of future development of the model will be to make it more 'user friendly', so that results may derived without an intimate knowledge of the program as a whole. This will be necessary if the model is to be used by non-Fortran literate economists. The extensions to the model suggested above will all result in greater or lesser degrees of additional complexity.

10.7 Final Conclusion

Our study has used elements from many areas of economic theory, but focussing on those studies directed towards extending the theory beyond that of equilibrium situations, in line with our assertions about the nature of technical progress in chapter 1.

In adopting behaviourally realistic decision rules for our model firms we recognise the criticisms of Simon and others, discussed in chapter 1, of neoclassical orthodoxy. Whilst day to day decisions of firms are by rule of thumb, our model of search recognises its explicitly profit seeking nature. In using the evolutionary approach of Nelson and Winter we have recognised the dynamic nature of competition. In adopting a multisectoral approach we recognise the importance of the interdependence of industries in economic development. It is in the bringing together of these elements that our study has sought to extend our understanding of technical progress and economic evolution.

Our results have been produced through the medium of our simulation model which incorporates our beliefs about the nature of economic development. Whilst the model clearly has many limitations, it has provided a detailed micro based description of the processes of economic growth, from which we have been able to draw a number of conclusions. On the one hand these have tended to affirm the beliefs built into the model, thus adding weight to them. On the other we have a series of conclusions about the behaviour of economic systems which complement those of other studies. To this extent our results may be considered as a useful addition to the understanding of technical progress and economic evolution.

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APPENDIX: THE COMPUTER SIMULATION PROGRAM

The computer program listed in this appendix is written in FORTRAN 77 as defined for a DEC 20 computer. In the listing below, line numbers relate individual lines of the program some of which take up two lines of the A4 page.

```
0005        COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
            SL(80,10,0:2),
0010        1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
0015        2EL(80,10,0:2), EC(80,10,0:2)
0020 C      DIMENSION(PROSS,FIRM,IND)
0025        COMMON /XYZ/ XX,YY,MM,SS,DD,XXX,YYY,M4,SS0
0030 C      DIMENSION(FIRM,IND)
0035        COMMON /N/N(10,0:2)
0040        COMMON /AVCOST/ AVCOST(0:2)
0045        COMMON /OUTPUT/ OUTPUT(10,0:2)
0050        COMMON/TOUTPT/ TOUTPT(0:2,2001,1)
0055        COMMON /DEMAND/ DEMAND(0:2)
0060        COMMON /SHARE/ SHARE(10,0:2)
0065        common /conc/ conc1(0:2),conc3(0:2)
0070        COMMON /FUNDS/ FUNDS(10,0:2)
0075        DIMENSION GROW(0:2),PERCAP(10,0:2),PERFUN(10,0:2),
            GDP(2001)
0080        DIMENSION EMP(2001)
0085        COMMON/NEWCAP/ NEWCAP(10,0:2)
0090
0095        COMMON /TOTALS/TOTSK1(10,0:2),TOTSK2(10,0:2),
0100        1,TOTSL(10,0:2) TOTOUT(10,0:2),TOTEK1(10,0:2),
            TOTEK2(10,0:2),TOTEL(10,0:2)
0105        COMMON /MARKUP/ MARKUP(10,0:2)
0110
0115        COMMON/NEWPRO/ NEWPRO(10,0:2)
0120 C      DIMENSION(SEARCH,FIRM,IND)
0125        COMMON /X/ X(6,10,0:2)
0130        COMMON /DRAWS/ DRAWS(6,10,0:2),gTDRaw(6,10,0:2),
            AGGX(10,0:2)
0135        COMMON /SEARCH/THETA(6,10,0:2),LAMDA(6,10,0:2),
            PHI(6),PATON
0140        DIMENSION AGGDRA(10,0:2),AGGTDR(10,0:2)
0145
0150
0155        DIMENSION SCHCST(10,0:2),SCHRES(10,0:2)
0160        COMMON /MPRICE/ MPRICE(0:2,2001,1)
0165        COMMON /FPRICE/ FPRICE(10,0:2)
0170        COMMON /T/T
0175        COMMON/RAV/ RAV(10,0:2)
0180        COMMON /SRCHP/ SRCHP(10,0:2)
0185        COMMON/UTILIS/ U(10,0:2),DESU(10,0:2),DELU(10,0:2)
0190        COMMON/WBILL/ WBILL(10,0:2)
0195        COMMON /STOCKS/ STOCKS(10,0:2),DSTOCK(10,0:2)
0200        COMMON /CAPCTY/ CAPCTY(10,0:2)
0205        COMMON /BASIC/ BASIC(10,0:2),BASMAX(0:2)
0210        COMMON /RETURN/ RFIRM(10,0:2),RECON
0215        DIMENSION TCAP(0:2),BASCAP(10,0:2),HOPE(10,0:2)
0220        COMMON /LEARN/ LEARN(10,0:2)
```

```
      DIMENSION BEK1(10,0:2),BEK2(10,0:2),BEL(10,0:2)
C     AVCOF IS INDUSTRY AVERAGE COEFFS
      DIMENSION AVCOF0(3),AVCOF1(3),AVCOF2(3)
      dimension bcof0(3),bcof1(3),bcof2(3)
      common /vary/ vary(0:2)
      DIMENSION TOTK1(0:2),TOTK2(0:2),TOTL(0:2)
      dimension loan(10,0:2),borrow(10,0:2),flow(10,0:2)
      DIMENSION PRLOAN(10,0:2),WSHARE(2001),TFPEC(2001)
      common /itfp/ tfpind(0:2),RIND(0:2)
      common /better/ better(10,0:2)
      DIMENSION patown(10,0:2),PATOUT(10,0:2),newpat(0:2),
      1fbcap(9,10,0:2),roylty(0:2),roypay(10,0:2)
      dimension schper(10,0:2),schind(0:2)
      dimension avmkup(0:2),gdpshr(0:2),
      loanin(0:2),fundin(0:2)
      CHARACTER BNKRPT*10
      REAL LAMDA,NEWCAP,MPRICE,MARKUP,MM,M4,
      LEARN,loan,loanin
      INTEGER DRAWS,T,F,TCOUNT,BASIC,gtdraw,aggdra
      integer newpat,basmax,patown,PATOUT

C     INITIALISE THE RANDOM NUMBER GENERATOR
c     g05cbf gives a fixed starting point, g05ccf a
      variable one
      call g05ccf
c     CALL G05CBF(0)
C     OPEN AN OUTPUT FILE
c     OPEN(20,FILE='FUNDS1')
c     OPEN(21,FILE='U1')
c     OPEN(22,FILE = 'SHARE1')
c     OPEN(23,FILE= 'DSTOC1')
c     OPEN(24,FILE = 'FPRI1')
c     OPEN(30,FILE='MKUP1')
c     OPEN(31,FILE = 'INTFP1')
c     OPEN(32,FILE = 'R1')
c     OPEN(35,FILE = 'IND01')
c     OPEN(33,FILE = 'IND11')
c     OPEN(34, FILE = 'IND21')
c     OPEN(36,FILE = 'NEWC1')
c     OPEN(37,FILE = 'N1')
c     OPEN(38,FILE = 'BASic1')
c     OPEN(39,FILE = 'BEK11')
c     OPEN(40,FILE = 'BEK21')
c     OPEN(41,FILE = 'BEL1')
c     OPEN(39,FILE = 'AVCF01')
c     OPEN(40,FILE = 'AVCF11')
c     OPEN(41,FILE = 'AVCF21')
c     OPEN(42,FILE = 'X1')
c     OPEN(43,FILE= 'aggx1')
c     OPEN(44,FILE='FTFP1')
C     OPEN (45,FILE='SCOST1')
C     OPEN (46,FILE = 'GTDRA1')
c     OPEN(47,file = 'aggdr1')
c     OPEN(48,FILE = 'BORRO1')
c     OPEN(49,FILE = 'ECON1')
c     OPEN(50,FILE = 'GROW1')
```

```
c     open(87,file = 'lin1')
c     open(88,file = 'lin2')
c     open(89,file = 'lin3')

c     open(84,file = 'l1')
c     open(85,file = 'l2')
c     open(86,file = 'l3')

      open(96,file = 'line4')
      open(97,file = 'line1')
      open(98,file = 'line2')
      open(99,file = 'line3')


      DATA BNKRPT/'BANKRUPT'/
      DATA (NEWCAP(I,0),I=1,10) /10*0.5555/
      DATA (NEWCAP(I,1),I=1,10) /10*0.2594/
      DATA (NEWCAP(I,2),I=1,10) /10*0.1713/
      DATA TWAGES /601.8/
      DATA ((SHARE(I,J),I=1,10),J=0,2) /30*0.1/
      DATA ((NEWPRO(I,J),I=1,10),J=0,2) /30*0/
      DATA ((DESU(I,J),I=1,10),J=0,2)/30*0.09/
      DATA ((U(I,J),I=1,10),J=0,2)/30*0.09/
      DATA ((N(I,J),I=1,10),J=0,2)/30*1/
      DATA (((X(I,J,K),I=1,6),J=1,10),K=0,2)/180*0/
      DATA(SK1(I,1,0),I=1,1)/5.0/
      DATA(SK2(I,1,0),I=1,1)/4.0/
      DATA(SL(I,1,0),I=1,1)/4.0/
      DATA(SC(I,1,0),I=1,1)/111.11/
      DATA(SK1(I,1,1),I=1,1)/4/
      DATA(SK2(I,1,1),I=1,1)/2/
      DATA(SL(I,1,1),I=1,1)/3.0/
      DATA(SC(I,1,1),I=1,1)/51.88/
      DATA(SK1(I,1,2),I=1,1)/5/
      DATA(SK2(I,1,2),I=1,1)/2/
      DATA(SL(I,1,2),I=1,1)/2/
      DATA(SC(I,1,2),I=1,1)/34.26/
C     THE FOLLOWING GENERATES COEFFICENTS FOR 10 IDENTICAL
      FIRMS
      DO 51 K = 0,2
      DO 51 J = 1,10
      LOAN(J,K)= 0
      MARKUP(J,K) = 0
      BASIC(J,K) = 1
      BORROW(J,K) = 0
      HOPE(J,K) = 2
C     IF (K.EQ.2) HOPE(J,K) = 1
      LEARN(J,K) = 1.0
      DO 51 I = 1,1
      IF (K .EQ.0) THEN
      BEK1(J,K) = SK1(I,1,0)
      BEK2(J,K) = SK2(I,1,0)
      BEL(J,K) = SL(I,1,0)
      SK1(I,J,K) = SK1(I,1,0)
      SK2(I,J,K) = SK2(I,1,0)
      SL(I,J,K) = SL(I,1,0)
```

```
      SC(I,J,K) = SC(I,1,0)
      ELSE IF (K .EQ.1) THEN
      BEK1(J,K) = SK1(I,1,1)
      BEK2(J,K) = SK2(I,1,1)
      BEL(J,K) = SL(I,1,1)
      SK1(I,J,K) = SK1(I,1,1)
      SK2(I,J,K) = SK2(I,1,1)
      SL(I,J,K) = SL(I,1,1)
      SC(I,J,K) = SC(I,1,1)
      ELSE IF (K .EQ.2) THEN
      BEK1(J,K) = SK1(I,1,2)
      BEK2(J,K) = SK2(I,1,2)
      BEL(J,K) = SL(I,1,2)
      SK1(I,J,K) = SK1(I,1,2)
      SK2(I,J,K) = SK2(I,1,2)
      SL(I,J,K) = SL(I,1,2)
      SC(I,J,K) = SC(I,1,2)
      END IF
51    CONTINUE
      DATA (((THETA(I,J,K),I=1,6),J=1,10),K=0,2) /180*2/
      DATA (((LAMDA(I,J,K),I=1,6),J=1,10),K=0,2) /180*3.0/
      DATA PHI/30.0,30.0,30.0,30.0,30.0,30.0/
      DATA MPRICE(0,1,1)/6.013/,MPRICE(1,1,1)/4.3632/,
      1MPRICE(2,1,1)/3.6046/,W/1/
      DATA (FPRICE(I,0),I = 1,10) / 10*6.013/
      DATA (FPRICE(I,1),I = 1,10) /10*4.3632/
      DATA (FPRICE(I,2),I = 1,10) /10*3.6046/
      DATA BASCAP(1,0)/1111.1/,BASCAP(1,1)/518.8/,
      BASCAP(1,2)/342.6/
      DATA R/0.005/,STDEV/0/,DEPN/0.002/
      DO 52 J = 0,2
      DO 52 I = 1,10
      DSTOCK(I,J) = 0
      IF (J.EQ.0) FUNDS(I,J) = 20.137
      IF (J.EQ.1) FUNDS(I,J) = 6.397
      IF (J.EQ.2) FUNDS(I,J) = 4.972
      IF (J.EQ.0) STOCKS(I,J) = 11.11
      IF (J.EQ.1) STOCKS(I,J) = 5.2
      IF (J.EQ.2) STOCKS(I,J) = 3.5
      IF (J.EQ.0) SRCHP(I,J) = 5
      IF (J.EQ.1) SRCHP(I,J) = 3
      IF (J.EQ.2) SRCHP(I,J) = 3.0*1.0

52    CONTINUE
      DATA (RAV(I,0),I=1,10)/10*0/
      DATA (RAV(I,1),I=1,10)/10*0/
      DATA (RAV(I,2),I=1,10)/10*0/

      DEMAND(0) = 100.0
      DEMAND(1) = 46.692
      DEMAND(2) = 30.834

      basmax(0) = 1
      basmax(1) = 1
      basmax(2) = 1

```

```
1040 C    THIS MAKES FIRM 1 OF  INDUSTRY 2 MORE PROFITABLE
          THAN THE OTHERS
1045 C    BASIC(1,2) = 2
1050 C    N(1,2) = 2
1055 C    SC(2,1,2) = 0.1
1060 C    SK1(2,1,2) = 5.0*0.75
1065 C    SK2(2,1,2) = 2.0*0.75
1070 C    SL(2,1,2) = 2.0*0.75
1075
1080 C    THIS IS THE NUMBER OF TIME PERIODS IN THE EXPERIMENT
1085      TCOUNT = 0
1090      DO 98 T = 1,1000
1095      do ind = 0,2
1100      newpat(ind) = 0
1105      end do
1110
1115      IF (T.lt.11) ECGROW = 0.05
1120      IF (T.LT.11) EMPGR = 0.05
1125 c    this increases wages and interest rate
1130 c    *************************************
1135 c    if (t.gt.100) w = tfpec(t-100)
1140 c    if (t.gt.11) r = ecgrow/10
1145
1150      TCOUNT =TCOUNT + 1
1155 C    LOOK AT EACH FIRM IN TURN TO RENUMBER PROCESSES
1160      DO 20 IND = 0,2
1165      DO 20 F = 1,10
1170
1175      IF(N(F,IND).EQ.0) GO TO 20
1180 C    CALL SUBROUTINE TO RENUMBER PROCESSES SO THAT
          UNUSED ONES ARE
1185 C    SCRAPPED AND THE LEAST PRODUCTIVE IN USE IS NO.1,
          THE BEST IS N
1190 3    CALL RENUM(N(F,IND),W,F,IND,T)
1195 20   CONTINUE
1200 C    CALCULATE DEMAND FOR EACH INDUSTRY
1205 30   DO  INDY =1,2
1210      DEMAND(INDY) = 0
1215      END DO
1220      DO 40 IND = 0,2
1225      DO 40 F = 1,10
1230      if (n(f,ind).eq.0) go to 40
1235      DEMAND(1) = DEMAND(1) + NEWCAP(F,IND)
          1*EK1(N(F,IND),F,IND)
1240      DEMAND(2) = DEMAND(2) + NEWCAP(F,IND)
          1*EK2(N(F,IND),F,IND)
1245
1250 40   CONTINUE
1255 c    control growthnof demand for controlled experiments
1260 c    demand(1) = demand(1)*1.005
1265 c    demand(2) = demand(2)*1.005
1270
1275      if (t.eq.1) demand(1) = 46.72
1280      if (t.eq.1) demand(2) = 30.83
1285      DEMAND(0) = TWAGES/MPRICE(0,T,1)
1290      if (t.eq.1) demand(0) = 100.0
```

```
         DO I = 0,2
         TOUTPT(I,T,1) = DEMAND(I)
         END DO
         TWAGES = 0

         CALL PRODN(T,STDEV,W,DEPN)
         DO 19  IND = 0,2
         DO 19 F = 1,10
         DO 19 I= 1,N(F,IND)
         EC(I,F,IND) = EC(I,F,IND)*(1.0-DEPN)
   19    CONTINUE

   c     this closes firms down when they have mothballed
         total capacity
   c     or shrunk to less than 0.1% of the industry
   c     go to 94
         do ind = 0,2
         do f= 1,10
         if (share(f,ind).lt.0.001) then
   96    share(f,ind) = 0
         funds(f,ind) = 0
         newcap(f,ind) = 0
         capcty(f,ind) = 0
         do i = 1,n(f,ind)
         ec(i,f,ind) = 0
         end do
         n(f,ind) = 0
         else if (capcty(f,ind).le.0) then
   95    share(f,ind) = 0
         funds(f,ind) = 0
         newcap(f,ind) = 0
         capcty(f,ind) = 0
         do i = 1,n(f,ind)
         ec(i,f,ind) = 0
         end do
         n(f,ind) = 0
         end if
         end do
         end do

   94    continue

         CALL TECPRO(T,R,W,TCOUNT,TFPEC(T),BTFP)

         IF (TCOUNT.EQ.1) THEN
   C     CALL SUBROUTINE TO CALCULATE INVESTMENT STRATEGY
         DO 27 IND = 0,2
         DO 27 F = 1,10
   c     in these circumstances the firm does not search
         IF (N(F,IND).EQ.0) GO TO 27
         IF (N(F,IND).EQ.79) WRITE(*,*) 79
         IF (N(F,IND).EQ.79) GO TO 27
         IF (BASIC(F,IND).EQ.9) GO TO 27
   C     ***********************************
         CALL INVEST(N(F,IND),SCHCST(F,IND),R,depn,
```

```
      1FUNDS(F,IND),SRCHP(F,IND),F,IND,T,
      LEARN(F,IND),HOPE(F,IND))

CC    CALL SUBROUTINE TO FIND THE SEARCH OUTCOME
      CALL OUTCOM(N(F,IND),NEWPRO(F,IND),
      F,IND,t,HOPE(F,IND))
27    CONTINUE
      END IF

c     THIS SWITCHES PATENTS ON AND OFF
C      PATON = 1 IS PATENT ON, PATON = 0 IS PATENT OFF
      DO IND = 0,2
      ROYLTY(IND) = 0.005*MPRICE(IND,T,1)
      END DO
      PATON = 0
      IF (PATON.EQ.0) GO TO 45
C     ********************************

C     THIS DECIDES OWNERSHIP OF PATENTS
      DO 43  IND = 0,2
      DO 43  F = 1,10
      IF (BASIC(F,IND).GT.BASMAX(IND)) NEWPAT(IND) =
      NEWPAT(IND) + 1
43    CONTINUE
      DO 44 IND = 0,2
      IF (NEWPAT(IND).EQ.0) GO TO 44
C     CHOOSE THE FIRM WITH HIGHEST AGGX AS PATENT OWNER
      BASMAX(IND) = BASMAX(IND) + 1
      NEWOWN = 0
      XMAX = 0
      DO F = 1,10
      IF (AGGX(F,IND).GT.XMAX) THEN
      XMAX = AGGX(F,IND)
      NEWOWN = F
      END IF
      END DO
      BASMAX(IND) = BASIC(NEWOWN,IND)
      PATOUT(BASMAX(IND),IND) = 250
      PATOWN(BASMAX(IND),IND) = NEWOWN
44    CONTINUE

      do ind = 0,2
      do f = 1,10
      roypay(f,ind) = 0
      end do
      end do
C     THIS ARRANGES ROYALTY PAYMENTS
      DO 45 IND = 0,2
      IF (BASMAX(IND).GT.1) THEN
      DO I = 2,BASMAX(IND)
      IF (PATOUT(I,IND).GT.0) THEN
      DO F = 1,10
      FUNDS(F,IND) = FUNDS(F,IND) - FBCAP(I,F,IND)
      *ROYLTY(IND)
      FUNDS(PATOWN(I,IND),IND) = FUNDS(PATOWN(I,IND),IND)
      1+FBCAP(I,F,IND)*ROYLTY(IND)
```

```
      IF (FUNDS(F,IND).LT.0) WRITE(*,*) F,IND,BNKRPT

      if (patown(i,ind).ne.f) then
      roypay(patown(i,ind),ind) = fbcap(i,f,ind)
      *roylty(ind) +
      1roypay(patown(i,ind),ind)
      roypay(f,ind) = roypay(f,ind) - roylty(ind)
      *fbcap(i,f,ind)
      end if

      END DO
      PATOUT(I,IND) = PATOUT(I,IND) - 1
      END IF
      END DO
      END IF
 45   CONTINUE
      TFUNDS = 0

      DO 26 IND = 0,2
      IF (T.GT.1) THEN
      GROW(IND) = (TOUTPT(IND,T,1)-TOUTPT(IND,T-1,1))*100/
      1TOUTPT(IND,T-1,1)
      END IF
      DO 26 F = 1,10
C     INSTAL NEW CAPACITY
      IF(N(F,IND).EQ.0) GO TO 26
      EC(N(F,IND),F,IND)=EC(N(F,IND),F,IND)+
      NEWCAP(F,IND)-SCHRES(F,IND)
      IF (IND.EQ.2) TNCAP = TNCAP +
      NEWCAP(F,IND)-SCHRES(F,IND)


C     CALCULATE INVESTMENT FUNDS TO BE CARRIED FORWARD
C     SUBTRACT COST OF NEWCAP FROM FUNDS, ADD CURRENT
      PROFITS TO FUNDS
C     AND THEN ADD INTEREST TO FUNDS CARRIED OVER TO NEXT
      PERIOD
C     AND PAY INTERST ON LOANS

      FUNDS(F,IND) = FUNDS(F,IND) - NEWCAP(F,IND)
      *(EK1(N(F,IND),F,IND)
      1*MPRICE(1,T,1) + EK2(N(F,IND),F,IND)*MPRICE(2,T,1))

      FUNDS(F,IND) = DEMAND(IND)*SHARE(F,IND)
      1*FPRICE(F,IND)  -WBILL(F,IND) + FUNDS(F,IND)
      FUNDS(F,IND) = FUNDS(F,IND)*(1 + R)-R*BORROW(F,IND)

      CAPCTY(F,IND) = CAPCTY(F,IND) + NEWCAP(F,IND)
      -schres(f,ind)
 26   CONTINUE

      DO 37 IND = 0,2
      TCAP(IND) = 0
      DO 37 F = 1,10
      TCAP(IND) = TCAP(IND) + CAPCTY(F,IND)
      BASCAP(BASIC(F,IND),IND)= BASCAP(BASIC(F,IND),IND)
```

```
      1+NEWCAP(F,IND)   - schres(f,ind)
      FBCAP(BASIC(F,IND),F,IND) =FBCAP(BASIC(F,IND),F,IND)
      1 +NEWCAP(F,IND) - SCHRES(F,IND)
      schres(f,ind) = 0
 37   CONTINUE
 C    LEARNING EFFECTS CALCULATED HERE
 C    ********************************
      TEACH = 0.1

      DO 38 IND = 0,2
      DO 38 F = 1,10
      if (n(f,ind).eq.0) go to 38
      BETTER(F,IND) = 0
      DO I = BASIC(F,IND)+1,10
      BETTER(F,IND) = BETTER(F,IND)+
      BASCAP(I,IND)/TCAP(IND)
      END DO
      LEARN(F,IND) = BETTER(F,IND)*TEACH + 1
 38   CONTINUE

 C    CALL SUBROUTINE TO CALCULATE CHANGED BEHAVIOURAL
      PARAMETERS
 C    IN RESPONSE TO CURRENT PERFORMANCE
      XX = 0.5
      M4 = 1.3
      YY = 0.5
      MM = 5.4
 c    if (t.gt.100) mm = 0.54
      SS = 0.15
 c    ss = 1.5
      SS0 = 0.15
      DD = 0.5
      XXX = 25
      YYY = 25
      CALL CHANGE(T,W,R)

 C    LOAN IS THIS PERIODS LENDING, BORROW IS CUMULATIVE
      BORROWING
 C    FLOW IS THE FRACTION OF A FIRMS FUNDS LENT/BORROWED
      FL = 0.5!! FL IS PARAMETER FOR EASE OF BORROWING
      TFUNDS = 0
      RWEIGH = 0
      DO 34 IND = 0,2
      fundin(ind) = 0
      DO 34 F= 1,10
      TFUNDS = TFUNDS + FUNDS(F,IND)
      fundin(ind) = fundin(ind) + funds(f,ind)
      RWEIGH = RWEIGH + FUNDS(F,IND)*RFIRM(F,IND)
 34   CONTINUE
      RAVGE = RWEIGH/TFUNDS
      TLEND = 0
      DO 67 IND = 0,2
      DO 67 F = 1,10
      if (n(f,ind).eq.0) go to 67
      FLOW(F,IND) = FL*((RFIRM(F,IND)
      1-RAVGE)/RAVGE)
```

```
        LOAN(F,IND) =FUNDS(F,IND)*FLOW(F,IND)
        TLEND = TLEND + LOAN(F,IND)
        BORROW(F,IND) = BORROW(F,IND) + LOAN(F,IND)
        FUNDS(F,IND) = FUNDS(F,IND) + LOAN(F,IND)
   67   CONTINUE

        DO 66 IND = 0,2
        DO 66 F = 1,10
        if (n(f,ind).eq.0) go to 66
        PRLOAN(F,IND) = 100*LOAN(F,IND)/
        (FUNDS(F,IND)-LOAN(F,IND))
   66   CONTINUE


        DO 23 IND = 0,2
        if (tcount.eq.1) schind(ind) = 0
        DO 23 F = 1,10
        if (n(f,ind).eq.0) go to 23

   C    CALCULATE TOTAL WAGES AND NEW CAPACITY
        TWAGES = TWAGES + WBILL(F,IND)
        NEWCAP(F,IND) = FUNDS(F,IND)/(EK1(N(F,IND),F,IND)*
        1MPRICE(1,T,1) + EK2(N(F,IND),F,IND)*MPRICE(2,T,1))
        SCHRES(F,IND) = SCHCST(F,IND)/(EK1(N(F,IND),F,IND)
        *MPRICE(1,T,1)
        1 +EK2(N(F,IND),F,IND)*MPRICE(2,T,1))
        if (tcount.eq.1) then
        schper(f,ind) = schcst(f,ind)*10/(output(f,ind)
        *fprice(f,ind))
        schind(ind) = schind(ind) +
        schper(f,ind)*share(f,ind)
        end if


   C    IF (TCOUNT.EQ.1) write(45,*) schper
        SCHCST(F,IND) = 0
        TFUNDS = TFUNDS + FUNDS(F,IND)
        DO  I =1,N(F,IND)
        SK1(I,F,IND) = EK1(I,F,IND)
        SK2(I,F,IND) = EK2(I,F,IND)
        SL(I,F,IND) = EL(I,F,IND)
        SC(I,F,IND) = EC(I,F,IND)
        END DO
        TOTSK1(F,IND) = TOTEK1(F,IND)
        TOTSK2(F,IND) = TOTEK2(F,IND)
        TOTSL(F,IND) = TOTEL(F,IND)
        TOTOUT(F,IND) = OUTPUT(F,IND)
   23   CONTINUE

        TWAGES = TWAGES*(1+R)
        IF (TCOUNT.EQ.10) THEN
        draws2 = 0
        draws3 = 0
        draws5 = 0

        do 68 ind = 0,2
```

```
      DO 68 F = 1,10
      dr2 = draws(2,f,ind)
      dr3 = draws(3,f,ind)
      dr5 = draws(5,f,ind)
      AGGDRA(F,ind) = 0
      AGGTDR(F,ind) = 0
      draws2 = dr2*share(f,ind) + draws2
      draws3 = dr3*share(f,ind) + draws3
      draws5 = dr5*share(f,ind) + draws5

      DO 68 I = 1,6
      AGGDRA(F,ind) = AGGDRA(F,ind) + DRAWS(I,F,ind)
      AGGTDR(F,ind) = AGGTDR(F,ind) + GTDRAW(I,F,ind)
68    CONTINUE

C     CALCULATE SOME MEASURES OF PERFORMANCE
      TVALUE = 0

      DO IND = 0,2
      TVALUE =TVALUE + MPRICE(IND,T,1)*TOUTPT(IND,T,1)
      TOTK1(IND) = 0
      TOTK2(IND) = 0
      TOTL(IND) = 0
      END DO
      DO I = 1,3
      AVCOF0(I) = 0
      AVCOF1(I) = 0
      AVCOF2(I) = 0
      bcof0(i) = 0
      bcof1(i) = 0
      bcof2(i) = 0

      END DO
      DO 56 IND = 0,2
      avmkup(ind) =0
      gdpshr(ind) = mprice(ind,t,1)*toutpt(ind,t,1)/tvalue
      loanin(ind) = 0
      DO 56 F = 1,10
      if (n(f,ind).EQ.0) GO TO 56
      PERCAP(F,IND) = 100*NEWCAP(F,IND)/CAPCTY(F,IND)
      PERFUN(F,IND) = (FUNDS(F,IND)-LOAN(F,IND))/
      1(OUTPUT(F,IND)*FPRICE(F,IND))
      TOTK1(IND) = TOTK1(IND) + TOTEK1(F,IND)
      TOTK2(IND) = TOTK2(IND) + TOTEK2(F,IND)
      TOTL(IND)  = TOTL(IND)  + TOTEL(F,IND)

      BEK1(F,IND) = EK1(N(F,IND),F,IND)
      BEK2(F,IND) = EK2(N(F,IND),F,IND)
      BEL(F,IND) = EL(N(F,IND),F,IND)
      avmkup(ind)= avmkup(ind)+
      markup(f,ind)*capcty(f,ind)/tcap(ind)
      loanin(ind) = loanin(ind) +
      100*loan(f,ind)/fundin(ind)
56    CONTINUE
      AVCOF0(1) = TOTK1(0)/TOUTPT(0,T,1)
      AVCOF0(2) = TOTK2(0)/TOUTPT(0,T,1)
```

```
AVCOF0(3)  = TOTL(0)/TOUTPT(0,T,1)
AVCOF1(1)  = TOTK1(1)/TOUTPT(1,T,1)
AVCOF1(2)  = TOTK2(1)/TOUTPT(1,T,1)
AVCOF1(3)  = TOTL(1)/TOUTPT(1,T,1)
AVCOF2(1)  = TOTK1(2)/TOUTPT(2,T,1)
AVCOF2(2)  = TOTK2(2)/TOUTPT(2,T,1)
AVCOF2(3)  = TOTL(2)/TOUTPT(2,T,1)

do f = 1,10
bcof0(1)  = bcof0(1)  + bek1(f,0)*share(f,0)
bcof0(2)  = bcof0(2)  + bek2(f,0)*share(f,0)
bcof0(3)  = bcof0(3)  + bel(f,0)*share(f,0)
bcof1(1)  = bcof1(1)  + bek1(f,1)*share(f,1)
bcof1(2)  = bcof1(2)  + bek2(f,1)*share(f,1)
bcof1(3)  = bcof1(3)  + bel(f,1)*share(f,1)
bcof2(1)  = bcof2(1)  + bek1(f,2)*share(f,2)
bcof2(2)  = bcof2(2)  + bek2(f,2)*share(f,2)
bcof2(3)  = bcof2(3)  + bel(f,2)*share(f,2)
end do
GDP(T)  = 0
DO IND = 0,2
GDP(T)  = GDP(T)  + MPRICE(IND,1,1)*TOUTPT(IND,T,1)
END DO
WSHARE(T)  = w*(TOTL(0)+TOTL(1)+TOTL(2))/gdp(t)
realw = toutpt(0,t,1)/(totl(0)+totl(1)+totl(2))
emp(T)  = totl(0)  + totl(1)  + totl(2)
schgdp = 0
do ind = 0,2
schgdp = schgdp +schind(ind)*
(mprice(ind,t,1)*toutpt(ind,t,1)/
1gdp(t))
end do
IF  (T.GT.11)  ECGROW =  (GDP(T)-GDP(T-10))/GDP(T-10)
IF  (T.GT.11)  EMPGR =  (EMP(T)  - EMP(T-10))/EMP(T-10)
IF  (T.lt.11)  ECGROW = 0.05
AVGEN = 0
DO I = 1,10
AN = N(I,2)
AVGEN = AVGEN + AN/10
END DO
dr2 = 0
dr3 = 0
dr5 = 0
avn = 0
sr  = 0
do f = 1,10
dr2 = dr2 + draws(2,f,2)/10
dr3 = dr3 + draws(3,f,2)/10
dr5 = dr5 + draws(5,f,2)/10
sr = sr + schper(f,2)/10
AAAAA = N(F,2)
AVN = AVN + AAAAA/10
end do
B4 = 0
B3 = 0
B2 = 0
```

```
3135        B5 = 0
3140        B6 = 0
3145        DO I = 1,10
3150        IF (BASIC(i,0).GE.2) B2 = B2 + 1
3155        IF (BASIC(i,0).GE.3) B3 = B3 + 1
3160        IF (BASIC(i,0).GE.4) B4 = B4 + 1
3165        IF (BASIC(i,0).GE.5) B5 = B5 + 1
3170        IF (BASIC(i,0).GE.6) B6 = B6 + 1
3175        IF (BASIC(i,0).GE.7) B7 = B7 + 1
3180        END DO
3185
3190        call  concn
3195
3200
3205 C      write(21,*) U
3210 c      write(20,*) PERFUN
3215 c      IF(T.GE.1491) write(22,*) SHARE
3220 c      write(23,*) DSTOCK
3225 c      write(24,*) FPRICE
3230 c      write(30,*) MARKUP
3235 c      write(35,*) MPRICE(0,T,1),TOUTPT(0,T,1),avmkup(0),
3240 c      1,GROW(0)gdpshr(0),loanin(0),schind(0)
3245 c      write(33,*) MPRICE(1,T,1),TOUTPT(1,T,1),avmkup(1),
3250 c      1,GROW(1)gdpshr(1),loanin(1),schind(1)
3255 c      write(34,*) MPRICE(2,T,1),TOUTPT(2,T,1),avmkup(2),
3260 c      1,GROW(2)gdpshr(2),loanin(2),schind(2)
3265 c      write(36,*) percap
3270 c      write(37,*) N
3275 c      write(38,*) BASIC
3280        write(*,*) T
3285 c      write(39,*) AVCOF0
3290 c      write(40,*) AVCOF1
3295 c      write(41,*) AVCOF2
3300 C      WRITE(42,*) X(1,1,2),X(4,1,2),X(6,1,2)
3305 c      write(43,*) AGGx
3310 c      see 15840c     write(45,*) SCHCST
3315 C      write(46,*) draws
3320 c      write(47,*) aggdra
3325 c      write(48,*)  PRLOAN
3330 c      write(49,*) ECGROW,TFPEC(t),schgdp,
3335 c      1MPRICE(0,T,1),MPRICE(2,T,1)
3340 c      WRITE(50,*) GDP(T),TOUTPT(0,T,1),TOUTPT(1,T,1),
3345 c      1TOUTPT(2,T,1),WSHARE(T),realw,emp,w,r
3350
3355 C      GR1.FOR
3360 c      write(84,*)BASCAP(2,0)*100/TCAP(0),tfpind(0),
3365 c      1bcof0(3),bcof0(2)bCOF0(1),BASCAP(3,0)*100/
            TCAP(0),BASCAP(4,0)*100/TCAP(0),
3370 c      2BASCAP(5,0)*100/TCAP(0),BASCAP(6,0)*100/TCAP(0)
3375
3380 c      write(85,*) BASCAP(2,1)*100/TCAP(1),
            tfpind(1),bcof1(3),bcof1(2),
3385 c      1bCOF1(1),BASCAP(3,1)*100/TCAP(1),
            BASCAP(4,1)*100/TCAP(1),
3390 c      2BASCAP(5,1)*100/TCAP(1),BASCAP(6,1)*100/TCAP(1)
3395
```

```
c     write(86,*) BASCAP(2,2)*100/TCAP(2),tfpind(2),
      bcof2(3),bcof2(2),
c     1bCOF2(1),BASCAP(3,2)*100/TCAP(2),BASCAP(4,2)
      *100/TCAP(2),
c     2BASCAP(5,2)*100/TCAP(2),BASCAP(6,2)*100/TCAP(2)

C     GR2.FOR
      WRITE(97,*) AVMKUP(0),LOANIN(0),RIND(0),GROW(0),
      GDPSHR(0)
      WRITE(98,*) AVMKUP(1),LOANIN(1),RIND(1),GROW(1),
      GDPSHR(1)
      WRITE(99,*) AVMKUP(2),LOANIN(2),RIND(2),GROW(2),
      GDPSHR(2)

C     GR3.FOR
c     WRITE(87,*) MPRICE(0,T,1),RECON,WSHARE(T),TFPEC(T),
      ECGROW
c     WRITE(88,*) MPRICE(1,T,1),RECON,WSHARE(T),TFPEC(T),
      EMPGR
c     WRITE(89,*) MPRICE(2,T,1),RECON,WSHARE(T),TFPEC(T),
      EMPGR
      write(96,*) recon,wshare(t),tfpec(t),empgr,ecgrow

C     GR4.FOR
C     REMEMBER TO CHANGE CALCULATION OF B2,B3
c     WRITE(87,*) B2,BASIC(9,0),PERCAP(9,0),FPRICE(9,0),
c     1SHARE(9,0),B3,B4,B5,B6,b7
c     WRITE(88,*) B2,BASIC(5,0),PERCAP(5,0),FPRICE(5,0),
c     1SHARE(5,0),B3,B4,B5,B6,b7

cc    GR5.FOR
c     WRITE(84,*) LOAN(9,0)*100/(FUNDS(9,0)-LOAN(9,0)),
      MARKUP(9,0),
c     1U(9,0),DSTOCK(9,0)*100/CAPCTY(9,0),SHARE(9,0)
c     WRITE(85,*) LOAN(5,0)*100/(FUNDS(5,0)-LOAN(5,0)),
      MARKUP(5,0),
c     1U(10,2),DSTOCK(10,2)*100/CAPCTY(10,2),SHARE(10,2)
      TCOUNT = 0
      TNCAP = 0
      END IF
      if (tcount.eq.10) then
      do ind = 0,2
      do f = 1,10
      do i = 1,6
      draws(i,f,ind) = 0
      end do
      end do
      end do

      end if

98    CONTINUE
      END

      SUBROUTINE PRODN(T,STDEV,W,DEPN)
```

```
      COMMON/NEWCAP/ NEWCAP(10,0:2)
      COMMON /STOCKS/ STOCKS(10,0:2),DSTOCK(10,0:2)
      COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
      SL(80,10,0:2),
      1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
      EL(80,10,0:2),
      2EC(80,10,0:2)
      COMMON/N/ N(10,0:2)
      COMMON/RAV/ RAV(10,0:2)
      COMMON /SHARE/ SHARE(10,0:2)
      COMMON /WBILL/ WBILL(10,0:2)
      COMMON/OUTPUT/ OUTPUT(10,0:2)
      COMMON/TOUTPT/ TOUTPT(0:2,2001,1)
      COMMON/UTILIS/ U(10,0:2),DESU(10,0:2),DELU(10,0:2)
      COMMON /CAPCTY/ CAPCTY(10,0:2)
      COMMON /MARKUP/ MARKUP(10,0:2)
      COMMON /FPRICE/ FPRICE(10,0:2)
      COMMON /FUNDS/ FUNDS(10,0:2)
      COMMON /MPRICE/ MPRICE(0:2,2001,1)
      COMMON /TOTALS/TOTSK1(10,0:2),TOTSK2(10,0:2),
      TOTSL(10,0:2)
      1,TOTOUT(10,0:2),TOTEK1(10,0:2),TOTEK2(10,0:2),
      TOTEL(10,0:2)
      COMMON /DEMAND/ DEMAND(0:2)
      DIMENSION TRANFR(10,0:2),TDSTOC(0:2),WBE(80,10,0:2)
      DIMENSION DIFSHR(0:2),TSHARE(0:2)
      REAL MOTHEC(60,10,0:2),NEWCAP,mprice,markup,using
      INTEGER F,T,count

      DO 25 IND = 0,2
      DIFSHR(IND) = 0
      TSHARE(IND) = 0
      TDSTOC(IND) = 0
      DO 25 F = 1,10
      if (n(f,ind).eq.0) go to 25
      TOTEK1(F,IND) =0
      TOTEK2(F,IND) = 0
      TOTEL(F,IND) = 0
      TRANFR(F,IND) = 0
      DO 5 I = 1,N(F,IND)
      MOTHEC(I,F,IND) = 0
      WBE(I,F,IND) = 0
5     CONTINUE

      DO 41 I = 1,N(F,IND)
      WBE(I,F,IND) = FPRICE(F,IND)*(1-RAV(F,IND)*
      STDEV)/EL(I,F,IND)

C     MOTHBALL ALL CAPITAL NOT BREAKING EVEN
      IF (W.Gt.WBE(I,F,IND)) THEN
      MOTHEC(I,F,IND) = EC(I,F,IND)
      END IF
41    CONTINUE

      CAPCTY(F,IND) = 0
      DO I = 1,N(F,IND)
```

```
      CAPCTY(F,IND) = CAPCTY(F,IND) + EC(I,F,IND)-
      MOTHEC(I,F,IND)
      END DO
      OUTPUT(F,IND) = U(F,IND)*CAPCTY(F,IND)
      1+ 0.1*NEWCAP(F,IND)  ! THIS BUILDS UP STOCKS
C     DSTOCK IS CHANGE IN REQUIRED
C     STOCKS AND IS USED IN SUBROUTINE CHANGE
      DSTOCK(F,IND) = OUTPUT(F,IND) - DEMAND(IND)
      *SHARE(F,IND)
      1 - 0.1*NEWCAP(F,IND)
C     STOCKS IS THE ACTUAL PHYSICAL LEVEL OF STOCK HELD
      CURRENTLY
      STOCKS(F,IND) = STOCKS(F,IND) +OUTPUT(F,IND)-
      1 DEMAND(IND)*SHARE(F,IND)
25    CONTINUE
      DO 42 IND = 0,2
      DO 42 F = 1,10
      if (n(f,ind).eq.0) go to 42
C     IF STOCKS ARE NEGATIVE THE FIRM BUYS STOCKS TO MEET
C     DEMAND, AND THEN IS PENALISED BY REDUCTION OF SHARE
      IF (STOCKS(F,IND).LT.0) THEN
1     TDSTOC(IND) = -STOCKS(F,IND) + 0.05*CAPCTY(F,IND)
      difshr(ind) = 0.1*share(f,ind) + difshr(ind)
      TRANFR(F,IND) = 0.05*CAPCTY(F,IND) - STOCKS(F,IND)
      STOCKS(F,IND) = 0.05*CAPCTY(F,IND)
      share(f,ind) = 0.9*share(f,ind)
      DSTOCK(F,IND) = 0
      U(F,IND) = 0.1
      MARKUP(F,IND) = markup(f,ind)+abs(markup(f,ind))*0.5
      output(f,ind) = 0.1*capcty(f,ind) +0.1*newcap(f,ind)

      IF (MARKUP(F,IND).LT.0) MARKUP(F,IND) = 0
      END IF
42    CONTINUE
      DO 43 IND = 0,2
      IF (TDSTOC(IND).GT.0) WRITE(*,*)TDSTOC,T
      DO 43 F = 1,10
      share(f,ind) = share(f,ind)*(1 + share(f,ind)
      *difshr(ind))
      TSHARE(IND) = TSHARE(IND) + SHARE(F,IND)
43    continue
      do ind = 0,2
      do f = 1,10
      share(f,ind) = share(f,ind)/tshare(ind)
      end do
      end do
      do 44 ind = 0,2
      do 44 f = 1,10
      STOCKS(F,IND) = STOCKS(F,IND)-
      TDSTOC(IND)*SHARE(F,IND)
C     ADJUST FUNDS TO PAY FOR STOCK TRANSFERS BETWEEN
      COMPANIES
      FUNDS(F,IND) = FUNDS(F,IND)
      +MPRICE(IND,T,1)*(TDSTOC(IND)*
      1SHARE(F,IND) - TRANFR(F,IND))
44    CONTINUE
```

```

      DO 15 IND = 0,2
      DO 15 F = 1,10
      count = 0
      if (n(f,ind).eq.0) go to 15
      WBILL(F,IND) = 0
C     USE THE MOST PRODUCTIVE CAPITAL TO PRODUCE DESIRED
      OUTPUT
c     using 10% of capital each month
      using = 0.1
      DLEFT = OUTPUT(F,IND)
16    DO 17 I = N(F,IND),1,-1
      if (using.lt.0.01) using = 0.01
      IF (DLEFT.LE.0.0) GO TO 15
      IF (DLEFT.GE.using*EC(I,F,IND)) THEN
      if (using.lt.0.01) using = 0.01
      WBILL(F,IND) = WBILL(F,IND) +
      EL(I,F,IND)*using*EC(I,F,IND)*W
      TOTEK1(F,IND) = TOTEK1(F,IND) +
      EK1(I,F,IND)*using*EC(I,F,IND)
      TOTEK2(F,IND) = TOTEK2(F,IND)
      +EK2(I,F,IND)*using*EC(I,F,IND)
      TOTEL(F,IND) = TOTEL(F,IND) +
      EL(I,F,IND)*using*EC(I,F,IND)
      ELSE
      if (using.lt.0.01) using = 0.01
      WBILL(F,IND) = WBILL(F,IND) + EL(I,F,IND)*DLEFT*W
      TOTEK1(F,IND) =TOTEK1(F,IND) + EK1(I,F,IND)*DLEFT
      TOTEK2(F,IND) = TOTEK2(F,IND) + EK2(I,F,IND)*DLEFT
      TOTEL(F,IND) = TOTEL(F,IND) + EL(I,F,IND)*DLEFT
      END IF
      DLEFT = DLEFT - using*EC(I,F,IND)
17    CONTINUE
      if (dleft.gt.0.0) then
      count = count +1
      IF (COUNT.GE.3) THEN


      END IF

      if (count.ge.5) stop
      using = 0.01
      if (using.lt.0.01) using = 0.01

      go to 16
      end if

15    CONTINUE
      RETURN
      END


      SUBROUTINE RENUM(N,W,F,IND,T)
      COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
      SL(80,10,0:2),
      1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
```

```
      EL(80,10,0:2),
      2EC(80,10,0:2)
      COMMON /FPRICE/ FPRICE(10,0:2)
      COMMON /MPRICE/ MPRICE(0:2,2001,1)
      DIMENSION PI(80),PROSS(80)
      INTEGER PROSS,Z,F,T
      REAL MPRICE
      IF (N.EQ.1) THEN
      EK1(1,F,IND) = SK1(1,F,IND)
      EK2(1,F,IND) = SK2(1,F,IND)
      EL(1,F,IND)  = SL(1,F,IND)
      EC(1,F,IND) = SC(1,F,IND)
      GO TO 30
      ELSE
      DO 10 I=1,N
      PROSS(I) = I
      PI(I) = FPRICE(F,IND)-R*(MPRICE(1,T,1)*SK1(I,F,IND)+
      1MPRICE(2,T,1)*SK2(I,F,IND))-W*SL(I,F,IND)
      IF (SC(I,F,IND).EQ.0) PI(I) = 0
10    CONTINUE
      N1=N-1
      DO 15 J=1,N1
      K=J
      L=K+1
      DO 20 I=L,N
      IF (PI(K).GT.PI(I)) K =I
20    CONTINUE
      TT=PI(J)
      Z=PROSS(J)
      PI(J)=PI(K)
      PROSS(J) = PROSS(K)
      PI(K) = TT
      PROSS(K) = Z
15    CONTINUE
      J=0
      NCOUNT = 0
      DO 25 I=1,N
C     AFTER THE SORT THE VALUE OF PROSS(I) IS THE I'TH
      WORST PROCESS
      IF (SC(PROSS(I),F,IND).GT.0) THEN
      NCOUNT = NCOUNT + 1
      J=J+1
      EK1(J,F,IND) = SK1(PROSS(I),F,IND)
      EK2(J,F,IND) = SK2(PROSS(I),F,IND)
      EL(J,F,IND)  = SL(PROSS(I),F,IND)
      EC(J,F,IND) = SC(PROSS(I),F,IND)
      END IF
25    CONTINUE
      END IF
      N = NCOUNT
30    RETURN
      END


      SUBROUTINE CHANGE(T,W,R)
      COMMON /SHARE/ SHARE(10,0:2)
```

```
      common /vary/ vary(0:2)
      COMMON /STOCKS/ STOCKS(10,0:2),DSTOCK(10,0:2)
      COMMON /CAPCTY/ CAPCTY(10,0:2)
      COMMON /FPRICE/ FPRICE(10,0:2)
      COMMON /MPRICE/ MPRICE(0:2,2001,1)
      COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
      SL(80,10,0:2),
      1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
      EL(80,10,0:2),
      2EC(80,10,0:2)
      COMMON/UTILIS/ U(10,0:2),DESU(10,0:2),DELU(10,0:2)
      COMMON /N/ N(10,0:2)
      COMMON /MARKUP/ MARKUP(10,0:2)
      COMMON /XYZ/ XX,YY,MM,SS,DD,XXX,YYY,M4,SS0
      COMMON /DEMAND/ DEMAND(0:2)
      COMMON /AVCOST/ AVCOST(0:2)
      DIMENSION  PCOSTB(10,0:2),TSHAR(0:2),MPLUS(10,0:2)
      DIMENSION DSHARE(10,0:2),OWNCST(10,0:2)
      dimension trend(10,0:2)
      INTEGER F,T
      REAL MPRICE,MARKUP,MM,M4,MPLUS

      DO 20 IND = 0,2
      DO 20 F = 1,10
      if (n(f,ind).eq.0) go to 20
c     IF (MPLUS(F,IND).GT.0)
      MARKUP(F,IND)=MARKUP(F,IND)-MPLUS(F,IND)
c     MPLUS(F,IND) = M4*(0.1-STOCKS(F,IND)/CAPCTY(F,IND))
      MARKUP(F,IND)=MARKUP(F,IND)- MPLUS(F,IND)
      MPLUS(F,IND) = M4*(0.1-STOCKS(F,IND)/CAPCTY(F,IND))

C     PCOSTB IS WAGE COST PLUS 1/20 OF CAPITAL COST FOR
C     THE BESTPROCESS IN USE BY THE FIRM
      IF (T.EQ.1) DSHARE(F,IND) = 0
      COST = 0
C     CHANGE MARKUP ACCORDING TO DSTOCK
      markup(f,ind) = markup(f,ind) -
       mm*(dstock(f,ind)/capcty(f,ind))
c     IF (MPLUS(F,IND).GT.0)
      MARKUP(F,IND)=MARKUP(F,IND)+MPLUS(F,IND)
      MARKUP(F,IND)=MARKUP(F,IND)+MPLUS(F,IND)

      DO 40 I = 1,N(F,IND)
      COST=COST+(1+MARKUP(F,IND))*(EL(I,F,IND)*W
      1+(R/((1+0.1*0.05)*0.09))*(MPRICE(1,T,1)*
      2EK1(I,F,IND)+MPRICE(2,T,1)*EK2(I,F,IND))
      3*(EC(I,F,IND)/CAPCTY(F,IND))
      OWNCST(F,IND) = COST/(1+MARKUP(F,IND))
 40   CONTINUE
      PCOSTB(F,IND) = COST
      FPRICE(F,IND) = 0*MPRICE(IND,T,1) + 1*PCOSTB(F,IND)
 20   CONTINUE

      DO 50 IND = 0,2
      MPRICE(IND,T+1,1) = 0
      DO 50 F = 1,10
```

```
        MPRICE(IND,T+1,1) =
        FPRICE(F,IND)*SHARE(F,IND)+MPRICE(IND,T+1,1)
  50    CONTINUE

        DO 10 IND = 0,2
        TSHAR(IND) = 0
  10    CONTINUE

        DO 30 IND = 0,2
        AVCOST(IND) = 0
        DO 30 F = 1,10
        if (n(f,ind).eq.0) go to 30
        IF (IND.EQ.0) THEN
        DSHARE(F,IND) = (SS0*(MPRICE(IND,T+1,1)-
        1FPRICE(F,IND))/MPRICE(IND,T+1,1))

c       this can limit the rate of share change if desired
c       if(dshare(f,ind)/share(f,ind).gt.0.02)dshare(f,ind)
c       1= 0.02*share(f,ind)
c       if(dshare(f,ind)/share(f,ind).lt.-0.02)dshare(f,ind)
c       1= -0.02*share(f,ind)
        share(f,ind) = share(f,ind)*(1+dshare(f,ind))
        if (share(f,ind).lt.0) share(f,ind) = 0
        ELSE
        DSHARE(F,IND) = (SS*(MPRICE(IND,T+1,1)-
        1FPRICE(F,IND))/MPRICE(IND,T+1,1))
c       if(dshare(f,ind)/share(f,ind).gt.0.02)dshare(f,ind)
c       1= 0.02*share(f,ind)
c       if(dshare(f,ind)/share(f,ind).lt.-0.02)dshare(f,ind)
c       1= -0.02*share(f,ind)
        share(f,ind) = share(f,ind)*(1+dshare(f,ind))
        if (share(f,ind).lt.0) share(f,ind) = 0
        END IF
        TSHAR(IND) = TSHAR(IND) + SHARE(F,IND)
c       trend is the trend of market share
        trend(f,ind) = 0.9*trend(f,ind) + 0.1*dshare(f,ind)
  30    CONTINUE

        DO IND = 0,2
        IF (TSHAR(IND).NE.1) THEN
        DO F=1,10
        SHARE(F,IND) = SHARE(F,IND)/TSHAR(IND)
        END DO
        END IF
        END DO

c       adjust utilisation rate
        DO IND = 0,2
        DO F=1,10
        AVCOST(IND) = AVCOST(IND)+OWNCST(F,IND)*share(f,ind)
        if (n(f,ind).eq.0) go to 1
        DESU(F,IND) = 0.09*(0.6+0.4*MPRICE(IND,T,1)/
        OWNCST(F,IND))
        IF (DESU(F,IND).GT.0.095) DESU(F,IND) = 0.095
        if (desu(f,ind).lt.0.05) desu(f,ind) = 0.05
        IF (IND.EQ.0) THEN
```

```
      XXXX = XX*(1 + XXX*ABS(trend(F,IND)))
      U(F,IND) = U(F,IND)-XXXX*DSTOCK(F,IND)/CAPCTY(F,IND)
      if (trend(f,ind).gt.0) then
      IF(DESU(F,IND).GT.U(F,IND))U(F,IND)=
      1U(F,IND)+DD*(DESU(F,IND)-U(F,IND))
      END IF
      ELSE
      YYYY = YY*(1+YYY*ABS(trend(F,IND)))
      U(F,IND) = U(F,IND)-YYYY*DSTOCK(F,IND)/CAPCTY(F,IND)
      IF (trend(F,IND).GT.0) THEN
      IF(DESU(F,IND).GT.U(F,IND)) U(F,IND)
      1=U(F,IND)+DD*(DESU(F,IND)-U(F,IND))
      END IF
      END IF
      IF (STOCKS(F,IND)/CAPCTY(F,IND).LT.0.05)
      U(F,IND)=U(F,IND)+0.01
      IF (FPRICE(F,IND).LT.W*EL(1,F,IND)) FPRICE(F,IND)
      1 = W*EL(1,F,IND)
c     IF (U(F,IND).LT.0) U(F,IND) = 0
      if(u(f,ind)*capcty(f,ind).lt.0.95
      1*share(f,ind)*demand(ind)) u(f,ind) =
      0.95*(share(f,ind)*demand(ind))/capcty(f,ind)
      IF (U(F,IND).GT.0.1) U(F,IND) = 0.1
1     END DO
      END DO

c     calculate variance of costs
      do ind = 0,2
      vary(ind) = 0
      do f = 1,10
      vary(ind) = vary(ind) + share(f,ind)*(owncst(f,ind)
      1-avcost(ind))**2
      end do
      end do

      RETURN
      END

      SUBROUTINE TECPRO(T,R,W,TCOUNT,TFPEC,BTFP)
      COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
      SL(80,10,0:2),
      1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
      EL(80,10,0:2),
      2EC(80,10,0:2)
      COMMON /N/N(10,0:2)
      COMMON/NEWCAP/ NEWCAP(10,0:2)
      common /itfp/ tfpind(0:2),RIND(0:2)
      COMMON/NEWPRO/ NEWPRO(10,0:2)
      COMMON /MPRICE/ MPRICE(0:2,2001,1)
      COMMON /FPRICE/ FPRICE(10,0:2)
      COMMON/TOUTPT/ TOUTPT(0:2,2001,1)
      COMMON /OUTPUT/ OUTPUT(10,0:2)
      COMMON /RETURN/ RFIRM(10,0:2),RECON
      COMMON /CAPCTY/ CAPCTY(10,0:2)
      COMMON /SHARE/ SHARE(10,0:2)
      COMMON /TOTALS/TOTSK1(10,0:2),TOTSK2(10,0:2),
```

```
      TOTSL(10,0:2)
      1,TOTOUT(10,0:2),TOTEK1(10,0:2),TOTEK2(10,0:2),
      TOTEL(10,0:2)
      DIMENSION TFPFIR(10,0:2),DTFPFI(10,0:2)
      DIMENSION DTFPIN(0:2),CAPVAL(10,0:2)
      DIMENSION INDCAP(0:2),INDVAL(0:2),TRATE(10,0:2),
      BESTTF(0:2)
      DIMENSION BESTPR(10,0:2),TRIND(0:2)
      REAL INDCAP,INDVAL,NEWCAP,MPRICE
      INTEGER F,T,TCOUNT

      IF (T.EQ.1) TFPEC = 1
C     CALCULATE TFP, CHANGE IN TFP AND RATE OF RETURN FOR
      DO 10 IND = 0,2
      DTFPIN(IND) = 0
      INDCAP(IND) = 0
      INDVAL(IND) = 0
      RIND(IND) = 0
      TRIND(IND) = 0
      DO 10 F = 1,10
      if (n(f,ind).eq.0) go to 10
      CALLTFP(F,IND,T,W,R,DTFPFI(F,IND),TFPFIR(F,IND),
      1BESTPR(F,IND),N(F,IND))
      CALL RRATE(F,IND,T,W,R,N(F,IND),RFIRM(F,IND)
      1,CAPVAL(F,IND),TRATE(F,IND))
      INDCAP(IND) =INDCAP(IND)+CAPCTY(F,IND)-NEWCAP(F,IND)
      INDVAL(IND) = INDVAL(IND) + CAPVAL(F,IND)
10    CONTINUE

      DO 25 IND = 0,2
      BESTTF(IND) = 0
      DO 25 F = 1,10
      IF(BESTPR(F,IND).GT.BESTTF(IND))
      BESTTF(IND) = BESTPR(F,IND)
25    CONTINUE

      BTFP = 0
      DO I = 1,10
      BTFP = BTFP + BESTPR(I,2)*SHARE(I,2)
      END DO

C     CALCULATE INDUSTRY AVERAGES
      DO 20 IND = 0,2
      STFP = TFPIND(IND)
      TFPIND(IND) = 0
      DO 21 F = 1,10
      if (n(f,ind).eq.0) go to 21
      TFPIND(IND) = TFPIND(IND)+TFPFIR(F,IND)*SHARE(F,IND)
      RIND(IND) =RIND(IND)+RFIRM(F,IND)*
      CAPVAL(F,IND)/INDVAL(IND)
      TRIND(IND) = TRIND(IND)
      +TRATE(F,IND)*CAPVAL(F,IND)/INDVAL(IND)
21    CONTINUE
      DTFPIN(IND) = TFPIND(IND)-STFP
      TFPIN2 = TFPIND(2)
20    CONTINUE
```

```
      RECON = 0
      TFPEC  = 0
      ECVAL = 0
      GDP = 0
      DO IND = 0,2
      ECVAL = ECVAL + INDVAL(IND)
      GDP = GDP + MPRICE(IND,T,1)*TOUTPT(IND,T,1)
      END DO
      DO IND = 0,2
      RECON = RECON + TRIND(IND)*INDVAL(IND)/ECVAL
      TFPEC = TFPEC + TFPIND(IND)*MPRICE(IND,T,1)
      1*TOUTPT(IND,T,1)/GDP
      END DO

      IF (TCOUNT.EQ.10) THEN
c     wrITE(31,*) TFPIND,BESTTF
c     wrITE(32,*) TRIND
c     wrITE(44,*) TFPFIR
c     WRITE(44,*) BESTPR
      END IF
1     RETURN
      END

      SUBROUTINE TFP(F,IND,T,W,R,DTFPFI,TFPFIR,BEST,N)
      COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
      SL(80,10,0:2),
      1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
      2EL(80,10,0:2),EC(80,10,0:2)
      COMMON/NEWCAP/ NEWCAP(10,0:2)
      COMMON /OUTPUT/ OUTPUT(10,0:2)
      COMMON/NEWPRO/ NEWPRO(10,0:2)
      COMMON /MPRICE/ MPRICE(0:2,2001,1)
      COMMON /FPRICE/ FPRICE(10,0:2)
      COMMON /CAPCTY/ CAPCTY(10,0:2)
      COMMON/TOUTPT/ TOUTPT(0:2,2001,1)
      COMMON/UTILIS/ U(10,0:2),DESU(10,0:2),DELU(10,0:2)
      COMMON /TOTALS/TOTSK1(10,0:2),TOTSK2(10,0:2)
      ,TOTSL(10,0:2)
      1,TOTOUT(10,0:2),TOTEK1(10,0:2),TOTEK2(10,0:2),
      TOTEL(10,0:2)
      REAL NEWCAP,MPRICE
      INTEGER F,T

c     Z1, Z2 ARE RENTAL PRICES OF CAPITAL
      Z1 = MPRICE(1,T,1)*R/((1+0.1*0.05)*0.09)
      Z2 = MPRICE(2,T,1)*R/((1+0.1*0.05)*0.09)
      VDENOM = 0
      VNUM1 =0
      VNUM2 = 0
      VNUML = 0
      avk1 = (totsk1(f,ind) + totek1(f,ind))/2
      avk2 = (totsk2(f,ind) + totek2(f,ind))/2
      avl = (totsl(f,ind) + totel(f,ind))/2
      avout = (totout(f,ind) + output(f,ind))/2
      IF(T.EQ.1) THEN
      Z10 = Z1
```

```
        Z20 = Z2
        TOTSK1(F,IND) = TOTEK1(F,IND)
        TOTSK2(F,IND) = TOTEK2(F,IND)
        TOTOUT(F,IND) = OUTPUT(F,IND)
        TOTSL(F,IND) = TOTEL(F,IND)
        END IF
        VDENOM = TOTSK1(F,IND)*z10 + TOTSK2(F,IND)*z20
        +TOTSL(F,IND)*W
        if (vdenom.eq.0) then
        dtfp = 0
        go to 1
        end if

C       V1,V2,VL ARE DIVISIA WEIGHTS
        V1 = TOTSK1(F,IND)*z10/VDENOM
        V2 = TOTSK2(F,IND)*z20/VDENOM
        VL = TOTSL(F,IND)*W/VDENOM

        IF (T.EQ.1) THEN
        DTFPFI = 0
        TFPFIR = MPRICE(IND,T,1)*OUTPUT(F,IND)/
        1(Z1*TOTEK1(F,IND)+Z2*TOTEK2(F,IND) +
        W*TOTEL(F,IND))

        ELSE
C       CALCULATE THE CHANGE IN TFP
        DTFPFI = ((OUTPUT(F,IND)-TOTOUT(F,IND))/avout)-
        1(V1*(TOTEK1(F,IND)-TOTSK1(F,IND))/avk1)- (V2*
        2(TOTEK2(F,IND)-TOTSK2(F,IND))/avk2) -
        3(VL*(TOTEL(F,IND)-TOTSL(F,IND))/avl)
        tfpfir = tfpfir*(1+dtfpfi)
        END IF

C       CALCULATE TFP OF BEST PROCESS
        BEST = MPRICE(IND,1,1)/(Z10*EK1(N,F,IND)
        1+Z20*EK2(N,F,IND) +W*EL(N,F,IND))

1       RETURN
        END

        SUBROUTINE RRATE(F,IND,T,W,R,N,pi,TVAL,TRATE)
        COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
        SL(80,10,0:2),
        1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
        2EL(80,10,0:2),EC(80,10,0:2)
        COMMON /MPRICE/ MPRICE(0:2,2001,1)
        DIMENSION RPROSS(80),CAPVAL(80),POVAL(80),RTREND(80)
        INTEGER F,T
        REAL MPRICE

C       CALCULATE PROCESS RATES OF RETURN
        DO I = 1,N
        RPROSS(I) = (MPRICE(IND,T,1)-
        W*EL(I,F,IND))/(MPRICE(1,T,1)*
        1EK1(I,F,IND) + MPRICE(2,T,1)*EK2(I,F,IND))
        CAPVAL(I) = 0
```

```
      RTREND(I) = (MPRICE(IND,1,1)-
      W*EL(I,F,IND))/(MPRICE(1,1,1)*
      1EK1(I,F,IND) + MPRICE(2,1,1)*EK2(I,F,IND))
      POVAL(I) = 0
      END DO

      TVAL = 0
      TVAL0 = 0
      DO I = 1,N
      CAPVAL(I) = MPRICE(1,T,1)*EK1(I,F,IND)
      +MPRICE(2,T,1)*EK2(I,F,IND)
      CAPVAL(I) = CAPVAL(I)*EC(I,F,IND)
      TVAL = TVAL +CAPVAL(I)
      POVAL(I) = MPRICE(1,1,1)*EK1(I,F,IND)
      +MPRICE(2,1,1)*EK2(I,F,IND)
      POVAL(I) = POVAL(I)*EC(I,F,IND)
      TVAL0 = TVAL0 +POVAL(I)
      END DO
c     pi is passed to main program as rfirm
c     as it is only used to calculate borrowing it
      measures the
c     best process in use, averaged over preceding 5 years
      if (t.eq.1) pi = 0.055
      pi = rpross(n)*0.05 + 0.95*pi

      AVRATE = 0
      TRATE = 0
      DO I = 1,N
c     AVRATE = AVRATE + RPROSS(I)*CAPVAL(I)/TVAL
C     CALCULATE CAPITAL SHARE WEIGHTED AVERAGE RATE OF
      RETURN
      TRATE = TRATE + RTREND(I)*POVAL(I)/TVAL0
      END DO
1     RETURN
      END

      SUBROUTINE INVEST(N,SCHCST,R,depn,
      1FUNDS,SRCHP,F,IND,T,LEARN,hope)
      COMMON /SEARCH/ THETA(6,10,0:2),LAMDA(6,10,0:2),
      PHI(6),PATON
      COMMON /FPRICE/ FPRICE(10,0:2)
      common /better/ better(10,0:2)
      COMMON /X/ X(6,10,0:2)
      COMMON /DRAWS/ DRAWS(6,10,0:2),gTDRaw(6,10,0:2),
      AGGX(10,0:2)
      COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
      SL(80,10,0:2),
      1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
      EL(80,10,0:2),
      2EC(80,10,0:2)
      COMMON /MPRICE/ MPRICE(0:2,2001,1)
      DIMENSION PE(0:2)
      DIMENSION EXPK1(6),EXPK2(6),EXPL(6)
      DIMENSION DELPX(6),EXPPI(6),EX(6)
      DIMENSION REACHX(6,10,0:2)
      REAL LAMDA,LEARN,mprice
```

```
      INTEGER DRAWS,SRCHDI,F,T,gtdraw,COUNT,REACHX
      double precision delpx
      HORIZN = 100.0
      w = 1

C     PATHOP INDUCES EXTRA SEARCH FOR THOSE WHO CAN GAIN A
      PATENT
      PATHOP = 1
      IF (PATON.EQ.1) THEN
      IF (BETTER(F,IND).EQ.0) PATHOP = 3.0
      END IF
      TDRAWS = 0
      DO INDI = 0,2
      PE(INDI) = MPRICE(INDI,1,1)
      END DO
      efpri = fprice(f,ind)*1.0

c     this adjusts the expected search price for
      experimenting
c     PE(2) = PE(2)*1.3
c     w = 1.3

      IF (FUNDS.LE.SRCHP) THEN
      schcst = 0
      DO I =  1,6
      DRAWS(I,F,IND) = 0
      END DO
      GO TO 60
      END IF

C     BESTPI = PROFIT FROM INVESTING IF THERE IS NO SEARCH
      PIN=efpri-R*(PE(1)*EK1(N,F,IND)+PE(2)*EK2(N,F,IND)
      1)-W*EL(N,F,IND)
      BESTPI = HORIZN*PIN*FUNDS/(PE(1)*EK1(N,F,IND) +
      1 PE(2)*EK2(N,F,IND))
      TRYK1 = EK1(N,F,IND)
      TRYK2 = EK2(N,F,IND)
      TRYL = EL(N,F,IND)
      DO I =1,6
      if (t.eq.1) gtdraw(i,f,ind) = 0
      DRAWS(I,F,IND) = 0
      IF (X(I,F,IND).EQ.0) REACHX(I,F,IND) = 0
      END DO

C     ENSURE THAT SEARCH IS OVER THE UNREACHED TAIL OF THE

C     PROBABILITY DISTRIBUTION
      DO I = 1,6
      END DO
      DO 5 I = 1,6
6     START = 0
      if (reachx(i,f,ind).ge.2500) go to 5
      DO Z = 1,REACHX(I,F,IND) + 1
      START = START + 1/Z
      END DO
      XXX = START*LAMDA(I,F,IND)*LEARN*PATHOP+
```

```
      THETA(I,F,IND)
      IF (XXX.LT.X(I,F,IND)) THEN
      REACHX(I,F,IND) = REACHX(I,F,IND) + 1
      GO TO 6
      END IF
5     CONTINUE

C     TRYK1 ETC ARE THE COEFFICIENTS GIVEN
C     THE CURRENT LEVEL OF DRAWS.
C     CALCULATE P(X) A FUNCTION OF RANGE 0,1 AND CHANGE
      DELP(X)
      DO I=1,6
      DELPX(I) = (LAMDA(I,F,IND)*LEARN*PATHOP)
      1/(REACHX(I,F,IND)+ DRAWS(I,F,IND)+1)
      delpx(i) = delpx(i)/(x(i,f,ind)+100)
      END DO
C     CALCULATE EXPECTED COEFFICIENTS FOR THE NEW
      PROCESSES.
      DO 50 I=1,6
      IF (I.EQ.1) THEN
      EXPK1(I) = (SIND(PHI(I))*DELPX(I) +1)*TRYK1
      EXPK2(I) = (1-COSD(PHI(I))*DELPX(I))*TRYK2
      EXPL(I) =TRYL
      ELSE IF (I.EQ.2) THEN
      EXPK1(I) = (1-COSD(PHI(I))*DELPX(I))*TRYK1
      EXPK2(I) = (1+SIND(PHI(I))*DELPX(I))*TRYK2
      EXPL(I) = TRYL
      ELSE IF (I.EQ.3) THEN
      EXPL(I) = (1-COSD(PHI(I))*DELPX(I))*TRYL
      EXPK1(I) = (1 + SIND(PHI(I))*DELPX(I))*TRYK1
      EXPK2(I) = TRYK2
      ELSE IF (I.EQ.4) THEN
      EXPK1(I) = (1 - COSD(PHI(I))*DELPX(I))*TRYK1
      EXPL(I) = (1 + SIND(PHI(I))*DELPX(I))*TRYL
      EXPK2(I) = TRYK2
      ELSE IF (I.EQ.5) THEN
      EXPL(I) = (1 - COSD(PHI(I))*DELPX(I))*TRYL
      EXPK2(I) = (1 + SIND(PHI(I))*DELPX(I))*TRYK2
      EXPK1(I) =TRYK1
      ELSE IF (I.EQ.6) THEN
      EXPK2(I) = (1 -COSD(PHI(I))*DELPX(I))*TRYK2
      EXPL(I) = (1 + SIND(PHI(I))*DELPX(I))*TRYL
      EXPK1(I) =TRYK1
      END IF
50    CONTINUE
C     CALCULATE SEARCH COSTS
      SCHCST = SCHCST + SRCHP
C     CALCULATE EXPECTED PROFIT IF SEARCH IS INCREASED BY
      1 DRAW
      DO I = 1,6
      EXPPI(I) = (efpri-R*(PE(1)*EXPK1(I) +
      1 PE(2)*EXPK2(I)) - W*EXPL(I))
      2*(FUNDS*HORIZN - SCHCST)/(PE(1)*EXPK1(I) +
      PE(2)*EXPK2(I))
      END DO
C     FIND WHICH EXPPI IS THE GREATEST, CALL IT PIMAX AND
```

```
C     COMPARE  WITH BESTPI. IF LARGER IT BECOMES BESTPI,
C     DRAWS INCREASE  AND WHOLE PROCESS IS REPEATED
      SRCHDI =0
      PIMAX = BESTPI
      DO I=1,6
      IF (EXPPI(I).GT.PIMAX) THEN
      SRCHDI = I
      PIMAX = EXPPI(I)
      END IF
      END DO
C     IF BESTPI IS NEGATIVE LIMIT SEARCH TO FIND
      IMPROVEMENTS
      IF (BESTPI.LT.0) THEN
      DELPI = ABS((BESTPI - PIMAX)/BESTPI)
      IF (DELPI.LE.0.97) THEN
      DO I =1,6
      DRAWS(I,F,IND) = 0
      END DO
      GO TO 60
      END IF
      END IF

      IF (SCHCST.GT.FUNDS) THEN
      SCHCST = SRCHP*TDRAWS
      GO TO 60
      END IF

      IF (BESTPI.LT.PIMAX) THEN
      DRAWS(SRCHDI,F,IND) = DRAWS(SRCHDI,F,IND) +1
      gtdraw(srchdi,f,ind)= gtdraw(srchdi,f,ind) + 1
      TDRAWS = TDRAWS +1
      BESTPI = PIMAX
      TRYK1 = EXPK1(SRCHDI)
      TRYK2 = EXPK2(SRCHDI)
      TRYL =  EXPL(SRCHDI)
C     IF (TDRAWS.GE.5) GO TO 60
      GO TO 5

C     IF POTENTIAL SEARCH IS NOT PROFITABLE PUT DRAWS =0
      ELSE IF (BESTPI.LE.0) THEN
      DO I = 1,6
      DRAWS(I,F,IND) = 0
      END DO
      SCHCST = 0

      ELSE
      TDRAWS = 0
      DO I = 1,6
      TDRAWS = DRAWS(I,F,IND) + TDRAWS
      END DO
      SCHCST = TDRAWS*SRCHP
      END IF
      W = 1
60    RETURN
      END

```

```
        SUBROUTINE OUTCOM(N,NEWPRO,F,IND,t,HOPE)
        COMMON /SEARCH/ THETA(6,10,0:2),LAMDA(6,10,0:2),
        PHI(6),PATON
        COMMON /SRCHP/ SRCHP(10,0:2)
        COMMON /LEARN/ LEARN(10,0:2)
        common /better/ better(10,0:2)
        COMMON /X/ X(6,10,0:2)
        COMMON /BASIC/ BASIC(10,0:2),BASMAX(0:2)
        COMMON /DRAWS/ DRAWS(6,10,0:2),GTDRAw(6,10,0:2),
        AGGX(10,0:2)
        COMMON /COEFF/SK1(80,10,0:2),SK2(80,10,0:2),
        SL(80,10,0:2),
        1SC(80,10,0:2),EK1(80,10,0:2),EK2(80,10,0:2),
        2EL(80,10,0:2),EC(80,10,0:2)
        REAL LAMDA,NEXTX,LEARN
        INTEGER DRAWS,F,BASIC,gtdraw,COUNT,t
        DIMENSION XMAX(6),PX(6),pass(10,0:2)

C       PATHLP IS EASIER SEARCH FOR A NOW PATENTED NEW BASIC
        PROCESS
        PATHLP = 1
        IF (PATON.EQ.1) THEN
        IF (BETTER(F,IND).GT.0) PATHLP = 1.3
        END IF


C       XMAX IS THE BEST OUTCOME FROM SEARCH FOUND IN EACH
        DIRECTION
        DO 10 I=1,6
        XMAX(I) = 0
        IF (DRAWS(I,F,IND).EQ.0)  GO TO 10
        DO J = 1,DRAWS(I,F,IND)
        VAR = LAMDA(I,F,IND)*LEARN(F,IND)*PATHLP
        NEXTX = G05DBF(VAR) + THETA(I,F,IND)
        IF (NEXTX.GT.XMAX(I)) XMAX(I) = NEXTX
        nextx = 0
        END DO
10      CONTINUE

C       IS XMAX BETTER THAN THE BEST X EXISTING PRIOR TO THE
        SEARCH
C       FOR ALL SEARCH DIRECTIONS IN WHICH CASE NO NEW
        PROCESS IS FOUND?
        COUNT = 0
        NEWPRO = 0
        DO I = 1,6
        IF (XMAX(I).GT.X(I,F,IND)) COUNT = COUNT +1
        END DO
        IF (COUNT.EQ.0) GO TO 20

C       NOW LOOK AT EACH SEARCH DIRECTION IN TURN TO SEE IF
C       IT IS AN IMPROVEMENT.
        DO I=1,6
        IF (XMAX(I).LT.X(I,F,IND)) THEN
        PX(I) = 0
        ELSE
```

```
      PX(I) = (XMAX(I) - X(I,F,IND))/(XMAX(I)+100)
      X(I,F,IND) = XMAX(I)
      END IF
      END DO

C     INCREASE THE NO OF PROCESSES BY 1 AND CALCULATE THE
      NEW COEFFS
      N = N +1
      NEWPRO = 1
      AGGX(F,IND) = 0
      DO 68 I = 1,6
      AGGX(F,IND) = AGGX(F,IND) + X(I,F,IND)
68    CONTINUE

C     THIS DECIDES IF A NEW BASIC PROCESS HAS BEEN FOUND
      if (pass(f,ind).eq.0) pass(f,ind) = 50
      IF (AGGX(F,IND).GT.pass(f,ind)) THEN

      BASIC(F,IND) = BASIC(F,IND) + 1

C     NEED TO ADJUST SEARCH ENVIRONMENT WHEN BASIC
      INCREASES
c     IF (BASIC(F,IND).EQ.6) PASS(F,IND) = 8000000
c     if (ind.eq.0) then
      if (basic(f,ind).eq.2) srchp(f,ind) =
      srchp(f,ind)*4.0
      if (basic(f,ind).eq.3) srchp(f,ind) = srchp(f,ind)*5
      if (basic(f,ind).eq.4) srchp(f,ind) = srchp(f,ind)*8
      IF (BASIC(F,IND).EQ.5) SRCHP(F,IND) =
      srchp(f,ind)*10
      if (basic(f,ind).eq.6) srchp(f,ind) =
      srchp(f,ind)*12
      if (basic(f,ind).eq.7) srchp(f,ind) =
      srchp(f,ind)*14
      if (basic(f,ind).eq.8) srchp(f,ind) =
      srchp(f,ind)*16
c     else if (ind.eq.1) then
c     if (basic(f,ind).eq.2) srchp(f,ind) = 18
c     if (basic(f,ind).eq.3) srchp(f,ind) = 180
c     if (basic(f,ind).eq.4) srchp(f,ind) = 1800
c     IF (BASIC(F,IND).EQ.5) SRCHP(F,IND) = 18000
c     if (basic(f,ind).eq.6) srchp(f,ind) = 60000
c     else if (ind.eq.2) then
c     if (basic(f,ind).eq.2) srchp(f,ind) = 18*1.0
c     if (basic(f,ind).eq.3) srchp(f,ind) = 180*1.0
c     if (basic(f,ind).eq.4) srchp(f,ind) = 1800*1.0
c     IF (BASIC(F,IND).EQ.5) SRCHP(F,IND) = 18000
c     if (basic(f,ind).eq.6) srchp(f,ind) = 60000
c     end if
c     end if

40    write(*,*) F,IND,BASIC(F,IND)

      pass(f,ind) = pass(f,ind) + basic(f,ind)

C     SET SEARCH OUTCOMES BACK TO ZERO
```

```
      DO I = 1,6
      X(I,F,IND) = 0
      gtdraw(i,f,ind) = 0
      END DO

C     THIS SETS THE COEFFICIENTS OF A NEW BASIC PROCESS
      IF (IND.EQ.0) THEN
      if (basic(f,ind).eq.2) then
      EK1(N,F,0) = 1.0*ek1(n-1,f,0)
      EK2(N,F,0) = 1.0*ek2(n-1,f,0)
      EL(N,F,0) = 1.0*el(n-1,f,0)
      ELSE if (basic(f,ind).eq.3) then
      EK1(N,F,0) = 1.0*ek1(n-1,f,0)
      EK2(N,F,0) = 1.0*ek2(n-1,f,0)
      EL(N,F,0) = 1.0*el(n-1,f,0)
      else
      EK1(N,F,0) = ek1(n-1,f,0)
      EK2(N,F,0) = ek2(n-1,f,0)
      EL(N,F,0) = el(n-1,f,0)
      END IF
      else IF (IND.EQ.1) THEN
      if (basic(f,ind).eq.2) then
      EK1(N,F,1) = 1.0*ek1(n-1,f,1)
      EK2(N,F,1) = 1.0*ek2(n-1,f,1)
      EL(N,F,1) = 1.0*el(n-1,f,1)
      ELSE if (basic(f,ind).eq.3) then
      EK1(N,F,1) = 1.0*ek1(n-1,f,1)
      EK2(N,F,1) = 1.0*ek2(n-1,f,1)
      EL(N,F,1) = 1.0*el(n-1,f,1)
      else
      ek1(n,f,1) = ek1(n-1,f,1)
      ek2(n,f,1) = ek1(n-1,f,1)
      el(n,f,1) = ek1(n-1,f,1)
      end if
      ELSE IF (IND.EQ.2) THEN
      if (basic(f,ind).eq.2) then
      EK1(N,F,2) = 1.0*ek1(n-1,f,2)
      EK2(N,F,2) = 1.0*ek2(n-1,f,2)
      EL(N,F,2) = 1.0*el(n-1,f,2)
      else if (basic(f,ind).GE.3) then
      EK1(N,F,2) = 1.0*ek1(n-1,f,2)
      EK2(N,F,2) = 1.0*ek2(n-1,f,2)
      EL(N,F,2) = 1.0*el(n-1,f,2)
      else
      EK1(N,F,2) =ek1(n-1,f,2)
      ek2(n,f,2) = ek2(n-1,f,2)
      el(n,f,2) = el(n-1,f,2)
      end if
      END IF
      ELSE

C     THIS IS OUTCOME OF INCREMENTAL INNOVATION
      EK1(N,F,IND) = EK1(N-1,F,IND)*(1+PX(1)*SIND(PHI(1))
      1- PX(2)*COSD(PHI(2))+PX(3)*SIND(PHI(3))
      -PX(4)*COSD(PHI(4)))
      EK2(N,F,IND) = EK2(N-1,F,IND)*(1 -
```

```
      PX(1)*COSD(PHI(1))
      1 + PX(2)*SIND(PHI(2))+PX(5)*SIND(PHI(5)) -
      PX(6)*COSD(PHI(6)))
      EL(N,F,IND) = EL(N-1,F,IND)*( 1 - PX(3)*COSD(PHI(3))
      1+PX(4)*SIND(PHI(4))-PX(5)*COSD(PHI(5)) +
      PX(6)*SIND(PHI(6)))

C     NOTE NEED TO CHANGE NEXT TWO LINES
c     IF NO INCREMENTAL INNOVATIONS ALLOWED
C     **********************************
c     N = N-1
c     NEWPRO = 0

      END IF
20    CONTINUE
      RETURN
      end


      subroutine concn
      common /share/ share(10,0:2)
      common /conc/ conc1(0:2),conc3(0:2)
      dimension tshar(3,0:2),itop(3,0:2)

C     THIS CALCULATES CONCENTRATION RATIOS
      do ind = 0,2
      do i = 1,3
      tshar(i,ind) = 0
      itop(i,ind) = 0
      end do
      end do

      do 10 ind = 0,2
      do 20 i = 1,3
      if (tshar(1,ind).eq.0) then
      do 30 f = 1,10
      if (tshar(i,ind).lt.share(f,ind)) then
      tshar(1,ind) = share(f,ind)
      itop(1,ind) = f
      end if
30    continue
      go to 20
      end if

      if (tshar(2,ind).eq.0) then
      do 40 f = 1,10
      if (itop(1,ind).eq.f) go to 40
      if (tshar(2,ind).lt.share(f,ind)) then
      tshar(2,ind) = share(f,ind)
      itop(2,ind) = f
      end if
40    continue
      go to 20
      end if

      if (tshar(3,ind).eq.0) then
```

```
      do 50 f = 1,10
      if (itop(1,ind).eq.f) go to 50
      if (itop(2,ind).eq.f) go to 50
      if (tshar(3,ind).lt.share(f,ind)) then
      tshar(3,ind) = share(f,ind)
      end if
   50 continue
      end if
   20 continue
      conc1(ind) = tshar(1,ind)
      conc3(ind) = tshar(1,ind)+tshar(2,ind)+tshar(3,ind)

   10 continue
      return
      end
```