SYSTEM DYNAMICS MODELS IN THE PROCESS OF CORPORATE AND PUBLIC POLICY

Submitted for the degree of Doctor of Philosophy

by

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Only those who have undertaken a doctoral thesis (especially in a social science discipline) when family responsibilities have existed can know of the strain it puts on your partner. I owe an enormous debt of gratitude to Carole, my wife and colleague, who has endured my extremely unsocial working hours and limited contribution on the domestic front, particularly whilst I have edged this thesis towards its final completion over these past two years.

The material contained herein was formatted using the Software Tools text processing software available on the PR1ME computers at the University of Salford and output on a Qume laser printer using an 'Elite' font. I am exceedingly grateful to Wendy Steers and Fiona Lowndes for keying in the first three chapters once they had deciphered the text from my handwritten scribblings. I had handled the final two chapters myself earlier on and it taught me nothing other than that I should learn to touch type.

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Chapter 4 of this thesis describes a model to support public policy in respect of the AIDS epidemic. The work has been developed in association with a colleague, Carole Roberts, and a number of publications have resulted. The University's PhD regulations require me to state the extent of my contribution in the case of joint work. In terms of detailed model development I have been primarily responsible for the base model, the variable infectivity model and the optimisation experiments, although the division of labour has rarely been starkly dichotomous. Regardless of originator, I take full responsibility for all the material submitted as chapter 4.

ABSTRACT

The thesis is a contribution to the literature on policymaking in business and government. By a critical examination of relevant published work in the field and by specific examples it seeks to demonstrate how the system dynamics modelling methodology can contribute to an improvement in the process of corporate and public policy design.

It is argued that the relative lack of use of models in the policy process may now be reversed. This is, in part, because of the development of user-friendly interactive modelling software on personal computers together with large screen colour projection facilities. But the most important stimulus to the fulfilment of the potential of modelling work in these areas will come with a realisation by policy makers of the proper role of the model in the overall process. This is a central tenet of the thesis: the model provides a fulcrum for debate and enhanced understanding and should never be viewed as an 'answer generator'. All too often miscasting models in this latter role has, in the author's view, seriously affected their adoption at the strategic policy level.

Three specific examples are used to support the above line of argument. These are concerned with:

(i) Technology policy and planning in the steel industry. A model is devised which addresses the crucial role of the blast furnace in an integrated steel works. The pursuit of economies of scale has led to larger and larger furnaces being installed. Given the often cyclical nature of customer demand for steel, together with forced interruptions to production in order to periodically reline the furnaces, it is argued that larger production units are not necessarily advisable.

(ii) Public policy considerations arising from the AIDS epidemic. The spread of AIDS and the implications of this for health planning has taxed governments worldwide. A model is presented which captures the spread of HIV disease within the U.K. homosexual population and policy issues arising from model runs are discussed. This is in contrast to some other models which attempt to 'forecast' the progress of the epidemic.

(iii) Financial policy in a firm which failed (Laker Airways). This example differs from the other two in that the policy issues surrounding the firm's financial management are directed at students. They are the 'clients' who would want to use this model in order to explore the implications of alternative strategic policies. System dynamics models of a real-life case study can be usefully harnessed in such a pedagogic role.

"One cannot teach a man anything.

One can only enable him to learn from within himself."

Galileo.

"I know that history at all times draws

The strangest consequence from remotest cause."

T.S. Eliot.

1 MODELS AND THE POLICY PROCESS

1.1 Introduction

This is a thesis about policy. It examines the process of policy making in business and government along with the role which formal mathematical models, and System Dynamics models in particular, have played in contributing to that process. The premise is that strategic policy models will never play a more significant role in the future unless a fuller understanding of the precise nature of their role is more widespread amongst senior management and civil servants.

Thus far, especially on this side of the Atlantic, the role of models in the policy process has been negligible which, in some ways, is rather surprising. Directors of large private-sector firms and senior civil servants and ministers are responsible for managing overtly complex, highly non-linear systems. Yet they seem prepared to discharge this task largely without recourse to methods and techniques which may augment their native wisdom. They prefer to verbalise with their immediate colleagues. Interaction with a human executive appears to be safer (and possibly less stressful) than interaction with an electronic one.

Nonetheless the objective advanced by this thesis is not an extravagant one. It is nothing more than a coherent plea for a slight shift in attitude on the part of those whose job it is to formulate policy. Having to wait, possibly two decades or more, for the boardrooms and ministerial committee rooms to become populated by a majority of individuals who are relaxed in terms of submitting themselves to a dialogue with a policy model is perhaps one view of the way things might evolve. But valuable time is lost in this way. If the System Dynamics modelling community feel they can lay claim to a methodology which is possibly the *only* one in the management scientist's armoury capable of generating insight into the workings of complex economic, corporate and societal systems then they should be prepared unstintingly to sell that methodology. This research offers what the author considers to be the best way of going about the task of selling it. If policy makers can be persuaded to fully understand the role and function of a System Dynamics model then they may become more open-minded in their attitude to such models. Rather than wait while today's business graduates reach senior positions, effective promulgation of System Dynamics policy models *now* might offer much earlier rewards.

In the light of the foregoing, therefore, it should be clear that the work reported is as much a statement concerning the proper role for a System Dynamics model as it is a statement about specific applications to policy issues in the private and public sectors. Nonetheless three such examples are included: on technology policy in the UK steel industry (chapters 2 and 3), on policy issues stemming from an epidemiological model of the spread of HIV/AIDS (chapter 4) and, finally, pedagogic lessons from a study of corporate financial collapse (chapter 5).

The thesis does not attempt in any way to describe the basis of System Dynamics modelling. It is assumed that the reader is reasonably familiar with the method and will therefore understand the material in chapters 3 to 5. Various accounts of the methodology are available. These include books by Forrester (1968), Coyle (1977), Roberts et al (1983), a paper by Sahin (1980) and, most recently, a book by Wolstenholme (1990). Additionally, Wolstenholme (1982) and Wolstenholme and Coyle (1983) emphasise the strengths of the methodology in purely qualitative modelling, a feature some systems practitioners had lost sight of.

1.2 Strategic planning and the use of models

The salient objective of this thesis is to promote policy models. In order to provide a perspective from which to assess this objective it will be helpful initially to examine reported accounts of the extent to which modelling has been adopted at the strategic level.

This review is confined to methods which are strictly associated with modelling at a strategic level of aggregation and some form of deterministic simulation model is normally employed for such purposes. By implication this means that Operational Research type optimising models (specifically mathematical programming) are excluded because these are not obviously *time-based* models. While it is conceded that large corporate-wide linear programming models have been built which involve time as one of the variable and coefficient subscripts, these models fall into the category of answer generators and are not most obviously useful for aiding policy analysis in the sense portrayed in this thesis.

A study commonly referred to is that by Grinyer and Wooller (1975). Their exercise was repeated later (1978) and the results compared. In the earlier survey they studied 65 companies with corporate models. They estimated from their research that about 9% of the largest UK companies already had or were developing such models. By 1978 the authors quoted 'a veritable explosion of corporate modelling and the figure is probably now in excess of 50% (of the top 1000 companies)'. They also attempted to discover whether companies found modelling to be advantageous in the sense of whether the benefits exceeded the costs. A total of 55% of the sample were very positive on this aspect implying "successful" models, a further 18% were fairly positive ("partly successful").

In a study carried out in the U.S.A. Naylor and Schauland (1976) reported that of 346 corporations who responded to their survey of corporate modelling activities, 73% were either using or developing such a model and a further 15% were planning to develop a model.

Higgins and Finn (1977a) surveyed 56 British organisations using a postal questionnaire mainly, although this was backed up by interviews in selected cases. Sixty per cent of respondents reported possessing either a financial or a corporate model. A comparison of the results of this and the Naylor and Schauland survey (extracted from Higgins (1985a)) is presented below.

Use	Naylor/Schauland Survey (%)	Higgins/Finn Survey (%)
Evaluation of policy alternatives	79	63
Financial projections	75	88
Long-term planning	73	81
(Analysis for) decision making	58	44
Short-term planning	56	38
Preparation of (financial) reports	47	44

Table 1.1 Uses of corporate models: a comparison from two surveys

While a healthy percentage report the use of strategic models for the "evaluation of policy alternatives" and in general the adoption of "corporate modelling" is quite high across all the surveys, it is difficult to disagree with an inference that the models concerned are primarily financial. Indeed Higgins (1985b) asserts that models using deterministic financial simulation were the most common ones in use for corporate modelling. In their results reporting the principal model users Higgins and Finn quote over 70% in use by accountants, 53% in use by planners and 59% in use by directors. In addition the Naylor and Schauland survey reports the most popular areas of application were cash flow analysis, financial forecasting, balance sheet projections, financial analysis, profit planning and budgeting.

In the results from the Higgins and Finn survey, the emphasis on 'plans' was quite marked. Mention was made of "making better plans" or "being able to plan in more detail" as a result of having a corporate model. By contrast no mention was made of managerial learning or improved understanding as a benefit. This buttresses the conclusion that little use is made of the sort of corporate models which are the subject of this thesis. Most emphasis seems to be on those models which lend themselves to the production of formal print-outs which then pass as the 'Corporate Plan'.

In a follow-up article to their earlier one in the same journal, Higgins and Finn (1977b) report on future possibilities for corporate modelling and these seem quite encouraging. Asked if they would use a corporate model to try out strategic decisions, 46% of their respondents said they definitely would while a further 22% said they might. So just over two-thirds of the sample had positive attitudes towards the utility of corporate models. An even larger proportion (75%) answered 'yes' to the question "would you personally authorise the building of a corporate model, given the availability of resources, if your company did not possess one?". The split of the 75% comprised 59% who had had some experience in the use of corporate models and a further 16% with none.

It is clear from the results of this survey that there is a reservoir of goodwill towards the idea of using a corporate model, which must be encouraging for the proponents of system dynamics models in a strategic policy support role. Although this type of 'corporate model' is quite different to the type implied by the Higgins and Finn survey, it is to be hoped that the goodwill has lasted to the present day when the potential for the use of system dynamics models is that much greater, not least because of the recent implementations of software for system dynamics on microcomputers.

The bias of corporate models towards the finance and accounting function is corroborated by a later survey undertaken by Higgins and Opdebeeck (1984). Although the survey was principally addressing the use of microcomputers, the information was collected from 106 senior finance executives. Forty-six companies responded and almost without exception the model application was overtly financial. While this surely does not mean that only financial executives are involved with modelling, the fact that this category were targetted by the survey authors possibly implies that they did not expect much use of corporate modelling on a microcomputer *outside of* the financial area. An update of this entire area of corporate modelling can be found in Shim and McGlade (1984).

One insight derived from these surveys is particularly pertinent. It is clear that for directors, senior executives and (in the public policy arena) ministers, money is virtually the only metric in use. To those who wish to promulgate System Dynamics type models for analysing policy issues in corporate and governmental systems, the message is quite clear: money is the metric which should be used as a performance criterion. It is no coincidence that, in two of the three example models described in later chapters, financial measurements feature strongly. If System Dynamics models are to be more effectively promulgated then, as far as possible, they should employ the language of those to whom the models are directed.

Recent surveys of System Dynamics modelling activity, while not exclusively directed at its use in business and government, have produced only mildly encouraging results. For instance, a survey by Sandra Joy (1988) attempts to assess the state of system dynamics in the United Kingdom. Although it is tempting to criticise an unpublished piece of work such as this, there are nonetheless important messages coming from the survey which she conducted. Its objective was "to assess the potential for the growth of the subject of system dynamics in the U.K.".

Her orientation was clearly the role of system dynamics within the "systems movement" (a more 'academic' orientation) and not an exploration of its pragmatic role in corporate strategic policy making which is the purpose of this thesis. Of the 66 questionnaires she distributed, only 16 were completed by non-academics and, of these, only 3 returned the supplement to the questionnaire specially created for people working in industry. (Analysis of this was duly abandoned.) Whether this indicates a lack of co-operation with academic surveys by those working in industry, an inability to uncover enough contacts in the industrial sector or a reflection of the truth about system dynamics in the UK is not addressed. But the message from the result, taken at face value, is that the majority of practitioners are in the academic sector. Indeed, Joy states that there are only four key practitioners in the UK and they are all in academic institutions!

Her final analysis, though, is encouraging. The use of system dynamics is clearly on an upward trend. Some 70% of respondents thought they were spending more time on system dynamics work than they did 10 years ago and the subject is "definitely increasing in popularity and it is growing".

The survey conducted by Wils (1988) reached some 200 practitioners world-wide but seems to be heavily biased towards members of the System Dynamics Society and workers at academic and government institutions. The survey, prompted by the Dutch Department of Science Policy, like that of Joy makes for interesting reading. Twenty-seven out of fifty-six questionnaires were returned from people in Western Europe. Again there was a marked lack of any mention of system dynamics in use in the private sector which confirms the suspicion that few people in this sector either use system dynamics regularly or are aware of its potential. The picture which must be inferred is that, whenever system dynamics *is* used within a private firm, it is often for a specific one-off project. Industrial practitioners feel no great loyalty to the method. Some academics, on the other hand, are teaching and researching the material regularly and see a continuing involvement with the subject. This is not particularly unexpected but the general inference does indicate that there is extensive opportunity to arouse the interest of managers in the private sector in Western Europe, principally because so few seem to have used it so far!

In the USA on the other hand there is apparently much more extensive use of the method by private sector companies and, by the government, in particular for determining energy policy. Many consultancies have grown up in the Boston area and are experiencing heavy demand for their services in building system dynamics models — for clients all over the country. The demand is not the result of particularly heavy advertising but rather information spread by word of mouth.

It has been stated earlier on in this thesis that the adoption of modelling tools for strategic policy is much more extensive on the other side of the Atlantic and the results from Wils' survey seem to concur with that view (though, curiously, not for Canada where it is said to be 'stagnating'). What is encouraging, however, is the tone of many of the responses made by practitioners of system dynamics. Clearly they see it in the same light as the message of this thesis and the following collection of comments reflects this:

> *"The ability to look at a wide range of scenarios clearly and quickly is becoming of greater importance".*
>
> *"The focus is shifting towards long term, high-tech scenarios and non-equilibrium situations. This provides an opportunity for system dynamics".*
>
> *"System dynamics is for learning more than problem solving".*
>
> *"Practising system dynamics aims at changing people's way of thinking and organisations' ways of behaving, but people and organisations have a great resistance to change".*

Wils own comments in assessing and synthesising the responses he had received are thought-provoking, none more so than the comments surrounding what he calls a 'new realisation' of the practice of management.

> *"The new realisation is that in practice the actual behaviour of managers is mostly controlled by, to a large extent, unconscious mental models. It does not suffice to have the right answers. What matters is to offer managers, in addition, a learning environment in which they are helped:*
>
> *- to observe the differences between actual reality and expected reality;*
>
> *- to interpret the actual reality, so that the right answers are found; and*
>
> *- to experiment and practice the new answers so that these can become integrated in their mental models".*

Wils' report ought to be seen as a catalyst for an agenda which practitioners on this side of the Atlantic should address. They must be prepared to promote the system dynamics method but, more importantly, do so by showing how it can best be employed. It is not sufficient merely to promulgate its technicalities. Unless this is prefaced by an exposition of the most effective way of utilising such a potentially powerful tool, anything that follows is likely to be misunderstood. If such an exposition can be put across to senior managers and civil servants, providing it concentrates on the themes of 'strategic policy-making', 'scenarios' and 'managerial learning' it should excite the curiosity of the intended clientele into wanting to know more about the method. An imminent recession in this country could be a contributory stimulus, for strategic policy issues are quite likely to occupy centre stage in many companies' internal deliberations over the next twelve months or so.

Already, mention has been made of how the appropriate role for system dynamics modelling can be easily miscast by those not thoroughly familiar with the subject. For instance, Naylor (1983) seems to connect the "Limits to Growth" study (Meadows et al, 1972) with forecasting when it was nothing more than a set of global scenarios capable of interpretation only by comparison of one with another. Now there is further evidence in a recent book on strategic policy by Dyson (1990). He correctly draws a distinction between deterministic financial simulation models incorporating only definitional relationships (and, it must be said, devoid of feedback influences) and behavioural simulation models based on system dynamics. However, he fails to make a sufficiently strong connection between the latter type of model and scenarios, which are treated quite separately in his book under a section headed "Assessment of Uncertainty".

His statement that "Corporate modelling and system dynamics models are modelling methods aimed explicitly at providing a formal corporate system model of the organisation" smacks of the all-embracing type of model. No mention is made of addressing specific policy *issues* through system dynamics and moreover the emerging concept of managerial learning does not seem to figure at all. However he certainly confirms the conclusion reached by Sandra Joy with his assertion that, "In recent years there has been a growing interest in the development of behavioural simulation models using ideas of system dynamics".

It is people employed at director (or equivalent) level to which the contents of this thesis are addressed yet there is just no current information available as to the type of models (if any) being used by this specific group. This informational vacuum concerning strategic policy models should be remedied urgently. The present author would now like to see a large survey conducted to investigate the extent of use of *any* type of model to support strategic policy making in business and government. The incipient recession could make such a venture particularly timely. Instead of practitioners, managers and civil servants would be targetted in order to elicit the views of the people who ultimately matter. The various types of model employed would emerge from the results of such a survey along with the extent of use of such models.

Besides the detailed factual information concerning the type of models employed, the survey should elicit senior managers' and directors' *attitudes* to embracing a modelling input in the first place. It would be interesting to know, for instance, if only a handful of system dynamics studies were conducted but they were very well received and led to some change in behaviour whereas a significant number of 'spreadsheet' type models were created but received little support from policy-makers, although the Higgins and Finn (1977b) survey certainly gave some evidence of positive attitudes to the use of such models. To avoid problems of comparability which have bedevilled surveys in the past, perhaps the same survey instrument could be disseminated to firms and government agencies on both sides of the Atlantic.

1.3 Time-based methods for modelling: a review

Within the field of management science there are just a few techniques which come anywhere near to being able to further the development of effective policy analysis. All of these have the characteristic that they are time-based. In their normal mode of use, they portray each constituent variable flowing over time. Because directors and others responsible for strategic policy are forever making mental projections of the effects of their collective policy choices it therefore seems sensible to limit feasible modelling techniques to those which, similarly, project behaviour over time. A consideration of these techniques now follows.

1.3.1 Discrete-event simulation

Few would deny the successes enjoyed by discrete-event simulation in management science. It has been used by many analysts for studies ranging from the design of a float glass line (Marks et al., 1982) to the organisation of a hospital X-ray department (O'Kane, 1981). Its progress is reviewed by Crookes (1982) and the relatively new development of visual interactive modelling is covered by Hurrion (1980) and Hollocks (1983) amongst others.

Unfortunately, discrete-event simulation is of no use for strategic policy studies in organisations. Case studies of problems dealt with by such methods inevitably describe tactical or operational issues and while it is recognised that some operational matters have what might be termed strategic overtones (e.g. the design of a complete new assembly line) these do not relate to strategic *policy-making* in the sense that System Dynamics does, with its emphasis on stability, growth, retrenchment, the reversal of decline or the interaction of an organisation with its economic environment (including competitors).

Discrete event simulation deals with *entities* -- single items such as a product, a machine or an operative -- which are programmed to mimic the real life system that they belong to. They take part in *activities* -- a 'live' state in which something is happening to them or they are doing something, for example an operative working on his machine -- or they are in a 'dead' state called a *queue*, for example an operative resting or awaiting further work. These are all detailed concepts at a low level of aggregation in the organisation, reflecting the bias towards operational issues manifest in discrete event simulation studies of, say, inventory control or queueing and congestion problems. System Dynamics studies are always conducted at a high level of aggregation where individual entities are lost in the blur. Strategic issues do not involve machines or operatives; Boards of Directors are interested only in the total company situation or at least that embracing major product groupings.

To many this may appear self-evident, but the number of texts which couple System Dynamics with discrete-event simulation modelling is not insignificant and it suggests a lack of understanding by some authors of what should be the essential purpose of System Dynamics modelling, a focussed exposition of which is the primary objective of this thesis.

1.3.2 Financial (spreadsheet) modelling

The personal computer revolution has propelled "business modelling" software into prominence and it is likely that few managers or planners have not heard of LOTUS 1-2-3 or EXCEL, to quote just two of the leading examples. While mainframe software for this type of modelling predates the take-up of personal computers (for example, FCS-EPS (EPS Consultants, 1984) which is still very widely used) its rate of adoption has, in all probability, been seriously affected by the PC-based offerings. (FCS-EPS is, however, now available on a PC as MICRO-FCS.) Not that this matters in reviewing its suitability for strategic policy modelling: all such software possesses the same basic underlying principle -- the spreadsheet.

Unlike System Dynamics models, spreadsheet models have no conceptual underpinnings. The variables are entered as numbered rows, either derivable from other variables or read in as data, while time is represented through the columns, which can be lettered in some packages. Perhaps the only underpinning is that accountants have traditionally written out such arrangements on large sheets of paper, with the assistance only of a calculator if one was available!

Spreadsheet models have been rapidly embraced by the accounting profession and it is true that they are almost always used for financial modelling. But they do not really deserve to be described as "business models" or "corporate models" inferring, as this does, some utility for dealing with strategic issues. Admittedly the financial aspects of a firm's operations are very important, but excessive concentration on policy from a purely financial angle can be shortsighted. The language of the accountant is not always the most effective language for strategic planning.

If the ubiquity of the information feedback process is accepted, trying to program such a notion into a spreadsheet model would be fraught with difficulty. Commonly, the first few lines of logic in a typical spreadsheet model include something like the following, using FCS-EPS syntax.

```
10 'VOLUME'
12 'PRICE/UNIT'
14 'REVENUE'=10*12
```

Elsewhere a data file would exist containing what are effectively forecasts of volume and price per unit. This data is exogenous to the model and, therefore, unaffected by what unfolds in the model as time creeps forward. For instance, an increase in labour costs may well force an upward revision of prices; this in turn could seriously affect volume sold. However, volume, being input exogenously, is unaffected by price changes as far as the model is concerned. The required feedback has to be introduced manually by the analyst in the form of "what if?" runs. In other words, separate runs have to be carried out to assess the effect of changes which in a System Dynamics type formulation can be allowed to happen automatically in the model. With the feedback loop as a conceptual framework, the policy levers programmed into the System Dynamics model can be expected to react to endogenously occurring state changes in a manner which accords with the strategic hypothesis that the model aims to represent.

Another example, similar to the above, concerns the area of corporate finance. Strategic policy here often centres on the gearing ratio (the ratio of debt to equity held by the firm). A financial modelling approach would almost invariably regard the gearing ratio as an output measure, yet a highly geared firm is not going to be looked on sympathetically by any merchant bank to whom a request for loan capital was made. Such a request would be all the more likely in a firm saddled with debt, for a high proportion of the cash inflow might be used in making interest payments on earlier loans. Also, the attractiveness of new share issues from a highly geared firm is diminished in line with its standing in the community of potential investors. So in these contexts the gearing ratio is very much an input measure. The influence diagram below captures the essential interrelationships here.

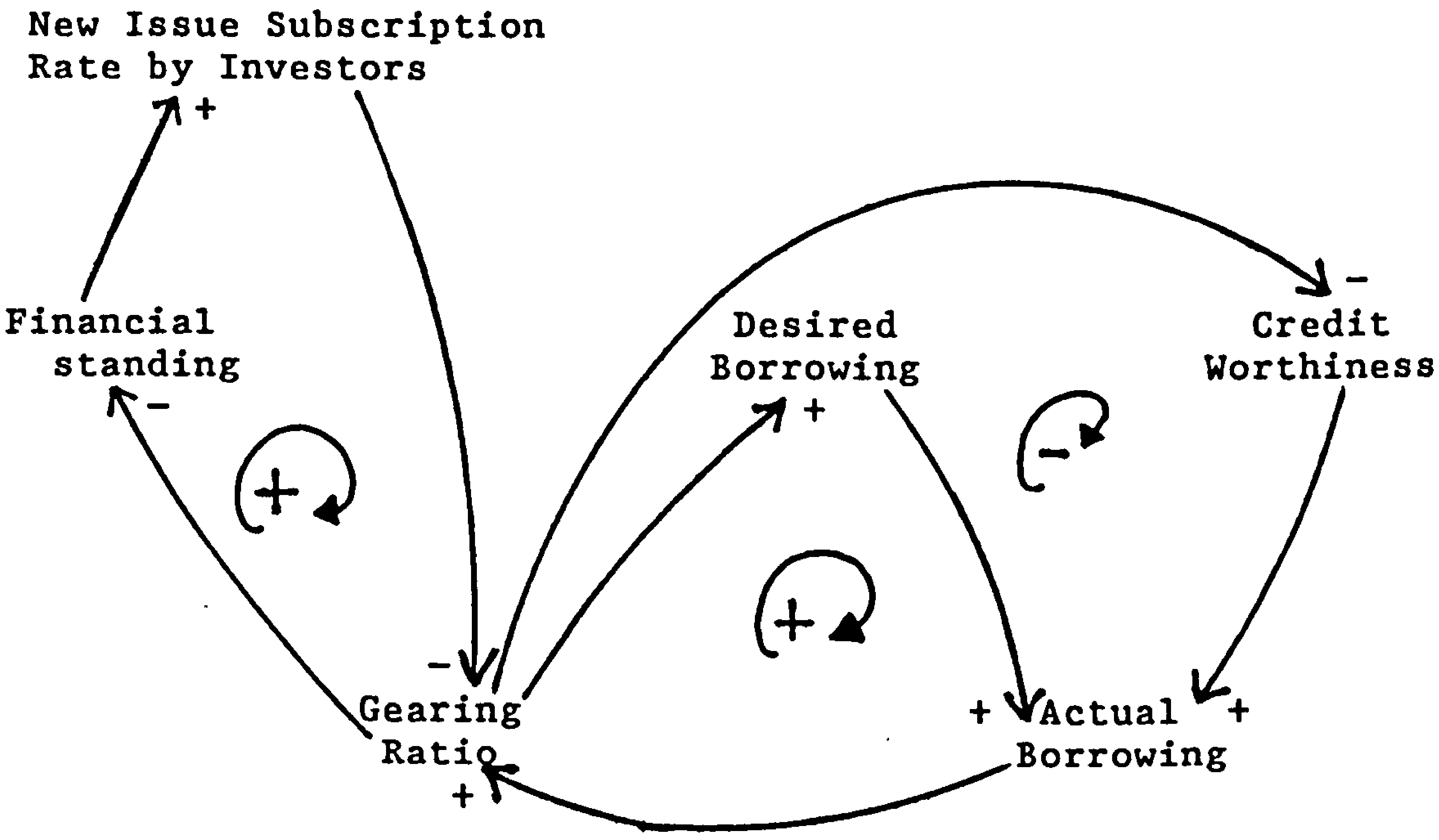

Figure 1.1 Gearing as an input and an output measure

Using TABLE functions, it would be relatively simple to capture these feedback processes in a System Dynamics model, whereas using a spreadsheet it would be extremely difficult, if not impossible, to accomplish. The feedback would have to be introduced manually by the analyst repeat-running the model in "what-if?" mode.

1.3.3 Forecasting

It is probably true to say that, of all the available methods, forecasting enjoys the most frequent use as a tool in the strategic planning process. Indeed, a few authors would go as far as to virtually equate strategic planning with forecasting. At a seminar on quantitative strategic planning held in London (Society for Strategic and Long Range Planning, 1985) a representative of British Airways commented that ordinary least squares (OLS) models tempered by judgement were found to be the most successful in use.

It is difficult to agree with this opinion because, as Eden and Harris (1975) point out, it is a manifestation of support for a rather strange proposition. This proposition is

> *".....that the past states of a single variable in a social system are only a direct function of time rather than related to events associated with a number of variables which occurred at particular times."*

Papers in the forecasting literature by Naylor (1983) and Capon and Hulbert (1985) have examined the relationship between strategic planning and forecasting. In the more recent of the two papers Capon and Hulbert argue that forecasting for strategic planning requires a multi-scenario approach involving a number of "what if?" forecasting runs. This distinguishes it from operational forecasting which is apt to take as given the firm's objectives and strategies. But while a move away from the naive operational forecasting approach is welcome, the thrust is still directed at forecasting -- some form of extrapolation, however crude or sophisticated the chosen approach is.

The purpose of a System Dynamics model is *not* to predict how a system will exist at a particular point of time in the future; its purpose is to ensure the system will do what it was intended to do under *any* circumstances in the future. Many authors do not appreciate this basic feature of System Dynamics models. Even Thomas Naylor (1983), a well-respected American author of texts on corporate simulation modelling, states

> *".......global simulation models, such as those by Jay Forrester and Dennis & Donella Meadows and others, seem to have a certain mystique about them that is independent of their forecasting accuracy or lack thereof".*

With System Dynamics the emphasis switches from forecasting the future to designing policies which are robust enough to insulate the corporate system from environmental shocks and yet allow it to grasp opportunities. While this is easy to say it is far from easy to implement because forecasting (extrapolating) is something almost all firms attempt. Suggesting a firm might drop the practice could well be organisationally unacceptable.

But while it is recognised that it is likely to be unacceptable to recommend that a firm cease to carry on the practice of forecasting, it must be somewhat risky for the same firm to place their trust in the supposition that the past is still a good guide to the future. This may well have been the case in the 1960's and early 1970's but now the economic environment is characterised by sudden discontinuities (Drucker, 1980). It is hardly the setting for effective use of statistical forecasting as an aid to strategic planning and policy design.

The engineering sciences have a long tradition of using dynamic models in technological design studies. Here, System Dynamics type models are the norm not the exception. Admittedly, the approach differs in detail, for engineering models are usually structured more closely to the differential and integral equations involved and the computer languages (e.g. CSMP, ISIS, CSL) used for their solution rely on this feature. Yet these languages are members of the same generic grouping, called Continuous System Simulation Languages (CSSL), to which the System Dynamics simulation languages belong. The basic philosophy of the modelling approach adopted, that of closed loop information feedback, is exactly the same in the version used by the engineering sciences as it is in the version adopted by the management and economic sciences.

One example of an engineering application of a dynamic model is in process control. The control strategy is to determine how to change a control input so that any deviation between desired and actual values of the process output is minimised. In essence, the idea is to keep the process variables at their *set points*. The problem is compounded by the fact that most processes possess inertia or lag: a sudden change in the control input will not result in an equally sudden change in the output.

To be more specific, the example might be from polymerisation control. The temperature in a jacketed reactor is controlled by manipulating the flow of coolant in the jacket. If there was likely to be a sudden change in the temperature, the design features of the plant (determined from the dynamic modelling studies) would accomodate the change and contain it. The notion of not incorporating those design features but of attempting instead to forecast the future temperatures in the reactor is clearly ridiculous but that is, in effect, an analogy of the methods by which many business firms go about their strategic planning.

1.3.4 Macro-economic forecasting

The view contained in this section, that statistically based forecasting procedures are an ineffective means of shaping the ground for strategic policy design, applies equally well at the level of the national economy as it does at the level of the individual corporate group. National economic policy is a central aspect of public policy and economic forecasting attracts significant publicity. Considerable sums are devoted to the maintenance and development of econometric models. For instance, in 1985 the Economic & Social Research Council in the U.K. reported ongoing support for macro-economic modelling research of an amount in excess of £2.6 million (Economic and Social Research Council, 1985). Virtually all of this research concerns the use of econometric models for forecasting the exact numerical values of various critical economic variables such as G.N.P., the balance of payments or the rate of inflation. Here is a perfect example of an over-emphasis on forecasting to the apparent exclusion of research on the structure and workings of the U.K. economy tied to the design of policies which will further its efficiency.

To seek to improve numerical forecasting of performance measures for a system whose complex workings are, at best, ill-understood is seemingly to put the cart before the horse. So as to illustrate this point consider which of the two following statements is likely to be most useful to those directly concerned with the management of the U.K. economy:

* "Earnings inflation is rising and is forecast to be 14% higher in a year's time."

* "The output graph shows that the policy adopted in the educational sector, which has had the effect of cutting-back the rate of flow of skilled recruits for all levels of industry, is subsequently causing overheating in the industrial sector as firms are being forced to pay significant wage and salary increases in order to retain skilled staff. The variable reflecting Trade Union pressure can be seen to be virtually stagnant and so little or no effect on earnings can be attributed from this source."

The latter statement could plausibly emerge from a System Dynamics model of the U.K. economy, which would capture the rich interactions between the flows of people and money, while the former would be that associated with a statistically-based forecasting model. The statement associated with the forecasting exercise is empty of significantly useful content and tends to produce a policy response equally lacking in substance and one which addresses the symptoms and not the cause, for example:

"Prepare the political ground for another incomes policy."

On the other hand, the policy prescription emanating from the systems model might be:

"An urgent investment in the numbers going through further and higher education is necessary so as to increase the rate of flow of well-educated and trained recruits for the industrial sector."

It is not immediately apparent why economists should hold a monopoly on commentary about a country's economic performance and yet the media turn exclusively to that profession when requiring informed comment on the latest economic news in the U.K. Management systems scientists have only themselves to blame about this state of affairs. The lack of a U.K. economic model utilising a paradigm other than econometrics means that no professional group have yet offered an alternative to the econometric models which attract so much publicity. Only two references describing System Dynamics models of the U.K. economy are known to the author (Hobbs, 1981; Tomkins, 1978) and in only the former case does the work seem to have been continued.

For years now, articles in the operational research literature have lamented its lack of impact on strategic issues. This is fair comment, for the practice of O.R. to date can arguably be summed up as concentration on improved decision making to the neglect of policy making. A systems model of the economy which eschewed forecasting as its ultimate purpose and attempted instead to achieve a better understanding of the complex interrelationships in a modern economy would go far towards redressing this imbalance. Statistical macro-economic forecasting rarely aids understanding of the processes at work in the economy. At best such models lack transparency to the (predominantly) laypeople who manage our economy and who desire a better understanding of the workings of the system. At worst econometric models are nothing more than data mining in an effort to push coefficients of determination as near to 1.0 as possible.

1.4 The distinction between policy-making and decision-taking

In a previous section it was pointed out that discrete event simulation methods were not appropriate for policy analysis because they were suited only for looking at the movement of individual items or people in an operational setting. In essence, then, the technique of discrete event simulation is ideal for aiding tactical *decision* making, usually the province of middle managers.

It is necessary to clearly distinguish between *policies* and *decisions* because steering on organisation involves only the former. The material in this thesis is addressed to those at the top of the organisational hierarchy and policy-making is their raison d'etre. The ability with which they discharge their role directly affects the performance of the organisation. While poor decision making can be compensated, poor policy can result in under-performance or even collapse of the enterprise (see chapter 5 on this particular aspect).

It is not always possible to identify a policy as such because it is not written down, it is merely implied by the collective actions of the board of directors. Sometimes, though, policy can be quite specific:

"This firm will refuse additional orders once the unfilled order backlog exceeds X000 units".

In other situations it might have to be deduced from action taken. If, in a situation of declining demand for a firm's major product, finished goods stocks are allowed to climb *before* any moves are made to shed direct labour then clearly the policy is implicit in the action taken. Nonetheless, there is a definite policy choice available here. Output could be tied much more directly to the level of customer demand which might mean greater volatility in the size of the labour force. Allowing finished goods stock levels to vary instead reflects the direction of the policy choice.

A choice between policies is also apparent on the question of the timing of major capital investments. Directors are almost always involved in these issues. They could choose a policy of sanctioning capital investment in times of a business slump, but it seems that few firms are proactive in this respect. Action to procure additional plant and machinery is most often instigated only after it has been shown that existing capacity is fully utilised. This policy choice has implications for the size of order backlogs and the reaction of customers to delivery delays. It can even disturb financial stability if a new investment comes on stream just after the market has experienced a downturn.

A policy can be viewed as an overall framework *within which* individual decisions are taken. Without some sort of policy guidance from senior management, decision making by middle management becomes a set of ad hoc exercises and, occasionally, this will lead to continual 'fire-fighting'.

As examples of policies providing a framework for decision making, consider the following. A consumer goods manufacturer might have a *policy* never to accept orders below a certain total value. So, if a small order comes in from a remote outpost in the Highlands, the order handling department can lose no time (or sleep) in making the *decision* to return it.

The second example illustrates how discretion can be built into policies. Parliament can lay down a *policy* of maximum sentences for certain types of crime. Individual judges can then make a *decision* as to the appropriate sentence for each individual defendant found guilty. This decision would be made in the light of the circumstances of each case.

The department in which the author has conducted this research has a very detailed *policy* for the honours classification of undergraduate degrees. The policy guidelines were drawn up some four years ago in response to an apparent lack of consistency in the treatment of candidates between one year and the next and also across the spectrum of candidates in any one year. While a certain amount of discretion is built in at the margin, it is noticeable that *decisions* about individual candidates are now made much more promptly and with little rancour between examiners than was the case certainly five years ago.

1.5 Desirable characteristics of models used for Policy Analysis

For effective policy analysis in business and government it is posited that the modelling methodology employed should exhibit the following characteristics:

(i) Be capable of providing insights into the workings of complex managerial feedback systems so as to influence the formulation of policy by moderating attitudes.

(ii) Not be seen as an 'answer generator' (the implied label for many Operational Research techniques) but be capable of adopting the role of a fulcrum for informed discussion and debate on policy evaluations. Rather than being convergent it should be the exact opposite. Explorations with the model should highlight unexpected features of the system or inconsistencies which require additional research. By this means policy-makers learn; their mental models are enhanced.

(iii) Be capable of using the nomenclature of the policy makers. Variables should be written down as English text (or by using mnemonics) and Greek or other similarly confusing notation avoided altogether.

(iv) Incorporate associated diagramming tools which allow policy makers to follow the underlying influences captured within model equations.

(v) Allow the inclusion of relationships based on beliefs or judgement. The admissibility of such influences brings a richer variety into the model but implies a revision of attitudes concerning rigour and precision. With many of the judgemental relationships it may not be possible to offer any formal statistical proof of their existence.

(vi) Generate output in the form of time series graph plots with numerical data acting only as a backup when detailed figures are required.

The first two characteristics are vitally important. Most people involved with policy design are extremely senior and often powerful individuals. They are not likely to cherish being told what to do by a computerised strategic planning model. Nor should they. Rarely in complex policy analyses is there an ideal result. Policy choices exist certainly, but a small number of those choices are likely to yield a range of outcomes which involve trade-offs. The role of the model is to aid the policy makers in evaluating such trade-offs. If factions develop around the boardroom table then each faction can use the model as an objective benchmark through which comparative scenarios can be judged. Differing mental models (the source of the conflict) may then be ironed out to yield just one which commands widespread support. An example of a model (not incidentally a system dynamics model) being used in just this way, and in an area as remote from business or government as you could imagine, is recited in the next section.

All of the above characteristics are consonant with a basic maxim concerning the successful use of models in the policy process, namely that the client and the analyst should work *jointly* on the construction of the model. Eden and Harris (1975) suggest that the joint approach

> *"...... becomes more viable the more analysts move away from the concept of optimising models involving sophisticated mathematical techniques to dynamic simulation models such as those associated with system dynamics. A model of a complex system can be easy to depict and develop when it uses constructs that are preceived to relate closely to the real system."*

1.6 To the top of Everest with the aid of a strategy model

One of the most interesting accounts of the way in which a model can be used to clarify thinking about policy and strategy is to be found in an unlikely source. In 1975 Chris Bonnington led an expedition to climb Everest by the South-West face: the hardest route to the summit. That they were successful is now a huge milestone in mountaineering history. In Appendix 2 of a book published a year later, Bonnington (1976) recounts how a computer model had aided his thinking about how to tackle the climb. He was responsible for 18 climbers, 60 sherpas and a large quantity of tentage, food, gas cartridges, oxygen cylinders and climbing gear. It was a formidable logistical problem irrespective of the climb itself.

Bonnington had used the services of Comshare Ltd (a computer time-sharing bureau) prior to an earlier expedition. A climbing friend, Ian McNaught Davis, happened to be managing director of Comshare and so offered the use of one of his staff at that time. Unfortunately the earlier expedition had been put together in something of a rush and full use of the computer model had not been made. However, Bonnington states that....

(the computer model)

> *"had shown me its value as a means, not so much of finding the perfect logistic answer, but one of checking out one's own planning thinking".*

In 1975 rather more use was to be made of a computer model. Stephen Taylor (the Comshare programmer who devised the model) used the APL programming language for the task and by April 1975 was able to visit Bonnington for three days and make final adjustments to the code. During May, and usually working late at night, Bonnington (in the Lake District) would be in telephone contact with Taylor (in the basement of Comshare's London offices) with suggestions to run through the model. Taylor would report back the results and Bonnington suggested further moves. So these 'conversations' with the assembled model progressed. In fact, using the computer Bonnington never reached 'the top', becoming stuck in a logistic bottleneck around the time that Camp 4 was being established.

It is indicative of the role which the model played that the Final Plan, as used by Bonnington, was never actually tested on the model before the expedition left for Katmandu. Taylor describes his reaction to this omission:

> *"I think that this gives a clue to the real benefits of the study. Chris handed me a copy of the Final Solution just before he left, announcing blithely that he'd reconsidered his plans and had come up with a new one. Momentarily, I was appalled. Was he going to reject the results of all the work that we had done?*

> *In fact not. The Final Solution was very much, I think, the child of the work that Chris had put into the study. The process of exploring and testing his ideas on the logistical problems had yielded the insights into the problem that we had originally been aiming for, and as a result of this he was able to construct the strategy that was so successfully employed, confident in his ability to modify it in action. My biggest thrill of the expedition was a card from the mountain reporting that Camp 4 had been established at the same time that Base Camp was cleared -- a point which had been established as critical".*

There is not much which can sensibly be added to the above. As near as possible it portrays the role which it is hoped System Dynamics models will come more and more to play in corporate and public policy.

1.7 Scenario generation and policy modelling

If numerous surveys have yielded results which suggest that most "corporate models" are, in fact, deterministic financial simulation models devoid of any feedback influences (save through the users of such models) yet models can be created which are capable of influencing policy choices, as in the case of Bonnington contemplating on assault on Everest, in what context then are policy models for business and government best presented? To this author a preferred answer is to see policy models as a means of creating one or more *scenarios* which can be used to confront managers' mental models. Unfortunately the literature on scenarios does not always relate their generation to the building of computer models. (See for example, Godet (1987).) A synthesis of the two is a primary goal of this section of the thesis. It is posited that scenario generation is a niche into which policy models of the System Dynamics type fit quite happily.

Scenario is a term claimed to be coined first by Herman Kahn. In a book published in 1979 (Kahn, 1979) he asserts that the term was used first in this sense by himself and fellow researchers at the RAND Corporation in the USA in the late 1950's. The term was thought to be apt because it deglamourised the projection being outlined. They would say, "remember it's only a scenario". This seems extremely sensible and in keeping with the theme of this thesis. Policy makers exposed to models capable of projecting one view of the future should appreciate such tools for what they are, namely distillations of the real world which do not lay claim to embracing the ultimate truth.

Scenarios must be distinguished from forecasts (Godet, 1987). As noted by Schnaars (1987) a scenario provides a more qualitative and contextual description of how the present will evolve into the future. A scenario does not seek numerical precision. It is one possible view of the future which, if generated by a System Dynamics model, is more a product of the structure of the system and its constituent delays than a function of model parameter values.

The style of policy modelling advocated herein emphasises a continuing interaction with the model. Comparisons are made across possible futures, each reflected in a separate run of the model; no attempt is made to produce sophisticated measurement of the variables of interest in *absolute* terms. Projections *relative to one another* are what matter in this context, as is stressed by, for example, Chandler and Cockle (1982).

Multiple scenarios would be considered and evaluated. All would be possible futures for the system but none would be assured. Rather than trying to predict what *will* happen in *the* future a System Dynamics model should aid contemplation of what *might* happen in *any feasible* future. Within the model (and its policy derivatives) futures are not merely some mathematical manipulation of past data but must be seen as the confluence of many forces: past, present and future. This is how Schnaars (1987) sees scenarios and coincidentally how System Dynamics models evolve a behaviour mode through time.

Huss and Honton (1987), in their contribution to the burgeoning literature on scenarios in business, describe three different approaches to scenario generation. These are intuitive logics, trend-impact analysis and cross-impact analysis. Each method is associated with an organisation which makes available its services on a commercial basis. All three of them are in the USA. A visibly shortened description of each method now follows.

Intuitive logics forms the basis of the way in which the Royal Dutch/Shell Group use scenarios and this empirical application by the Shell Group is described later. The method posits that policies are based on a complex set of relationships among economic, political, technological, social, resource and environmental factors. Most of these factors are external to a company but need to be understood to provide insights. Some of the variables involved are precise, quantitative measures and are predictable. (An example here is demographics.) Others, however, are imprecise, qualitative and much less predictable, for example consumer attitudes, life style and product demand.

A major step in the method involves the definition of 'scenario logics' which are organising themes, principles or assumptions that provide each scenario with a 'coherent, consistent and plausible logical underpinning' (Huss and Honton, 1987). These logics are not necessarily meant to cover every distinct possibility. They are not the logical underpinnings for optimistic/pessimistic scenarios or high, medium and low postulates. Instead they describe alternative futures such as a regulated versus a de-regulated market. Because both opportunities as well as threats are considered, they cannot be viewed as either exclusively optimistic or pessimistic.

The latter stages of the method involve combination of the scenario logics with the (earlier) environmental analyses. It would be at this stage that a System Dynamics model would assert its value. The model would be able to combine the scenario logics with environmental aspects so as to allow time-based futures to evolve. Here would be starkly visible the detailed implications for policy actions. The Directors would have both a time-phased sequence and a portrayal of the degree of concern. Food for thought surrounding When? and How Bad? (threat) and When? and How Good? (opportunity) would be offered.

Trend-impact analysis (Becker, 1983) on the other hand relies on a formal forecast of the key indicator (dependent) variable. This is then adjusted based on the occurrence of impacting events. Probabilities have to be established of both the timing and the extent of these impacting events, including years to first impact, years to maximum impact, level of maximum impact, years to steady state impact, level of steady state impact and so on.

It is at the stage of modifying the extrapolation that System Dynamics models would be of use. It might be possible to design policies which offer a defence or an encouragement to impacting influences irrespective of the timing and the extent of their occurrence.

The use of a formal means of making the initial projection also features in the method of cross-impact analysis. (In fact, both this method and the trend-impact method can be distinguished from the intuitive logics approach because of the use made of formal statistical or econometric forecasting methods at an early stage in the analysis.) A formal forecast for a set of key indicators (for example number of imported vehicles, size of the Public Sector Borrowing Requirement) is carried out. Following this attempts are made to identify possible future events which might significantly affect one or more of the key indicators. Interviews with experts and literature searches would be adopted towards this end.

The feature which distinguishes cross-impact analysis from trend-impact analysis is that the former allows an assessment of the way impact events may affect other impact events in addition to affecting the key indicators. Cross-impact matrices are drawn up and an indication entered in each cell of the extent to which (using an arbitrary index scale) the occurrence of the column state would change the probability (previously) assigned to the occurrence of the row state.

All this information is taken account of by specially written computer software which then produces multiple projections covering consistent sets of impact events, that is those particular combinations which will most likely occur together. With more and more computer runs conducted, a range of possible future paths for each indicator variable is created.

Now it must be appreciated that these future paths (scenarios) are nothing more than projections of the behaviour of environmental influences. In certain circumstances these paths themselves may be created, not by the sort of simplistic model implied by the previous paragraph, but by a System Dynamics model. One example here would be utilisation of the M.I.T. National Model of the U.S. economy (Forrester, 1989) to create scenarios which would form the input to a corporate strategic policy model. As noted by Becker (1983) the costs of creating large 'environmental' models purely for the generation of scenarios, to be used as inputs to policy models or debates, are largely prohibitive for any organisation. It does imply, however, that there is likely to be a ready commercial market for economic environmental model outputs. Indeed, this has already started in the UK where London Business School and the Henley Forecasting Centre (amongst others) market the results of their econometric model projections.

So it is clear then that the descriptions of scenario generation in the literature concentrate on environmental influences. They are a more sophisticated means of determining the likely form to be taken by the exogenous factors affecting a corporate or governmental system. However, it is readily admitted by proponents of scenario analysis that the next step is a particularly crucial one: how these scenarios are going to impact on the strategic policy choices of the organisation concerned. This is one important aspect of scenarios developed by Leemhuis (1985).

To further the discussion it would be useful at this point to introduce a discriminating terminology. It is posited that scenarios should be conceptualised separately as external scenarios or internal scenarios. The former relates to the understanding of scenarios which is mirrored in the general body of literature on the subject. As described above, this sees a scenario are being basically a projection of some facet of the system's environment. The projection is created using a systematic approach and by no means can it be considered a mere extrapolation. As has been indicated above, the extrapolation element is just the starting point for the formulation of an external scenario. Impacts against that extrapolation are then considered.

An internal scenario, on the other hand, is one which projects possible consequences of alternative policies adopted by the organisation. It can be viewed as a conjunction between candidate policies and the possible futures being offered by the external scenarios. In some situations the chosen policies may be adopted as a direct consequence of the specific external scenarios. External scenario generation is a logically prior activity to consideration of internal (policy) scenarios. Millett (1988) uses the term 'cascading scenarios' (although in his case not quite in the same context) and this is an apt way of thinking about the two processes.

A niche for System Dynamics modelling activity is in the creation of internal scenarios. If an external scenario(s) has been made beforehand then this would be used as an exogenous input to the model but it is not absolutely necessary for this particular procedure to be adopted.

For instance, there is no evidence that Bonnington, in considering his policy choices on Everest, specifically input, say, an avalanche descending on camp 2 or a violent storm breaking out just as some of the team reached the summit (although both these events did, in fact, take place).

At this point, therefore, it is appropriate to recount examples of the use of System Dynamics models in the context of scenario generation in business. While it might be expected that the vast majority of these accounts relate to internal scenarios, in fact two relate to external scenarios and these are considered first. It is recognised, however, that the classification of individual examples into either external or internal scenarios is not easy. Some of the documented examples address both.

In sum they amount to little more than a handful, covering mainly United Kingdom and Western European blue chip companies. It is a rather sad testimony that the present author has not been able to uncover many more examples of the use of system dynamics and similar models for assisting the policy-making process. There are other occasional examples but it is only those recorded below which are felt to properly reflect the utility of the method at the top (policy level) of the organisation. If the message of this thesis is adequately promulgated then it is to be hoped that by the year 2000 there will be very many more case histories which could be cited.

1.7.1 Applications of System Dynamics models for external scenarios

ICI use System Dynamics in their Planning Department in London. A macro-economic model has been built using this methodology. A early version was described by Hobbs (1981). It was developed in response to a need for corporate managers to better understand the economic environment in which they were operating. This need has grown in intensity since the mid 1970's because of the increasing turbulence in the economy. Large econometric forecasting models are technically opaque and have little value as tools in the promotion of understanding and improvement of communication. Numerate economists may understand them but it is unlikely that corporate managers would.

The model is structured into six sectors: households, trading companies, government, financial managers, banks and overseas. It is directed towards an understanding of the mechanisms at work during the business cycle of between four and five years duration. Therefore its time horizon is no more than ten years with the emphasis being on the next five. Of particular interest in respect of System Dynamics is the fact that the model is not merely a means of simulating the National Accounts. Econometric models need past data in order to allow estimation of their coefficients and, as such, include only those variables for which data is available in the National Accounts. However, within the economy there are forces at work, such as lead times and 'business confidence', which should be properly included in any national economic model. The System Dynamics method does not prohibit inclusion of certain model variables merely because of the absence of time series data for those variables.

Pink (1988) in a recent review of the work of the Planning Department at ICI remarks that the time horizon in the macro-economic model has been extended because the initial model now incorporates a 'Futures' capability. This projects social and technical trends with the objective of raising eyes collectively beyond current horizons to try to spot changes and even discontinuities in markets and technology. Pink states,

> *".....(the model) encourages use of this insight in identifying threats to existing business and also new opportunities of high potential".*

Naylor (1986) describes how the management consultancy firm PA Computers and Telecommunications (PACTEL) used the methods of System Dynamics to create scenarios for the development of non-voice communications over a ten year period. The study was commissioned by the Eurodata Foundation on behalf of European telecommunications authorities. It involved developing scenarios for each of the 14 countries involved. The scenarios encompassed the current position for each national authority and then considered the likely future developments in telecommunications. In other words they were quantitative pictures of the future. The scenarios were internally consistent and, what is more, reachable by a feasible path from the present day. Their scope encompassed technology, competition, services and user demand, concentrating solely on business communications.

Part of the model development involved the construction of influence diagrams and Naylor had this to say on the effectiveness of this particular tool:

> *"Influence diagramming proved to be a very successful way of describing complex relationships and providing a means of communication between the manager's view of the world and that of the expert analyst. The diagrams also proved to be a useful analytical tool, highlighting exogenous variables and allowing inferences to be drawn about expected chains of cause and effect".*

The relative utility of an influence diagram as a tool of system enquiry *in its own right* had previously been commented on by Wolstenholme (1982). Whilst not denying that the influence diagramming technique is often the prelude to a full computer simulation study (such as that subsequently conducted by Naylor), Wolstenholme notes how the technique can "facilitate identification of critical factors or restrictions and leverage points where the biggest impact on performance might be achieved" and "... in multiple ownership situations (can be) used to demonstrate to the owners of system subsectors how their respective policies interact with one another". Given Naylor's comment on the tool as a means of communication, Wolstenholme's concluding remark on multiple ownership situations, "This (the influence diagram) is particularly useful in comparing individual perceptions of systems and enhancing communication and compromise", is quite apposite.

The objective of the PACTEL study was not merely to provide scenarios for each of the telecommunication authorities but to provide also the model from which these scenarios could be generated. This model could then be used by planners and policy-makers *within* each of the national authorities as a means of providing an input to their own internal planning models.

Baets (1987), who describes corporate strategic planning within the Belgian telephone company (RTT), is an example of one such planner. His company used the PACTEL model not only directly but also to provide an exogenous framework for an econometric model (BLIKSIM) which is employed for the elaboration of alternative strategic options.

1.7.2 Applications of System Dynamics models for internal scenarios

Coincidentally the first case study to be considered in this section is also within the telecommunications industry. Probert (1982) describes the development of a large strategic planning and policy model for British Telecom. It first became operational in 1978 and by 1982 was in fairly wide use inside the company. The author notes how a colour graphics interface, developed at a late stage in the overall project, succeeded in rendering the model far more acceptable to senior managers than had been the case beforehand. Through this interface it appears that the modelling team have broken down artificial barriers between the model and the users. Probert notes (in keeping with the theme of this thesis):

> *"We now try to convey the idea that dynamic models should be viewed merely as alternative forms of information and subsequent insight rather than as the corporate 'oracle' which necessarily represents any absolute truth".*

The model consists of four modules: Marketing, Technology, Personnel and Finance. Spread over these areas are around 300 policy parameters available to the user, who might typically alter ten parameters prior to a 30 year run to generate another specific scenario. The sort of issues which can be tackled are:

"What scope is there for the development of video services such as cable TV and viewphones?"

"What are the benefits of mounting an 'all-out' attack on a market immediately after launch?"

"What are the ideal tariff differentials between advanced and basic services?"

Morecroft (1984) gives a description of the use of a strategy support model for a supplier of advanced office equipment. (It could be argued that the term 'strategy support' -- apparently coined by Alan Graham at M.I.T. -- could be more appropriately replaced by 'policy support' since the latter is free of overtones of 'marketing' and 'competition'.) Morecroft experienced many of the same enthusiastic reactions reported by Probert in respect of the graphically-based outputs. The model is used in exactly the same dialectic role as the British Telecom model -- to offer another viewpoint, to confront the opinions of senior management and to mobilise their perceptions. Morecroft notes that there is no direct operational impact with such a model. It exists as an insight generator (not an answer generator) and as such does not get implemented in the same sense as many Operational Research models are. Further, if a specific strategic recommendation does flow from the model, it will have to pass through the usual communication and administrative channels so as to be fleshed out into the detail needed to state precisely how it is to be converted into specific operating procedures.

On the dialectic role of the model, Morecroft states:

> *"A most natural extension of the dialectic method is the introduction of a formal model into the discussion with which to temper the prevailing opinions. In the standard dialectic method, debate and discussion draw on opinion from the 'mental models' of a management team. A formal model merely adds another viewpoint, which, though perhaps more carefully formulated, is nevertheless an opinion.*
>
> *To be effective, the model must be seen as a vehicle for extending argument and debate -- quite different from the customary role of models. The model must be brought down from the pedestal of the infallible black box (where it is often ignored) to occupy a more modest position as a complement to the thinking and deducing powers of management. The model must be seen as a generator of opinions, not answers. Executives must be encouraged to challenge and debate model conclusions, and members*

> *of the modelling team must be capable of engaging in executive, non-technical argument".*

It is claimed that the model did indeed produce certain insights which the management team had not previously realised. For instance, a reduction in the sales force employed to market the advanced office equipment concerned caused a loss of sales effort far greater than could be explained by the smaller number of individual salesmen. Further scenario runs suggested that what was happening was that the revenue-generating base of customers not yet supplied with the firm's product was being eroded by the actions of competitors. This erosion was making it more difficult for the sales team to repeat past revenue performances and this led to demotivation and lowered productivity. If a reduction of the sales team was added into the model then it was observed that the original downward trend was amplified since the maintenance of overall performance by the remaining members of the sales team was rendered even more difficult.

Another insight concerned additions to the sales force and the consequent effect on market share. As more salesmen were added to the team, customers converted much sooner to the new technology office equipment offered by this *and other* firms. This is the natural result of the salesmen doing their jobs properly. However, it could not be guaranteed that all customers would ultimately select the firm's (rather than a competitor's) product. Inevitably some would go to the competition with the unavoidable consequence for market share.

The final case study concerns the evolution of the use of scenarios by the Royal Dutch/Shell company referred to earlier. Although formal computer models were not part of their policy-making process when scenario planning was first introduced, they now contribute to the enhancement of managerial learning, just as Bonnington experienced by confronting the model created prior to the successful Everest expedition. This initiative with modelling was taken by the Group Planning department.

The account in this section does not dwell on any one specific policy application by Group Planning (for the source material concerned does not describe any model in detail) but that is not a sufficient reason to exclude an account of the progress towards dynamic modelling for policy planning by one of the world's major companies. On the other hand, a description of the adoption of the method by Shell's Business Consultancy department, mentioned later, does include some specific applications.

Shell introduced scenario planning on an experimental basis in 1971 (Lorenz, 1980a; 1980b). It had been initiated as a direct consequence of collective unease about 'planning by forecasting' which had been the ethos in the company in the sixties. There was a growing feeling in the Planning Department that the next ten years or more were going to be characterised by extreme turbulence. A single line 'forecast' would not be sufficient. Beck (1982) offers an early exposition of Shell's disenchantment with forecasting which he describes as "providing the equivalent of a straight line route through a minefield".

Beck makes a number of poignant comparisons between forecasts and scenarios. From amongst the many it is possible to extract three of these:

> *"A forecast stands alone, to be considered, accepted or rejected on its own. A scenario is designed to be considered in conjunction with other scenarios; it is valueless on its own".*
>
> *"A forecast is intended to be regarded as an authoritative statement. A scenario is intended to be regarded as a tool to assist understanding -- as a backdrop to the decision-making process, rather than as an integral part of the decision itself".*
>
> *"Forecasts are based on the belief that the future can be measured and controlled. Scenarios are based on the belief that it can not".*

Whereas the initial use of scenarios in Shell concerned global viewpoints ten to fifteen years into the future, their use has spawned additional scenario planning that concerns, firstly, the forces at work over the medium-term business cycle of 4-5 years and, secondly, scenarios for individual 'local' business sectors and operating companies (Financial Times, 1980). (For example, Galer and Kasper (1982) describe how scenarios were developed to aid policy-making in Shell's Australian operations.) It is these two latter approaches to scenario based planning from which the evolution to computer models seems to have occurred.

Wack (1985a, 1985b) charts in some depth the use of scenarios in Shell, taking up the story started by Beck. It is in his articles that the reader can discern how Shell latched on to System Dynamics models specifically. Wack talks of "changing the decision makers' assumptions about how the world works and compelling them to reorganise their mental model of reality". He also speaks of "exposing and invalidating an obsolete world-view" and planners needing to "link the new realities of the outside world to the managers' microcosm".

Further reasons for a steady progression towards utilising System Dynamics must surely revolve around the 'intuitive logics' approach to scenarios, discussed earlier on, and which Shell subscribe to. In addition there is the mode of presentation of the results. Intuitive logics as a method can be viewed as the equivalent of a manually designed and operated System Dynamics model. In using the intuitive logics approach there is a need to design an internally consistent and coherent network of possible effects which are intuitively extrapolated to yield various time-series based scenario projections. So the consonance with the System Dynamics method exists even down to time series graphs being a major component of output. The limitation of the manual approach is in handling the interactions and, in particular, the feedback effects. Seen in this context it is easy to appreciate why Shell moved on to computer models which, as near as possible, captured the spirit of their own brand of scenario generation for policy making.

The introduction of computer models into Shell's planning process is documented by De Geus (1988) who has written a recent instalment of their progress in planning. He talks of managers needing to become adaptive, in short to learn about the complex systems of which they are a part. The caption above the title of the article says it all: *"At Shell, planning means changing minds, not making plans"*.

De Geus notes that in his experience it can take some 12 to 18 months for a received signal to be acted upon. It takes this long for the manager's mental models to develop a few new hooks and for them to start responding meaningfully to the stimulus. Obviously, therefore, the question must be asked as to how institutional learning can be accelerated. De Geus sets out to describe how computer models are quite appropriate for this task, a task which is central to effective planning. Only managers have the power to act so the planner's role should not be to try and engage them into putting their imprimatur onto a formal plan, but rather to get them to think and learn about policy; in other words, to expand the managers' collective mental models by introducing them to a new policy support tool.

Trying to teach senior managers by formal classroom-type methods is manifestly ineffective. De Geus notes that maybe only 25% of what is taught is actually received. At best this might reach 40%. Further, a staff member (planner) cannot walk into a boardroom and start talking about strategy. Such a person would not have authority over the audience. In the normal teaching situation this is resolved because students will acknowledge their teacher's presumed superior understanding. In the case of the most senior managers in a company, notice should be taken of the old Chinese proverb:

I hear and I forget
I see and I remember
I do and I understand.

If managers can be introduced to a computer model *which they themselves manipulate and interact with* then maybe institutional learning will be accelerated. This is what Shell are currently exploring. It derives from considering a System Dynamics model as a 'transitional object' (De Geus, 1988) which can be used to play back and forth manager's mental models. The computer model is assembled to capture the models that exist in the minds of the participating group of senior managers/directors and not the real-world. (It follows from this the model builder should engage in extensive discussions and workshop type sessions before the first equation is even written. It is likely that influence diagramming tools, so useful in the PACTEL study mentioned earlier, would be instrumental in eliciting the mental models of the policy-makers and forging this into a collective one for the group to work with.)

De Geus acknowledges that learning is enhanced whenever senior managers meet to thrash out an issue. However, he goes on to assert that in his experience at Shell the computer model *accelerates* learning. He mentions three reasons for this:

(i) Managers can deal with, at most, three or four variables at a time. By using a computer model a much more interacting set of influences can be simultaneously considered.

(ii) Computer models emphasise how cause and effect can be separated. In creating a desired effect managers should not necessarily look for the most immediate cause, but should seek other trigger points which may be separated in time and place. Conversely, undesirable effects can be shown by a computer model to emerge from seemingly sound policy decisions taken remotely from the immediate cause of concern.

(iii) A computer model can be the vehicle which highlights what the relevant information is which policy makers really need to know. In any large corporate system a great deal of regular information is placed before these important groups of people. But do they really need it all? Conversely, might there not be something which they don't regularly receive but which they should?

By virtue of their interaction with the computer model the planners' individual mental models are enriched and possibly restructured. The quality of debate is on a higher plane than if dialogue were conducted *without* a computer model to organise that debate around. This arises, in addition to the reasons put forward by De Geus, because the model creates additional paths of interaction between the members of the policy-making body.

Within Shell International the developments in effective managerial learning have extended from Group Planning to the Business Consultancy department which, in essence, is Shell's OR department. Lane (1989) documents in detail their adopted consulting philosophy of *"Modelling as Learning"*. He bemoans the modus operandi of 'expert consultancy', the traditional style of consultancy which involves 'experts' being called in who then go away and conduct analyses of some complexity, return and offer the client their 'answer' usually in the form of a thick report which in all probability then gathers dust on a shelf.

What is striking about this classic consultancy approach, argues Lane, is that it is seemingly never applied to top level policy issues which senior management are grappling with. But by following a re-orientation which makes the consultant's role a facilitator rather than an expert, by *involving* members of senior management in the model-building process and, most important of all, using a system dynamics modelling methodology, it is now possible to gain a foothold in the boardroom.

One interesting aspect of Lane's paper is his notion of a trade-off between model size and model transparency. The expert consultancy approach implies that the bigger the model is by definition the better it is. However, the bigger it is the less chance client management will have of understanding it and even less that they will change their behaviour because of it. The answer is to develop relatively small models, in a close alliance with the management team, and which each address a particular issue which is selected for analysis. The key alliance with management is important for they are hardly likely then to summarily reject insights coming out of a model they themselves have played such a significant part in building!

Lane sets out a statement of "Modelling as Learning" and this is reproduced here:

> *"Modelling as Learning is a Shell consultancy process which involves the use of analytical tools in close association with a client. It consists of the capturing of clients' ideas and assumptions and their expression using modelling tools which can be readily understood. The resulting models are not forecasting tools. Rather, they give a client the ability to check the consistency and consequences of a certain set of ideas. They also provide a representation of a business system on which experiments with policy and strategy can be performed. The goal is then to enhance understanding of the issues in the client's mind, to focus discussions and to generate new options and ideas".*

Lane selects four examples to illustrate the Shell philosophy. These cover new product launch, future developments of a natural gas market, a high technology start-up company (which is reviewed in depth in Morecroft, Lane and Viita (1989)) and commodity production and trading. With the possible exception of the new product launch study, which involved assessing the likely actions of a competitor, all the projects reviewed utilised the system dynamics methodology for structuring a debate around a series of *internal* scenarios.

Two interesting vignettes emerged from all this work and which serve to further underline the benefits arising from this style of strategy modelling. Firstly, what the clients considered a highly unlikely scenario emerged in one of the studies. This was 'wrong' only in the sense that the logic operating in the present would not operate in the future. But the message for the clients was that this logic would have to be changed in the next few decades *and they would have to play some part in changing it.* The second interesting feature centred on the model addressing commodity production and trading. Here the model was being used to attempt to resolve a disagreement between two separate functional areas and which was threatening to degenerate into a "Yes it will/No it won't" event. After being exposed to the system dynamics model, one of the two parties acquiesced and were able to reconstruct their mental model of the likely scenario without even conducting confirmatory simulation runs based on the changed assumptions. The consultants, though, did so out of curiosity!

Shell's pioneering work using System Dynamics models to accelerate the corporate learning process, via debate organised around model-generated scenarios, clearly has longer to run. It is heartening that they have allowed so many publications by their personnel and it is to be hoped that a sufficiently detailed description of their future experiences is also forthcoming.

1.8 The Technology supporting policy debate around a model

Having identified various uses of System Dynamics models at the strategic policy level it is clearly necessary to review a little of the infrastructure which supports this particular process of learning. This is the setting for that which Morecroft (1988) calls a *microworld* for policy debate, following Papert (1980). A microworld is an 'incubator for knowledge', a setting in which policy-makers engage in a learning experience through interaction with text, systems diagrams and computer simulations. In the examples reviewed above, the detail included on this facet was sometimes sketchy. However, this section can be considered as offering an opinion on a combination of hardware and software which will facilitate, in conjunction with a System Dynamics model, the policymaking process.

1.8.1 Hardware

For the purposes of eliciting hypotheses and beliefs ingrained in the managers' mental models it is not computer hardware which functions best but a pedagogic piece of hardware -- namely a whiteboard. Lane (1989) notes how an experienced consultant using a whiteboard and working with up to six senior managers can develop an influence (causal loop) diagram which draws out the complexity and the dynamics of the issue under investigation. Such a session would last maybe two to three hours and, if it is going well, the attendees would want to move to the whiteboard to add to or change the diagram. The whiteboard holding the emerging diagram is the focal point and, as such, is indispensable.

This is underlined by Vennix et al (1988) when they describe the conceptualisation of a health care model. Three sub-groups were formed to look at different aspects of the problem in isolation. When they returned for the plenary session their efforts were aggregated on a whiteboard into one influence diagram using different colours to reflect relationships identified by the different groups. On merging the sub-models various feedback loops were created and the consequences of these loops discussed.

In terms of computer hardware, the 'Operations Room' depicted in colour photographs on the inside of the dust cover of Beer's "*Platform for Change*" (1975) is likely to be too intimidating for senior managers and directors. The room described by Beer was set up in Santiago, Chile when he was consulting to the Chilean government in the early 1970's. It included a number of comfortable armchairs incorporating keypads on the arms. Different keystrokes would cause different types of colour display to appear on large screens affixed into the walls of the room. Ministers and government officials could summon up-to-the-minute plots of industrial production and other relevant economic variables. In addition they could evaluate potential policy changes in the light of system dynamics simulations of the future also instigated by a special keypad sequence.

While this is perhaps too clinical, too akin to a laboratory rather than a boardroom, it is undeniable that some form of large-screen colour display is needed if all the people present are expected to contribute to the debate. It is possible to use a device that sits on top of an overhead projector screen. This device can relay information from the computer screen onto the wall-screen directly. Although these systems can be useful in a classroom environment their widespread use is questionable especially since the quality of the image is often not high and also they transmit only in monochrome (although, at the time of writing, colour versions are starting to appear).

Much better are proper RGB projectors which produce a large-screen colour image. These are the mainstay of what are now known in the UK as 'Boardroom Systems', commercially available hardware/software installations used for quality presentation of boardroom information. A good account of such systems is given by Preedy and Bittlestone (1985). In the UK in 1988 three different vendors had boardroom systems on offer commercially. British Airways had developed their own, called AIMS. At present these systems are used only for reporting information in a meaningful way. They do not involve any modelling, either of the firm in question or indeed any policy issue it may be grappling with. This must be the next step, however, and this author sees the integration of system dynamics modelling with boardroom systems as a highly promising (and logical) development in policy support tools.

Sometimes progress in several separate lines of development needs to be fused in order to allow an applied discipline to make a quantum leap forward. Besides the advent of boardroom systems, developments in 'group decision support systems' (Eden and Radford, 1990) seem to offer immense scope for the further promotion of system dynamics models in a policy support role. In fact, boardroom systems would be seen by some as part of the formal achitecture of a group decision support system, something which has been defined by Huber (1984) as "a set of software, hardware and language components and procedures that support a group of people engaged in a decision-related meeting". However, given the precise nature of most group decision support systems, it would be somewhat inappropriate to integrate such processes into a formal board meeting. A more suitable context would be an ad hoc meeting which may be called purely to explore a specific issue, perhaps at a location away from the normal office environment.

In terms of hardware, Ackermann (1990) writing in the Eden and Radford book, sees such an environment as "including a series of terminals or workstations linked together through some form of networking, a large main screen visible to all and controlled by the facilitator, large sheets of paper and a three-colour video projector or large monitor". The large screen display is seen as important because, if each participant had their own display screen together with a capability to control what appeared on it, there would be hardly any interaction between them either verbally or non-verbally.

Further contributions to the volume by Eden and Radford include those by Huxham (1990) and by Hickling (1990). Their chapters explore the advantages and disadvantages of particular types of room layout and of the supporting facilities in those rooms. Here there is less emphasis on the role of the computer itself but rather in the use of whiteboards (in particular photocopying whiteboards) and other non-computing hardware.

1.8.2 Software

The last three years of the decade just ended have seen a remarkable transformation in system dynamics software and this transformation has been made possible by the vastly increased power of microcomputers. Not only are such devices so much more inherently user-friendly, they allow direct control of a graphics image on-screen using standards which have successively improved the resolution and the maximum number of permissible colours.

As long as the use of computers implied a terminal hooked up to a mainframe or minicomputer, an installation to act as a vehicle for assisting policy debate and dialogue was always going to be a rather uncommon sight in corporate offices. Networked links were liable to disruption and in any case the bandwidth of the line was often a limiting factor, predisposing the graphics screen image to be created far too slowly.

Coincidentally and totally independently the three main systems for system dynamics simulation on a personal computer (PC), Professional DYNAMO (Pugh-Roberts Associates, 1986), DYSMAP2 (Dangerfield and Vapenikova, 1987) and STELLA (Richmond, 1987), appeared within two years of one another. The author has been closely involved with the creation of DYSMAP2 from its forerunner, DYSMAP (Cavana and Coyle, 1982), which was designed purely for mainframe and minicomputer installations.

What singles out these systems is the fact that they allow one equation for each model variable which can be placed anywhere in the list. The software automatically sorts the equations into a computable sequence and then executes the model. All three systems include special library functions which are of direct help in this kind of modelling work, together with an integrated graph plotting capability, so necessary for reviewing the results from policy explorations.

In essence, these software systems provide an environment which makes it feasible to conduct real-time policy explorations using simulation models. Professional DYNAMO has extensive menu facilities and a DYNEX (executive) user interface which can be customised to suit corporate tastes. DYSMAP2 has an Interactive Command Processor environment from which groups of variables can be plotted, additional runs created and executed and equations, written in a user-friendly algebra if desired, reviewed. In this package, variable names of up to 32 characters are possible, including the underscore character, and so any non-numerate executive is put more at ease by seeing equations such as

Total_revenue = Unit_price * Amount_sold

rather than

TR = UP * AS

or even worse

$\tau = \upsilon \cdot \alpha$

DYSMAP2's co-plot facility is particularly useful in a learning context as it permits a side-by-side comparison of the effects of different policy scenarios for a single variable.

There is no question that, of the three, STELLA has attracted the most attention. It suffers from the disadvantage that it is written only for the APPLE™ Macintosh range of personal computers which are much less common in corporate offices at least on this side of the Atlantic. Also users of earlier versions of the software (before the MacIIc range of computers appeared) had to be content with a monochrome screen only.

However, practitioners such as Morecroft, Lane and Viita (1989) report an enthusiastic response when using this tool in a managerial learning situation. STELLA allows a model to be developed on-screen using icons to represent various parts of the modelling symbology. The icons are manipulated as part of a Graphical User Interface (GUI) by means of a mouse. Animation facilities permit direct observation of resource flows because 'tanks' (representing state variables) can be seen filling up or draining out. Graph plots of variables can be displayed whilst the model is executing rather than merely at the end.

Whichever program is selected for the purpose, however, there is no denying that it is capable of discharging the task of providing, in conjunction with a suitable model, a means to learn and understand the consequences of strategic policy. Quite simply no other general purpose languages or specialist systems can match the combination of free-ordering of equations, simple syntax, powerful function library and rapid graph plotting which these three offerings make available.

All the developments described above are underscored by the results of a survey which was conducted by the British business magazine *"Business Computing and Communications"* in 1987. The magazine surveyed 1500 chief executives, managing directors and finance directors of organisations employing over 750 people. Questionnaires were returned by 118 executives, 49% of whom worked for companies with an annual turnover in excess of £100 million. Just over 40% of respondents worked for manufacturing companies in the metal goods, engineering and vehicle industries. Relevant results in the present context were that almost one-third of respondents would like to see information provided in more comprehensible, graphic form. Of greatest importance, however, was the finding that 40% would like "the provision of possible scenarios for strategic planning". In other words, they were appealing for the availability of data on scenarios, but put into a more conducive (graphical) form. This encouraging finding shows that there may have been little dissipation of the goodwill towards the use of models at the strategic level, evidenced by Higgins and Finn (1977b) and discussed earlier.

The developments in group decision support, referred to above, have a 'software' element too. This is the process by which the strategic issue is tackled. Eden (1989) has been associated with the development of one such process called Strategic Options Development and Analysis (SODA). The use of formal computer simulation models as an ingredient of this process is not prohibited and so the software element can be defined to embrace both process and content. Indeed Eden (1990) offers a very interesting opinion:

> *"There are indications that the use of computers for any future improvement in decision-making by very senior managers may incorporate a class of certainty-geared models that serve to clarify thinking about the dynamic interdependencies of complex systems. ..... Cognitive maps (Eden et al, 1983) and system dynamics models (Morecroft, 1984) are not only similar in that the causal relationships between variables typically are 'hard-wired' (rather than probabilistic) but also because they are typically 'information-free', that is, built on impression, belief, judgement, wisdom and intuition rather than on formally gathered data. Representing the world through the construction of a 'processual toy' which can become a learning*

> *instrument seems to be a promising development (DeGeus, 1988). 'In a sense, such models have exhausted empiricism and placed no bounds on rationality' (attributed to Rohrbaugh at the Toronto conference on which this book is based)."*

Unfortunately the contribution by Ackermann, which follows on directly from the section in which the above quotation appears, does not support the sentiment expressed by Eden. Here Ackermann, quoting Winograd and Flores (1986), suggests that the appropriate role for the computer in group decision support is not as a surrogate expert but rather a sophisticated medium of communication. The emphasis is on data and the capability to access it concurrently. Whatever is emphasised in system dynamics models it is certainly not formal statistical data, as Eden's quote bears testimony. DeGeus (1988) would agree and he argues counter to Ackermann. Indeed, DeGeus would say, in support of the theme of this thesis, that a computer model *should* be utilised as a 'surrogate expert'.

Tomlinson (1990) offers a taxonomy which is useful for putting the ideas of 'group decision support' in context. He distinguishes between 'process' models and 'product' models. The former describe the relationships between the decision-making group and the process by which the decision can be reached. Group decision support emphasises the 'process' model to the apparent exclusion of product models which incorporate the values, beliefs and concerns of senior managers; this category would include system dynamics models.

There must be many types of strategic problems in business and government for which the adoption of a group decision support method *alone* would mean that there was a well-defined *process* but little or no substantial *content*. This imbalance would operate to the detriment of the process and also, possibly, the enthusiasm of the participants. Similarly, to press ahead with a system dynamics model which was not embedded within a group decision (or more appropriately policy) process might risk a very real miscasting of the role of that model by those involved. Earlier sections of this thesis have elaborated on the desirability of setting out very carefully the proper role for system dynamics models in the policy process. For deliberations made outside of a formal board meeting with its fixed agenda, the ideas of group decision support seem to offer the best platform via which this role can be discharged.

1.9 Modelling public policy issues

Thus far, the material in this chapter has been devoted almost exclusively to corporate strategic policy and the role of system dynamics models in shaping that policy. But the emphasis on firms is not intentional, indeed the title of this thesis clearly implies that system dynamics has a role to fulfill in the context of public policy determination. Consequently, this section is devoted to an exploration of the nature of public policy issues and whether the models which can be employed to support evaluation of such issues need to be any different from those associated with corporate strategic policy. There is also some comment on the apparent contrast between the extent to which public policy modelling has been embraced on both sides of the Atlantic.

It should be made clear at the outset that it is impossible to do justice, in this relatively short section, to the subject matter of 'policy analysis', as it is known in government. The whole area of policy evaluation and implementation, and the political framework within which it is set, is a subject in its own right, firmly entrenched in the discipline of political science. Not only books but specialist journals exist which are devoted solely to the determination and evaluation of public policy. In dipping a somewhat alien toe into these waters it is with the specific purpose of assessing the strength of the current running in favour of (or against) the use of models to inform the policy-making process.

As with earlier coverage of corporate strategic policy-making, the neglect of 'tactical' issues will be apparent. System dynamics models are of greatest use for supporting strategic policy issues possessing a time evolutionary quality. Although the optimal siting of pelican crossings, say, is an important issue for local authorities it is not something which system dynamics can shed much light on.

Similarly there are more strategic public issues which are the province of other academic disciplines. In this category would come the maximum speed limit on motorways, the drink-driving laws or the extent of the dissemination of welfare benefits, all of which are (or should be) supported by an input from statistical science. In the same vein questions surrounding farming and processing of food require an input from medical and biological science; nuclear waste one from physics and chemistry.

The areas of public policy which have already received attention from practitioners of system dynamics include the criminal justice system (Hunzeker, 1980; Beijdorff, 1986), energy planning (Naill, 1977), urban studies (Forrester, 1969), the national economy (Forrester, 1989), occupational health and safety (Crawford, 1988) and, in Scandinavia, forestry (Stenberg, 1980). The famous 'Limits to Growth' study (Meadows et al, 1972) is not strictly comparable since it implied more of an international public policy effort than the other examples quoted, being a model of the world's use of resources.

Clearly, then, there are a range of studies which fall within the framework of public policy and to which system dynamics models can contribute. That no great store of applications should exist on this side of the Atlantic perhaps will come as no great surprise, especially given the findings from Joy's (1988) survey discussed earlier on. What is more serious, however, is the relative lack of *any* modelling or analytical studies conducted as part of the public policy process in this country.

There is a tendency (and, it must be stressed, not wholly confined to the U.K.) to uphold the view that evaluation of public policy takes place *after* implementation. Indeed, the book by Rossi and Freeman (1985) is an example of this emphasis. But as a method of approach it is flawed and it is unnecessary. In fact it is the very antithesis of the modus operandi known as the scientific method. More ex ante evaluation of public policy is both feasible and warranted. System dynamics models, by promoting better understanding, can contibute significantly at this stage in the process.

Over the period January to May 1983, the Royal Institute of Public Administration held a series of seminars to examine policy analysis in British government (Gray and Jenkins, 1983). The gist of the contributions seemed to indicate that while government departments had embraced formal management information systems with some relish, there was a distinct lack of analysis of the pertinent issues and policy choices. Information systems mean better standards in the auditing sense but definitely not in the ex ante explorative sense.

Walter Williams made a contribution (Williams, 1983). He was on a sixth month sabbatical with the Central Policy Review Staff (CPRS), coming over from the University of Washington where, following a lengthy spell within the U.S. government, he was employed as Director of the Institute for Public Policy and Management. Having written two books (Williams, 1971; 1980) on his experiences as an advisor to the U.S. government he is uniquely qualified to comment. His opinion is forthright about the British scene:

> *"Policy analysis has become a significant factor throughout the American decision-making process. In Britain, policy analysis has not emerged prominently either at the centre or at the top of ministries. British government has remained pre-modern in terms of the use of what I label 'hard-edged' policy analysis techniques".*

(He later defines these techniques to rest on the logic-of-choice approach to decision-making, drawn from economics, statistical decision theory and operational research.) While he stresses that modern tools of policy analysis and strategic planning are not panaceas, he affirms that "they do increase the probability of more effective governance".

Williams puts down the lack of policy analysis in British government to three things: an absence of any desire by ministers and higher civil servants to see it implemented, the paucity of understanding of the techniques of policy analysis by the latter and, finally, pervasive secrecy in the conduct of government. His spell with the CPRS terminated just as Mrs Thatcher abolished the unit and he remarks on this irony in the conclusion to his contribution: ".... her act underscores both the dearth of policy analysis in the British government and the present Administration's lack of understanding of the need for information and analysis -- how fitting a symbolic gesture for what I have tried to say".

One area of governmental policy making which to some extent goes against the trend described by Williams is, of course, macro-economic policy where a number of large econometric forecasting models exist, including the Treasury's own model. For most people this would be the one area where they could cite with confidence that models helped in the formulation of policy. But a closer examination of the statistical models involved reveals that the preparation of forecasts of the main macro-economic variables is their raison d'etre. As discussed earlier in this chapter, forecasting is not the same as policy evaluation and although econometric models are increasingly being used for policy simulations, they are not as ideally suited to policy explorations surrounding *specific issues* as are system dynamics models.

Public policy issues, in contrast with those concerning business policy, are characterised by the greater number of people involved in or affected by the issue. The consequence is that, usually, the process of policy change is much more complex and slow-moving. It is, in effect, akin to a bargaining process between a large number of interest groups, each with many members (Stenberg, 1980). Nevertheless there seems no logical reason why a system dynamics model might not be employed to assist the various interest groups in 'thinking through' the consequences of alternative policy prescriptions. Stenberg reported a positive response by such interest groups to informed discussion centred around a model. There was possibly less rancour because the representatives of the interest groups could dispense with tactical manoeuvres and "consider their situation in a larger context and with a longer time perspective than usual". He concluded that the sessions devoted to consideration of simulation runs were often the most thought-provoking for all participants.

In these circumstances models should not be large. Interest groups coming from a varied set of educational backgrounds will not be able to cope with models running into thousands of equations. Such efforts would be counterproductive in the context of providing a pivot around which sometimes diametrically opposed viewpoints could be explored and perhaps reconciled. Large models are often predicated by the need to reproduce the past with high historical accuracy. Participants to the sessions where a model acts as a 'strategic counsellor' must be fully briefed that the purpose of the exercise is not to explain in great detail what may have transpired in the past, but rather to contemplate a better way of designing the future. Any member of the participating interest groups with experience of econometric modelling should be a first target for such a briefing.

Because econometric modelling represents such a large proportion of all the modelling work associated with UK public policy, it is perhaps worth establishing quite clearly the different function of such a model as compared with the use a system dynamics model might have in the sphere of economic policy. Greenberger et al (1976), in their authoritative text on the uses of models to underpin public policy, identify unconditional and conditional forecasting roles. The former exists when an econometric model is used simply to forecast the future value of, say, unemployment or interest rates. The assumption is that the policy makers do nothing; they are just being forewarned about emerging problems which will require their attention. Conditional forecasting, on the other hand, is the process whereby the 'forecast' is contingent on the actions which the policymakers take. Such forecasts deal with the likely consequences of policy decisions and are the result of, for example, using an econometric model for simulating alternative possible actions. The implication is that one (or a mixture) of the alternative actions will eventually be selected. In the discussion of the major decisions taken by the British Steel Corporation in the 1970's (see chapter 2) mention is made of how a number of financial projections were prepared, each supposedly the result of a specific action of the Board, who obviously then selected that policy choice offering the best return.

However, Greenberger et al also recognise that there is, in addition, "a more elusive and indirect use of models" and that is in education. This is the role in the policy-making process where a system dynamics model would figure heavily. Greenberger et al in effect support the view offered on many occasions in the above description of the appropriate use of system dynamics models within the corporate sector. They talk of "refining the intuitions of policymakers" and "stimulating the inventiveness and sharpening the perceptions of decision makers". The phrase that best sums up this use is attributed to Brewer (1973): using a model for *"descriptive clarification"*.

That public policy models can be contextualised in the role of providing a learning experience for participants in the policy process is also endorsed by Drake et al (1972) in their seminal book on the use of models in the public arena. They state, "By virtue of explicitly examining many of the difficult issues of a particular problem, their abilities to think systematically about complex aspects of public problems will likely improve". Drake et al are convinced by the formalisation of the public policy decision making process. The model-based approach is said to stimulate insightful thinking about the interactions of various parts of the problem and, by forcing an explicit consideration of the entire problem, it can be a catalyst for generating new alternatives to be evaluated as well as pinpointing the need for additional data. What is more, discussion can go beyond merely listing the pros and cons of each alternative and reach the stage of *balancing* them against each other.

Yet further support on this point comes from Dror (1975) who berates the methods of management science with its strong foundations in optimising mathematics and neglect of unquantifiable variables. He argues for the development of what he calls "policy sciences" which, while not neglecting the modelling ethos of management science, would fit more appropriately into the 'soft' context in which most policy issues are embedded. He infers that the system dynamics methodology might fit his specification for an analytical approach to underpin his vision of policy sciences, although it is unlikely to fulfill all of his requirements. The inference emerges in his recognition of the "pioneering efforts" of Forrester to integrate behavioural science knowledge into formal computer models, particularly in the urban dynamics model (Forrester, 1969).

It has been posited that effective learning in the context of using models in the public policy process is closely linked with both the nature of the model employed and its size. By way of illustration, consider the following plausible initiative which might be undertaken by one of the interest groups involved in the well-documented skills shortage in the UK (National Economic Development Office, 1989). The Committee of Vice-Chancellors and Principals (CVCP) of British universities decide to commission some research to explore the link between graduate-level skills shortages, wage inflation and hence price inflation. (This is, in fact, a possible future public policy research project for the author and colleagues at the University of Salford.) A model could help to articulate the reasoning involved: skills shortages lead to the bidding-up of salaries with the result that an increasing rate of price inflation can emerge once the economy loses momentum in a downturn. This happens because employers who recruit to certain graduate skill occupations find that they must compete by offering high enough salaries or lose valuable employees to their competitors. While demand is strong they can withstand the consequences for costs by virtue of the volume effect on total revenue. However, in times of slack or weakening demand this effect is lost. Because salary increases once given are never withdrawn, in less prosperous economic circumstances it means that a price effect is needed to replace the volume effect. The prices charged for the company's output must, therefore, be raised in order to maintain profitability.

If such a model were to be constructed then a relatively compact system dynamics model would surely be the most effective choice. This model would include the flows of recruits to graduate-level occupations, product sales and, finally, money which would represent industry's cost and revenue flows. Carefully crafted, such a model could be a potent catalyst to thought and a means whereby the CVCP could marshall public opinion in favour of increased public expenditure on the universities. This, of course, is an entirely appropriate role for a system dynamics model in the public policy process. It is quite clear, however, that it would be wholly inappropriate to have recourse to a huge model like the US National Economic model (Forrester, 1989) for this purpose irrespective of whether such an all-embracing model could be focussed so as to shed some light on the specific issue of skills shortages. Similarly the notion that an econometric model should be constructed would be a facile suggestion. Even if all the necessary data series were regularly recorded, a large proportion of the series may be irrelevant not least because the process described above could well be of relatively recent origin, being associated with the 'third industrial revolution' of electronics and information technology.

It is to be hoped that this section has eradicated any suggestion that public policy is so inherently different from corporate strategic policy as to invalidate the contribution of system dynamics models to the public policy-making process. One of the desirable characteristics of all participants in this process should be a willingness to learn, and learning can be accomplished by examining policy issues with the aid of such a model which, merely through the act of its creation, is capable of releasing understanding in a situation of some complexity.

But care should be exercised in the sort of system dynamics models which are produced as a contribution to public policy making. The days of creating 'glory models', which sometimes seem designed to cloak the intended audience in a mixture of bewilderment and forced acquiescence, should be banished forever. Specific issues call for specific models. Parsimony replaces comprehensiveness. Properly constructed and couched in the context of a learning tool, a system dynamics model supporting an issue of public policy has far greater potential to elevate the level of policy debate than has the yield from any other modelling method.

1.10 A Conclusion by way of an Introduction

In the foregoing sections an attempt has been made to set out the proper role for a system dynamics model in the context of the process of policy formulation concerning corporate and public issues. Not until quite recently (see for example Morecroft (1988)) has it occurred to proponents of the system dynamics method that this aspect ought to be emphasised. Perhaps this neglect goes some way to explaining both the relative lack of use of system dynamics as a modelling tool generally and the apparent inability of some authors not completely familiar with the method to properly position it in a taxonomy of modelling methods. In some small way, therefore, this thesis will hopefully augment the as yet embryonic literature devoted to an exposition of the appropriate *context* for a system dynamics model in corporate and public policy.

However, were that achievement to be the sole feature of this thesis then its content would be reduced by perhaps some 75 per cent. That this is not so is due to three illustrations of system dynamics models of specific corporate and public policy issues. Thus, in concluding this first chapter it is necessary to introduce the models contained in the four remaining chapters. (References for each chapter, including this one, are placed at the end of the chapter, rather than as one overall listing at the back of the thesis.) Each model has been assembled with the purpose of enlightening the issue for those senior managers, directors, civil servants, professionals and students who are variously concerned with its resolution. Each example should conform to the framework for effective use of system dynamics models set out above. The first one concerns production technology policy in the U.K. steel industry, the second the transmission of HIV infection and the third, by means of a model of a corporate collapse, defines one use of a system dynamics model in the business school curriculum.

The steel industry model is described in detail in chapter 3 although some relevant background material on the structure, technology options and strategic policy over the last twenty-five years has been included separately in chapter 2. This is because a full understanding of the setting for the model will considerably assist the reader in evaluating its utility as a catalyst to thinking about technology policy in the industry. The model challenges widely held views about the benefits of economies of scale. It focuses particularly on the 'heavy end' of steel making which operates as a continuous process. Within this sphere of operations the blast furnace is singled out principally because this production unit has perhaps, above all others, exhibited significant increases in size designed to procure lower unit costs of production.

An extension of the steel industry model explores the greater flexibility arising from adoption of the leading-edge production technology in the industry, namely the electric arc furnace. Steel production by this method eliminates the iron-making stage altogether; arc melting shops take steel scrap as their raw material. As compared with the blast furnace process route, electric steelmaking avoids lengthy periodically enforced maintenance work which can often coincide with a boom in the steel cycle and result in rapidly extending delivery delays for the customers.

The model describing the spread of the human immuno-deficiency virus, the causative agent of AIDS, within the male homosexual population of the U.K. should be seen as the first stage in the production of a more comprehensive model which will inform public policy on AIDS. This is not to denigrate the existing model which addresses spread within the risk group accounting for some 80% of known AIDS cases in the United Kingdom. However, cases within the other two main risk groups, intravenous drug users and non-monogamous sexually-active heterosexuals, are now growing rapidly, far more so than in the male homosexual population. Because the total number of cases in the heterosexual community is potentially so much greater, there is a pressing need to produce models which will focus debate on what could conceivably happen in this risk group and when, and also to identify the scope for effective intervention by the various agencies involved.

The model of the spread of HIV disease is, first and foremost, to be viewed as an initiative in producing a public policy support tool. However, in going some way towards achieving this goal, a degree of medical and scientific detail has been unavoidably incorporated. It is possible that one outcome of the work will be some new pointers for the conduct of epidemiological modelling but, if this should transpire, it is to be regarded as a by-product and not the primary purpose of the research. Any promising avenues of inquiry in this direction can be explored further by the relevant specialists in epidemiology and public health.

Having described two, quite different, system dynamics models in the work situation it is perhaps appropriate to include also an example showing how such models can be harnessed in the teaching situation. System dynamics models have a quite considerable potential to offer insights to students as part of their learning process almost irrespective of their subject of study, although clearly business and economics students have most to gain.

Four specific target groups of individuals can be identified covering post-experience / continuing education and undergraduate / postgraduate studies. These groups are (i) senior managers or directors who help to shape policy in a firm or in government, (ii) middle managers who take decisions within a given policy framework, (iii) MBA students on Business Policy type courses and finally (iv) students on business and other courses who have a reasonably high standard of numeracy.

The first group are typically very senior people and their 'learning' is best conducted as part of their normal policy-making activities at work. The steel model described in chapter 3 might be typical of the kind of policy model with which they are confronted in an effort to challenge accepted beliefs (their 'mental models'). They would rarely, if ever, leave their work situation in order to receive continuing education. This is not the case with managers in category (ii) who can be placed in workshop and learning laboratory situations designed to help them better understand, through model-based gaming activities, the consequences of their particular role in the operations of their firm. Kim (1989) describes one such "managerial practice field" designed for claims managers in the insurance industry. Gaming activities are hardly appropriate for category (i) people. As DeGeus (1988) comments, "We didn't feel we could go to executives who run some of the biggest companies in the world and say, 'Come on, let's have a little game'".

Model-based games for students in category (iii) are also starting to appear (Sterman, 1988). Along with the model content of the learning laboratory concept for category (ii) people, such initiatives are driven by the fact that the 'students' cannot be expected to formulate model equations and therefore have to be presented with a simple interface which can allow the model (play) to be stopped at periodic intervals and action choices polled from the teams. But do the participants actually learn anything from such games? As soon as an element of competition is introduced into the workshop situation, 'playing to win' may overcome the notion of 'playing to learn'. Halting the model at pre-determined intervals is questionable also. In real-life, executives will intervene strategically when they agree that action needs to be taken. The corollary for system dynamics modelling software is quite clear in this context: real time colour graph plotting needs to be augmented with a capability to intervene at any time in order to revise policies and not only when the model has reached one of the periodic 'decision points'.

The model of a real-life case study presented in chapter 5 is designed for category (iv) students. No element of competition is involved. A small group would study the case and then either create a model which represented the situation as it existed, following this with explorations investigating alternative strategic policies, or merely conduct the explorations using a model reflecting the 'as was' situation and which had been formulated previously by the instructor. In either choice, avoidance of a gaming environment would be achieved. Via the model, students would obtain rapid feedback on the effects of chosen alternative policies and their learning concerning the formulation of system dynamics models would be consolidated with their learning concerning business policy. Moreover, the inevitable small-group debate and discussion would prepare such students well for their subsequent work experience. If the students of today are used to learning via dialogue based around scenarios derived from a computer model, then there is every reason to expect that the policy-makers of tomorrow will want to do the same.

REFERENCES FOR CHAPTER 1

F ACKERMANN (1990) "The Role of Computers in Group Decision Support". In C EDEN and J RADFORD (Eds.) *"Tackling Strategic Problems: the Role of Group Decision Support"*, Sage Publications, London. 132-141.

W BAETS (1987) "Corporate Strategic Planning in an Uncertain Environment", *European Journal of Operational Research*, 32, 169-181.

P W BECK (1982) "Corporate Planning for an Uncertain Future", *Long Range Planning*, 15, 12-21.

H S BECKER (1983) "Scenarios: a tool of growing importance to policy analysts in Government and Industry", *Technological Forecasting and Social Change*, 23, 95-120.

S BEER (1975) *"Platform for Change"*, Wiley, Chichester.

R O BEIJDORFF (1986) "CRISYS: A Model of the Criminal Justice System in the Netherlands", *Proceedings of the 1986 International Conference of the System Dynamics Society*, Seville, Vol. 1: 101-103.

C BONNINGTON (1976) *"Everest the Hard Way"*, Hodder and Stoughton, London.

G D BREWER (1973) *"Politicians, Bureaucrats and the Consultant"*, Basic Books, New York.

N CAPON and J M HULBERT (1985) "The Integration of Forecasting and Strategic Planning", *International Journal of Forecasting*, 1, 123-133.

R Y CAVANA and R G COYLE (1982) *"DYSMAP User Manual"*, University of Bradford.

J CHANDLER and P COCKLE (1982) *"Techniques of Scenario Planning"*, McGraw-Hill, London.

R G COYLE (1977) *"Management System Dynamics"*, Wiley, Chichester.

C M CRAWFORD (1988) *"Estimation of Bias in Cross-Sectional Evaluations of Endogenous Feedback Systems: Modelling the Impact of the Occupational Safety and Health Administration"*. Unpublished PhD thesis, State University of New York, Albany, U.S.A.

J G CROOKES (1982) "Simulation in 1981", *European Journal of Operational Research*, 9, 1-7.

B C DANGERFIELD and O VAPENIKOVA (1987) *"DYSMAP2 User Manual"*, University of Salford.

A DeGEUS (1988) "Planning as Learning", *Harvard Business Review*, 66, 70-74.

A W DRAKE, R L KEENEY and P M MORSE (Eds.) (1972) *"Analysis of Public Systems"*, M.I.T. Press, Cambridge, U.S.A.

Y DROR (1975) "From Management Sciences to Policy Sciences". In M J WHITE et al (Eds.) *"Management and Policy Sciences in American Government"*, D C Heath, Lexington, U.S.A. and reprinted in C POLLITT, L LEWIS, J NEGRO and J PATTEN (Eds.) *"Public Policy in Theory and Practice"*, Hodder and Stoughton, Sevenoaks, 1979, 270-291.

P F DRUCKER (1980) *"Managing in Turbulent Times"*, Harper and Row, New York.

R G DYSON (Ed.) (1990) *"Strategic Planning: Models and Analytical Techniques"*, Wiley, Chichester.

ECONOMIC AND SOCIAL RESEARCH COUNCIL (1985) *"Research Supported by the ESRC"*, London.

C EDEN (1989) "Strategic Options Development and Analysis -- SODA". In J ROSENHEAD (Ed.) *"Rational Analysis for a Problematic World"*, Wiley, Chichester.

C EDEN (1990) Introduction to Part IV: Computer Supported Group Decision-Making. In C EDEN and J RADFORD (Eds.) *"Tackling Strategic Problems: The Role of Group Decision Support"*, Sage Publications, London, 129-131.

C EDEN and J HARRIS (1975) *"Management Decision and Decision Analysis"*, MacMillan, London.

C EDEN, S JONES and D SIMS (1983) *"Messing About in Problems"*, Pergamon, Oxford.

C EDEN and J RADFORD (Eds.) (1990) *"Tackling Strategic Problems: The Role of Group Decision Support"*, Sage Publications, London.

EPS CONSULTANTS (1984) *"FCS-EPS Decision Support System Reference Manual"*, London.

FINANCIAL TIMES (1980) "Shell's 'Multiple Scenario Planning': a realistic alternative to the crystal ball", April 7, reprinted in A J ROWE, R O MASON, K E DICKEL and N H SNYDER, *"Strategic Management: a Methodological Approach"*, 3rd Edn., Addison-Wesley, New York, 1989.

J W FORRESTER (1968) *"Principles of Systems"*, M.I.T. Press, Cambridge, U.S.A.

J W FORRESTER (1969) *"Urban Dynamics"*, M.I.T. Press, Cambridge, U.S.A.

J W FORRESTER (1989) "The System Dynamics National Model". In P M MILLING and E O K ZAHN (Eds.) *"Computer-Based Management of Complex Systems"*, Springer-Verlag, Berlin, 1-12.

G GALER and W KASPER (1982) "Scenario Planning for Australia", *Long Range Planning,* 15, 50-55.

M GODET (1987) *"Scenarios and Strategic Management"*, Butterworths, London.

A GRAY and W JENKINS (1983) *"Policy Analysis and Evaluation in British Government"*, Royal Institute of Public Administration, London.

M GREENBERGER, M A CRENSON and B L CRISSEY (Eds.) (1976) *"Models in the Policy Process"*, Russell Sage Foundation, New York.

P H GRINYER and J WOOLLER (1975) "Computer Models for Corporate Planning", *Long Range Planning*, 8, 14-25.

P H GRINYER and J WOOLLER (1978) *"Corporate Models Today"*, Institute of Chartered Accountants, London.

A HICKLING (1990) " 'Decision Spaces': A Scenario about Designing Appropriate Rooms for Group Decision Management".
In C EDEN and J RADFORD (Eds.) *"Tackling Strategic Problems: The Role of Group Decision Support"*, Sage Publications, London. 169-177.

J C HIGGINS (1985a) *"Computer-based Planning Systems"*, Edward Arnold, London.

J C HIGGINS (1985b) "Some Trends in Corporate Modelling", *Omega*, 13, 495-500.

J C HIGGINS and R FINN (1977a) "Planning Models in the UK: a survey", *Omega*, 5, 133-147.

J C HIGGINS and R FINN (1977b) "The Chief Executive and his Information System", *Omega*, 5, 557-566.

J C HIGGINS and E J OPDEBEECK (1984) "The Microcomputer as a Tool in Financial Planning and Control: some survey results", *Accounting and Business Research*, 14, 333-340.

G D HOBBS (1981) "A model of the U.K. Economy: an Aid to Understanding Economic Behaviour", Proceedings of the *1981 System Dynamics Research Conference*, Rensselaerville, New York.

B HOLLOCKS (1983) "Simulation and the Micro", *Journal of the Operational Research Society*, 34, 331-343.

G P HUBER (1984) "Issues in the Design of Group Decision Support Systems", *MIS Quarterly*, 8, 195-204.

W A HUNZEKER (1980) "The Dynamics of Criminal Justice Systems". Unpublished paper presented to the 1980 *International IEEE Conference on Cybernetics and Society*, Boston.

R D HURRION (1980) "An Interactive Visual Simulation System for Industrial Management", *European Journal of Operational Research*, 5, 1980, 86-93.

W R HUSS and E J HONTON (1987) "Scenario Planning: what style should you use?", *Long Range Planning*, 20, 21-29.

C HUXHAM (1990) "On Trivialities in Process".
In C EDEN and J RADFORD (Eds.) *"Tackling Strategic Problems: The Role of Group Decision Support"*, Sage Publications, London, 162-168.

S A JOY (1988) *"An Investigation into the Present State of System Dynamics in the UK"*. Unpublished M Sc thesis, University College of Swansea.

H KAHN (1979) *"The Japanese Challenge"*, Crowell, New York.

D H KIM (1989) "Learning Laboratories: Designing a Reflective Learning Environment". In P M MILLING and E O K ZAHN (Eds.) *"Computer-Based Management of Complex Systems"*, Springer-Verlag, Berlin, 327-334.

D C LANE (1989) "Management Learning by Simulation". In Proceedings of the *Third European Simulation Congress*, D MURRAY-SMITH, J STEPHENSON and R N ZOBEL (Eds.), Edinburgh, 321-339.

J P LEEMHUIS (1985) "Using Scenarios to Develop Strategies", *Long Range Planning*, 18, 30-37.

C LORENZ (1980a) "Shell strikes a refined way of exploring the future", *Financial Times*, March 4.

C LORENZ (1980b) "How Shell made its Managers think the Unthinkable", *Financial Times*, March 5.

I G MARKS, F M HAMER, and S CHOAT (1982) "The Impact of O.R. on the Design of a Float Glass Line", *Journal of the Operational Research Society*, 33, 705-711.

D H MEADOWS et al (1972) *"The Limits to Growth"*, Universe Books, New York.

S M MILLETT (1988) "How Scenarios Trigger Strategic Thinking", *Long Range Planning*, 21, 61-68.

J D W MORECROFT (1984) "Strategy Support Models", *Strategic Management Journal*, 5, 215-229.

J D W MORECROFT (1988) "System Dynamics and microworlds for policymakers", *European Journal of Operational Research*, 35, 301-320.

J D W MORECROFT, D C LANE and P S VIITA (1989) "Modelling a Biotechnology Start-up Firm". In P M MILLING and E O K ZAHN (Eds.) *"Computer-Based Management of Complex Systems"*, Springer-Verlag, Berlin, 157-176.

R F NAILL (1977) *"Managing the Energy Transition"*, Ballinger Publishing, Cambridge, U.S.A.

NATIONAL ECONOMIC DEVELOPMENT OFFICE (1989) *"Switching on skills: new approaches to skill shortages in UK electronics and IT"*, London.

D NAYLOR (1986) "Scenarios for European Telecommunications". Unpublished paper presented at the *Eighth European Conference on Operational Research*, Lisbon.

T H NAYLOR (1983) "Strategic Planning and Forecasting", *Journal of Forecasting,* 2, 109-118.

T H NAYLOR and H SCHAULAND (1976) "A Survey of Users of Corporate Planning Models", *Management Science,* 22, 927-937.

P C O'KANE (1981) "A Simulation Model of a Diagnostic Radiology Department", *European Journal of Operational Research,* 6, 38-45.

S PAPERT (1980) *"Mindstorms",* Basic Books, New York.

A I H PINK (1988) "Strategic Leadership through Corporate Planning at ICI", *Long Range Planning,* 21, 18-25.

D K PREEDY and R G A BITTLESTONE (1985) "O.R. and the Boardroom for the 90s", *Journal of the Operational Research Society,* 36, 787-794.

D E PROBERT (1982) "System Dynamics Modelling within the British Telecommunications Business", *Dynamica,* 8, 69-81.

PUGH-ROBERTS ASSOCIATES (1986) *"Professional DYNAMO Reference Manual",* Cambridge, USA.

B RICHMOND (1987) *"A User's Guide to STELLA",* High Performance Systems, New Hampshire, USA.

N ROBERTS et al (1983) *"Introduction to Computer Simulation: a system dynamics modelling approach",* Addison-Wesley, USA.

P H ROSSI and H E FREEMAN (1985) *"Evaluation"* 3rd edition, Sage Publications, New York.

K E SAHIN (1980) "System Dynamics Modelling", *Omega,* 8, 333-344.

S P SCHNAARS (1987) "How to Develop and Use Scenarios", *Long Range Planning,* 20, 105-114.

J K SHIM and R McGLADE (1984) "The Use of Corporate Planning Models: Past, Present and Future", *Journal of the Operational Research Society,* 35, 885-893.

SOCIETY FOR STRATEGIC AND LONG RANGE PLANNING (1985) Seminar on *"Quantitative Approaches to Strategic Planning: Uses and Abuses",* organised in collaboration with the Operational Research Society, London, 4 November.

L STENBERG (1980) "A Modelling Procedure for Public Policy". In J RANDERS (Ed.) *"Elements of the System Dynamics Method",* M.I.T. Press, Cambridge, U.S.A., 292-312.

J D STERMAN (1988) *"People Express Management Flight Simulator",* Software and Documentation available from J D Sterman, E52-562, MIT, 77, Massachusetts Ave., Cambridge, MA 02139.

R TOMKINS (1978) "A System Dynamics model of the U.K. Economy", *Proceedings of the UKSC Conference on Computer Simulation,* IPC Science and Technology Press, Surrey.

R TOMLINSON (1990) "Of Tools, Models, Methods and Methodology". In C EDEN and J RADFORD (Eds.) *"Tackling Strategic Problems: The Role of Group Decision Support"*, Sage Publications, London, 178-188.

J A VENNIX, J W GUBBELS, D POST and H J POPPEN (1988) "A Structured Approach to Knowledge Acquisition in Model Development", *Proceedings of the 1988 International System Dynamics Conference*, La Jolla, 419-433.

P WACK (1985a) "Scenarios: uncharted waters ahead", *Harvard Business Review*, 63, 73-89.

P WACK (1985b) "Scenarios: shooting the rapids", *Harvard Business Review*, 63, 139-150.

W WILLIAMS (1971) *"Social Policy Research and Analysis: the Experience in the Federal Social Agencies"*, Elsevier, New York.

W WILLIAMS (1980) *"Government by Agency"*, Academic Press, New York.

W WILLIAMS (1983) "British Policy Analysis: Some Preliminary Observations from the U.S.". In A GRAY and W JENKINS *"Policy Analysis and Evaluation in British Government"*, Royal Institute of Public Administration, London, 17-24.

W WILS (1988) *"Overview of System Dynamics the World Over"*, Consultancy Report from Croon DeVries, Maarssen, The Netherlands.

T WINOGRAD and F FLORES (1986) *"Understanding Computers and Cognition"*, Ablex Publishing, New Jersey.

E F WOLSTENHOLME (1982) "System Dynamics in Perspective", *Journal of the Operational Research Society*, 33, 547-556.

E F WOLSTENHOLME (1990) *"System Enquiry"*, Wiley, Chichester.

E F WOLSTENHOLME and R G COYLE (1983) "The Development of System Dynamics as a Methodology for System Description and Qualitative Analysis", *Journal of the Operational Research Society*, 34, 569-581.

2 THE BRITISH STEEL INDUSTRY: STRUCTURE, TECHNOLOGY AND POLICIES

2.1 A History of the Organisation of the Steel Industry since 1967

The production of steel in the United Kingdom is dominated by the British Steel Corporation (now British Steel plc) formed through the Iron and Steel Act of 1967. This Act transferred, on 28 July 1967 (Vesting Day), the fourteen largest crude steel producing companies to public ownership. Companies whose annual crude steel output averaged less than 482,600 tons remained in the private sector and in the same year the British Independent Steel Producers Association (B.I.S.P.A.) was created to represent the interests of such firms who numbered some one hundred and fifty initially (Vaizey, 1974).

The role of the independent steel producers should not be underplayed; throughout the 1970's they averaged 22% of steel delivered to UK consumers and stockholders (Bryer et al, 1982). While the majority were re-rolling and finishing concerns, taking the bulk of their supplies from the Corporation itself, a number of them were engaged in iron making, to supply foundries with pig iron, and steel making of predominantly special grades. The re-rolling and finishing firms possessed twin advantages of small size and flexibility; they could easily handle small orders for particular sizes or quality of product. Further, inasmuch as the independents are virtually the sole propagators of the "mini-mill" concept in UK steel production, their role could be even more important, as is explained later.

Of the firms taken into public ownership by the British Steel Corporation there were thirty-nine crude steel producing works, including twenty-one that were fully integrated, which means that they possessed a blast furnace(s) from which molten iron could be generated, for use in steel making.

Following renationalisation in 1967 the Corporation was organised around individual companies mainly grouped according to a geographical basis. There were four groups established and their main constituent companies are indicated below:

Midland Group	based on English Steel and United Steel in the Sheffield/Rotherham area, together with Appleby/Frodingham at Scunthorpe and the Workington and Barrow works of United Steel.
Northern and Tubes Group	based on Dorman Long; South Durham; Stewarts and Lloyds and Consett.
Scottish and North West Group	based on Colvilles; John Summers and Lancashire Steel.
South Wales Group	based on Richard Thomas and Baldwins; The Steel Company of Wales and Guest Keen's Cardiff works.

Using figures provided by Cockerill (1974) it is possible to estimate the respective shares of these groups to the national total of such companies' finished steel production. This is given in Table 2.1

Midland Group	20%
Northern & Tubes Group	26%
Scottish and N.West Group	21%
South Wales Group	33%
	100%

Table 2.1 Estimated proportion of Finished Steel Production accounted for by the four geographical groupings on formation of the B.S.C.

N.B. (i) Based on 1964-65 figures for finished steel production, with 1963-64 figures used for three works.

(ii) Certain works output figures were spread over more than one of the above groups.

Despite deficiencies in the compilation of Table 2.1 it is still possible to discern the importance of sheet, strip and coil products to the total national output, for these are predominantly the product types made in South Wales and which are purchased mainly by the consumer durables and motor vehicle industries.

This scheme of multi-product groupings was to last but three years. Following arguments, put forward by the Corporation, that employees' loyalty was more to their individual company than to the Corporation as a whole, pressure was put on Ministers to dissolve the company structure and transfer their entire assets fully to the British Steel Corporation. Further advantages said to be obtainable from this move concerned the promotion of rationalisation and the effective planning of capacity on a product basis. Accordingly, in the Iron and Steel Act of 1969, the company structure was dissolved and one year later emerged an organisation by product grouping which was to last for some seven years.

Six products divisions were created in 1970 but two involved constructional engineering and chemicals. The four remaining steel product groups were General Steels, based on Glasgow; Special Steels based on Sheffield; Strip Mills Division based on Cardiff and Tubes Division based on Corby.

An analysis of the Annual Report and Accounts of the Corporation for 1987-88 shows that the Strip Products Group accounted for 45% of total liquid steel production, 47% of total deliveries and contributed 45% of the home and export turnover of £3.7 billion. Therefore, given its prominence together with the known fluctuations in demand for the products of this sector, it is the strip mills which seem a reasonable focus of attention although it must be stated that the model developed in chapter 3 could apply equally well to a works producing general steels.

Demand fluctuations arise through the unique chain of supply leading from the steel mills to steel stockholders and thence to the motor vehicle/durable consumer goods industries. The fortunes of end-user firms in the motor vehicle and durable goods manufacturing sector are inextricably linked to the demand for steel and this is widely recognised (NEDO, 1986; Jones and Cockerill, 1984). In the case of crude steel making (the "heavy-end" of operations) it is the same production structure irrespective of which finished products are made; product differentiation arises from the ingot stage onwards and is described in the next section.

Organisational restructuring did not end with the scheme implemented in 1970, however. On 4 April 1976 yet another new divisional set-up was created which bore some resemblance to a synthesis of the two previous schemes. Five manufacturing divisions were formed on a geographical basis, each being related to one of the major steelmaking areas and acting, previously as a profit centre, but now as a cost or performance centre. These were: Scunthorpe; Teesside; Sheffield; Scottish; Welsh. Additionally certain smaller steelworks and also non-integrated rolling mills were to be allocated to one or other of the five manufacturing divisions on the basis of either geographical proximity or affinity of product, providing they were not otherwise incorporated into one of the continuing or new profit centres.

An important consequence of this was that marketing policies, along with individual plant loadings, were not to be handled by the manufacturing divisions themselves but rather by four Product Units, each of which would be responsible for a range of products across the entire Corporation. These were:-

BSC Billet, Bar & Rod Products

BSC Sections

BSC Plates

BSC Strip Mills Products

In effect, three of the existing four product divisions in being in 1975 (General Steels, Strip Mills and Special Steels) were replaced; the fourth, Tubes Division, remained intact but was extracted from the mainstream iron and steelmaking sector to form a profit centre in its own right.

The new organisation effectively implied, for those three steelmaking divisions replaced, that changed circumstances had prevented control of their manufacturing and commercial functions continuing through the same organisation. This feature was satisfactory where sales and manufacturing of a single product division could be carried on without significant overlap but, in the climate anticipated in the mid-1970's, multi-product plants in certain of the Corporation's major steelmaking centres (e.g. South Teesside and Ravenscraig) were seen in part as essential to sound development.

Another feature, which, it is suggested by Charteris (1975), had surrounded the pattern of organisation adopted from 1970 to 1975, was that the separate divisions, each then possessing their own commercial and plant loading responsibilities, could choose to manufacture what was convenient and profitable from their own point of view, rather than what the overall market situation dictated. With the removal of the divisional management layer, the necessary degree of control could now be exercised directly over the steel producing centres.

A White Paper (H.M.S.O., 1975) which was laid before Parliament on 7 August 1975 contained the details of the new organisational structure outlined above and, in particular, stressed how emphasis was to be placed on customer service through the Product Units. Customer service staff, providing a fundamental element in the link between manufacturing and sales, were to be introduced at every works under the line command of the sales function but operating closely with works management. Under this regime, it was hoped the best possible relationship between works and customer would be established.

The crucial function of future capacity planning was also to be continued on a product basis. Development planning units for the main product groupings were to be established. These, although part of Head Office, would be located near the related Product Unit and would work closely with that unit so that proper account was taken of commercial considerations from the early stages of planning investment proposals.

Subsequent to 1975 little happened on the organisational front within the BSC. The period coincided with a downturn in the market which became much more severe over the turn of the decade. The Corporation were concerned with external issues rather than internal organisational matters. The external threat emanated from Brussels; the BSC needed to fight their corner because the EEC declared a Manifest Crisis in the steel industry in 1980.

In the mid 1980's profitability returned and the government decided it was time for the largest organisational change yet. The British Steel Corporation became British Steel plc with the passing of the British Steel Act of 1988. The prospectus was issued in November and the company returned to private ownership (albeit as a single entity) one month later (Aylen, 1988).

2.2 The Technology of the Steel Industry since the Bessemer process

2.2.1 Iron Making

Apart from electric arc steelmaking, whichever process is employed for the production of molten (crude) steel it is necessary, firstly, to provide a source of molten iron (or pig iron) which is the product of one or more blast furnaces. A flow block diagram of the main inputs and outputs in the production of pig iron is shown in figure 2.1 .

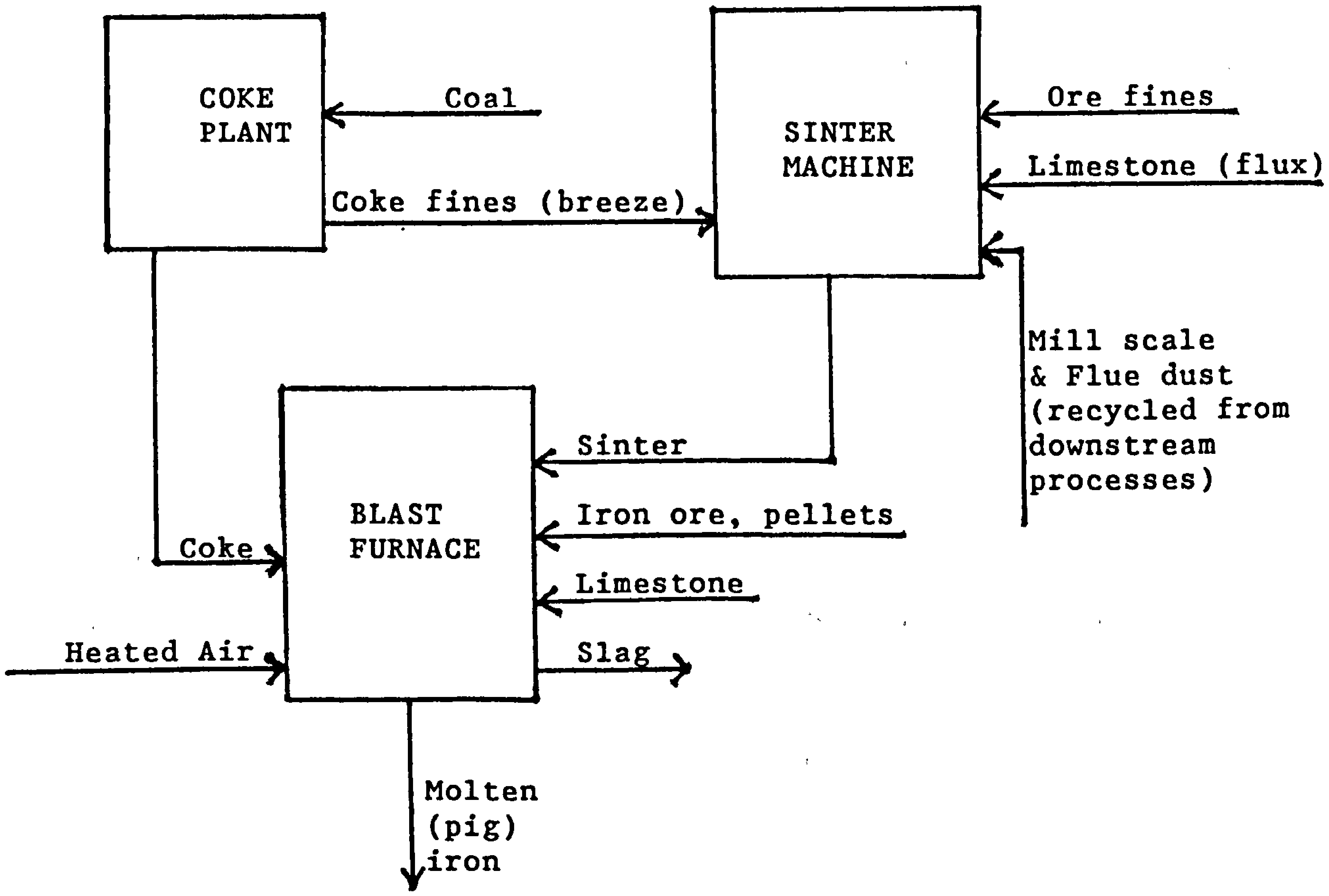

Figure 2.1 Flow Block Diagram of the production of pig iron

The coke plant heats coal in the absence of air thus resulting in the separation of some portion of the non-carbon constituents of the coal from the product itself, which is coke (a mixture of 90% carbon, the remainder being ash and sulphur).

Sintering is the process that agglomerates fine ore particles to form an iron-rich clinker which is charged into the blast furnace. It has the effect of increasing blast furnace efficiency by decreasing the weight of the charge required in the furnace to produce a ton of pig iron. The production of the clinker is accomplished by mixing heated coke dust with an ore and flux charge. This offers an additional advantage in that mill scale and flue dust, from the downstream finishing and steel making processes respectively, can be recycled, further justifying the term "integrated steelworks".

Iron-making in the blast furnace(s) is the essential first process in the manufacturing cycle for finished steel products. Molten iron is produced by the reduction of iron ore (a chemical term which in this context means that elemental iron is separated from the oxygen with which it is combined in iron ore) and this comprises the main proportion of the "burden" or charge fed in at the top of the furnace. Other components of the burden are sinter, coke and limestone in controlled proportions. The whole of the charge is fired and fanned to white hot intensity by blasts of superheated air blown in from the bottom. This results in the separation of molten iron from slag which floats on the surface and which is periodically drawn off.

The metallic part of the ore is thus separated from the non-metallic and from impurities. It is then tapped off ready for the steel conversion process. "Hot metal" is the term used in the industry to describe this molten iron which is 90%-95% pure but which still contains certain impurities, the most important of which are carbon, sulphur, phosphorus, manganese and silicon.

By the nature of the processes involved, therefore, the production of molten iron in a blast furnace is a continuous one. The charging of the burden at the top carries on alongside the tapping of the slag and the molten iron from the bottom. It is a cycle which can often continue uninterrupted for anything up to six years or more until such time that the refractory (heat-resistant) brick lining of the furnace begins to deteriorate, at which point re-lining is indicated. This continuity of production from a blast furnace, with interspersed periods of enforced downtime, is an important feature of the overall steel making process and plays a significant part in the model of the strategic technology issues in the industry, described in the following chapter. Further, the physical output per unit time is obviously fixed by the capacity of the furnace and only variations in the quality of the burden allow a yield variation from the furnace. This is typically of the order of 15% of the furnace's nominal capacity.

Over the years, blast furnaces have reduced in number while the output per furnace per annum has increased quite markedly. Figure 2.2 shows a graph depicting this long-term trend in the case of the UK steel industry. The increased volume of output, achieved in circumstances where the average number of furnaces in blast was falling, was a direct result of an increase in the size of furnaces installed; figure 2.3 presents this feature through two histograms of blast furnace hearth diameter, one relating to 1955 and the other to 1988. In 1955 the largest furnace had a hearth diameter just in excess of 7 metres while by 1988 the largest had increased to 14 metres. This stemmed directly from the desire to achieve economies of scale in both construction and operating costs, a desire that was apparently in evidence world-wide. In Japan, for instance, where steel-making only took off in the 1950's, their reliance on large scale plant led to the position in 1968 where they "had seven of world's ten largest blast furnaces" (Cockerill, 1974).

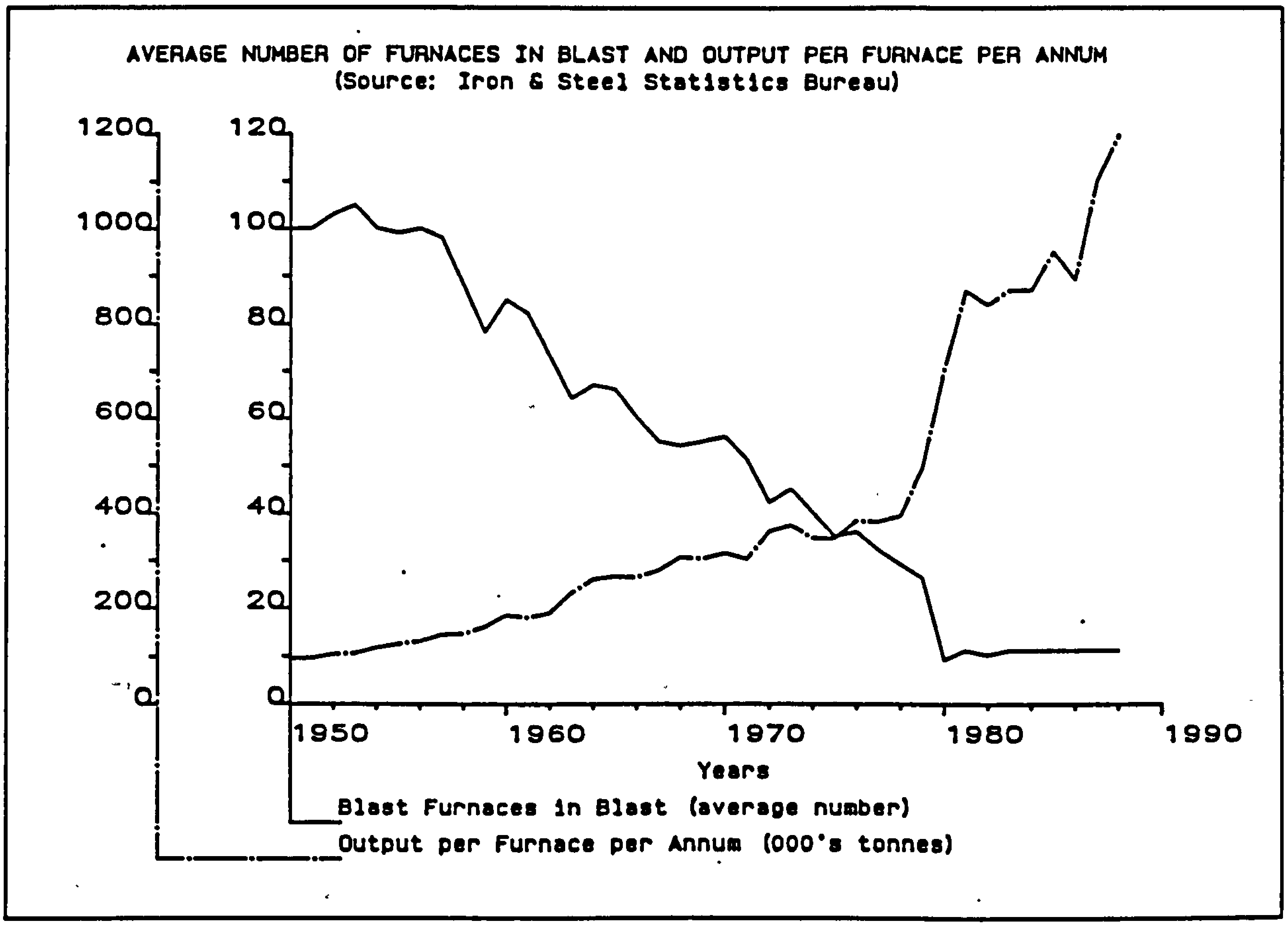

Figure 2.2 Average number of furnaces in blast and output per furnace per annum

An analysis of the number of blast furnaces of all sizes, using the data underlying the two histograms in figure 2.3, reveals a reduction from 138 furnaces in 1955 to 17 furnaces in 1988. The data underlying the graph in figure 2.2 gives 99 furnaces in 1955 and 11 in 1988. However, figure 2.2 is based on the average number of furnaces in blast while the histograms merely relate to furnaces in existence; the need to 'blow out' furnaces for relining explains the discrepancy in the figures.

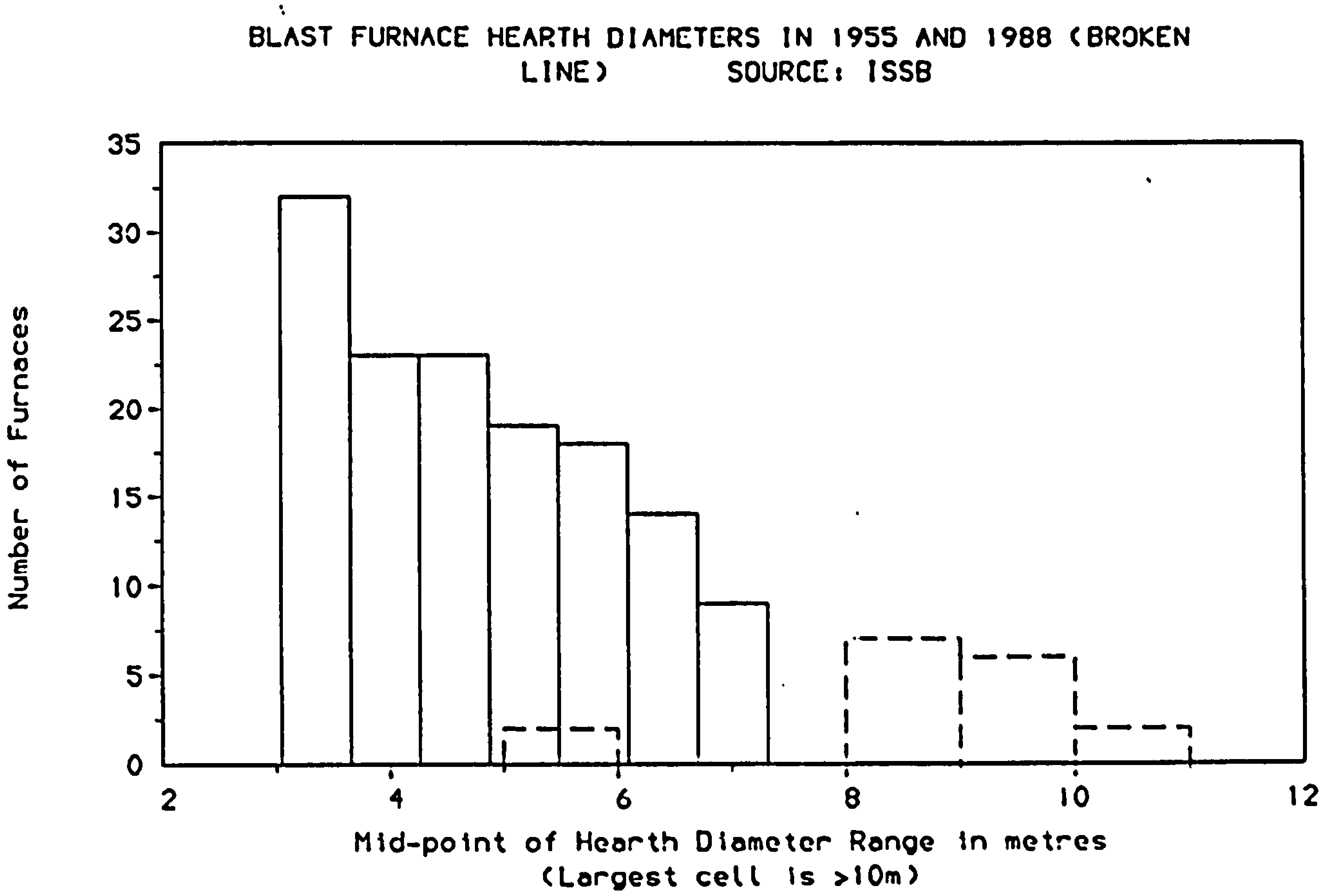

Figure 2.3 Frequency distribution of blast furnace hearth diameters

2.2.2 Steelmaking: Overview

While iron-making employs the chemical reaction of reduction, steel-making makes use of the opposite, which is oxidisation. The various impurities in the molten iron, listed above, are removed from the metallic charge because they combine with oxygen (oxidise) according to their affinity for oxygen at the prevailing temperatures. The practical result of this is that a slag is formed on the surface of the molten metal and this slag is then drawn off. With the impurities removed, the molten iron is converted into molten steel.

In this century there have been essentially four main technologies involved in the production of molten (liquid) steel, the earliest of which was the Bessemer process. Cockerill (1975) notes, though, that as early as the First World War the Bessemer process had begun to be replaced by the Siemen open-hearth process which, in turn, has been superseded by the Basic Oxygen System (B.O.S.). Electric arc furnaces, however, have been around for some time and lately their attractiveness has come to be recognised more widely.

An account will now be given of each of these latter three technologies in some more detail.

2.2.3 Steelmaking: Open Hearth Process

This incorporates a long shallow bath (hearth) into which the hot metal is poured, along with scrap and limestone, and then the charge is exposed (open) to a sweep of flames. The high temperature reaction causes unwanted elements to oxidise and combine with the limestone to form slag which separates from the metal. This process can be assisted by the injection of oxygen into the furnace through water-cooled lances. A flow block diagram of the process is shown as figure 2.4.

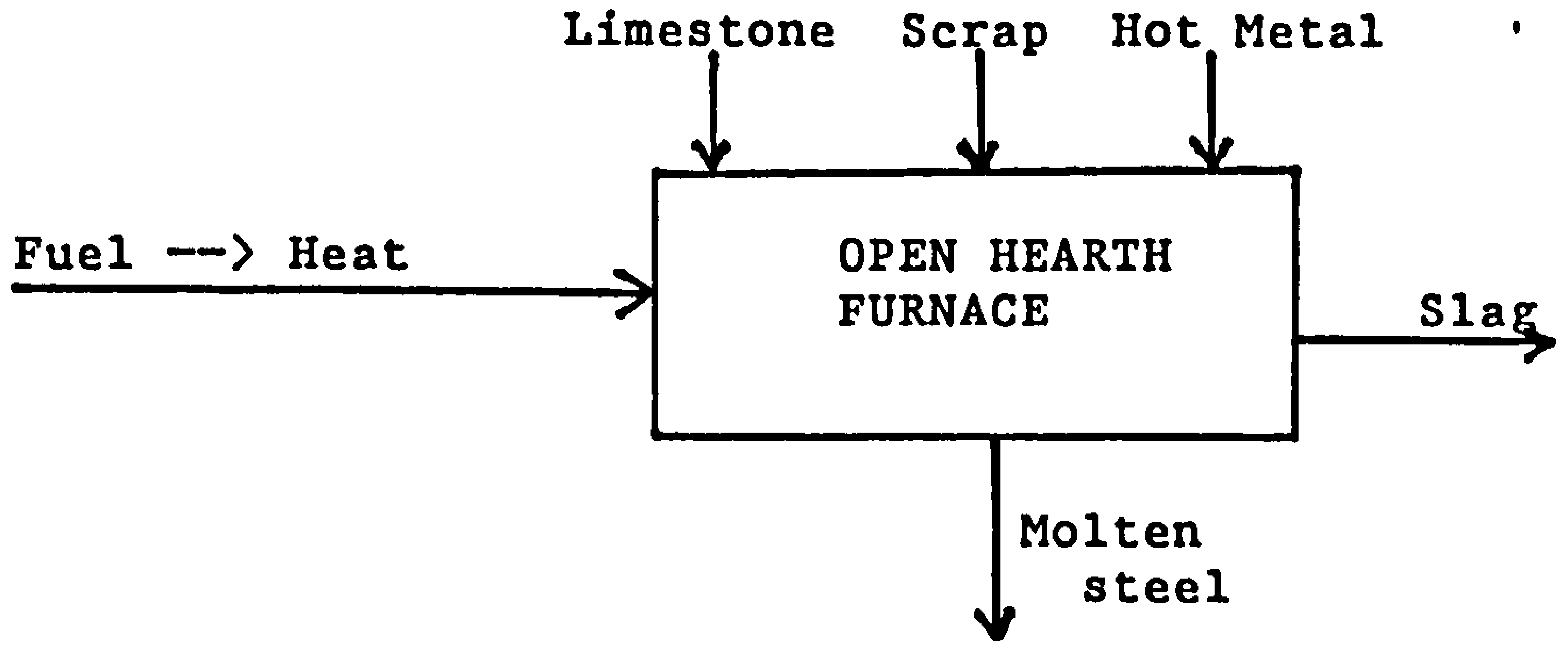

Figure 2.4 Flow Block Diagram of the Open Hearth Process

Because the operation takes so much longer than the Bessemer process, a greater degree of control over the composition of the charge (and the resultant quality of the steel) can be exerted. Indeed, sampling of the metal takes place at regular intervals in order to assess its quality.

Further advantages which this process has, relative to the Bessemer process, are as follows:

(a) A larger proportion of scrap may be used in the charge. The open hearth process is the most flexible of the three in this respect. Anything from 30% to 100% of scrap may be utilised in the charge (Russell and Vaughn, 1976). Obviously, this was the main reason for its popularity over the Bessemer process earlier in this century, because the supply of steel scrap dramatically increased with the output of manufactured goods.

(b) The process is more adaptable with regard to impurity content since the molten iron does not have to provide sufficient impurities to keep the charge molten as in the Bessemer process.

(c) Air-blasting is required in the Bessemer process and the nitrogen component in this can dissolve, adversely affecting the quality of the mild steel demanded by the motor vehicle industry. In the Open Hearth process air is not blasted through the molten metal.

The adoption of the Open Hearth process meant that, by the beginning of the 1950's, almost 90% of British steel was made using that technology (Cockerill, 1975). The last plants using this process were finally closed in 1980.

2.2.4 Steelmaking: Basic Oxygen Process

In the decade beginning 1950 much research effort was exerted on improving the efficiency of the steel conversion process. The breakthrough came in Austria where the Linz-Donawitz (L-D) process was devised. This involves blowing oxygen down onto the surface of the charge using a water-cooled lance held two feet above it. It represented a viable proposition given the newly available capabilities of large-scale oxygen generating plant.

The charge is placed in a cylinder-shaped converter which is tilted to facilitate this operation. On returning to its vertical position, oxygen blowing commences while lime is added as a flux to help carry off the oxidised impurities as a floating layer of slag. Once the metal has been refined, it is tapped out into a ladle until only the slag remains. The vessel is turned completely upside-down to remove the slag which is disposed of to a slag pool. A flow block diagram of this process is shown below as figure 2.5.

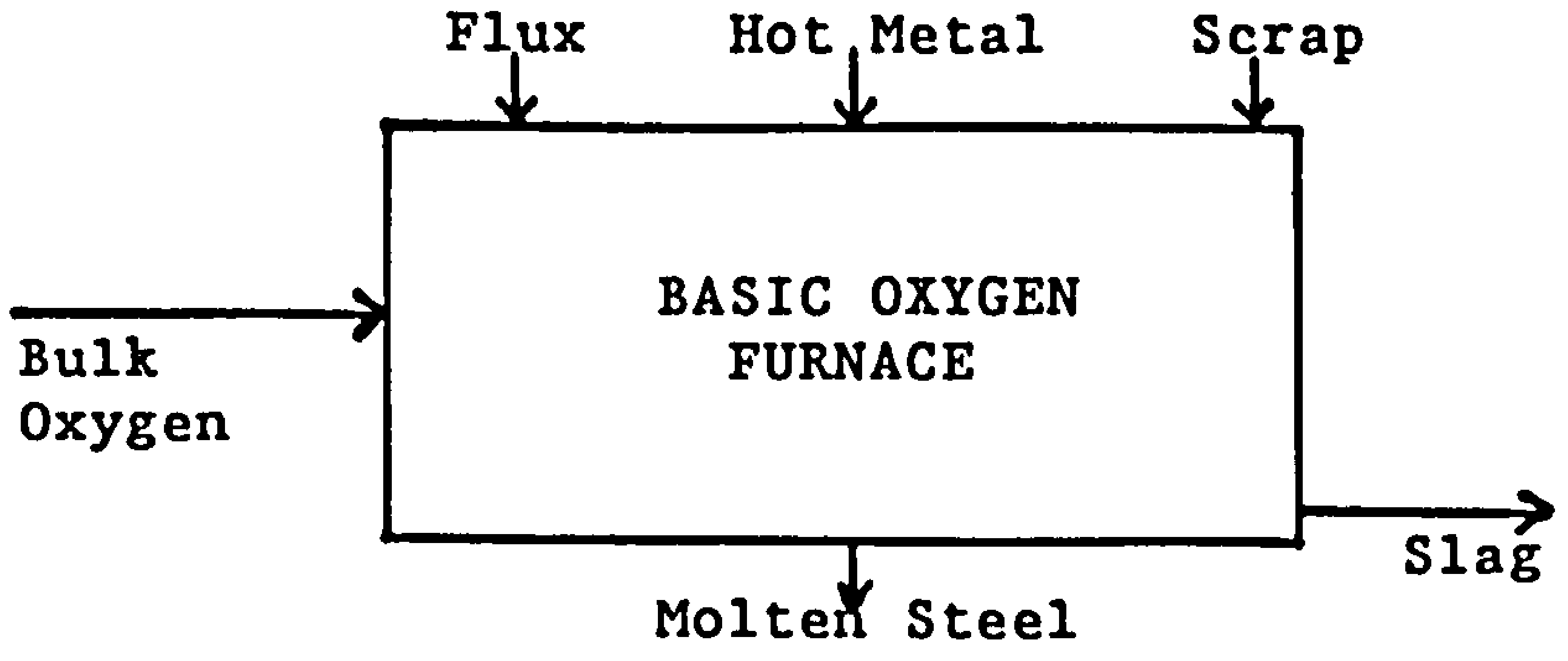

Figure 2.5 Flow Block Diagram of the Basic Oxygen Process

The essential features and advantages of the process can be summarised as follows:-

(a) Raw materials of varying phosphorus content may be used and a wider range of steels produced.

(b) Oxygen converter steel does not suffer from nitrogen brittleness and so has an improved quality.

(c) The scrap added to the charge acts as a coolant thereby improving the thermal efficiency which is high enough to offset the cost of tonnage oxygen. (However, the scrap content is not as variable as with the Open Hearth process nor as significant as in the Electric Arc process; normally no more than 30% of the charge will be scrap, the rest being molten iron or high grade iron ore.)

(d) The process is capable of higher production rates than the Bessemer or Open Hearth methods.

Perhaps its most significant advantage stems from (d) above. The increased speed with which this process could rid the molten iron of impurities allowed considerable cost savings per ton of steel produced. These savings were reinforced by the potential for increasing the size of the steel converter vessels and reducing the production cycle time. Whereas an Open Hearth furnace might take 10 hours to convert 350 tonnes of iron into steel, a Basic Oxygen furnace will take a charge of 350 tonnes or more and convert it into steel in 40 minutes (British Steel Corporation, 1972). Comparisons between the Basic Oxygen System and the Open Hearth method can be found in Rosegger (1980) and Dilley and McBride (1967).

The Basic Oxygen System (B.O.S.) became the industry standard for bulk steel-making and lay at the heart of international developments that dramatically increased the optimum scale of steel-making operations from the point of view of production efficiency. Increasing the rate of steel conversion generated the expansion of blast furnace size (previously discussed) because, with about 70% of the total charge being hot iron, the process can be installed only at works having blast furnaces.

However, the consequences of all these developments could be more damaging than beneficial and one of the purposes of the model described later is to assess the effects of the vastly increased scale of operations such as has occurred.

2.2.5 Steelmaking: Electric Arc Furnace

Originally, this method of steel-making was confined to special high quality steel but now it can be employed in the production of large tonnages of the more widely used steels. Indeed, it is claimed to be on the point of being one of the technologies capable of producing flat steel products (Barnett and Crandall, 1986). The furnace itself consists of a circular bath with a movable roof through which three carbon electrodes are either raised or lowered. At the start of the process the electrodes are withdrawn and the roof is swung clear allowing the steel scrap (the sole content of the charge) to be dropped in. Next the roof is swung back, the electrodes inserted and a powerful electric current is passed through the charge. An arc is struck and the heat generated melts the scrap. Lime, fluorspar and iron oxide additions are made and these combine with the impurities in the metal to form a slag. Once this has been removed the furnace can be tilted and the molten steel is tapped off. In this way a large electric arc furnace produces about 150 tonnes of steel in 4 hours (British Steel Corporation 1972). A flow block diagram of this process, which eliminates the need for coking, sintering and blast furnaces, is given below in figure 2.6 .

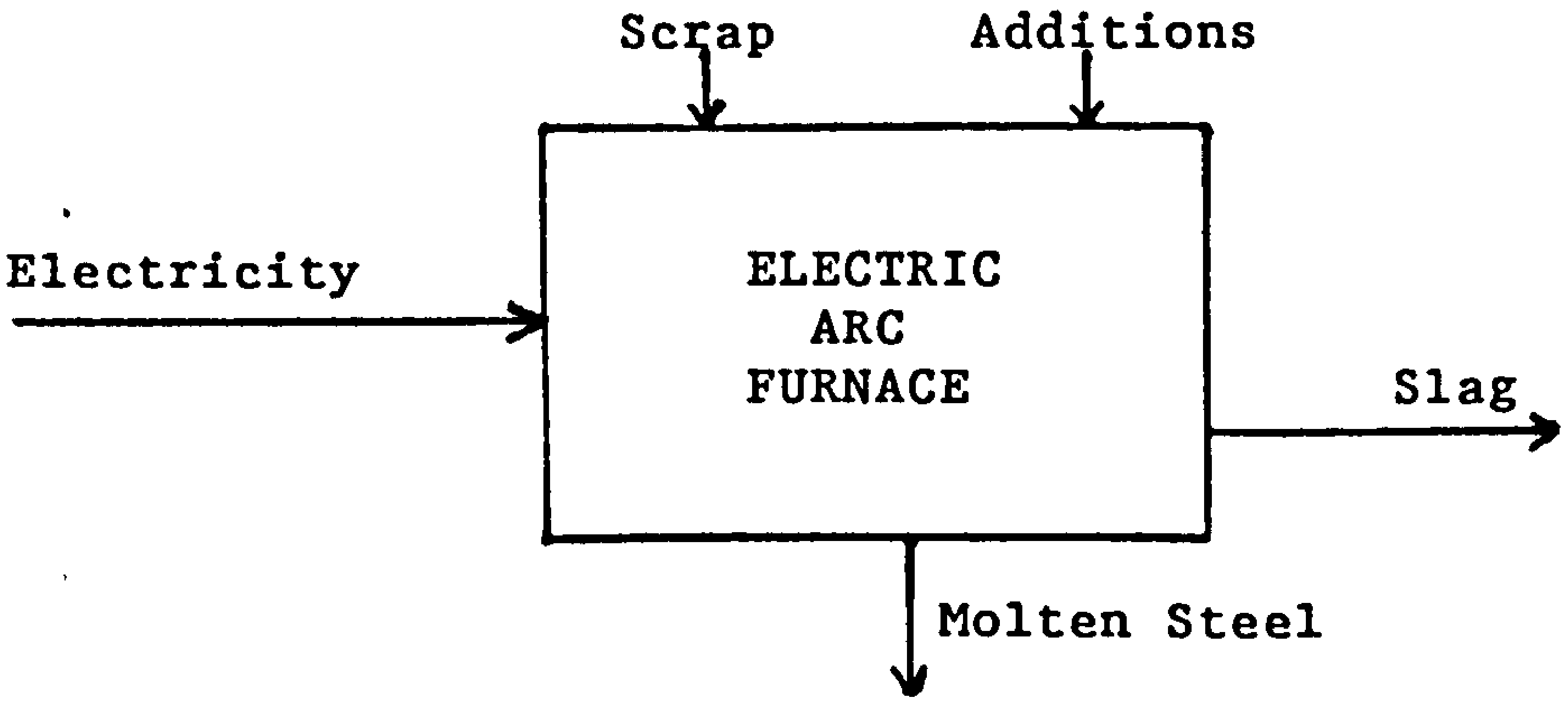

Figure 2.6 Flow Block Diagram of the Electric Arc Process

The main advantages of electric arc furnaces, from the point of view of metallurgical processes, are listed below.

(a) A definite and reliable removal of sulphur is achieved.

(b) The carbon content of the steel can be held steady.

(c) The addition of alloying elements can be made with precision.

(d) All the conditions are chemically clean.

(e) Temperature control is easy.

However, as will be described in the following chapter, this method of steel-making also has certain technological, financial and operational advantages which have propelled it to the forefront of discussion as regards choice of process route.

Clearly, its total reliance on the availability of scrap renders the electric arc process one which cannot be sited without due consideration to sources of supply. However, relative movements in the prices of fuels, scrap and hot metal mean that its popularity is growing. Smaller scale steelworks (known as mini-mills) have grown up using this technology, usually allied with continuous casting, which is described later. These works originated in the USA, where there are considerable numbers often located close to industrial areas that both supply the scrap and consume the finished product. Now, more of these smaller configurations are to be found in Western Europe and the UK, with outputs of anything up to one million tonnes per year, although half of Italy's mini-mill capacity, for example, is in plants making 200,000 tonnes a year or less (Aylen, 1989). Mini steel works have fewer of the enormous overheads associated with large integrated works; a comprehensive assessment of their advantages can be found in Barnett and Crandall (1986).

Figure 2.7 shows crude steel production by process over the last four decades. It is clear that both electric arc and B.O.S. production suffered as a result of the 1980 steel strike and the UK recession during the period 1980-86, although

B.O.S. production has recovered significantly towards the end of the decade.

It is readily apparent that, of the three steel making processes, the Open Hearth method was one which experienced somewhat rapid decline. A glance at figure 2.7 serves to emphasise just how more important B.O.S. technology in the UK had become during the 1960's, although Cockerill (1975) notes, on the basis of an international comparison, that by 1968 only just under 33% of UK steel was produced using the B.O.S. process whereas in Japan the corresponding figure stood at almost 75%. For 1974 he claims that the UK figure for B.O.S. produced steel was still less than 50% of the total and figure 2.7 confirms this.

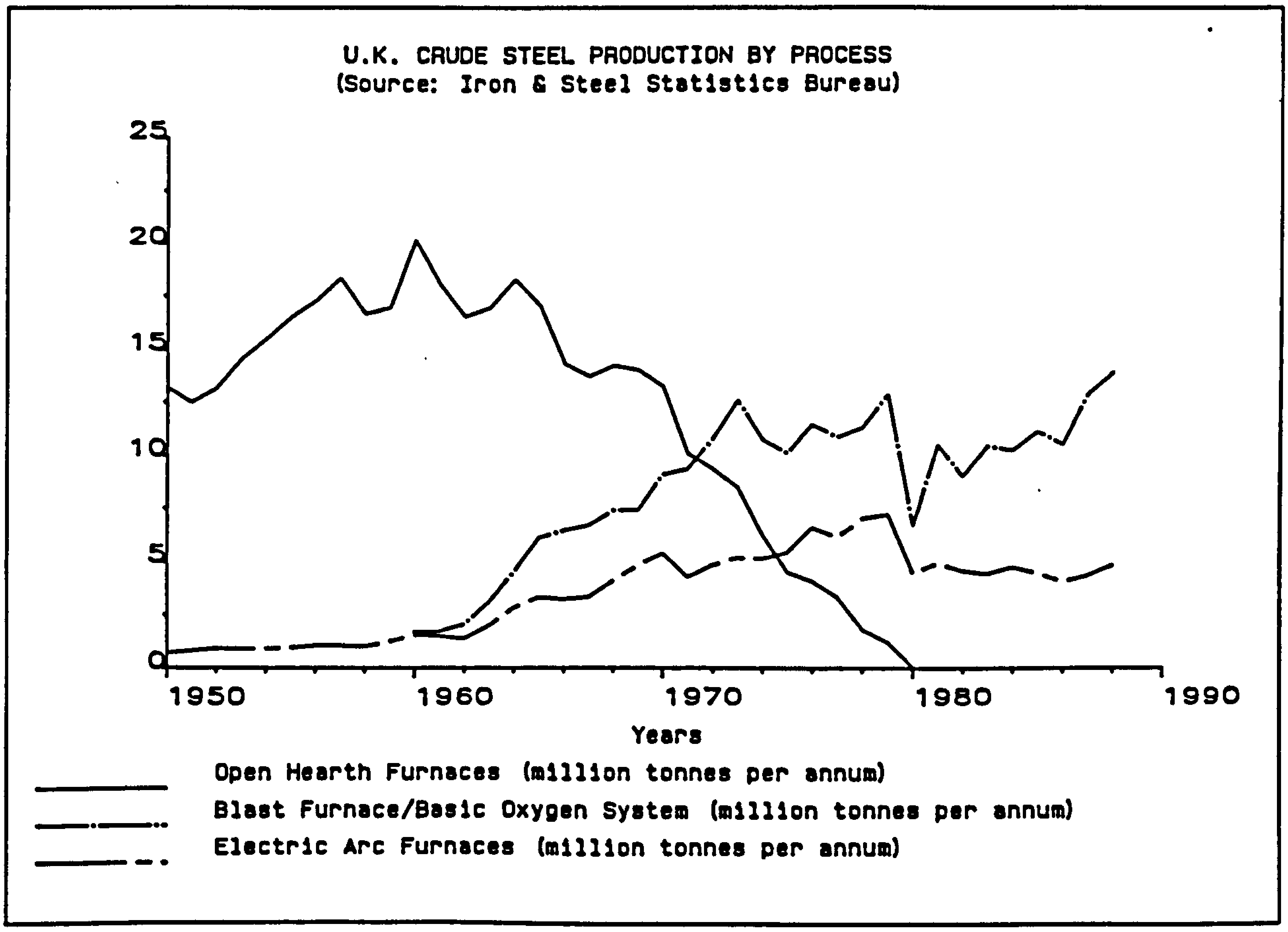

Figure 2.7 UK Crude Steel Production by Process

2.2.6 Semi-Finished Shaping via Ingot Casting

The ingot is the basic unit of the steel industry. It is formed when molten steel is poured into a special mould and allowed to cool. Afterwards, the mould is removed and the solidified steel remains. Moulds can be of differing dimensions and weights depending on the ultimate use to which the ingots are going to be put; they are reheated in soaking pits and rolled to produce 'semis' -- either slabs, blooms or billets. A slab is the basic semi-finished shape in the strip mills and in cross-section it is rectangular with a typical size being 6 inches thick and up to 60 inches wide (or at least twice as wide as it is thick). A bloom is square in cross-section, being up to 8 inches square, while a billet is normally much smaller than a bloom although retaining its square cross-section. It is likely to measure up to 4 inches square. Both the latter two semi-finished shapes are characteristic of output from what was the General Steels Division until 1976.

A billet is derived by hot-rolling of a bloom and the extra rolling makes billets suitable for lighter steel section products, while blooms are used for heavy sections. This is depicted in figure 2.8 .

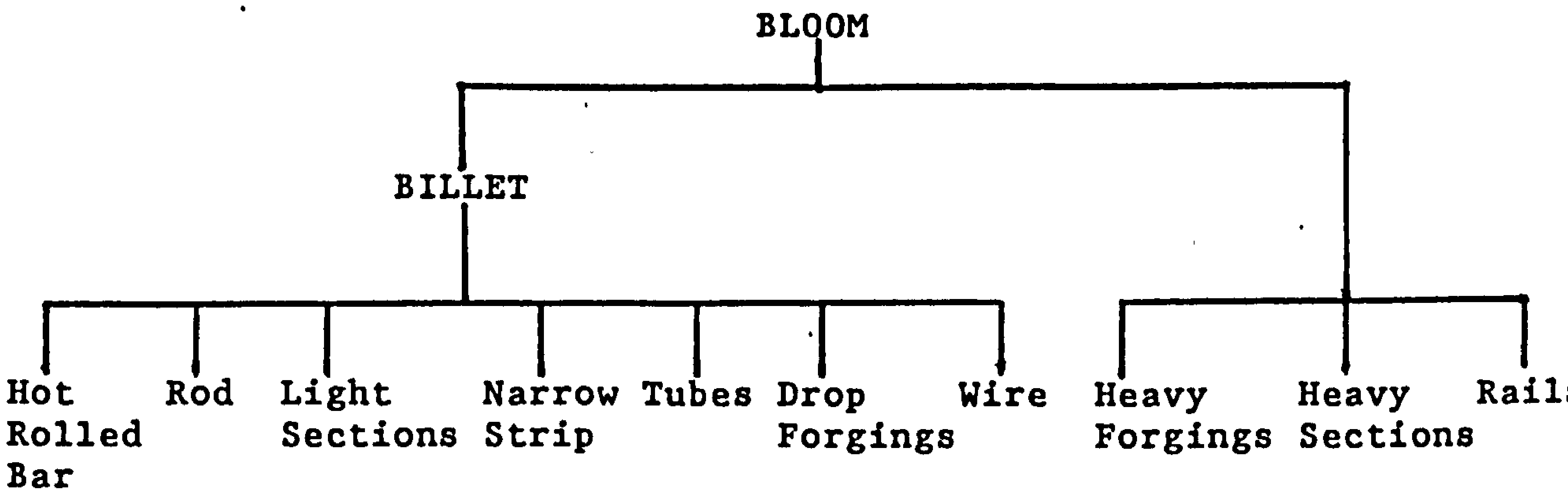

Figure 2.8 Hierarchical tree diagram of the processing of blooms

Slabs, on the other hand, are input to the strip mills to be flat-rolled into plate, sheet and strip, such products being differentiated according to their thickness.

Blooms, billets and slabs are subject to further processing at the finishing stage (described below) either within an integrated steel mill or, following sale, by one of the independent steel producers who have finishing (but no production) facilities. Such firms are often called "re-rollers".

Two points should be noted in respect of semi-finished shaping via the ingot casting route. Firstly, there is a time delay between the ingot being cast, its subsequent removal from the mould and immersion in the soaking pits. Therefore, it is possible to stockpile ingots at this point although the industry prefers to keep little more than an in-process inventory because of the need to subsequently re-heat the ingots in soaking pits. Thermal loss occurs if ingots are stocked for any appreciable length of time and so most are processed quite quickly into semi-finished shapes.

Secondly, as in many stages of steel production, there is a loss in yield due to scrap, scale and dust. In particular, scrap loss occurs in pouring, unmoulding, rolling and trimming. Russell and Vaughan (1976) have estimated the scrap loss from steel furnace to semi-finished shape at 14.3%; overall losses in yield between these two stages are put at 16%, the figure for slabs being slightly higher while that for blooms and billets is slightly lower.

2.2.7 Semi-Finished Shaping via Continuous Casting

This is a technique for directly producing the desired semi-finished shape from crude steel and has the advantage of by-passing the increasingly expensive and time-consuming operations of ingot casting and primary rolling. The molten metal is poured into a trough from which it flows into one or more water-cooled moulds which cause the metal to solidify on the outside. From this point on, rollers propel the shape through further direct water sprays and eventually hydraulic shears or torches cut the desired length. Yields are somewhat higher with this method; the estimate given by Russell and Vaughn (1976) is 96.3% from molten steel to semi-finished shape.

Given below is a flow block diagram of the casting of semi-finished shapes by both methods.

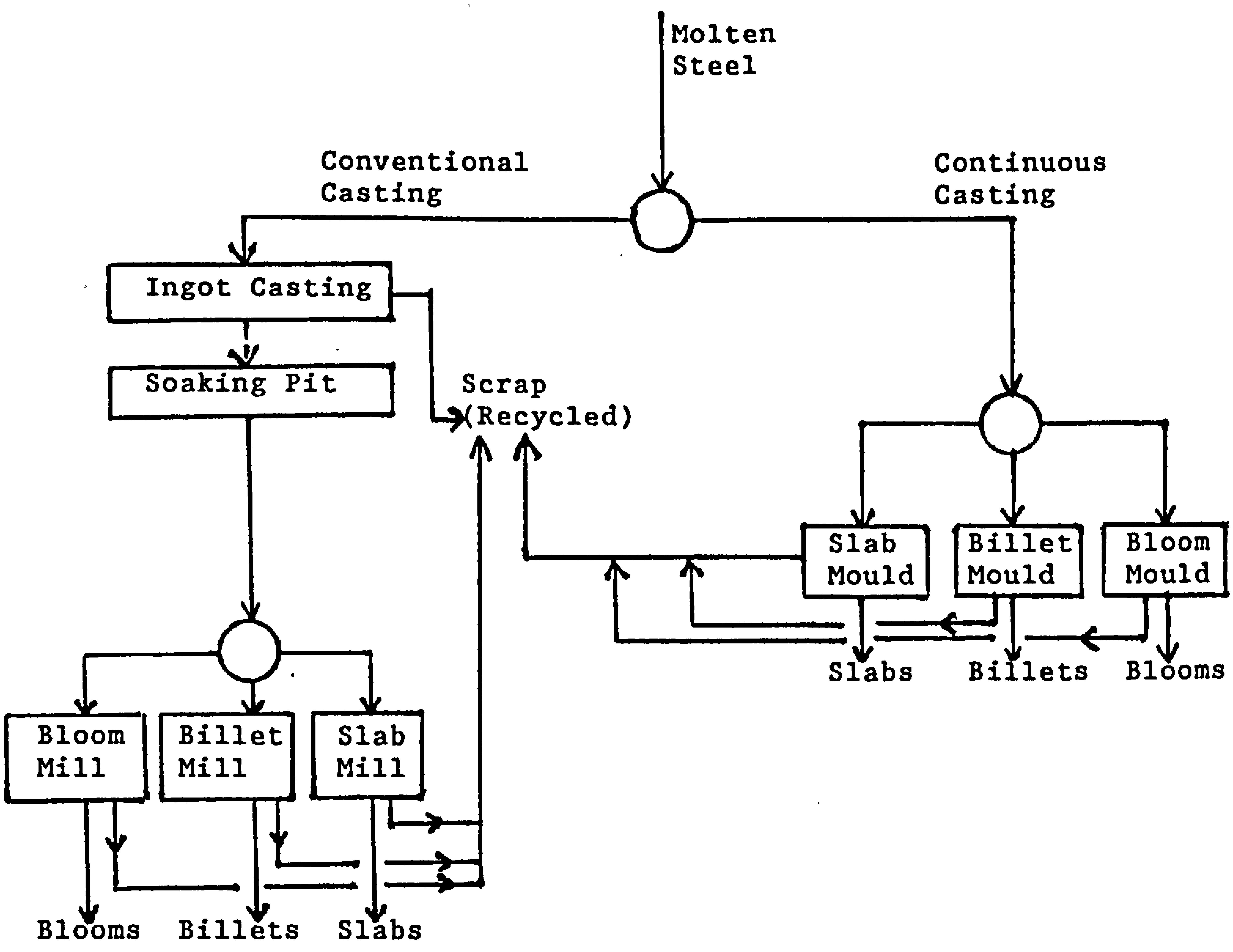

Figure 2.9 Flow Block Diagram of the Casting of Semi-Finished Steel

2.2.8 Steel Finishing Processes

It will be convenient if the finishing processes are illustrated by the sequence appropriate to slabs because these are converted into flat products (coil and strip) the product sector suffering the most volatile customer demand. While the finishing processes in the case of blooms and billets are similar to those for slabs, they exhibit less variety.

Slabs held at the head of the hot strip mill (the first of the finishing processes) are the main strategic stock of semi-finished steel. Indeed, the end of the slabbing mill can be thought of as representing the dividing line between the continuous process phase of steel-making (the "heavy end") and batch production runs of finished products. Customer orders are associated with specific quantities of steel only after the slabbing stage.

Initially, slabs are reheated to bring them up to the required working temperature. While this process is similar to that undergone by ingots it is less extensive, hence the preference in the industry for stocking slabs as opposed to ingots. A further reason for a strategic stock of slabs is, as mentioned above, that it just happens to represent the primary source of steel which can be sensibly earmarked to a customer order. Steel stocked downstream from this point is usually just in-process stock necessitated by the physical need to decouple successive processes from one another. In addition, changes in the chemistry of the metal after hot-rolling (e.g. age hardening) make it financially important that no stocked steel is scrapped due to lack of sufficient customer orders.

Once the required reheating temperature is attained the white-hot slab is passed between rolls (hence the term "hot-rolling") to break off the scale present on the surface of the metal and latterly to promote a reduction in thickness and an increase in length. A consequence of this is an increase in speed: a slab may enter the hot strip mill at 4 to 5 m.p.h measuring 20 feet long and 5 inches thick and be transformed in the space of a few minutes into a strip of steel 1000 feet long and about one-tenth of an inch thick travelling at 30 m.p.h. along the run out table. The hot-rolled steel can then be presented as either guillotined lengths (plate and sheet) or rolled onto a core (coil). The difference between plate and sheet/coil is one of thickness; plate refers to any flat steel product at least 3mm thick.

In scheduling the hot strip mill a certain sequence of width and guage changes is adhered to in order to prevent an excessive rate of wear on the rolls. For a given guage of steel the metal is processed in a sequence of widths which, from one run to the next, form the pattern of a coffin, as depicted in figure 2.10. A maximum limit on the amount rolled of any width is set according to quality standards. Exceeding this limit causes fleck scale to appear on the surface of the metal.

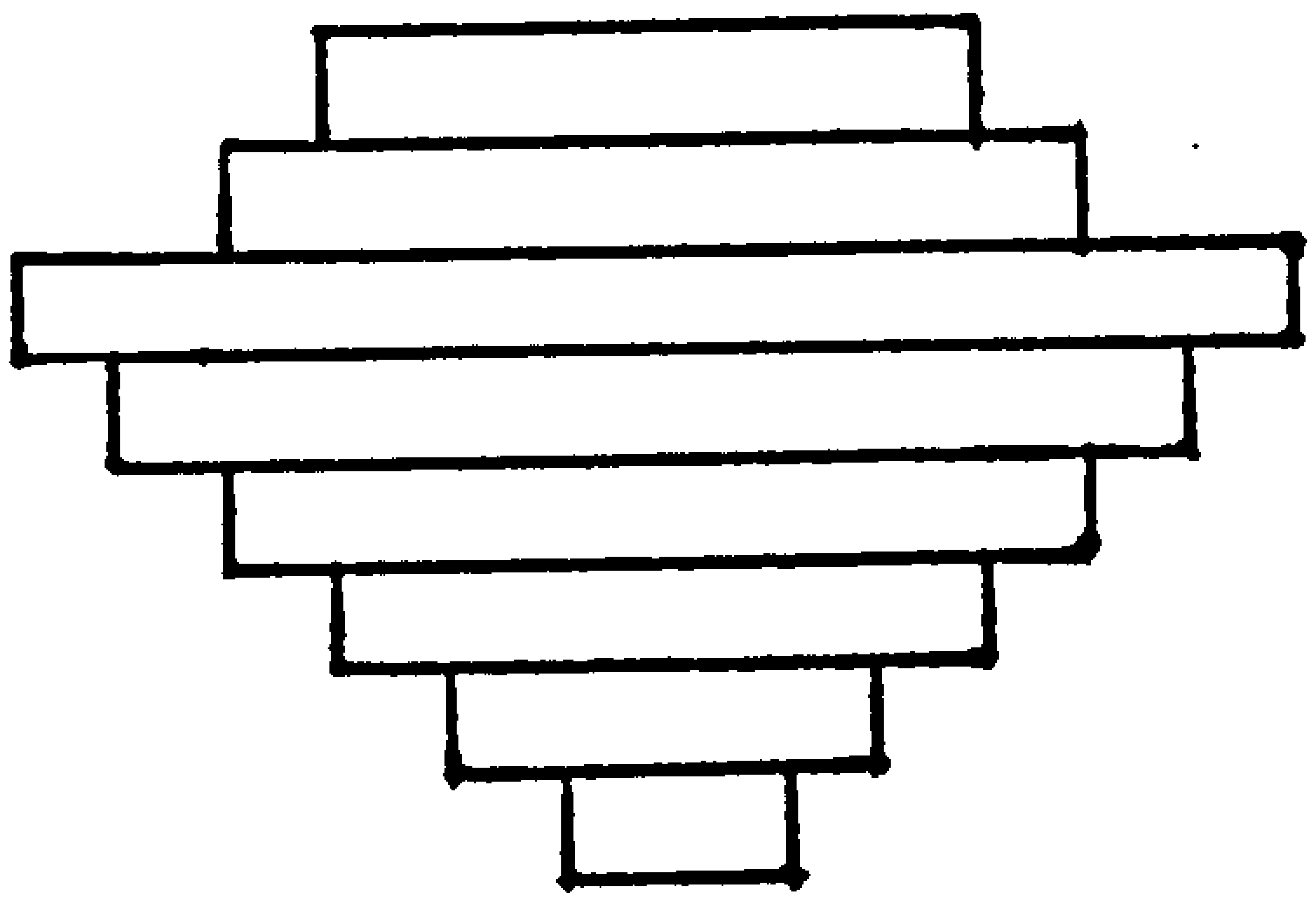

Figure 2.10 The usual sequence of widths used for Hot Rolling batches

One complete sequence, according to the above pattern, is called a "round" and a series of rounds, of increasing guages of steel, is done each week. Every 1-2 weeks it is necessary to replace the rolls with the back-up group and this involves a machine set-up.

While hot rolling of steel produces a material which can be sold "as is", the process itself limits the thickness to which the metal can be rolled together with the quality of the surface produced. For very thin guages or metal with a high quality surface finish it is necessary to have the steel subjected to cold reduction which is the next process downstream.

Hot rolled coil is sold for heavier end-use applications than cold reduced while the private sector re-rolling concerns also take hot rolled steel, as an alternative to slabs, for input to their own finishing operations.

Prior to entry into the cold reduction mill it is necessary to pass the coils through a continuous pickling line. This is a series of baths containing dilute acid that have the effect of removing surface scale, which has formed during storage of the steel or as part of the hot rolling processes.

The major finished product arising from the processing of slabs is cold reduced sheet or coil. The latter is more common nowadays because customers have available their own de-coiling, slitting, trimming and guillotining equipment and so accepting the steel in coil form (an average length of 8000 feet) presents no difficulties. Quantities of fixed lengths to requested dimensions (sheets) are still available but comprise a very small proportion of total production.

The route followed in the cold reduction mill depends on whether the steel is to be sold "as is" or sent for further processing, for example as tinplate, widely used in the food processing industry, galvanised or plastic coated steel. For standard cold reduced coil (e.g. for use in the motor industry and durable goods industries) the steel is merely passed through a four-stand (four pairs of rollers) cold reduction process. Because no heat is involved, thinner guage metal can be obtained whilst at the same time a finer surface quality can be achieved.

When the steel is to be subject to further processing, however, it must be annealed and tempered. The cold reduction process work-hardens the strip as well as reducing its thickness and the metal becomes brittle. Annealing (or softening) involves slow heating and cooling in an oxygen free atmosphere, takes anything from 15 to 45 hours to accomplish, and rids the metal of its brittleness. Finally, temper rolling allows the restoration of a reasonably hard surface to the strip while maintaining the ductility brought about during the annealing process. This is achieved by passing the metal through a pair of hard steel rolls which are loaded heavily enough to restore the hard surface of the metal without further reducing its thickness.

The flow block diagram below, figure 2.11, shows the detailed processes involved in finishing and which have been described above. Beyond the temper rolling stage it can be seen that the steel can be subject to a process of coating. Which process is involved depends on the final use of the steel. For example, electrolytic tinning is used for the tinplating process while dipping the metal in baths of zinc produces galvanised steel. Plastic-coated steel is also available in a variety of colours. British Steel has a technological lead in this process which is carried out at its plant in Shotton, North Wales.

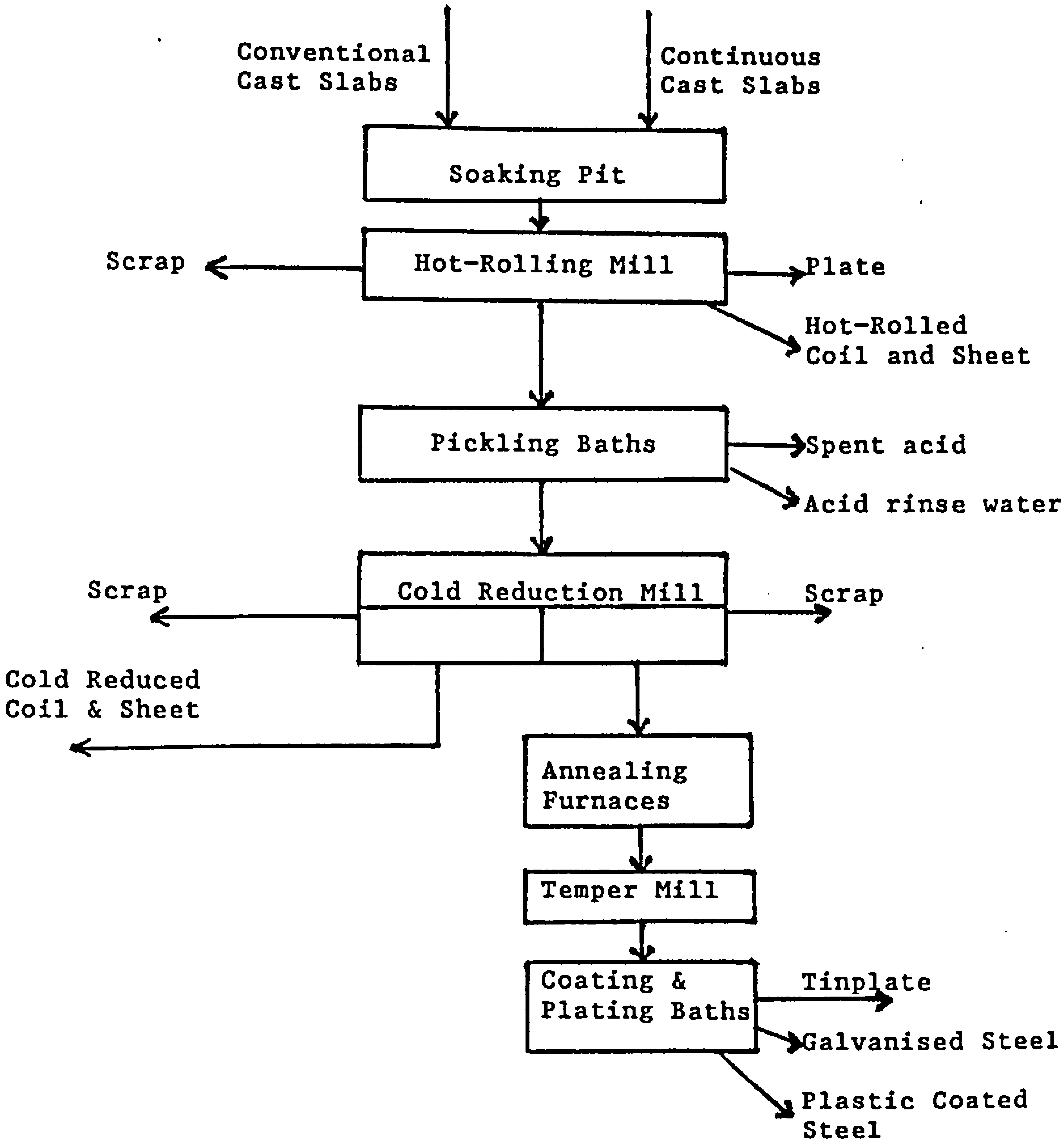

Figure 2.11 Flow Block Diagram of the Steel Finishing Processes

The diagram above indicates that scrap loss occurs yet again in the processing of the metal. This feature is as common in the finishing stages as it is in the "heavy-end" of steel making. Russell and Vaughn (1976) estimate that the overall yield of final finished shapes from semis is 0.866 and from molten steel 0.73 .

Clearly there is a considerable range of finished steel products and it might be useful to establish a percentage split in the total amount produced. Data shows that Llanwern steelworks, for example, exhibits the following split:

Hot Rolled Coil	39%
Hot Rolled Sheet	4%
Cold Reduced Coil	41%
Cold Reduced Sheet	9%
Pickled Coil	5%
Pickled Sheet	2%
	100%

These figures also serve to reinforce the point made earlier in relation to sales of cut lengths (sheet); this is now only a relatively small proportion of total output.

At another major works in (what was) the Strip Mills Division, Port Talbot, the following end-use split of production has been estimated. Here, no subdivision exists as between sheet and coil.

Hot Rolled	15%
Cold Reduced	35%
Tinplate	40%
Electrozinc	10%
	100%

The importance of Port Talbot's output going into tinplating is underlined by the above figures.

Finally, to complement the above locally-produced figures it is perhaps worth presenting the national picture of the split in net home deliveries by UK steel producers. This table excludes material for conversion into other products listed and covers the entire product range.

Ingots, blooms, billets and slabs	5.6%
Rods and bars for reinforcement	7.0%
Wire rods and other rods and bars in coil	7.5%
Hot rolled bars in lengths	7.5%
Bright steel bars	4.0%
Light sections other than rails	2.2%
Heavy and light rails and accessories	1.5%
Other heavy sections	12.8%
Plates 3mm thick and over	14.3%
Sheets, under 3mm thick, coated and uncoated	14.3%
Hot rolled strip	2.1%
Cold rolled strip	3.6%
Tinplate and backplate	6.1%
Tubes and pipes (all sizes)	8.4%
Tyres, wheels, axles and rolled rings	0.4%
Forgings (other than drop forgings)	0.7%
Castings	2.0%
	100.0%

Table 2.2 Percentage split into the main product areas in the supply and disposal of finished steel

From this table it can be seen that flat products account for 40.4% of net home deliveries and this would certainly be higher if a more detailed split of the 5.6% of the total accounted for by "ingots, blooms, billets and slabs" were available.

This part of the chapter has dealt in some detail with the processes and technology involved in present-day steelmaking in Great Britain. For the purposes of the model outlined in the following chapter, however, some of this detail will be superfluous. Nonetheless, it is necessary to cover this ground in order that the reader can appreciate the complexity of operations in the industry and obtain an enhanced understanding so that both numerical estimates of model parameters and technological policy options can be appraised intelligently.

In conclusion figure 2.12 is presented. This shows, in simplified form, an overall schematic diagram of iron and steel making (flat products). In the diagram finished products, as opposed to processes, are set in a double rectangle. The split between the 'heavy end' and finishing operations is important and is encapsulated in the model described in the following chapter.

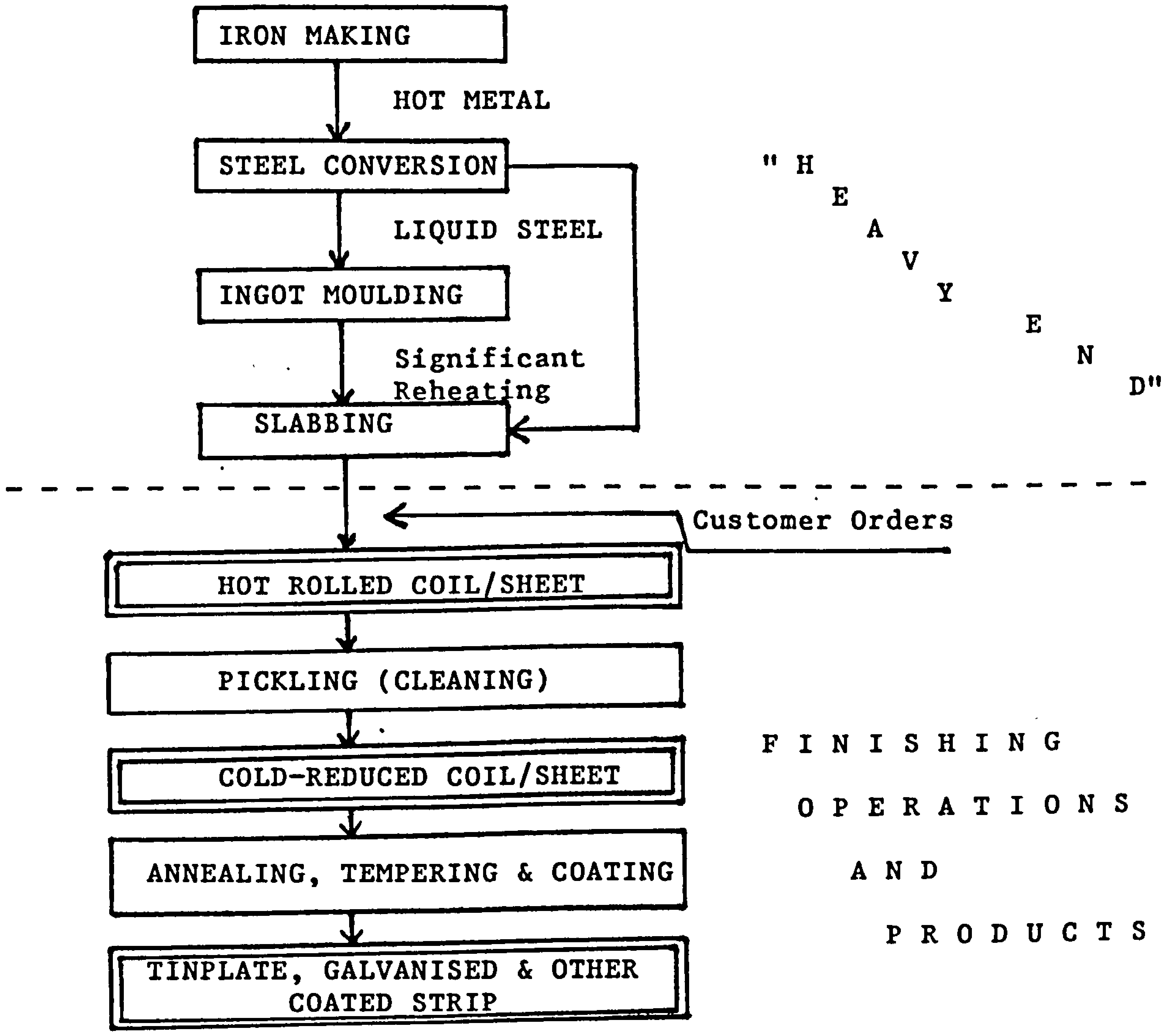

Figure 2.12 Simplified schematic diagram of steelmaking operations and major finished items in the flat products division

2.3 A History of Policy in the Steel Industry over the last twenty-five years

The initial period following vesting of the British Steel Corporation in 1967 concerned a preoccupation with what was termed the 'Heritage Strategy'. This involved concentrating developments on the large integrated steel plants inherited from the private sector. The corporation saw the future as one with the main bulk production of steel concentrated in large hot metal based plants using the basic oxygen system (B.O.S.) for steel making. These plants were to be located at or near coastal sites and served from major iron ore terminals.

By 1971 the results from many of these proposals were in place. Two-vessel B.O.S. plants were installed at the five main sites: Llanwern, Port Talbot, Ravenscraig, Teesside and Scunthorpe. Further, much of the older open hearth plant had been closed down or was scheduled for closure. Coincident developments of iron ore ports to serve the large steelworks were also largely completed during this period.

Whilst the Heritage Strategy was, to all intents and purposes, carried through, it was not particularly profitable. B.S.C. had stated in their Annual Report and Accounts for 1967/68 that proposals for new capital expenditure would be judged on the profitability of the investment and its discounted cash flow return. But by the early seventies it had become clear that, despite surviving government scrutiny and subsequent approval of the capital expansion, the Heritage Strategy was not going to be particularly profitable even when fully completed. The Corporation were in a dilemma. Their solution was to back the technological implications of the Heritage Strategy with all the strength they could muster but in the form of a brand new Corporate Plan. A Corporation Development Plan was initiated in 1971 and this formed the basis of the B.S.C.'s Ten Year Development Strategy published as a White Paper in 1973 (H.M.S.O., 1973).

The appearance of this document effectively signalled the death of the Heritage Strategy. In its place came a policy to build even larger plants at an even lower cost per tonne than anticipated by the abandoned strategy. Unit costs were paramount with little attention being given to the consequences of demand (and hence revenue) forecasts failing to be achieved. On this score, the only concession made by the B.S.C. was that the construction of the proposed new plants would merely be delayed should market forces dictate. The plan outlined a programme that would take B.S.C.'s capacity from 27 million tonnes of liquid steel per annum (1973) to 33-35 million tonnes by the late 1970's and to 36-38 million tonnes during the first half of the 1980's. The five major steelmaking plants were each to be brought up to optimum capacity (which in the case of Port Talbot meant 6 million tonnes per annum) and a brand new steel complex would be created on the South bank of the Tees.

Although the government had trimmed back B.S.C.'s expansion plans (for their 1971 Corporate Plan had opted for *two* new works) the entire plan was, within five years of its inception, shown to be hopelessly optimistic. A detailed analysis of the Corporation's economic planning (and much else besides) is contained in a book written by three University of Warwick academics (Bryer, Brignall and Maunders, 1982) who describe themselves as management scientists but appear to have strong accounting and financial expertise. Their analysis shows how optimistic B.S.C. had been. In 1973 B.S.C. forecasted that liquid steel consumption would be 30 million tonnes in 1980. The out-turn was not much above 20 million tonnes.

The Bryer et al analysis is a strong indictment of the Corporation's planning processes. Forecasts were made as point estimates with no consideration of possible deviations from the trend line. D.C.F. techniques and a 'computerised economic planning model' were deployed as part of the evaluation of the available options prior to selection of the plan adopted. There is independent evidence that this was indeed the case (Morris, 1974). Sensitivity tests carried out on the discount rate chosen by the Corporation (16%) amounted to plus or minus 2%. Overall, it would appear that the level of sophistication brought to bear on the background modelling work was not far from being diametrically opposite to the methods it is the objective of this thesis to promulgate.

In 1975/76 it was patently obvious that a significant recession had enveloped the UK steel industry. This recession heralded an important phase in the trend of steel consumption. For the first time since the Second World War, the trough in the steel cycle was at a point significantly lower than the previous one and it took production levels back to where they had been in the early 1960's. This is shown in figure 2.13 along with another feature which has been investigated already by other authors and is discussed in chapter 3: steel production fluctuates far more than consumption of finished steel. (The severe drop in production in 1980 was due to a major strike in the industry.)

The growth in imported steel (also shown in figure 2.13) is disturbing. Imports rose markedly in the years 1971–74 during a period of rapid economic expansion and much of the imported steel was a direct result of B.S.C.'s inability to supply. But it appears as though a ratchet mechanism operated in the 1970's, perhaps for the first time. Once imports had ramped up they stayed that way, possibly because good customer relations were subsequently forged between UK steel importers and the (mainly EEC) foreign suppliers. The recent further increase in imports (coincident with another economic boom) is even more disturbing. It will be interesting to see if the ratchet effect of the 1970's is repeated.

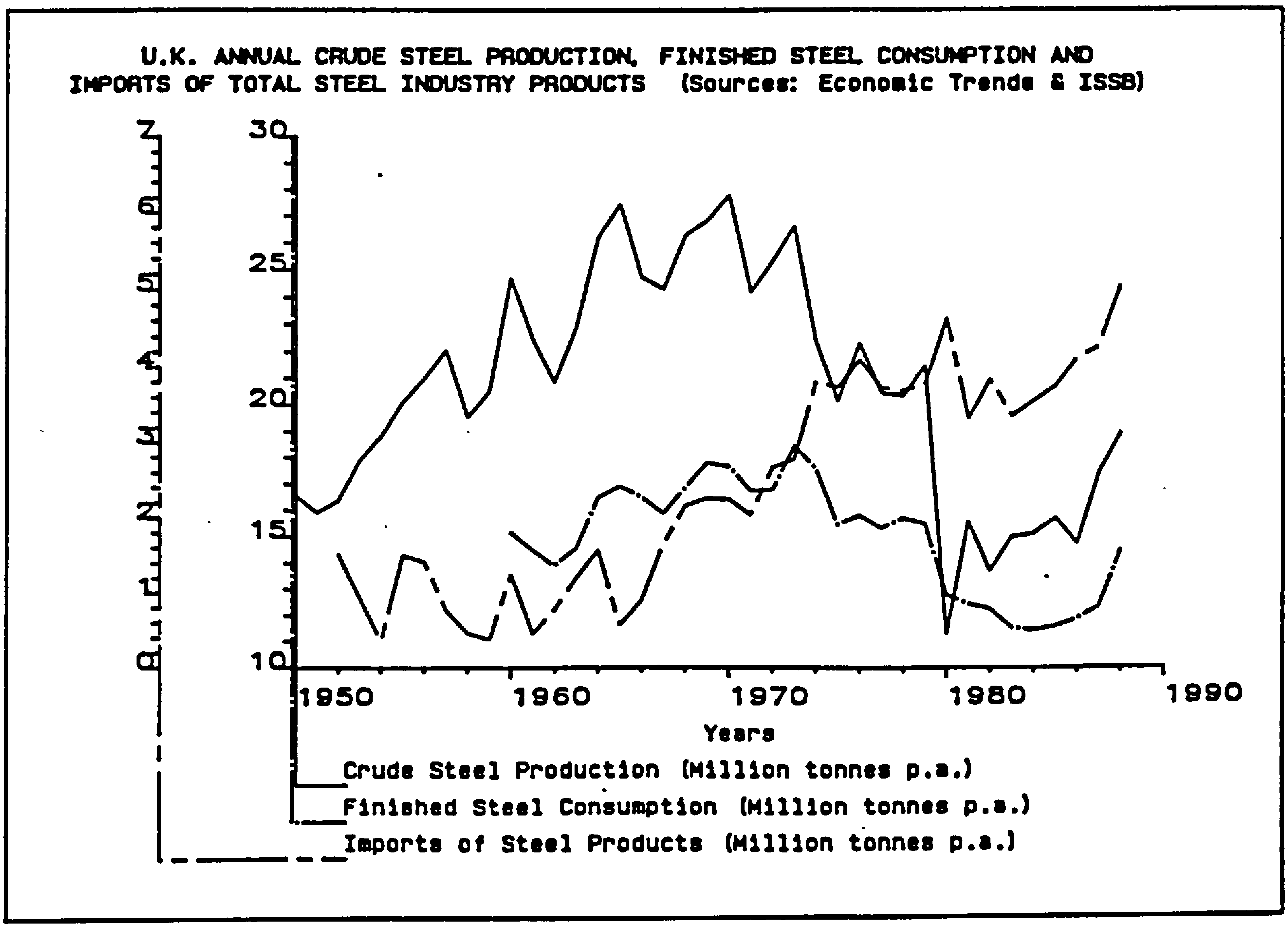
U.K. ANNUAL CRUDE STEEL PRODUCTION, FINISHED STEEL CONSUMPTION AND IMPORTS OF TOTAL STEEL INDUSTRY PRODUCTS (Sources: Economic Trends & ISSB)

Figure 2.13 Crude steel production, finished steel consumption and imports of steel products

During the 1970's the private sector of the UK steel industry had been making significant progress. B.S.C. lost productive output to the private sector, to imports and, to a much lesser extent, to a fall in the overall UK steel market. As mentioned earlier, the private sector share of the market was around 22% throughout the 1970's. Up until they began to lose market share B.S.C. included an analysis of the split in deliveries to U.K. consumers and stockholders in their annual report. Bryer et al (1982) attempted to extract figures for the latter years of that decade from the Corporation but were refused. A copy of the correspondence is included as an appendix in their book.

The reasons for B.S.C.'s losses to the private sector have been put down to the latter increasing its independent steel making capacity, modernising its rolling plant and increasing profitability (N.E.D.O., 1986). Private sector new investment rose from £36 million in 1968 to £120 million in 1975. The analysis by Bryer et al (1982) is quite unequivocal in its assertion of the reason for the success of the private sector. In modernising from the Open Hearth steelmaking technology they had gone for Electric Arc furnaces (E.F.), producing steel in small-scale plants which have become known as 'mini-mills'. These had several cost advantages over the large integrated steel works. Capital costs per tonne, operating costs per tonne and better labour productivity combined to ensure that, for certain throughput rates, the mini-mill was a more desirable production configuration than an integrated works. W.F. Cartwright, one time Deputy Chairman of B.S.C., suggested that the unit cost curves of the Blast Furnace/Basic Oxygen System and the Electric Furnace process routes were as shown in figure 2.14. The diagram is extracted from a paper he published in 1971 (Cartwright, 1971).

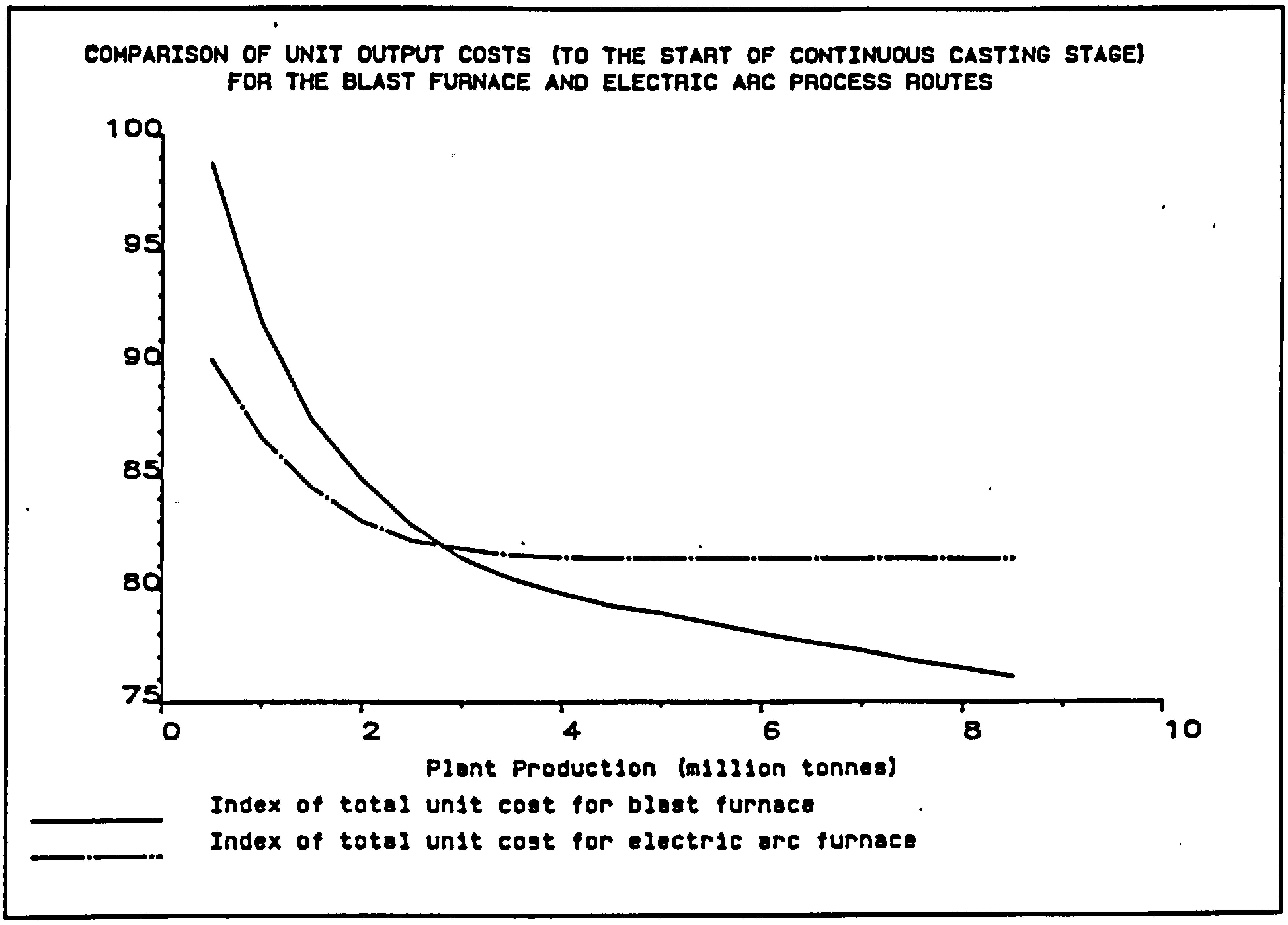

Figure 2.14 Comparison of cost per tonne graphs for the BF/BOS and EF process routes

The exact cut-off point between the two methods of steel making is determined by factors such as the price per tonne of coking coal and iron ore used by the integrated works set against the price per tonne of scrap and of electricity both used by the electric arc furnaces in the mini-mills. Despite the obvious support of a Deputy Chairman, the B.S.C. never embraced the mini-mill concept. In the 1971 Ten Year Development Plan the construction of two small new works based on the electric arc steelmaking technology was mentioned but construction had not even started before yet another White Paper called a halt to any expansion of steelmaking capacity.

The epitaph on the Ten Year Development Strategy came with the publication of the 1978 White Paper, this time entitled 'British Steel Corporation — the Road to Viability' (H.M.S.O., 1978). This was as gloomy a document as its predecessor five years earlier had been expansionist. Now B.S.C. policy was to get back to profitability by closing down either the entirety or the steel making end (heavy end) of those works which were not 'large-scale producers'. In other words they proposed to buttress their arguments concerning low cost production in large integrated plants by closing down the smaller ones which, by implication, must be high cost plants (Bryer et al, 1982). Despite the initiation of a government review of the closure proposals (conducted by Lord Beswick) steelmaking ceased at Corby, Consett and Shotton over the following five years. Bryer et al claimed that all three of these plants were financially viable.

The recession deepened over the turn of the decade and the EEC was forced to declare a period of 'Manifest Crisis' in the industry in 1980. In 1980 alone UK crude steel production fell by 48% to 11.3 million tonnes from 21.5 million tonnes the year before, although 1980 was somewhat exceptional in that it also was the year of a three month steel strike (N.E.D.O., 1986). The EEC Declaration heralded a community-wide quota system for output and this was to last five years. B.S.C. policy dictated severe retrenchment. The labour force had already been cut by 42% between 1974 and 1980. It fell by a further 45% in the four years 1980-84 (N.E.D.O., 1986). Things reached such a critical state that steelmaking at one of the 'big five' integrated works (Ravenscraig) was likely to cease and the plant was earmarked for closure. However, the Scottish plant survived following a government review in 1985 but it lost its associated cold rolling plant at Gartcosh.

The steel cycle turned for the better in 1985-86 when, for the first time in a decade, B.S.C. made a profit. From that point onwards, and at least until the time of writing, policies on technology have not been called into question. Until the last eighteen months or so, demand has been trending upwards and in 1987-88 B.S.C. made its largest ever profit. It was privatised, to become British Steel (B.S.), at what will possibly turn out to be the peak of the current steel cycle.

Postscript In 1990 it was announced that Ravenscraig was to lose its hot strip mill in April 1991. With three hot strip mills in the Strip Products Group (Ravenscraig, Llanwern and Port Talbot) each was running at only, say, 70% of capacity because of a demand downturn. B.S.C. financial policy dictated that this was highly disadvantageous. The closure of one would mean that the other two could then operate at around, say, 95% of capacity and be profitable even after allowing for the extra transport costs of moving slabs from Scotland to South Wales. While this policy might provide a short-term gain to British Steel plc it begs the question of whether the organisation will be able to respond when demand turns up again in the mid to late 90's. The import ratchet may then once more move up a notch.

REFERENCES FOR CHAPTER 2

J M AYLEN (1988) "Privatisation of the British Steel Corporation", *Fiscal Studies*, 9, 1-25.

J M AYLEN (1989) *"Choice of Process Route in Steelmaking"*. Unpublished paper presented at the 3rd European Electric Steel Congress, Bournemouth.

D F BARNETT and R W CRANDALL (1986) *"Up from the Ashes: the Rise of the Steel Minimill in the United States"*, Brookings Institution, Washington.

BRITISH STEEL CORPORATION (1988) *Annual Report and Accounts 1987-88*

BRITISH STEEL CORPORATION (1972) *"Making Steel"*, Information Services Department, London.

R A BRYER, T J BRIGNALL and A R MAUNDERS (1982) *"Accounting for British Steel: a financial analysis of the failure of the BSC 1967-80 and who was to blame"*, Gower Press, Aldershot.

W F CARTWRIGHT (1971) "The Economic Survival of the Blast Furnace", *Journal of the Iron and Steel Institute*, 209, 89-95.

K CHARTERIS (1975) "Reorganisation for B.S.C.", *British Steel* (House Journal), 11-14.

A COCKERILL (1974) *"The Steel Industry - International Comparisons of Industrial Structure and Performance"*, Cambridge University Press, Cambridge.

A COCKERILL (1975) "Steel Strategy", *Management Today*, November, 44-49.

D R DILLEY AND D L McBRIDE (1967) "Oxygen Steelmaking: Fact vs. Folklore", *Iron and Steel Engineer*, 44, 131-152.

HMSO (1973) *"British Steel Corporation: Ten Year Development Strategy"*, Cmnd. 5226.

HMSO (1975) *"B.S.C. Organisation Review 1975"*, House of Commons Paper No. 604, Session 1974-75, 6 August.

HMSO (1978) *"British Steel Corporation: the Road to Viability"*, Cmnd. 7149.

T T JONES and A COCKERILL (1984) *"Structure and Performance of Industries"*, Philip Allan, Oxford.

P H MORRIS (1974) *"Economic Planning in the B. S. C."*. Unpublished paper presented at steel industry seminar, University of Liverpool.

NEDO (1986) *"Steel: the World Market and the UK Steel Industry"*, London.

G ROSEGGER (1980) "Comparing a New Technology with its Predecessor: Steel Making", *Omega*, 8, 533-543.

C S RUSSELL & W J VAUGHAN (1976) *"Steel Production: Processes, Products and Residuals"*, Johns Hopkins University Press, Baltimore.

J VAIZEY (1974) *"The History of British Steel"*, Weidenfeld and Nicolson, London.

3 A MODEL FOR TECHNOLOGY POLICY IN THE STEEL INDUSTRY

3.1 Introduction

Having outlined the different technologies available in steelmaking and the way these have changed over the last three decades, together with the policies adopted by B.S.C. management, it is now appropriate to evaluate, with the help of a model, those and other strategic policies insofar as they relate to the steelmaking technology employed. It will be seen that strategic policy in this industry fuses strongly with the technology in use. As already explained, the British Steel Corporation (B.S.C.) declared that the way forward for the UK steel industry involved large integrated works which, in turn, implied a commitment to a certain type of steel technology. Profitability (arising directly from low unit costs of production) was paramount in the criteria which the directors of B.S.C. assessed when deciding on their policy.

Unfortunately the achievement of low unit costs of production and its continued attainment over the course of the typical four year economic cycle do not always go hand in hand. Their seeming neglect of the revenue side of the profitability equation meant a potent force which could undermine the selected strategy went ignored. For a more robust strategic policy to emerge, especially in connection with an industry where the chosen technology is such an important facet to evaluate, the market *as well as* the cost side needs to be considered.

The model described below attempts to capture the essential facets affecting strategic policy considerations in the steel industry insofar as they relate to the available steel making technologies. Perhaps for the first time a policy support tool is provided which considers both the cost and market aspects of strategic policy choices. Further, it is hoped that the model will act as a focus of debate by industrial economists who, while able to conduct sound empirical and theoretical analyses of the cost side of the industry, are denied a suitable analytical tool which is capable of handling the implications of strategic policy choices for the revenue side.

Before the detail of the model is described it will be useful to set the whole thing in context by describing some of the other modelling work which has been conducted in the steel industry. This involves techniques ranging from OR type optimising approaches through to econometric methods and system dynamics.

3.2 A Review of Modelling Studies in the Steel Industry

It is hardly surprising that the steel industry has been the subject of numerous modelling studies over the years. Given the large-scale nature of integrated steelworks, the fact that the production function features strongly in the studies reported is also unexceptional. The work undertaken can be categorised into O.R. type projects dealing with tactical and operational problems, econometric models examining the industry in aggregate and finally systems studies which concentrate either on a particular works, division or the entire industry.

In very general terms and devoid of references to specific projects Disley (1990) gives an account of some of the problem areas which have been the subject of OR Studies in the British Steel Corporation (and now British Steel plc). One much more detailed account is given by Sutton and Coates (1981) and this is a prime example of the sort of project which examplifies the classical OR approach. The problem was to "provide a more scientific and objective base for the buying and use of raw materials" by BSC Stainless, a part of BSC Holdings. With an annual raw material purchase bill of £100 million the incentive was certainly there to optimise on the raw material mix used each day. The system developed was based on a mathematical programming model with results available for interrogation by personnel at several different locations within BSC by means of VDU screens and printers. A typical mix calculation considered up to 50 materials and up to 23 elements in each material with up to 10 calculations executed in any one working day. This was a vast improvement over the manual approach previously undertaken by Mixture Clerks.

In a similar vein Jagers and Huisjes (1986) describe OR studies done in the Dutch steel industry, specifically for the Hoogovens Group. One concerns the decision of which finished products to produce in a strip mill and in what quantities. Again mathematical programming was employed to maximise the profit subject to constraints such as the capacities of the rollers and the finishing lines together with bounds on the sales of different finished products.

Another project described by these two authors concerned the problem of combining coils for pickling lines. Hot-rolled coils of steel have to be stripped of scale (an oxide skin) before being cold rolled. This involves uncoiling the steel and drawing it through a number of tubs filled with acid. Unpickled coils, on entry to the process, are welded to form an unending strip and at the end of the production line the strip is sheared to form coils. A pickled coil has to contain an integer number of coils for the customer.

In combining the input coils to form the output coils, questions like at which point should the strip be sheared and which order to enter the coils into the pickling line need to be answered with the objective of, amongst others, minimising the number of welds in the output coils. To carry out this project a heuristic approach was devised consisting of two parts. In the first part the most important cost component (called the basic cost) of all possible solutions is determined. In the second part a more precise study of costs takes place, starting with the most promising point emerging from the first part. The authors note that the cost analysis inherent in the solution methodology led to insights which resulted in improvements in the production process *and these improvements were independent of the method adopted for combining coils.*

Noordman, Gillebaart and Seeder (1986) describe other projects carried out for the same Dutch steel company. One project, for the tubes manufacturing division, involved the determination of how to best slit narrow steel strips longitudinally from wide steel rolls, the strips to be eventually welded to form tubes (seam-welding). Objectives included maximising the roll-width utilisation and standardising the strip widths cut by each machine in order to minimise the number of machine set-ups. In its simplest form this is (again) a standard mathematical programming problem but such an approach could not be employed because complications in the formulation meant that the resultant model became too large for computer solution in a reasonable time and with regard to the computing facilities available to the company. Consequently a heuristic method was devised and programmed in FORTRAN. This provided results in an acceptable amount of time but the accuracy of the resultant solutions was doubtful.

Discrete-event simulation has (in addition to mathematical programming) been used reasonably often in the steel industry and Noordman, Gillebaart and Seeder go on to describe one such study involving coke manufacture. This process takes place prior to producing hot metal in the blast furnaces. In fact, coke is an irreplaceable raw material in the blast furnace and it is manufactured by heating coal in an enclosed oven so as to remove undesirable volatile gases. Once the coal has been converted to coke, the heat source to the ovens has to be extinguished and the coke dampened with water.

Many coke ovens exist side-by-side. In the plant under investigation there were 100 coke ovens in a space 200 metres long and 15 metres high. These produced 1.5 million tons of coke per annum. The production process involves successively emptying and filling the ovens. Filling is carried out by a coal charging car which takes coal from a bunker and charges it into the coke oven which has just been emptied. (The emptying is done by a machine involving a sequence of operations.) Each oven must be emptied and filled during the minimum cooking time for the previous coke oven. The production process has a cyclic form: as one operation is completed the next to be performed becomes due in the sequence.

The simulation program, written in the SIMULA language, allowed the evaluation of trade-offs such as that between greater output and uniformity of cooking time. It may well be, given the possibility of machine breakdown, that a more uniform cooking time will make it easier to control the process. However, a longer cooking time automatically reduces production output. With many factors affecting the operations in the coke oven plant it is clear that the analysts were correct in using a discrete-event simulation model. It was the obvious form which the OR model should take for that particular type of production problem.

While all of these studies are important in the context of the individual firm concerned (and indeed they may generate interest by other steel making firms) they are not studies at the policy level. It is unlikely that such problems would preoccupy the minds of the board of directors of those firms in discharging their role of providing strategic guidance.

A more strategic orientation is taken by Anandalingam and Bhattacharya (1985). They describe a process model of the Indian iron and steel industry which handles material and energy flows within the industry. The objective of their study was to assess the impact of different technologies on those flows and to compute an overall production cost with particular emphasis on energy costs. The electric arc furnace technology was not included (presumably because it did not then exist in India) and so the comparison was primarily between the Open Hearth and Basic Oxygen systems. After analysis using a deterministic process simulation they concluded that, although a number of cost-effective energy-conservation measures exist, none of them would lead to large reductions in energy use in the Indian steel industry.

In a subsequent paper Anandalingam (1987) describes extensive parameter sensitivity analyses on the model which was programmed in LOTUS 1-2-3 and executed on a microcomputer. As before, analysis of the results revealed that energy-conservation technologies would have an insignificant impact on performance.

Econometric studies are often conducted at a high level of aggregation and although such models are hampered by complete reliance on the availability of time series data and the need to obtain a good statistical fit, two studies, which are useful in the context of this thesis, have been reported.

Blake (1965) investigates the phenomenon mentioned in chapter two: that fluctuations in steel consumption are somewhat less than the fluctuations in steel production. Although more data are now available than he had at his disposal, it is clear from figure 2.13 in the previous chapter that the phenomenon still exists. For an econometric study, Blake's contribution is unusual in that, firstly, he uses tonnage (not monetary) data and, secondly, he is concerned with inflexibility in supply (and the reasons for it) which makes the study interesting to *management* and not just other economists.

He recognises that consumption and production have to be related by an information flow: in this case orders booked by steel consumers and stockholders. His model consists of two hypotheses, firstly, the way in which consumption of steel affects future orders booked and, secondly, the way order flow determines output. He states that "both relationships are inter-connected by a complicated feedback mechanism, according to which current orders and current output are separately affected by ...... the change in the backlog of undelivered orders ...." Had he been aware of the tools of system dynamics there is no doubt that he would have been able to more easily explain the phenomenon than by using multivariate least squares techniques on what data he could uncover.

His supply hypothesis relates the changes in steel deliveries to changes in orders booked and the change in the order backlog. The demand hypothesis relates orders booked to the difference between finished steel consumption and deliveries together with a variable representing stock adjustment by consumers. In both cases a reasonably good statistical fit to the data was obtained.

In the conclusions section of his paper Blake makes some interesting observations which touch on the purpose of the steel works model described later on in this chapter. He describes a "characteristic sequence" whereby, once steel demand changes, delivery dates are adjusted and capacity is brought in or taken out. There then follows a burst of precautionary orders from customers (when demand has increased). Thus, true demand is somewhat accelerated, production of steel eventually responds but it overshoots when demand falls away again and consequently consumers' stocks of steel then grow rapidly. At the next general demand upsurge these stocks are used up first and then the entire cycle is repeated.

Two enhancements would have been useful in the research conducted by Blake. Firstly, he might have investigated the role of the steel stockholders in amplifying customer demand by virtue of their stock control procedures. He recognises that these independent firms provide an information barrier to the steel producers, standing as they do between producer and end-consumer. That such amplification takes place and the detailed reasons for it are recounted in Forrester's classic study (1961). Secondly, he might have given further thought as to *why* steel producers respond rather slowly to overall demand changes. One factor contributing to this important facet of the steel market, with ensuing disadvantages to all parties involved, is offered in a later section of this chapter.

Vinell (1973) uses econometric methods in his comprehensive study of demand-generated steel cycles in Sweden. His study, while examining a broader sweep of issues, has much in common with the work of Blake. Vinell's objectives were to explain why the steel market in Sweden showed such a markedly cyclical behaviour, how demand cycles spread through the steel sector and how they affected the short-term marketing policies of steel producers.

Vinell's statistical work confirmed that steel cycles were a function of firms' inventory behaviour. Although a short section of his work examines the activities of steel stockholders there is no apparent attempt at isolation of the role of stockholders in *amplifying* steel cycles. The stockholders are strongly associated with the cyclical patterns of Swedish imports. These, in turn, are sensitive to variations in the capacity:demand ratio, a variable he used as a proxy indicator of the delivery flexibility of the Swedish steel works.

Vinell asserts that cycles can best be explained by consuming firms' investments in 'goods in process'. Because firms purchase both for consumption and for stockbuilding, total steel purchases (and hence orders on the steel mills) will fluctuate around steel consumption.

Although he admits that the stockholding behaviour of consuming firms plays a part in generating cycles in orders placed with the mills, like Blake he does not investigate how the mills themselves may contribute to an exacerbation of that cycle. However, in common with other authors on the steel industry he does accept the inflexibility of the large integrated works. He states:

> *"........ we know that steel production capacity is inflexible in the short run. The producing units have always (at least in modern times) been comparatively large and the optimum size of plant has been increasing. To raise capacity substantially is a very time consuming process. The time elapsing from investment decision to increase of output is a matter of years. The steel works have therefore no possibility of quickly adjusting their capacity to an upswing in demand".*

He goes on to consider the situation prevailing when demand turns down. Excess capacity prevails and "firms will try to supply a quantity equal to their available capacity in order to get some contribution to their big fixed costs".

In the model dealing with an explanation of Swedish steel imports, delivery times feature as an explanatory variable. Not untypically for an econometric investigation Vinell has no data on delivery times directly available and resorts to manufacturing some from those data series he does have, in this case using estimated realised demand divided by the production capacity one period ago. His conclusion on Swedish imports states that the formulated function "received a certain amount of empirical support from the variables discussed".

At least two studies have been conducted on the steel industry using the methods of system dynamics. The purpose of the model created by Kumar (1983) and Kumar and Vrat (1989) is quite different from that developed by Carnell (1974) and, although the latter shares some common ground with the model described later, neither overlap it to any great extent.

Kumar describes a study examining the future of steel making in India. It is an assembly of a number of separate but connected models, running to some 3500 statements. Modules represent the general Indian economic situation, steel demand, steel production, the supply of coking coal and power, inventories and, finally, a financial model. The purpose is to identify, for the steel plant management, potential production bottlenecks over a ten year planning horizon and to permit the evaluation of rationalisation and modernisation projects already contemplated.

Kumar's model differs from the other Indian model described earlier (due to Anandalingam) in that, besides employing a different modelling methodology, it was carried out for a specific (named) steel plant and is also much more wide-ranging in its coverage and content.

The steel demand model is related to the model describing the general Indian economic situation. Within the demand model is generated the demand for nine different varieties of steel. In turn, the steel demand model drives the production model which considers in detail 26 production sectors covering such as coke ovens, sinter plant, blast furnaces, open-hearth furnaces, melting shops and all the finishing facilities. It can be seen that the production model is at the core of the whole thing and, to employ the dichotomy developed in chapter 1, it generates a set of internal scenarios. But it is also embedded within a system of models which allow for the generation of external scenarios too, the latter directly impinging on the steel production model via the demand model.

Compared to the model developed later in this chapter, the Indian one is much more wide-ranging. There is no mention of any specific examination of the technology used at the heavy end and the part that this sector might play in supply inflexibility. Despite its enormity, which predisposes it to stifle effective managerial learning, it is nonetheless a notable example of a system dynamics model which has actually been used in a practical policy-making context.

The final study reviewed in this section, that by Carnell (1974), comes the nearest to touching on facets of the model developed subsequently in this chapter. It was a study conducted in the early 1970's while he was working in the OR department of the (then) Strip Mills Division of the British Steel Corporation. System dynamics models were constructed to examine two major aspects of steelmaking: the industry-market interactions and production flows.

Of these two models, aspects of the former one are also considered in the model developed below. The market model examines the relationships between BSC and its customers. It probes the purchasing behaviour of end users of steel and also that of stockholders. In contrast with the model below, these sectors are modelled explicitly. Equations are included which represent the assumed forecasting and stock control procedures adopted by BSC's customers. In other words these sectors are endogenous to the model of the Corporation's activities.

Carnell explores detailed features of BSC's order processing procedures and stock-holding policies with a view to showing that market dynamics have potentially internal causes. For instance, the delay in responding quickly to new customer orders in a boom leads to a flood of precautionary orders because purchasing officers in the consuming firms wish to cover themselves against loss of supply. This, of course, is exactly what Blake (1965) was saying in his paper discussed above. Carnell demonstrates that certain delays inherent in the processing of steel orders, together with the Corporation's stockholding policies, are tending to exacerbate this undesirable behaviour pattern by its customers.

The role of steel stockholders is also investigated and, as would be expected from a priori considerations, this sector, standing as it does between producer and end-user, amplifies any fluctations induced by the behaviour of the steel consuming industries. Imports and orders for imports are specifically included, showing one more consequence of BSC's inability to supply quickly enough. However, at no point does Carnell consider the inflexibility of steel making technology at the heavy end (especially the blast furnace) as possibly contributing to the problem of supply lags.

Although this is arguably one of the first in-house system dynamics studies conducted in the UK it is clear that the author had a grasp of the realities of utilising models such as this. He notes that "the conclusions reached and recommendations made are only likely to influence the general tide of opinion". Further, he notes that "the simulation aspect must be viewed as a tool used during the (policy) analysis processes rather than as the purpose of the study".

The production flow model, Carnell's second one, represents each main aspect of the steel making process from ingot production through to deliveries. This dovetails less well with the model developed later in that it was constructed mainly to analyse inter-process stocking policies and finishing mill scheduling. Of particular importance was an examination of process interruption, caused by plant breakdowns, and the way in which the subsequent undesirable dynamics are transmitted through the works. This model runs to several hundred equations and the author clearly feels it to be of some merit claiming that it was probably the most detailed production flow model, outside of the petro-chemical industry, then in existence in the UK.

To the present author, the production flow model resembles what may be called 'classic system dynamics' with an emphasis on operational procedures and the need to consider the totality of the production system in order to be able to improve matters. This comment is no way meant in a derogatory sense, but rather to emphasise the difference between that type of study and the purposes for which system dynamics should now be used if it is to fulfill its potential: namely to act as a fulcrum for debate in the strategic policy-making process. Models of multi-echelon production and distribution systems will doubtless continue to be built, but system dynamics has the potential to be elevated to a much more significant, and as yet underutilised, role in corporate management.

Carnell's contribution was an early one yet there is unfortunately no postscript describing how the market dynamics model (in particular) was received by senior management and whether it had any perceptible influence on attitudes. Given that it must have been one of the first occasions when the method had been used in the UK, it is difficult, when judging the two studies as a single entity, not to come to the conclusion that the technique came before the applications. It was as though Carnell's department felt they could do something useful with the method and subsequently picked out two main areas for investigation. Certainly his thesis and its title strongly emphasises the technique whereas nowadays it would be more fruitful to work from a policy issue orientation. Concentrating on a relatively focussed issue -- like the role of blast furnaces in supply inflexibility -- implies a trend away from more all-embracing models, such as those developed by Kumar and Carnell. This is surely the key to grabbing the attention of senior management and hopefully challenging their preconceived mental models.

3.3 Description of the Steel Industry model

3.3.1 Overview of model purpose and model boundary

The purpose of the model should be made quite clear at the outset. It is to provide the B.S. directors with a tool which should inform their debates about future policy. While it might not contradict the view that mistakes have been made in the past, the model has been created not in a spirit of assessment but rather in one of learning. (That policy planning is a learning process has been well documented by De Geus (1988) who has been referred to earlier in this thesis.) If the ideas generated by collective interaction with the model help B.S. to define policies which are robust enough to see the company through the 1990's, then it will have served the purpose for which such a model should be created. The model will have enshrined the true role of a policy support tool.

In the light of this model purpose, along with the need to consider certain features of different steel making technologies, it seems sensible to draw the model boundary around a single works, together with its market interactions. Accordingly, a model has been created of a works which supplies a nominal total of 2.88 million ingot tonnes per annum. The setting should be considered primarily as a works in what was once called the Strip Mills Division, supplying sheet and coiled steel to motor manufacturers and other durable household goods manufacturers, for example those producing white goods such as washing machines, fridges, and freezers. This does not rule out its applicability to other (also now organisationally redundant) product divisions, most notably General Steels Division. However, it is within the flat products sector that the bulk of sales by volume are generated. Some 44% of all products sold in the 1987/88 operating year came from the flat product mills (Financial Times, 1988).

Throughout, the units of production and sale are measured in ingot tonnes. It is well known that, for instance, production of one tonne of cold rolled coil requires rather more (in fact some 30% more) than the ingot equivalent. This is primarily because of shearing loss during the various processes of manufacture. Both shearing loss and chemical reaction loss affect yields at all stages of steel production. Standard conversion factors have been established at each stage but, for the purpose of the present model, it is not important if such complications are ignored. Comparative runs are conducted *across* technology options. Yield changes are cancelled out as a result. This would not be the case if the model's purpose was to explore, say, interprocess stocking policies *within* a structure determined by a given technology.

The broad outline of the assumed structure of the model is given in figure 3.1 below.

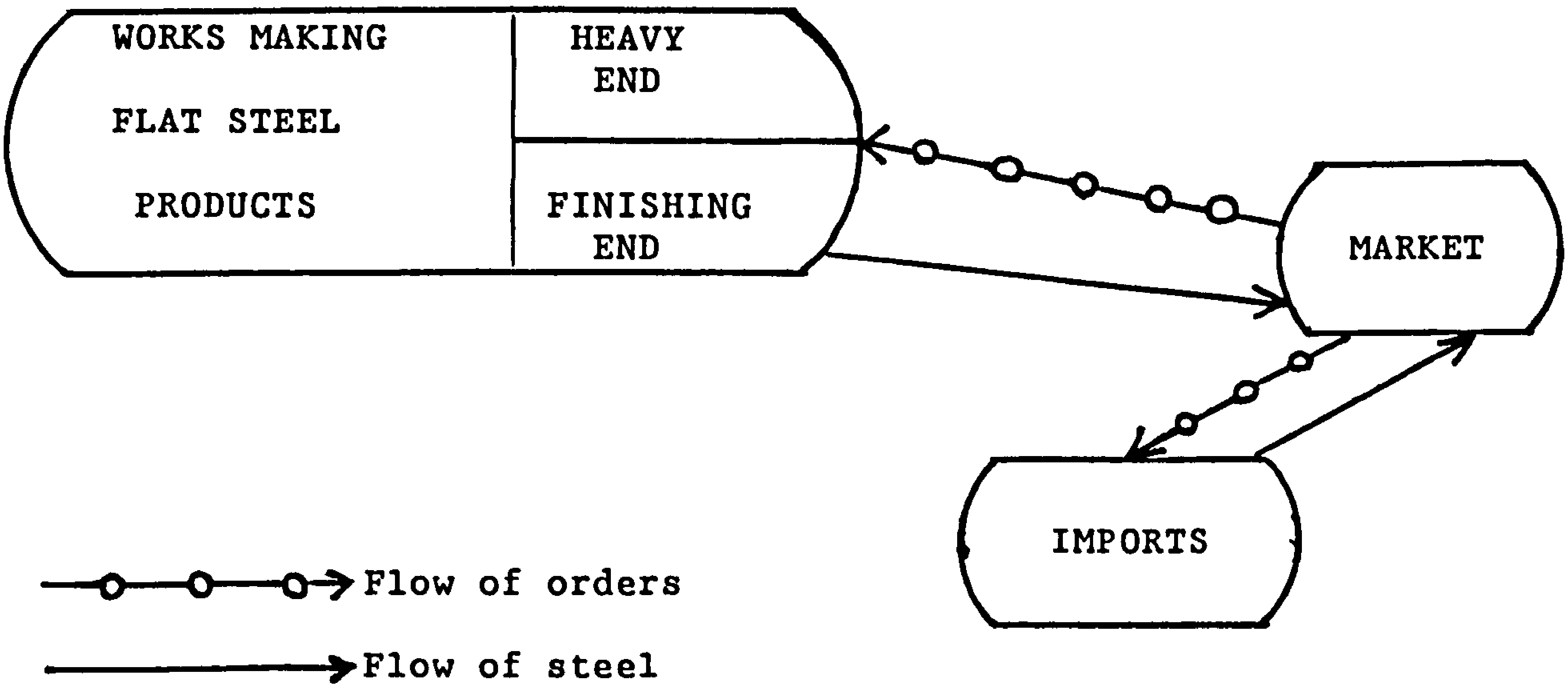

Figure 3.1 Broad overview of the model structure

Industry - market interactions are centred around the ordering of steel and its eventual delivery. Lead time is a crucial determinant of supplier performance and in the case of a product like steel it is essential for supplies to be maintained, especially in times of economic booms. Unfortunately this is not always the case and steel users (particularly motor vehicle manufacturers) are forced to source their supplies from other steel makers. Over the previous twenty years more and more this has meant that supplies are imported. Imports are a safety valve which steel users can activate if the home industry cannot supply in the required quantities.

A more detailed picture of the model's structure is given by the influence diagram in figure 3.2 . The loop which links the customer order backlog, the delivery lead time perceived by customers and the volume of home orders placed is a crucial feedback loop. It embodies the processes described above for, when lead times become so extended that customers find that their own production schedules are being jeopardised through lack of sufficient raw material, they must source elsewhere. In the case of the British steel industry this means going abroad, to European steel producers for example.

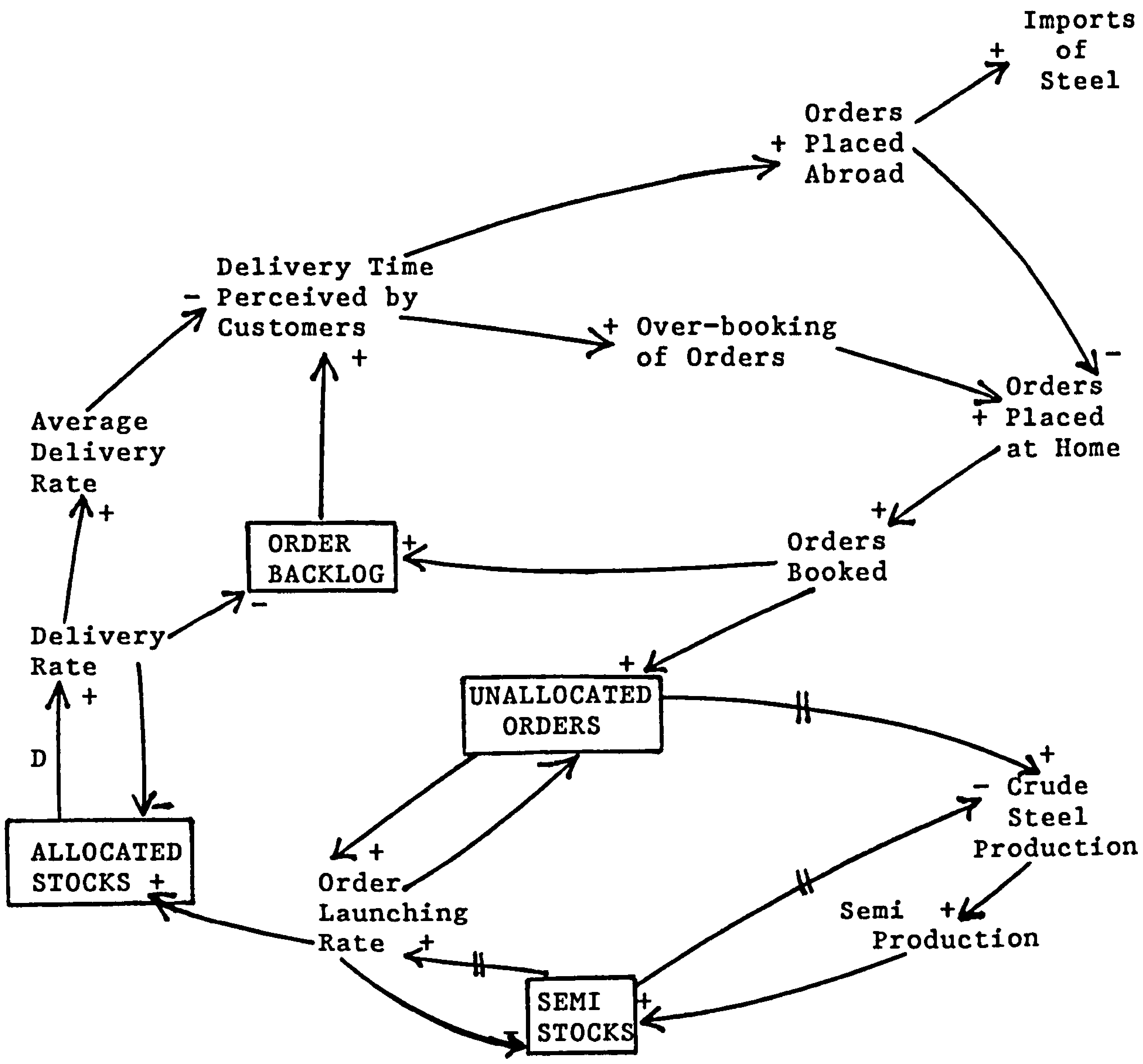

Figure 3.2 Influence diagram for the model

3.3.2 Detail of the Finishing End sector

The Customer Order Backlog (COBG) is the only variable which the market has collective sight of. Relating this to the Average Delivery Rate (ADR) of steel calculated over a period of three months, enables customers to acquire market intelligence about the steel mills' delivery performance.

Unfortunately all too often in the past steel users have been victims of extended delivery periods to such an extent that steel buyers in both end-user and stockholder industries over-order at the first sign of supply difficulties. The argument runs along the lines of: "If we send in duplicate orders then at least one is likely to be satisfied". It almost amounts to the reasoning which suggests that if you have more tickets in a large lottery the greater your chance of success.

While customers have knowledge of the total order backlog the mills decompose this into two groupings. Firstly, there are UNALLocated Orders (UNALLO) which represent the sum total of orders received from consumers and stockholders which have not yet been associated with semi-finished steel in the process of being rolled. In the context of the description of the stages of steel production given in the previous chapter, it will be recalled that it is prior to the hot rolling mill that customer orders are "allocated" to specific semi-finished steels, be they slabs, billets or blooms. Once allocated customers cannot normally cancel an order. The variable concerned with ALLOCated Stocks (ALLOCS) represents what in the finishing mills is effectively "work-in progress" and when the steel has passed through the final stage of the appropriate finishing process it is delivered to the customer immediately. Because it is not the intention here to examine detailed production processes, the variable ALLOCated Stocks covers a range of possible finished steels which emerge from successive processes in the finishing mills. These are hot rolled strip and coil, cold reduced strip and coil, annealed steel and galvanised and coated steel.

Inter-process stocks are held between each stage of crude steel making and between the various finishing processes. Save for the strategic holding of SEMi-finished steel Stocks (SEMS) referred to above, all the other stockholdings are genuine inter-process buffer stocks. There are sound production and metallurgical reasons why steel is not held at any other of these points in great volume. For instance, ingots (one stage upstream from the semi-finished stage) require re-heating which can be very expensive if they have been allowed to cool excessively. Also cold reduced products are subject to surface deterioration if they are left in store too long. Customers may not be willing to accept such a reduced quality when taking delivery. It can be seen, therefore, that stocks of "semis" as they are known in the industry occupy a pivotal role in terms of customer delivery performance. If these stocks are too low, hot rolling cannot commence; they therefore represent an important constraint to the finishing mills.

In normal production and delivery circumstances a customer would expect delivery some six weeks following receipt of an order at the mills. This time would be split into two components: some two weeks (or half a month) in the UNALLocated Order backlog and four weeks (one month) going through the finishing processes. When there is a general increase in customer orders it is the UNALLocated Orders which can grow excessively. If this general increase coincides with a lack of semi-finished steel then the effect can be quite startling. Figure 3.3 depicts the movements in the lead time for cold reduced sheet steel between 1970 and 1980. This spans the steel boom which took place in 1973/74 and gives testimony to sharp changes which can occur in demand. Lead times increased over four fold in that period, reaching in excess of twenty weeks (five months). As a consequence the B.S.C. were forced to, exceptionally, introduce a system of prohibition on further orders to try and contain the backlog and enable them to quote realistic delivery dates. Whilst lead time data of this nature is of enormous help to the analyst it is not the sort that is widely available. (The Government, for instance, do not appear to include any data on lead times in their vast array of published statistics.) Unfortunately the data below could not be extended beyond 1980 as the trade magazine concerned became a victim of the economic recession.

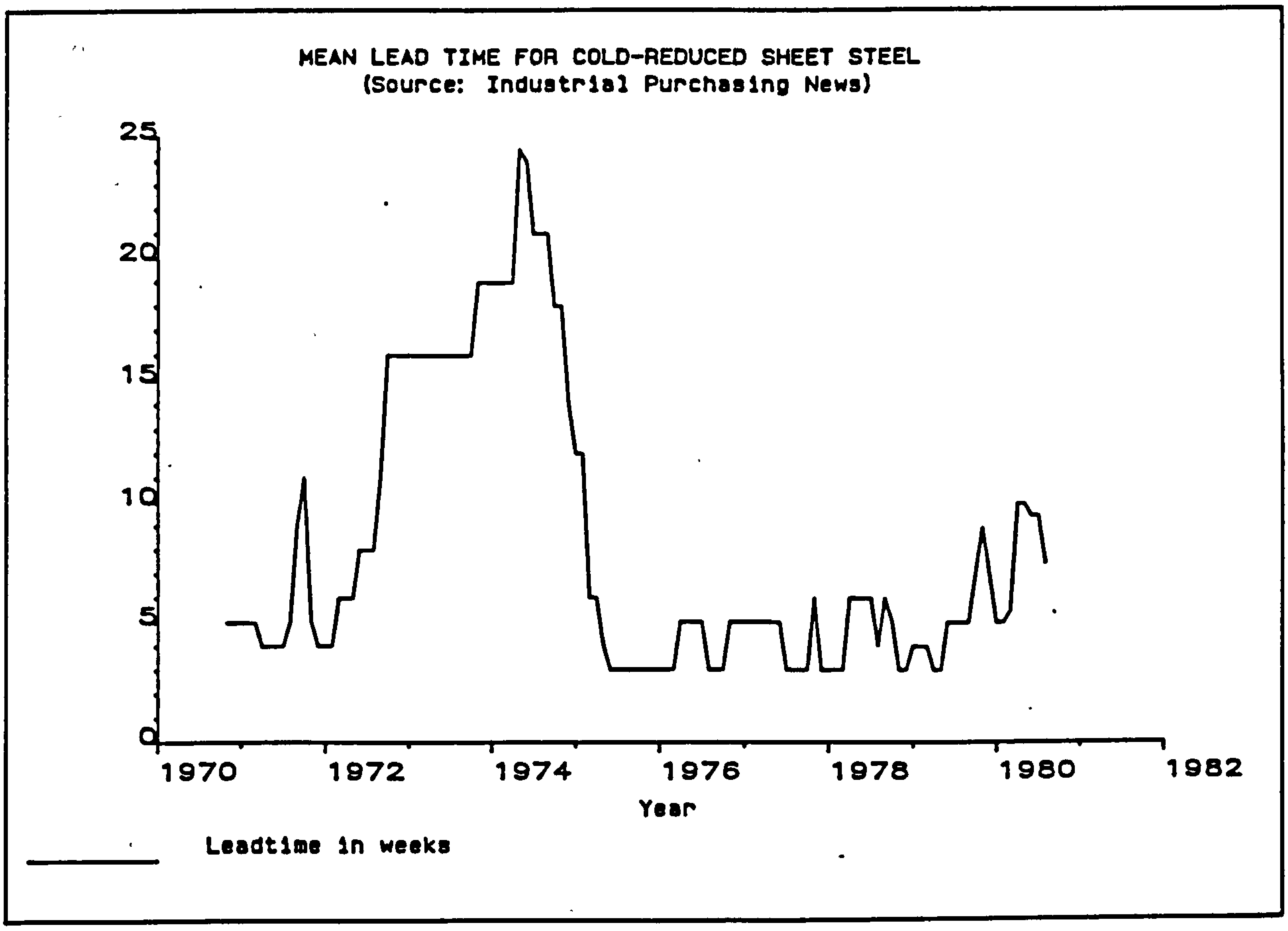
MEAN LEAD TIME FOR COLD-REDUCED SHEET STEEL
(Source: Industrial Purchasing News)

Figure 3.3 Mean lead times for cold reduced sheet steel 1970-80

The delay in progressing allocated steel through the finishing processes, assumed to be a month on average, is explained in terms of the batching system which goes on. Were a single uniform product to be rolled then the delay would be much less because, in consequence, no changes to the settings on the machines would be required. As it is, a range of products of varying widths and guages have to be rolled and so batches of each are rolled out. This means that a given product specification can, once a batch of that product has been rolled out, take up to a month or even longer before another batch of the same specification is processed. The normal regime is to roll out in accordance with a coffin shape as described in the previous chapter.

The incorporation of the finishing processes into the model is managed using a third order delay with the average delay constant, the Finishing Process Lead Time (FPLT), set at one month. Thus, Delivery Rate (DR) is simply a third order delay of the Order Launching Rate (OLR) which represents the flow of hot rolled steel through the rolling mills. This is the first process involved in converting semis into finished steel and also the point at which a customer order is associated with the product.

3.3.3 Detail of the Heavy End sector

Having described features of the model as they pertain to the finishing end of the process, it is now appropriate to move upstream and consider those aspects of the model which relate to the so-called 'Heavy-End'. These are the stages involved in the manufacture of liquid steel and its ultimate presentation in stocks of semis.

The heavy end operates continuously and this is an important feature of steel making which should not be lost sight of. Whilst the scope for variation in output at the finishing end is considerable (and is caused by variations in the size of the unallocated order pool together with the stock of available semis) variation in output at the heavy end is nothing like as flexible. This makes for considerable management problems and it is the purpose of the model to evaluate the consequences of these problems.

The blast furnace may be at the centre of the inflexibility. Once fired, such a furnace will continue to produce pig iron for anything up to six years or more, usually until their heat-resistant refractory linings need replacing. The model assumes, initially, that three of these furnaces are operating at the works. Their current cumulative throughputs have been selected so as to ensure that they are withdrawn for refractory relining at different points in time. This is in line with B.S.C.'s normal policy, for bunching of relines has to be avoided if at all possible. Once a blast furnace has been taken out of commission its entire pig iron output is, of course, lost to the downstream processes for an average of 3.5 months (the reline itself) together with losses associated with a slow build up to maximum output when it has been refired. For environmental and safety reasons, molten pig iron cannot be moved from one works to another and so bunching of relines can ultimately have a serious effect on availability of finished steel for delivery. (This happened to the B.S.C. with some degree of severity in 1974 (Waterstone, 1975).)

The diagram below (figure 3.4) shows the cumulative throughputs of each furnace by way of a vertical bar chart. Normal blast furnace throughput before a reline is required is set at 5 million tonnes although this can be extended if market conditions warrant it.. Initially, three blast furnaces are assumed to be operating and with their average annual output being 960,000 tonnes this means there is an overall throughput of 2.88 million tonnes per annum of pig iron. An explanation of the detailed operational policies for blast furnaces which has been incorporated in the model is given below.

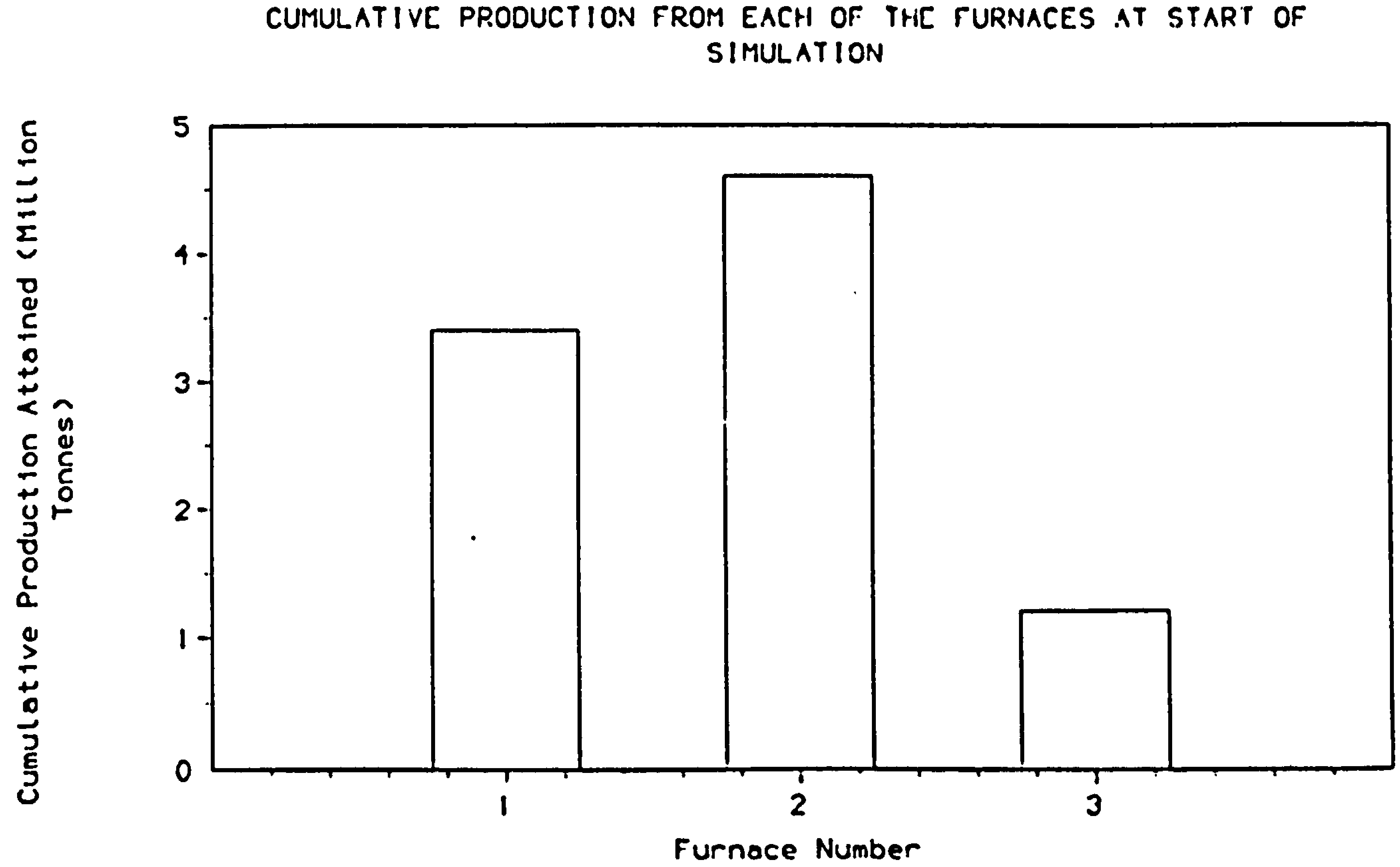

Figure 3.4 Cumulative production from each blast furnace at the start of the simulation

The flow of pig iron from the blast furnaces is passed through to the steel furnaces. In the first runs of the model two Basic Oxygen System (BOS) converters form the assumed technology and such a configuration, allowing up to 3.5 million tonnes per year of liquid steel to be produced (Cockerill, 1974), is entirely compatible with that found nowadays in integrated steel mills the world over.

Steel is drawn off from the BOS converters at intervals of approximately 45 minutes and then *either* passed through the ingot casting and semi finishing mill *or*, as is more commonly the case nowadays, continuously cast into semi finished shapes. B.S.C. now claims over 80% of its steel is produced using continuous casting plant (Financial Times, 1988). Figure 3.5 summarises the flow of production at the heavy end.

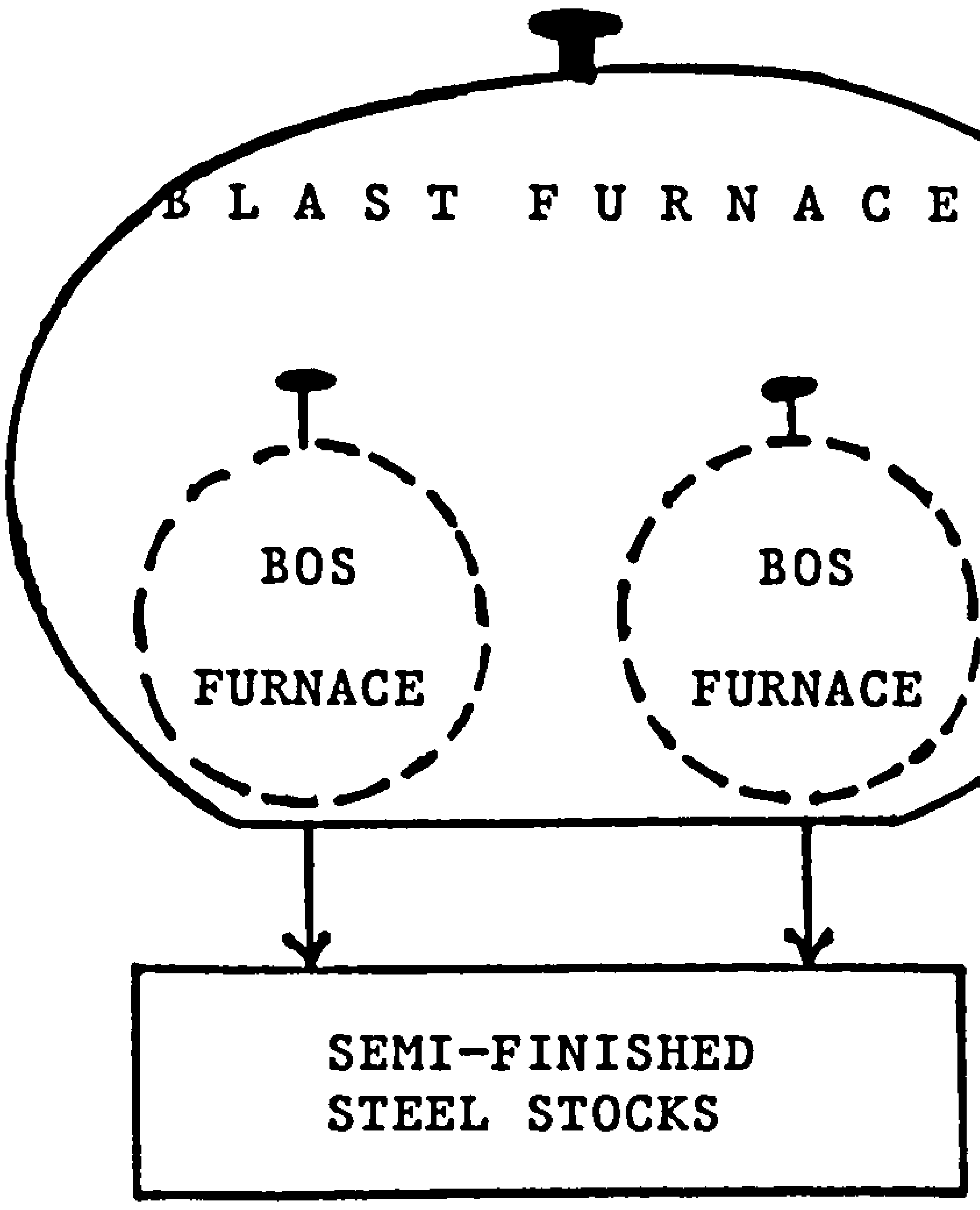

Figure 3.5 Schematic diagram of the production flow configuration assumed in the initial model

As is the case with the finishing end, the model's purpose is not compatible with inclusion of the degree of detail encountered in practice. Production from the blast furnaces is assumed to cover the flow through to semi-finished steel. Stocks of semis are included in the model but not ingot stocks or pig iron stocks. These are not strategic stocking points and the quantities arise as a consequence of the processes going on directly upstream and downstream from them.

It is a matter of hours between iron being smelted in the blast furnace and its subsequent progress through the BOS converters, ingot mill and slabbing mill. Thus these processes, which are effectively delayed actions consequent on blast furnace operations, are not included directly. In System Dynamics terms they represent material delays with very small average delay constants when taken in the context of the 120 month duration of the present simulations. To include these processes in the model would implicitly require an extremely small value for DT because this value needs to be a sufficiently small fraction of the smallest average delay time in the model so as to prevent mathematical instability in the results.

To summarise, it can be seen that any exploration of 'inflexibility' in the industry centres primarily on the heavy end of steel mills and that, for the purposes of the model, blast furnace production is equated with semi production. The intervening stocks are ignored but the available stock of semis is crucial and is obviously included. Semis stocks are the watershed between the heavy and finishing ends of steel production.

3.3.4 Blast furnace operations: equations and table relationships

In view of the strategic importance of blast furnace operations, both in the B.S.C. and in the model, the detailed aspects of operational policy on blast furnaces are now described. Capturing this assumed policy unfortunately involves some fairly complicated equation structures and these are given, along with a detailed commentary, rather than restrict the reader to studying the full computer listing of the model in the appendix at the end.

As mentioned previously, three furnaces are assumed to be operational initially. Their monthly outputs are 75,000, 80,000 and 85,000 tonnes respectively. The combined total output exactly matches the assumed customer demand of 240,000 tonnes per month or 2.88 million tonnes per annum.

Naturally there are week-to-week variations of both blast furnace output and incoming customer orders for steel. This noise element is handled through the NORMRN function available in DYSMAP2 (Dangerfield and Vapenikova, 1987) which returns normally distributed values with given mean and standard deviation. In the case of customer orders the standard deviation is assumed to be 10,000 tonnes per month. For the blast furnace output *in total* to exhibit the same extent of variation, each furnace's standard deviation for output is set at $10000/\sqrt{3} = 5773.5$ tonnes per month.

The following operational policies are handled in the blast furnace sector of the model:

(a) A furnace will normally be de-commissioned for a reline after a campaign throughput of 5 million tonnes. At average model throughput rates this would be between 5 and 5.5 years.

(b) If demand at the time is strong, a furnace's campaign life can be extended by a period equivalent to the lesser of the time for a further one million tonnes throughput and the time of a subsequent fall-off in demand.

(c) Following completion of a reline, a furnace will not be re-fired unless customer demand warrants it. In effect, the interregnum period is extended.

(d) If customer demand falls to a critically low level than a furnace can be de-commissioned *in advance of* its anticipated reline date. Strategically this is a major decision (Gold, Rosegger and Boylan, 1980).

In addition, the following normal features of blast furnace operations are included:

(e) Towards the end of a campaign a furnace will exhibit a greater number of operational problems than normal and consequently its usable output is somewhat reduced (Gold, Rosegger and Boylan, 1980).

(f) Once relined and re-fired, a furnace will not immediately yield its maximum output but will exhibit a learning curve effect over a period of months until full output is attained.

(g) Variability in blast furnace output (over and above the variations caused by noise) is extremely limited and maximum output is assumed to be only 15% higher than the nominal rated throughput for the furnace. The variation in driving rate is engineered by varying the quality of the burden in the furnace (Boylan, 1980).

(h) When one furnace is within six months of its expected reline date, in a feed-forward effect the output from the others at the works is boosted so as to generate a build up of stocks of semis to attempt a compensation for the loss of pig iron over the duration of the reline. This action is abandoned if demand falls off during the six months lead-in period.

In the case of all example equations listed below, blast furnace number 1 is used. However, these equations are replicated for the other two blast furnaces. The only differences concern the assumed cumulative campaign throughputs at the start of the simulation, together with the slight difference in mean production per month across the three furnaces. The equations below handle features (a), (e) and (f) above.

```
A PF1.K=CLIP(PF1EC.K,PF1N.K,6,(NTF-CPF1.K)/MNPF1)

A PF1EC.K=SWITCH(MNPF1,CLIP(0,NORMRN(MNPF1,SDPF1)*REFE1C.K,CPF1.K,
X MXTF1.K),TIME.K)

A REFE1C.K=TABHL(REFECT,(NTF-CPF1.K)/MNPF1,0,6,1)
T REFECT=0.6/0.72/0.82/0.9/0.95/0.98/1

A PF1N.K=SWITCH(MNPF1,CLIP(0,NORMRN(MNPF1,SDPF1)*PFF1.K*BEF.K,
X CPF1.K,MXTF1.K),TIME.K)
A PFF1.K=TABHL(PFFT,MPF1.K,0,2,0.2)
T PFFT=0.05/0.07/0.11/0.185/0.28/0.39/0.53/0.705/0.875/0.97/1

A MPF1.K=CPF1.K/MNPF1


D CPF1=(T) CUMULATIVE PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
*          FURNACE NO. 1

D MNPF1=(T/MTHS) MEAN PRODUCTION FOR BLAST FURNACE NO. 1

D MPF1=(MTHS) MONTHS' OF PRODUCTION (IN CURRENT CAMPAIGN) BY
*             BLAST FURNACE NO. 1

D MXTF1=(T) MAXIMUM THROUGHPUT BY BLAST FURNACE NO. 1 (BEFORE
*           RELINE REQUIRED)

D NTF=(T) NORMAL THROUGHPUT OF BLAST FURNACE (BEFORE
*           RELINE REQUIRED)

D PF1EC=(T/MTHS) PRODUCTION FOR B.F. 1 AT END OF CAMPAIGN LIFE

D PF1N=(T/MTHS) PRODUCTION OF CRUDE STEEL FROM BLAST FURNACE
*               NO. 1 NORMALLY

D PFF1=(1) PRODUCTION BUILD-UP FACTOR FOR BLAST FURNACE NO. 1

D REFE1C=(1) REDUCED EFFICIENCY FACTOR AT END OF B.F. 1'S CAMPAIGN
```

The term (NTF-CPF1.K)/MNPF1 in the CLIP function for PF1 determines whether the blast furnace is within six months of its expected reline date. If it is, then the equation for

PF1EC is used for the production rate. Embedded in this equation is another CLIP function which assesses whether the furnace's cumulative throughput has exceeded its maximum for that campaign (CPF1.K > MXTF1.K). If so, the production rate is zero, otherwise it equates to a value returned from a normal distribution with a mean of 75000 tonnes per month and standard deviation 5773.5 tonnes per month. However, the value returned is multiplied by a factor between 0 and 1 which reflects the greater extent of operational problems encountered with a furnace towards the end of a campaign. The table function for this variable is illustrated in figure 3.6 .

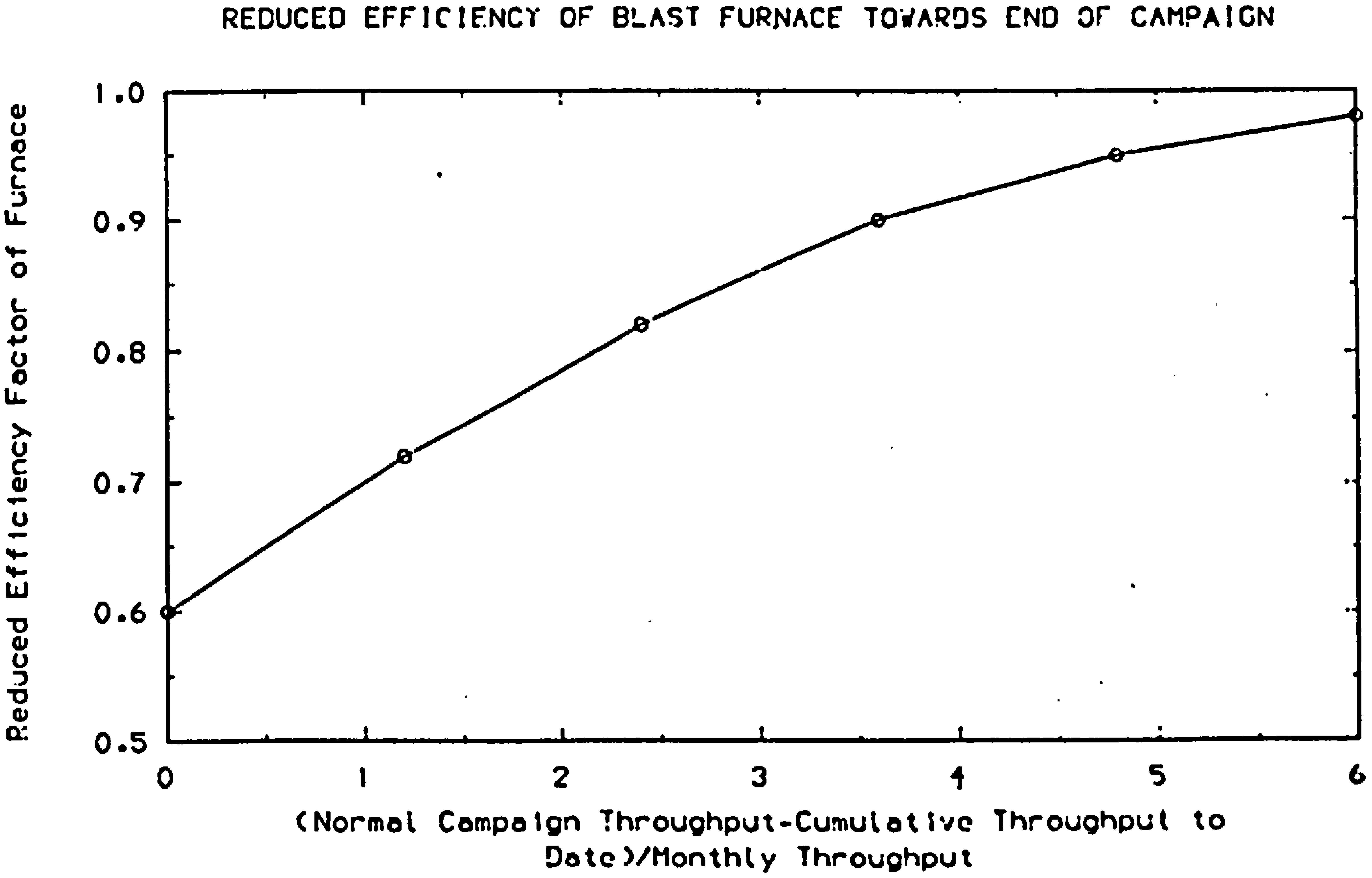

Figure 3.6 Table function for reduced efficiency of a blast furnace towards the end of a campaign

As the number of months of its campaign life fall below six, the output from the furnace is trimmed, slowly at first but then more quickly as the time for the reline nears. At this point output is 60% of normal. If the furnace's campaign is extended because of market conditions (see below) then the term (NTF-CPF1.K) will go negative. Output will then remain at 60% of normal because a TABHL function is used.

Returning to the equation for PF1 it is now necessary to consider the equation used for blast furnace production when the furnace is *not* within six months of a reline. The relevant equation here is PF1N which, with its embedded CLIP function, is of exactly the same form as that for PF1EC. The difference between the two concerns the factors which adjust the value for production rate returned by the normally distributed random number function. In the case of the production rate in the normal situation (PF1N), being within six months of the end of a campaign is not considered. PF1N handles the situation at all other stages of a campaign and takes into account the Production build-up Factor for the Furnace (PFF1) at the beginning of a campaign as well as the variable which handles adjustments to the driving rate of the furnace via changes in the quality of the materials constituting the burden, the Burden Efficiency Factor (BEF). This is discussed below.

The SWITCH functions used in the equations for PF1EC and PF1N ensure that, at the start of each simulation run, the relevant production rate is equal to the mean production rate for that furnace.

The table relationship which models the Production build-up Factor for the Furnace (PFF1) is shown in figure 3.7. It is a relationship between the average number of months of production to the proportion of nominally rated throughput actually achieved. When a blast furnace begins a campaign it is assumed to take up to two months for it to regularly achieve the anticipated throughput value. There are inevitable teething problems to overcome, for the furnace will have been cold for 3.5 months undergoing refractory relining.

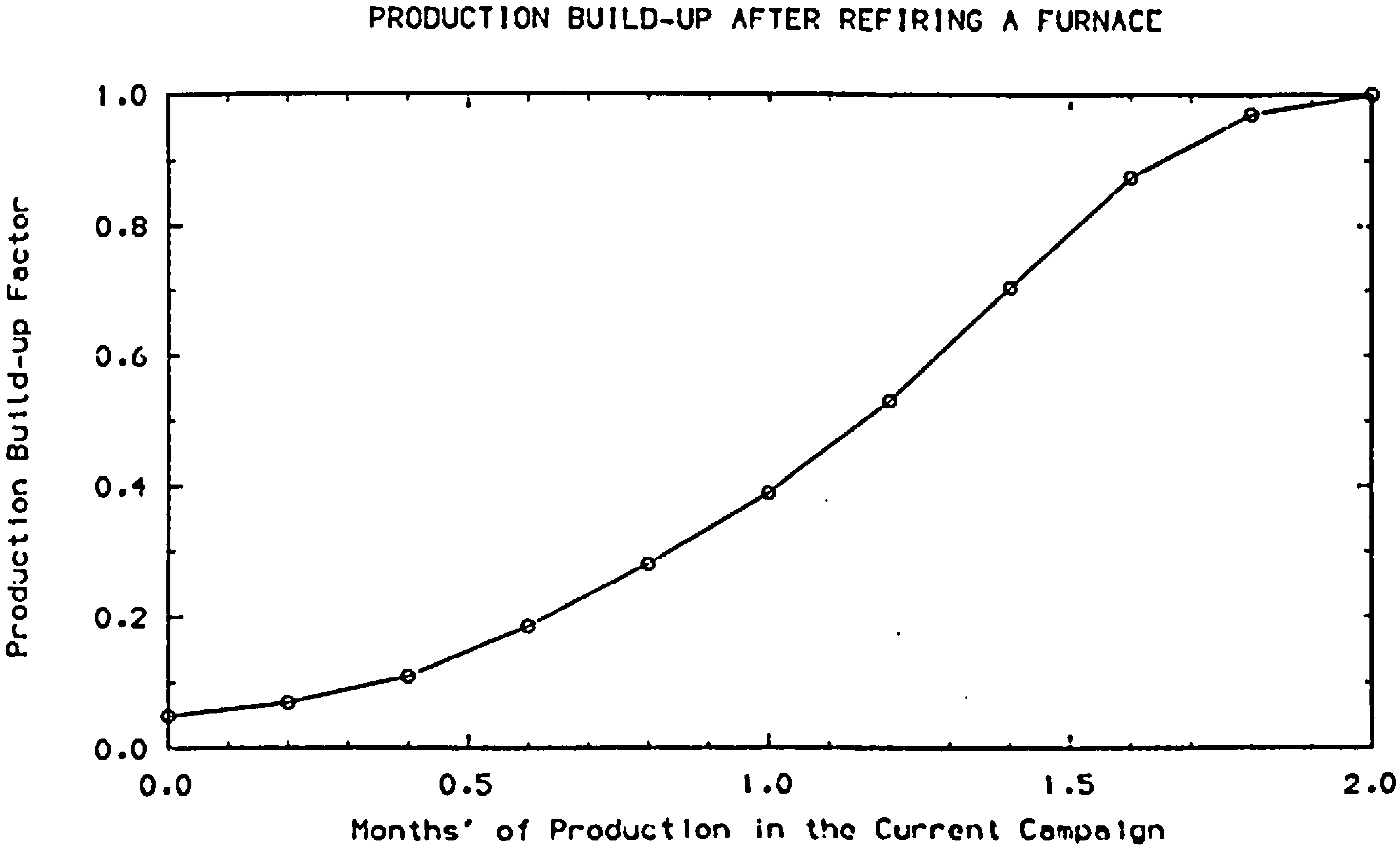

Figure 3.7 Table function of production build-up factor for a blast furnace at the start of a campaign

The driving rate for a blast furnace, controlled in the model by the Burden Efficiency Factor (BEF), was mentioned above and is now considered in more detail. This is item (g) in the list of features of blast furnace operations.

A blast furnace is, in its very nature, a rather inflexible item of production plant. It must be operated continuously and offers little scope for increasing output if conditions warrant it. An assumed value of 15% over the nominal rated throughput is used in the model. One particular instance when output needs to be at this maximum is if another of the furnaces is due for a reline. For a period of six months prior to an expected reline date, production is increased to enhance stocks of semis so that rolling of customer orders is little compromised while the furnace is out of commission. This is item (h) in the list of features. The equations for items (g) and (h) are as follows.

```
A BEF.K=NCLIP(1.15,PBEF.K,6,(NTF-MALLF.K)/AMTPF,MUNO.K,2)

A PBEF.K=TABHL(PBEFT,MUNO.K,1,6,1)
T PBEFT=1/1.005/1.035/1.088/1.135/1.15

A MUNO.K=UNALLO.K/NOLR


D AMTPF=(T/MTHS) AVERAGE MONTHLY THROUGHPUT PER FURNACE

D BEF=(1) BURDEN EFFICIENCY FACTOR

D MALLF=(T) MAXIMUM CUMULATIVE THROUGHPUT OVER ALL BLAST FURNACES

D MUNO=(MTHS) MONTHS' OF UNALLOCATED ORDERS

D NOLR=(T/MTHS) NORMAL ORDER LAUNCHING RATE

D NTF=(T) NORMAL THROUGHPUT OF BLAST FURNACE (BEFORE RELINE
*         REQUIRED)

D PBEF=(1) POTENTIAL BURDEN EFFICIENCY FACTOR

D UNALLO=(T) UNALLOCATED ORDERS
```

In normal circumstances, the Potential Burden Efficiency Factor (PBEF) will operate. The table function which relates this to the number of months' equivalent of outstanding orders takes into account only the unallocated orders, that is those for which hot rolling has not yet commenced. It is calculated by dividing the amount of UNALLocated Orders (UNALLO) by the Normal Order Launching Rate (NOLR).

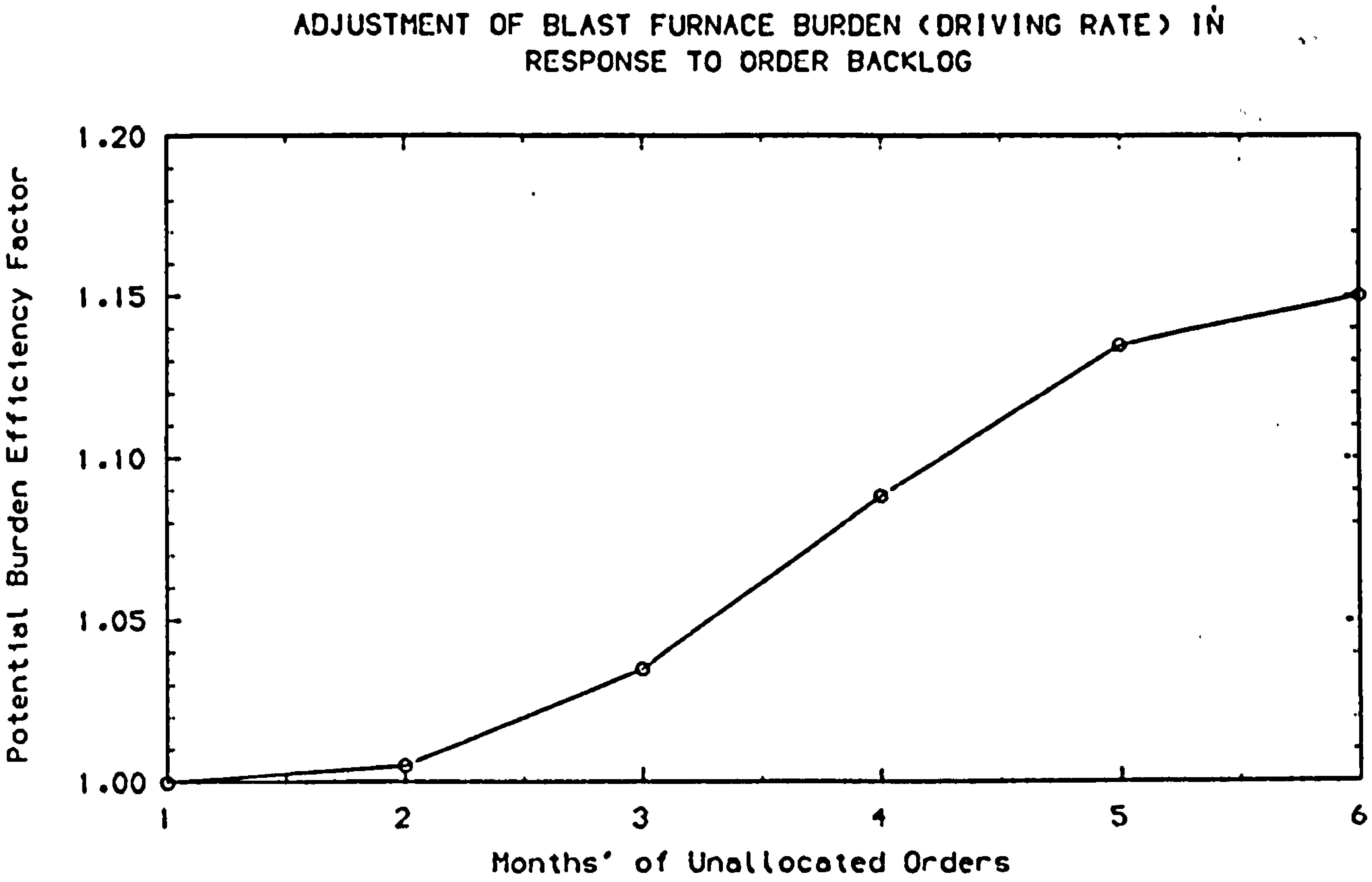

Figure 3.8 Table relationship between Potential Burden Efficiency Factor and Months of Orders on Hand

Obviously, as the number of months' equivalent of UNALLocated Orders increases there is a stronger pressure to increase the supply of semis so as to maintain the necessary hot rolling rate. The graph shows that this pressure increases slowly at first, but as the number of Months' of UNALLocated Orders (MUNO) increases so does PBEF, eventually smoothing off at 15% over the nominal rated throughput for the furnace.

On the occasions when one of the furnaces is within six months of a reline, the Burden Efficiency Factor (BEF) is set permanently at the maximum extra 15% of output and this factor will be applied to the production rates at the other operational furnaces. However, there is one important caveat to this policy. If the Months' of UNallocated Orders (MUNO) falls below 2.0, the Burden Efficiency Factor falls back to whatever is dictated by the table function in figure 3.8 above, regardless of whether a reline is due. This assumption seems appropriate, for a low level of unfilled customer orders should not cause the absolute maximum driving rate to be implemented. The consequential growth in stocks of semis would not be warranted.

If the furnace with the largest cumulative throughput has a reline deferred because of market conditions then the value of (NTF-MALLF.K) in the equation for BEF will go negative. In this eventuality, the Burden Efficiency Factor stays at 1.15. The value of MALLF will fall back after the newly relined furnace's cumulative campaign production is reset to zero for the beginning of the next campaign. MALLF will then take on the value of the maximum cumulative production from the remaining furnaces.

Of the list of features of blast furnace operations listed earlier on only items (b), (c) and (d) have not yet been expounded. Item (b) is relatively simple and is covered next. This feature centres on the maximum furnace throughput in a campaign before a total reline of the refractory brickwork is required. The normal campaign throughput is set at 5 million tonnes but this can be extended by up to a further 1 million tonnes should market conditions dictate. Four equations handle this and are listed below.

```
A MXTF1.K=NTF+EXTF1.K*SWEXTF1.K

A SWEXTF1.K=NCLIP(1,0,AVMOH.K,4,CTDECF1.K,(NTF-CPF1.K))

A EXTF1.K=CLIP(0,1E6,CPF1.K,NTF)

A CTDECF1.K=(MNPF1+3*SDPF1)*PNDEC

A AVMOH.K=DLINF3(MOH.K,TRCMOH)
```

```
D AVMOH=(MTHS) AVERAGE MONTHS' OF ORDERS ON HAND

D CPF1=(T) CUMULATIVE PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
*          FURNACE NO. 1

D CTDECF1=(T) CRITICAL THRESHOLD FOR DECISION ON EXTENDING
*             B.F. 1 CAMPAIGN

D EXTF1=(T/MTHS) EXTRA THROUGHPUT OF B.F. 1 (IN ADVANCE OF RELINE)

D MNPF1=(T/MTHS) MEAN PRODUCTION FOR BLAST FURNACE NO. 1

D MOH=(MTHS) MONTHS' OF ORDERS ON HAND

D MXTF1=(T) MAXIMUM THROUGHPUT BY BLAST FURNACE NO. 1 (BEFORE
*           RELINE REQUIRED)

D NTF=(T) NORMAL THROUGHPUT OF BLAST FURNACE (BEFORE RELINE
*         REQUIRED)

D PNDEC=(MTHS) PRIOR NOTICE FOR DECISION ON EXTENDING A B.F.
*              CAMPAIGN

D SDPF1=(T/MTHS) STANDARD DEVIATION OF PRODUCTION FOR BLAST
*                FURNACE NO. 1

D SWEXTF1=(1) SWITCH TO CONTROL EXTRA THROUGHPUT FOR B.F. 1

D TRCMOH=(MTHS) TIME TO RECOGNISE CHANGES IN MONTHS' OF ORDERS
*               ON HAND
```

The maximum campaign throughput (MXTF1) is enlarged to six million tonnes only when the switching constant (SWEXTF1) is activated. Two conditions have to be met for this to occur. Firstly, the critical threshold for a decision to extend the campaign must have been reached. The prior notice required in order to make this decision is related to the furnace's normal statistical maximum throughput (three standard deviations above the mean throughput) in one month. It is determined whether this has become greater than the remaining throughput which could be achieved before relining at the normal due date. If it has and the Average Months of Orders on Hand (AVMOH) is above 4.0 then a decision would be taken to extend the campaign for that furnace. However, if at any time during the extended campaign the value for AVMOH falls below 4.0 then the switching constant is de-activated, cumulative production for the furnace would be above the maximum and the furnace would be decommissioned.

In reality there is some risk attached to extending a blast furnace campaign. They have to be relined eventually (they can literally fall apart otherwise) and the phasing between relines across the group of furnaces can be progressively eroded as a result. In a three furnace arrangement deliberately having two furnaces out simultaneously at the same works would not be contemplated save for a slump in demand of unprecedented proportions. The B.S.C. suffered from a bunching of blast furnace relines across the flat products division in the latter phases of the last major upturn in steel demand (1974) prior to the present one (Waterstone, 1975). This was caused by extended campaigns and neglect of the normal reline schedules.

The Average Months of Orders on Hand (AVMOH) is obviously a critical variable in the above decision. It is modelled using a DLINF3 function with a smoothing constant of three months. This reflects the quarterly assessment by the B.S.C. of the order position and such a discrete delay in the planning process justifies the use of DLINF3 rather than SMOOTH (DLINF1). AVMOH includes both UNALLocated Orders (UNALLO) and ALLOCated Stocks (ALLOCS). On the face of it only the former should affect blast furnace decisions, but extending a campaign is nearly as important a decision as terminating one prematurely and the senior management would wish to take a rounded view of the total order position before sanctioning an extended campaign.

The most complicated equations centre on the remaining features of blast furnace operations -- premature interruption of a campaign because of market conditions and delayed re-firing of a furnace for the same reason, items (d) and (c) respectively. The following active equations are used and it is not possible to disentangle the separate effects of (c) and (d). Hence, the explanation for these two features is given as one. The equations now follow.

```
A FSCMC.K=NCLIP(0,10E6,1.5,AVMOH.K,SEMSR.K,1.5)

A TPICF1.K=CPF1.K-MALLF.K-FSCMC.K

R ADDRPIC1.KL=NCLIP(10E6/DT,0,TPICF1.K,0,MXTF1.K,CPF1.K)

L CPF1.K=CPF1.J+DT*(PF1.J+ADDRPIC1.JK-RZCPF1.JK)
N CPF1=3.4E6

A IVLF1.K=CLIP(LENGTH,DT,CPF1.K,MXTF1.K)

A HTMF1.K=SAMPLE(TIME.K,IVLF1.K,0)

R RZCPF1.KL=NCLIP(PULSE(CPF1.K/DT,TIME.K,DT),0,TIME.K,(HTMF1.K+
X TRLF-DT),FSCMC.K,1)


D ADDRPIC1=(T/MTHS) ADDITIONAL RATE FOR PREMATURE INTERRUPTION
*                   OF B.F. 1 CAMPAIGN

D AVMOH=(MTHS) AVERAGE MONTHS' OF ORDERS ON HAND

D CPF1=(T) CUMULATIVE PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
*          FURNACE NO. 1

D FSCMC=(T) FACTOR FOR SUSPENSION OF CAMPAIGN DUE TO MARKET
*           CONDITIONS

D HTMF1=(MTHS) HELD (I.E. FROZEN) TIME FOR BLAST FURNACE NO. 1

D IVLF1=(MTHS) INTERVAL OVER WHICH FROZEN TIME IS HELD FOR BLAST
*              FURNACE NO. 1

D MALLF=(T) MAXIMUM CUMULATIVE THROUGHPUT OVER ALL BLAST FURNACES

D MXTF1=(T) MAXIMUM THROUGHPUT BY BLAST FURNACE NO. 1 (BEFORE
*           RELINE REQUIRED)

D RZCPF1=(T/MTHS) RE-ZERO CUMULATIVE PRODUCTION FOR BLAST FURNACE
*                 NO. 1

D SEMSR=(1) SEMI STOCKS RATIO
```

```
D TPICF1=(T) TEST FACTOR FOR PREMATURE INTERRUPTION OF CAMPAIGN
*            IN B.F. 1

D TRLF=(MTHS) TIME TO RELINE A BLAST FURNACE
```

The value of FSCMC is set to either zero or an arbitrarily large number (10E6). If it is zero then a blast furnace campaign will be suspended. It will only ever be set to zero when two conditions are met -- when the AVerage number of Months' Orders on Hand is below 1.5 and the SEMis Stocks Ratio (months' of semis stocks relative to normal) is in excess of 50% above normal. Only if FSCMC is zero is it possible for TPICF1 to also equate to zero. Yet this will not happen unless furnace 1's cumulative production is equal to the maximum cumulative production for *all* furnaces (MALLF). If it is not then the chosen furnace will be one of the others. Only one furnace will have TPIC made equal to zero on any occasion when FSCMC permits it. Hence it is impossible for more than one furnace to be de-commissioned prematurely.

Also, if one furnace happens to be out already for a scheduled reline when FSCMC becomes zero then that coincidence will be deemed to equate with a premature decommissioning. No other furnace will then have its campaign terminated early. However, a furnace on a scheduled reline can join one already decommissioned. Having more than one idle blast furnace arises in the rare situation when demand conditions have been such that a de-commissioned furnace has been kept cold for so long it coincides with a scheduled reline by one of the other furnaces.

The importance of the test variable TPICF1 can be seen by considering the way it is used in the equation for ADDRPIC1. If TPICF1 equates to (or is greater than) zero (remember for most of the time it will be a large negative number), *and* the furnace's cumulative production has not yet exceeded its allowed maximum prior to a reline, then ADDRPIC1 will be set to such a large value (dimensioned in tonnes per month because ADDRPIC1 models a rate of flow) that it will push cumulative production well over the threshold for requiring a reline. Production from that furnace will then cease and a period for relining will commence.

The second check, as to whether cumulative production is larger than the campaign maximum, is necessary to prevent successive pulses of ADDRPIC1 (equal to 10E6/DT) from being generated. Only one pulse is necessary to trigger a de-commissioning and no pulses at all are required if the chosen furnace happens to be out *already* for a scheduled reline.

Once cumulative production is in excess of the maximum cumulative campaign production, the variable IVLF1 will change from an interval of DT to an arbitrarily long interval (LENGTH, the duration of the simulation). The equation for HTMF1 will then "hold" the sampled value of the system variable TIME for as long as is necessary to carry out the reline (assumed to be 3.5 months) and ensure that market conditions are compatible with a re-firing of the furnace.

Re-zeroing cumulative campaign production, handled by the variable RZCPF1, will not happen unless *both* the reline has been completed and market conditions are favourable. It will be recalled from earlier discussion that it is necessary for

CPF1 to be less than MXTF1 before the furnace can re-commence production. The first argument in the NCLIP function used in the equation for RZCPF1 generates the required pulse height to re-zeroise cumulative production. The fact that this will be calculated every time step is of no consequence because, being embedded in an NCLIP function, it is activated only when the third argument is greater than or equal to the fourth *and* the fifth argument is greater than or equal to the sixth. If both of these conditions are not simultaneously met, then RZCPF1 will be zero.

The third argument, the system variable TIME, determines, by comparison with the expression making up the fourth argument, when the reline is completed. This is TRLF months on from the point at which the furnace was de-commissioned (HTMF1). The "-DT" term is required so that cumulative production can be re-zeroised during the final time step of the reline period. A new campaign will commence in the following time step unless the value of FSCMC is less than 1.0 . There is only one value which FSCMC can hold which is less than 1.0 and this value is zero. FSCMC holding a value of zero prevents a new campaign starting if the market conditions do not warrant it. The tests for this are deemed to be exactly the same as those assessments used in deciding whether to prematurely de-commission a furnace.

3.3.5 Other Table relationships in the model

In the previous section table relationships relating to blast furnace operations were explained at appropriate points. It is now necessary to examine other uses of table relationships in the model.. A discussion of these relationships can assist the reader in following important assumptions built into the equations.

It will be recalled that orders are attached to specific steel semis prior to hot rolling. The Order Launching Rate (OLR) determines the flow of production "starts" and it is equated to a Normal Order Launching Rate (NOLR) tempered by the operation of two factors -- one is a factor which transmits the effects of semis stock availability, SEMis Stocks Factor (SEMSF), and the other is a factor which reflects the influence of the size of the backlog of outstanding unallocated orders, the Order BackloG Factor (OBGF).

The table relationship for SEMSF is depicted in figure 3.9 . It has a maximum value of 1.0 which means that it can only reduce the value of the Order Launching Rate (OLR). This seems a reasonable representation of reality for, if the amount of semis stocks falls (causing a fall in the Months' of SEMi Stocks (MSEMS)) then the Order Launching Rate must be compromised. Little effect will be experienced at first, but as MSEMS becomes lower the effect is felt more and more strongly. In the unlikely event of there being no stocks of semis available, then there will be no hot rolling.

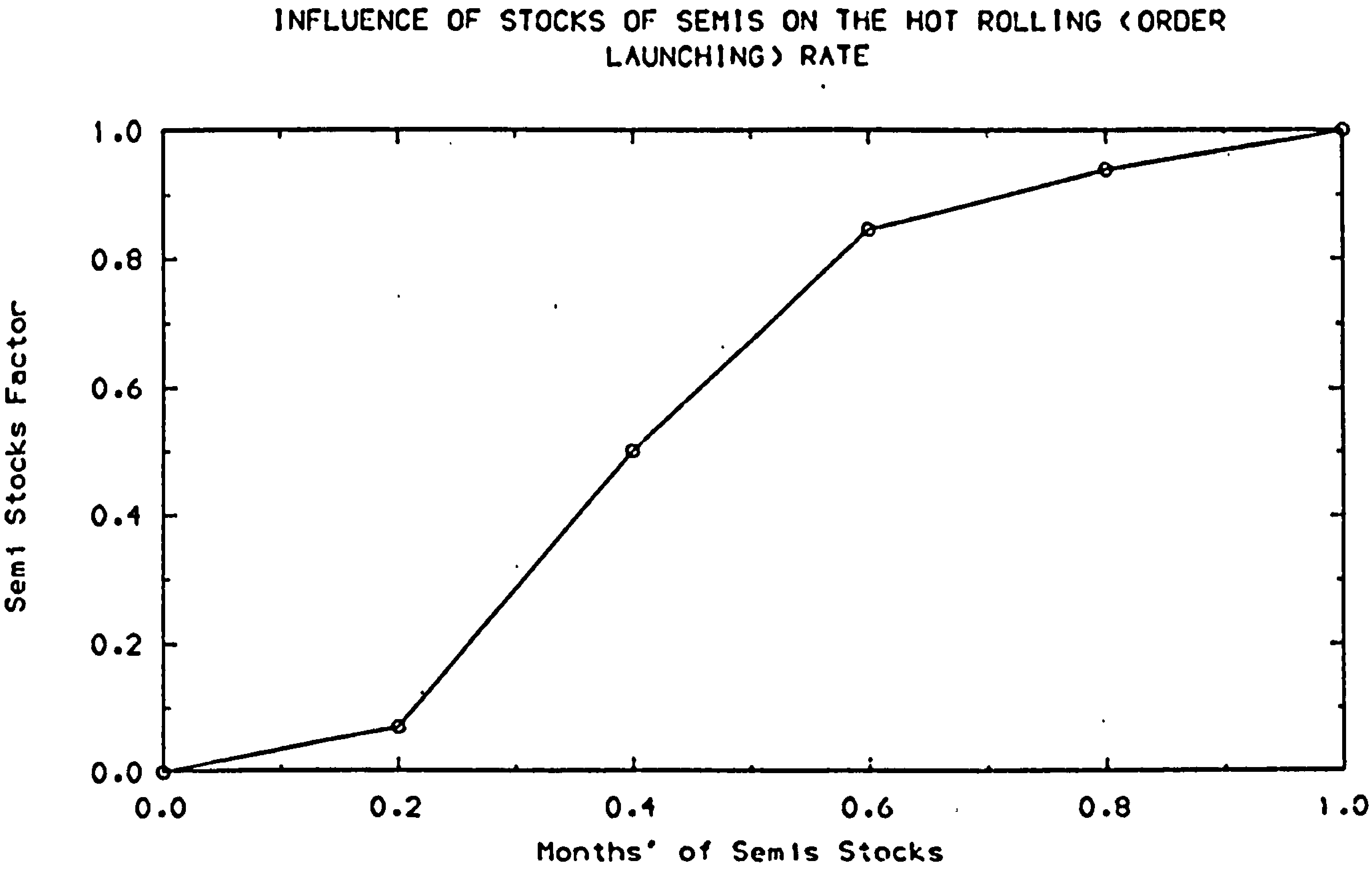

Figure 3.9 Table relationship between the stock of semis and its effect on the hot rolling rate

The Order BackloG Factor (OBGF) has a maximum of 1.2 (figure 3.10) which prohibits order rolling of more than 20 percent in excess of the nominally rated throughput for the plant in times of extremely strong customer demand. This maximum throughput rate is achieved only when the Months' of UNallocated Orders Ratio (MUNOR) approaches a value double what it is normally. The maximum extra throughput at the heavy end is only 15% above normal but it is not unusual in steel works for the finishing end capacity to be slightly higher than that at the heavy end. As MUNOR falls below 1.0, reflecting a weaker market, the value of OBGF falls almost in line with the drop in MUNOR. Were there ever to be no unallocated customer orders then no hot rolling would take place.

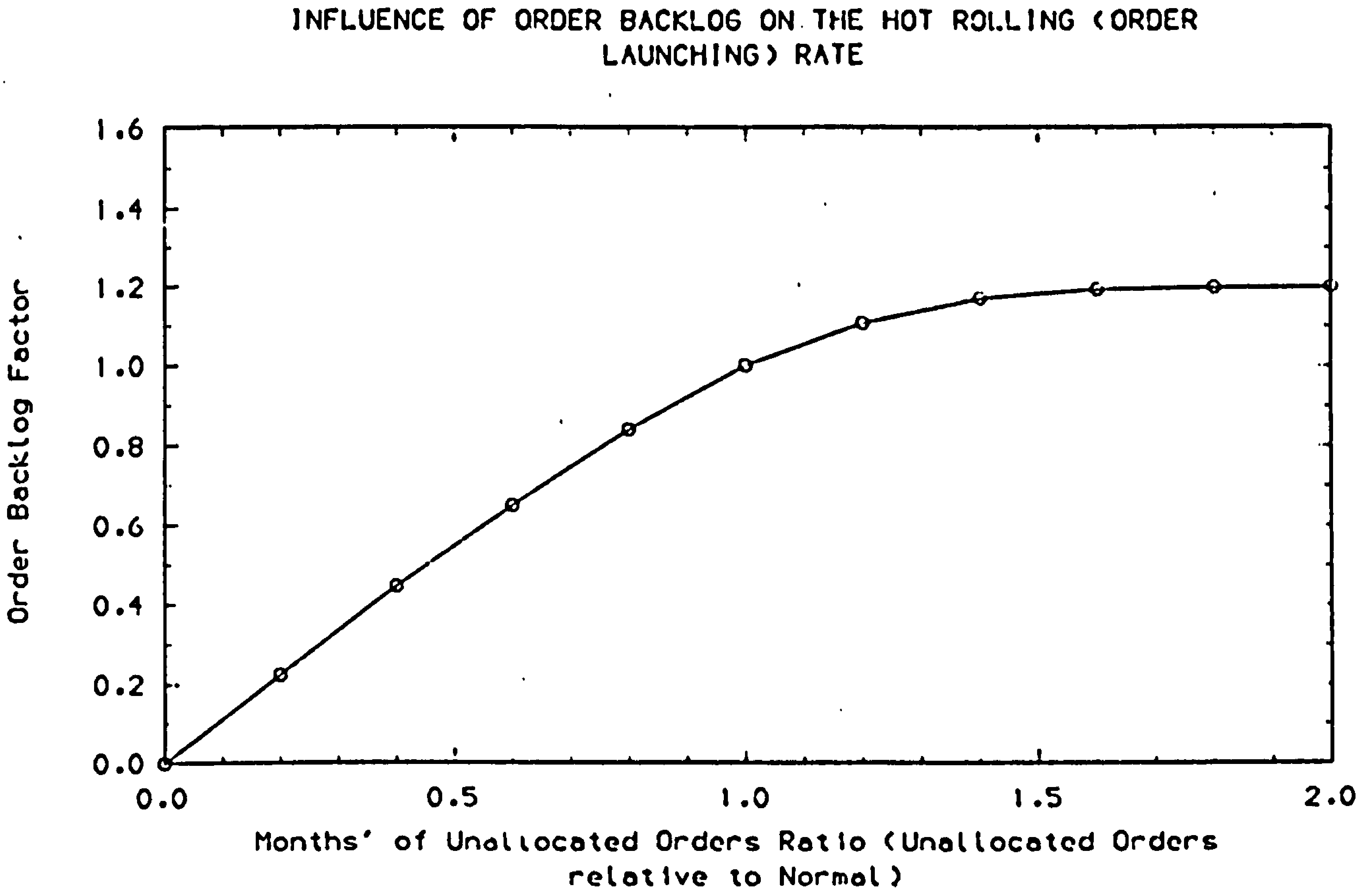

Figure 3.10 Table relationship between unallocated orders and their effect on the hot rolling rate

Figure 3.11 below shows the effect the Delivery Lead Time Perceived by the Customer (DLTPC) has on the generation of multiple orders for the same steel. As the delivery time climbs in excess of 3 months in a boom then multiple ordering is assumed to take place, slowly at first but more quickly as the delivery position worsens. If the lead time reaches 5 months, which has been known to happen and was discussed in the previous chapter, then overbooking will occur at a maximum rate of 20 percent. That means one-fifth of the tonnage ordered each month is over and above that required to satisfy customers' real needs. Customers' steel buyers overbook as an insurance against the B.S.C.'s likely inability to be able to ship the required amount in the normal delivery time.

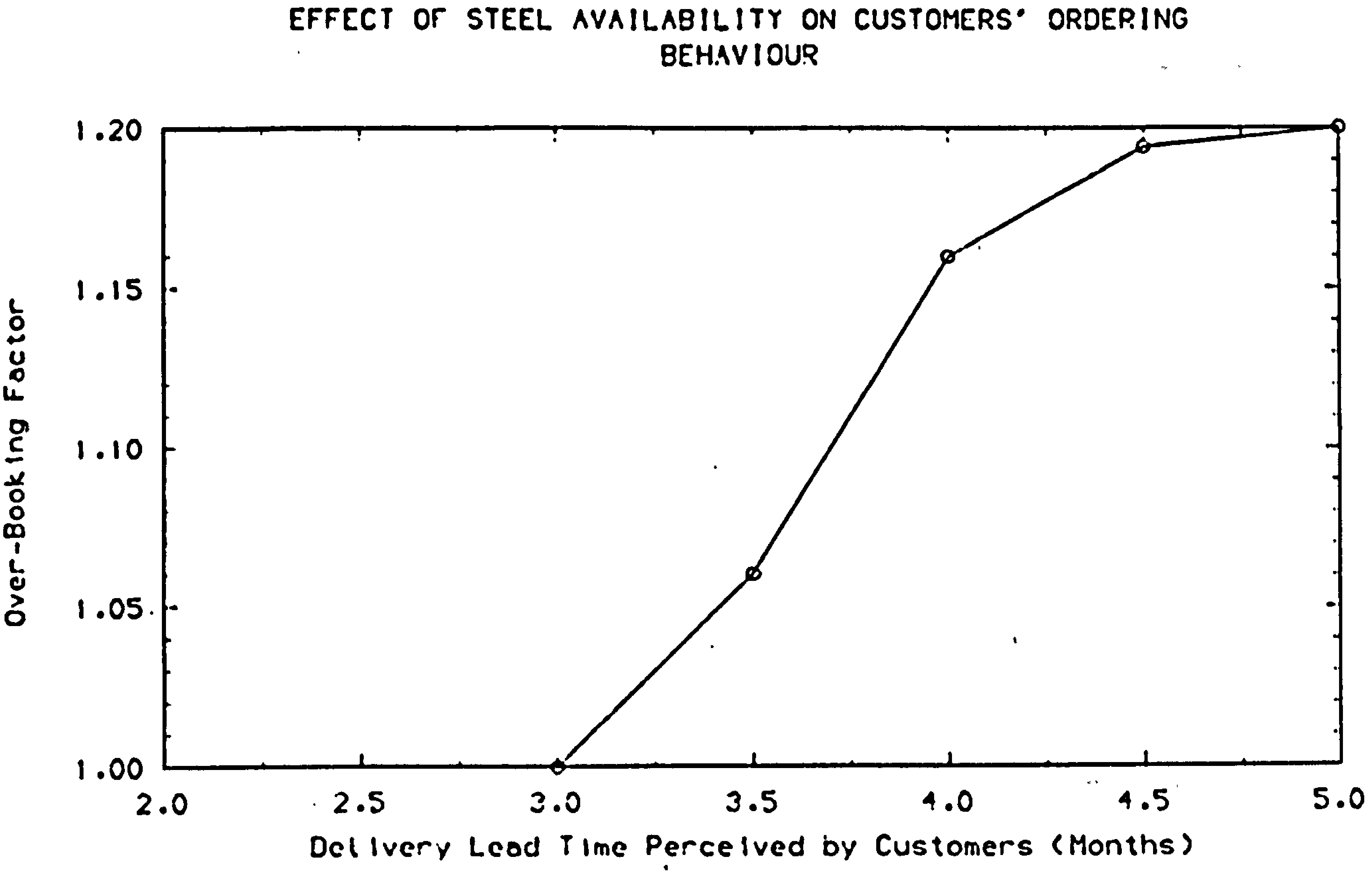

Figure 3.11 Table relationship between delivery lead time experienced by customers and excessive orders

Finally in this review of table relationships in the model comes that concerned with customers ordering abroad. If the lead time on steel delivery climbs then not only is there a multiple ordering effect as described above, but steel buyers turn to overseas sources, particularly in Europe, in order to obtain much needed supplies (N.E.D.O., 1986). Figure 3.12 shows that the Fraction of Orders PLaced Abroad (FOPLA) rises such that if the delivery lead time reaches six months then all orders placed will go abroad. This may not be particularly unrealistic. In 1973 when lead times reached values at the upper end of the DLTPC axis, the British Steel Corporation prohibited any further orders until such time as they had managed to reduce the backlog.

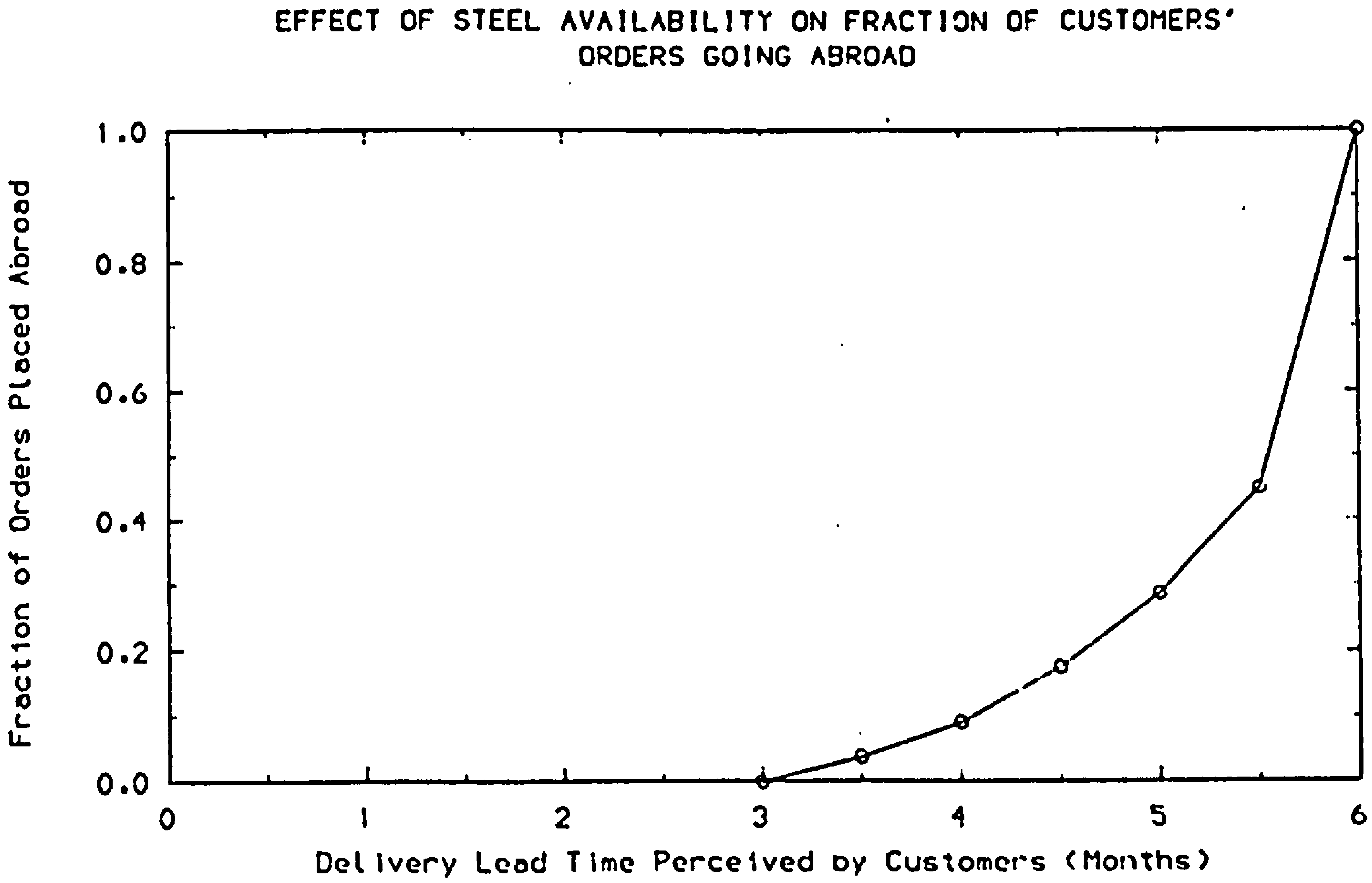

Figure 3.12 Table relationship between delivery lead time experienced by customers and the fraction of orders being placed abroad

It was the 1973 boom in steel and B.S.C.'s inability to supply which saw inroads starting to be made into the UK market by European producers. Bryer et al (1982) quote the case of British Leyland who reduced their intake of British steel from 79% of their sheet requirements in 1973 to 64% in 1974 simply because B.S.C. could not supply enough. (It will be recalled from the previous section that during 1974 B.S.C. experienced bunching of blast furnace relines: supply difficulties were particularly acute at this time.) Bryer et al quote a British Leyland executive:

> *"In the event of supply constraints within B.S.C. it is essential that our supply of vital raw materials is safeguarded. Therefore, it is important to have connections with the EEC mills so*

> *that in the event of additional tonnage being required we receive consideration and help due to a regular customer".*

It appears that similar views were taken by a large number of B.S.C. customers. P-E Consulting Group, retained by B.S.C. in 1976 to carry out a survey of the opinions and attitudes of B.S.C.'s customers, reported (according to Bryer et al p.159)

> *"........part of the market share left in the past five years will not be retrieved because some of the customers who now import have adopted a policy of second-sourcing."*

3.4 Explorations using the model

This section describes various experiments conducted with the model. These experiments are illustrative of the way in which System Dynamics models can aid thinking and learning about effective policy design. The runs conducted and results described are obviously those chosen by the author. Other people, working in the steel industry itself, may have chosen quite different issues to address and may even have structured their model rather differently from the one described above. Nonetheless this does not undermine the utility of System Dynamics models in the policy process. Such models will exhibit differing structure and content depending on the purpose for which they were created. Of more importance is a willingness on the part of senior executives to expand (or revise) their mental policy models in the light of interactions with a simulation model based on the concepts of information feedback.

3.4.1 Three blast furnace configuration

An initial experiment involved running the model of the three blast furnace situation with demand described by normally distributed random values such that the mean was 240,000 tonnes per month and the standard deviation 10,000 tonnes per month. At this stage no cycle was superimposed to reflect market dynamics. This will be introduced in a later experiment.

Figure 3.13 shows that as blast furnaces are taken out for relining, oscillations are set up in the customer order backlog. A furnace taken out deprives all the downstream processes of their feedstock and this obviously eventually affects the ability of the works to satisfy customer orders as quickly as is the case when all three furnaces are operating.

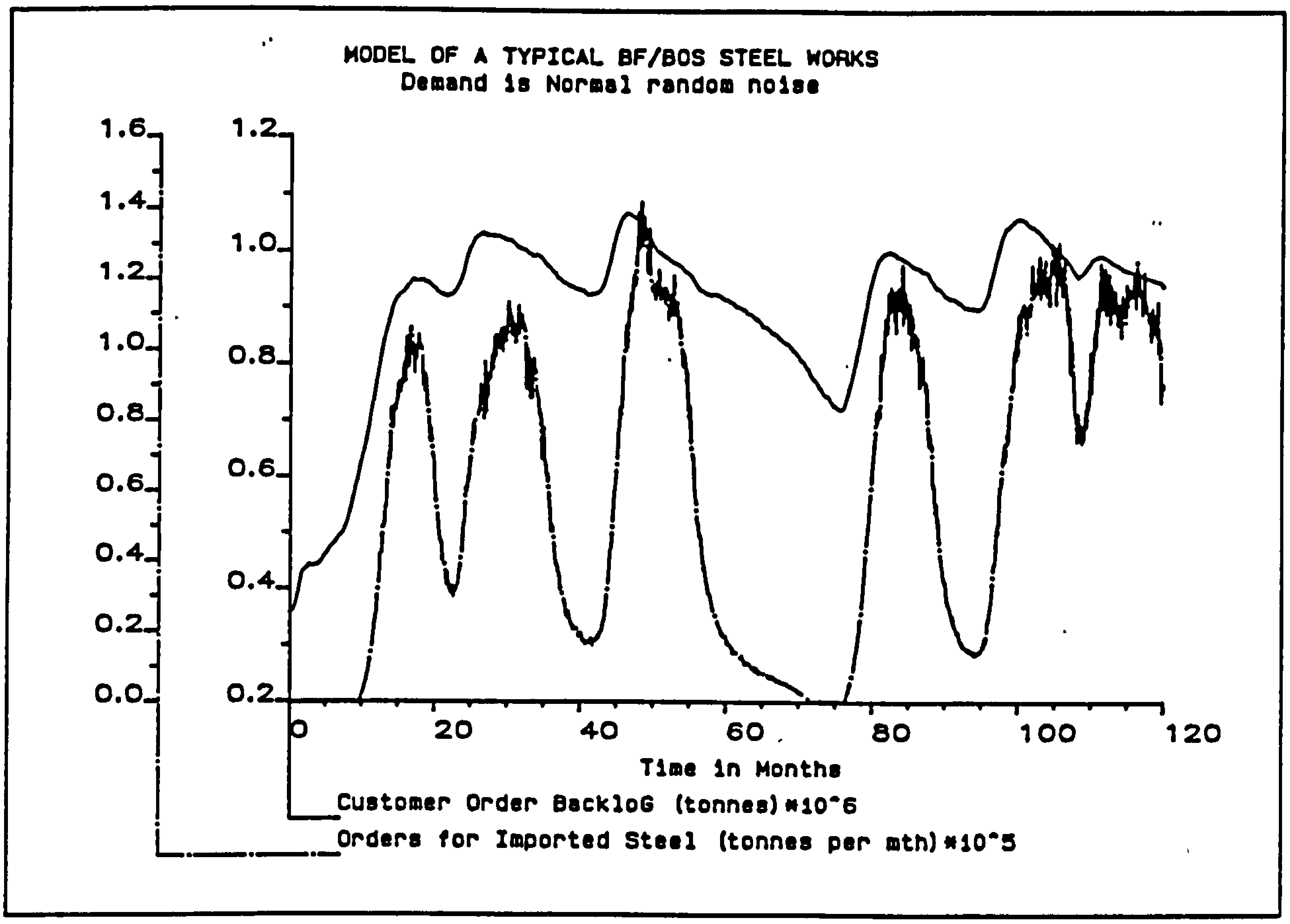

Figure 3.13 Oscillations in customer order backlog and orders for imports arising from blast furnace relines: demand is normal random noise

Customers eventually appreciate the changed supply position and over-order to compensate. Ultimately they may despatch orders abroad and thereby swell the imports of steel into this country.

This is not a particularly novel result. But it does offer the view that actions taken within the industry can have repercussions in the market. Customers' behaviour is not something which can be viewed as a purely exogenous influence. In manufacturing generally, mismanaged production policies on either product availability or quality (or both) can store up an unfavourable market reaction which may take many months to manifest itself. The sudden loss of one-third of pig iron production for between 3 and 4 months every 5 years or so may not seem a particularly significant event to a steel plant manager intimately involved, but the results provide evidence that market repercussions *are* felt despite anticipatory actions like the build-up of stocks of semi-finished steel in advance of the reline.

As mentioned previously, Carnell (1974) had looked at market dynamics as one aspect of his studies. He concluded that seasonal and longer term cycles in order placement were amplified by consumers and stockholders but that the Strip Mills Division itself further exaggerated these fluctuations. He deduced from this that capacity was not being used effectively.

Although Carnell did not specifically consider the role of blast furnaces in any of his models, it is clear from the above graph that elimination of the pig iron output from a furnace undergoing a reline is one of the contributory mechanisms whereby the steel industry itself can effect an exaggeration of order variations. He instances some other internal mechanisms such as the rate of release of customer orders by the sales office to production and the availability of adequate interprocess stocking capacity at peak periods. These aspects obviously contribute, as will any other managerial process which increases the delivery lead time to such an extent that customers react by submitting duplicate orders. The areas selected by Carnell are recognised as legitimate areas of concern but are not included in the model described here which is attempting to focus on a central issue: the role of the blast furnace.

Because the demand for finished steel does vary cyclically, principally related to movements in aggregate demand in the national economy, it is more realistic to augment the variable handling demand in the model (OPL, Orders PLaced) with a cyclical component, rather than leaving it as just normal random noise. Accordingly, a sine wave with an amplitude of 48000 tonnes per month (equivalent to plus or minus 20% of mean annual demand) and a periodicity of 48 months (typical of post-war economic cycles) was superimposed on the mean annual demand. Figure 3.14 shows the effect of this change on the order backlog. Since the same variable arising in the situation of no cyclical component in demand is also plotted (reproduced from figure 3.13) the difference in severity of the oscillations in the backlog of customer orders, arising directly from cyclical demand, can be readily seen.

Operational policy in respect of the blast furnaces is hardly rendered any easier by the presence of a demand cycle. If it turns upwards while a large furnace is out for relining (as happened in 1973-74) then lead times extend rapidly and customer dissatisfaction is manifest.

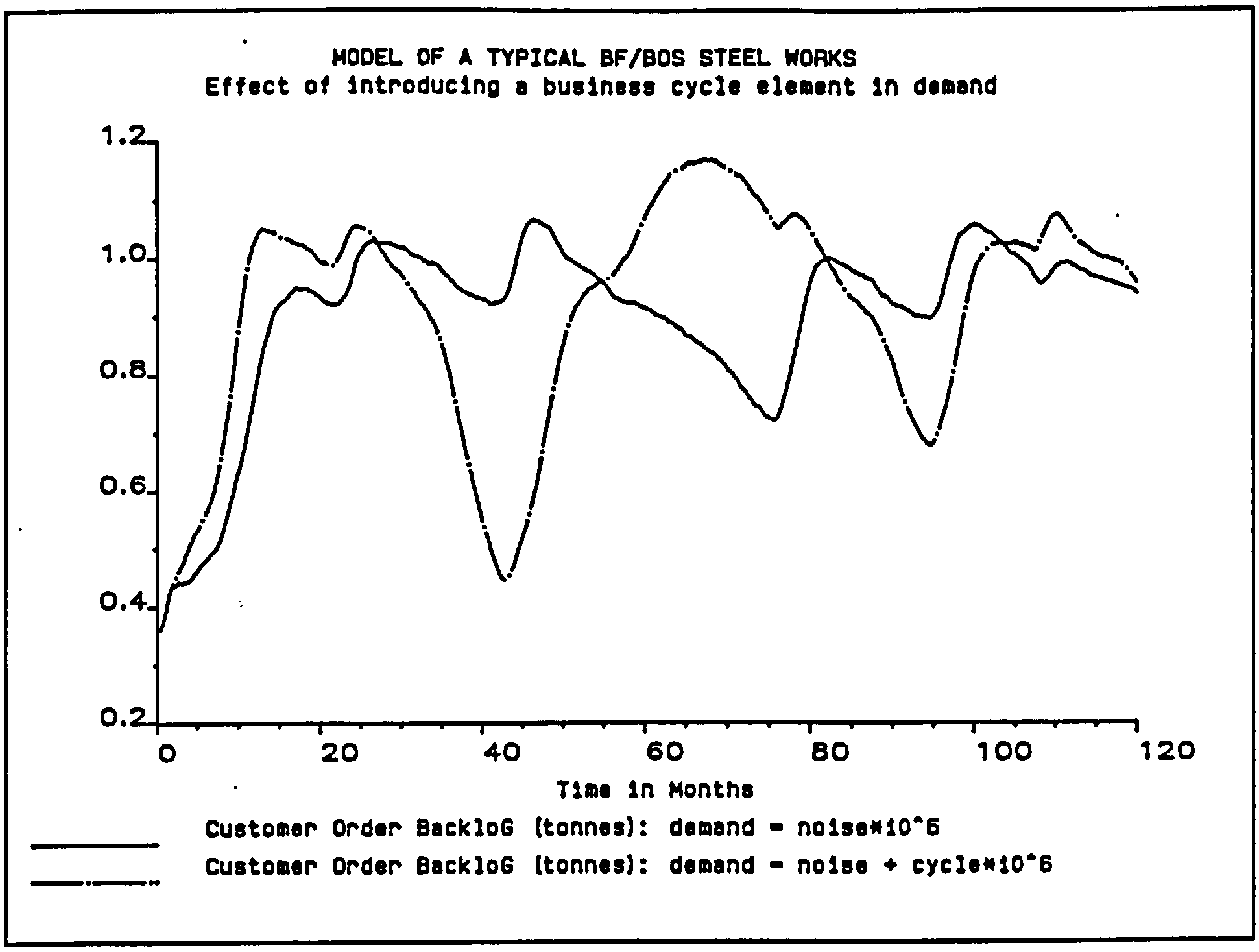

Figure 3.14 Oscillations in customer order backlog arising from demand modelled as (i) normal random noise (ii) a four year cycle superimposed on (i).

3.4.2 Configurations of three and five blast furnaces: volume comparisons

The trend towards larger blast furnaces (documented in chapter 2) and driven by unit output (and capital) cost considerations means that a more significant proportion of material for steelmaking is lost to the works on the occasion of a reline. Hence it seems reasonable to investigate the effects of having a configuration comprising a larger number of smaller blast furnaces. Accordingly an assessment has been made of the effects of operating with five blast furnaces (each having an average throughput around 48000 ingot tonnes per month) compared to the existing configuration assumed (outputs close to 80000 tonnes per month). Obviously the overall output for each specimen configuration is the same, being 240,000 tonnes per month.

It should be made clear at the outset that a five blast furnace operation is potentially much more costly. Increasing economies of scale have been avidly pursued in respect of process plant, propelled it seems solely by industrial engineering estimates which derive from the fact that the volume increases more rapidly than the enclosing surface of rectangular, cylindrical and spherical shapes and that output is highly correlated with volume and investment and operating costs with size of the enclosing surface. A rule of thumb in common use suggests that a doubling of capacity requires investment of only about six-tenths.

Bela Gold has conducted empirical studies of economies of scale, for instance in respect of Japanese blast furnaces (Gold, 1974), and claims no evidence as to the existence of such economies can be unearthed. In a number of studies on economies of scale (Gold, Rosegger and Boylan, 1980; Gold, 1982) he questions whether this aspect of theoretical industrial economics is one possessed of any empirical substance. The study described below can be seen in some small way as contributing to this growing store of knowledge on economies of scale.

Initially, the results are reported without reference to a financial performance measure. However, it is clear that no comparison can be made between the two blast furnace configurations under investigation *without* including costs. Accordingly, this performance measure is developed in the subsequent sections.

For the moment, consider figure 3.15 which depicts the production of semi-finished steel and the lead time perceived by customers under the two alternative configurations. Demand is modelled as normal random noise with a business cycle component superimposed.

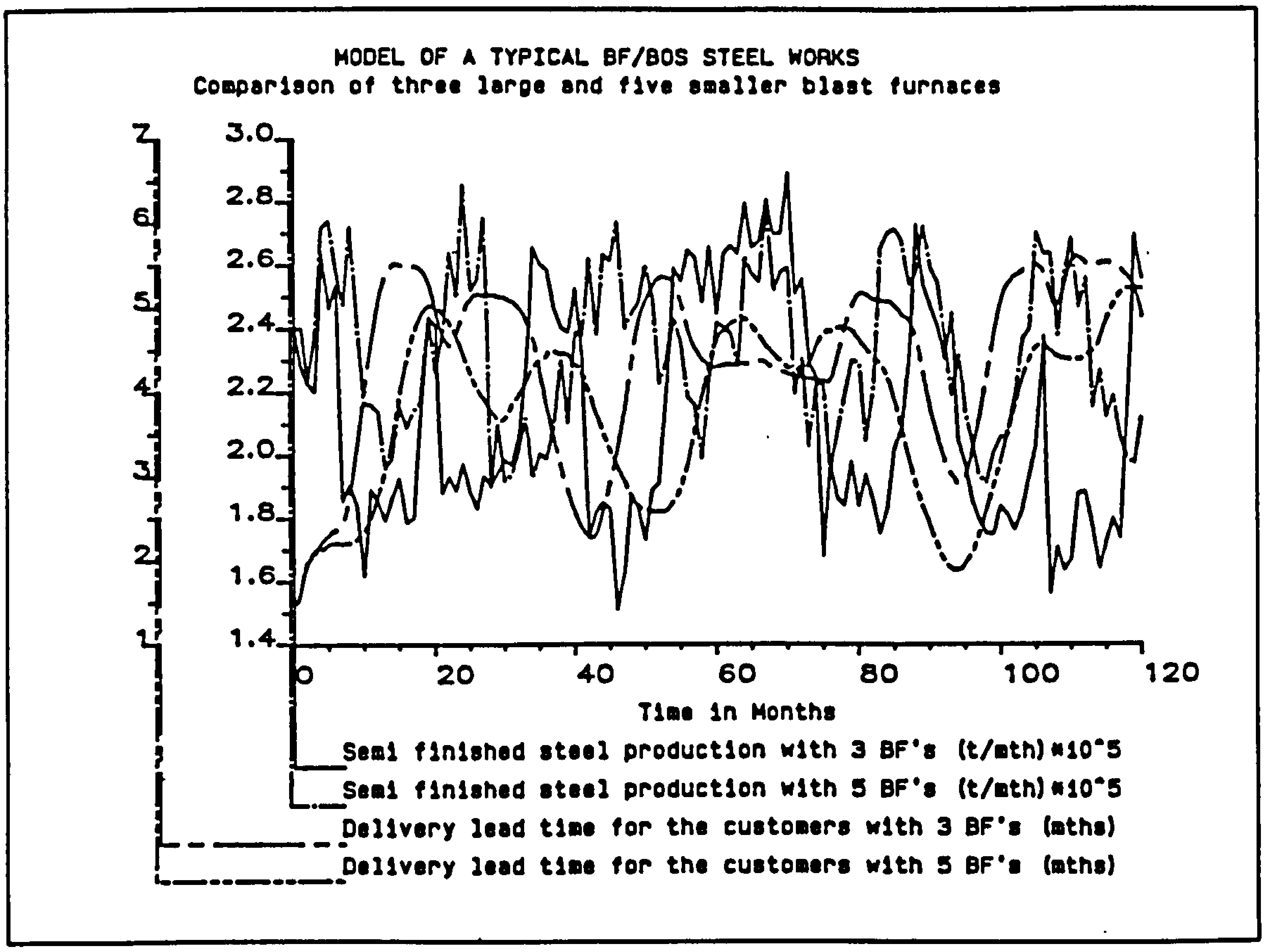

Figure 3.15 Semi production and lead times perceived by customers arising from (i) a configuration of three large blast furnaces and (ii) five smaller blast furnaces

Clearly production is rather less volatile under the five blast furnace configuration and lead times are somewhat lower. This is important: when lead times do not escalate as much, steel buyers are tempted less to switch their purchase orders abroad. The flexibility of the smaller plant is the essential point here. Time and again contributions to the literature on economies of scale -- in the case of the steel industry Barnett and Crandall (1986); Jones and Cockerill (1984); and Bryer et al (1982) -- make the point that, while the larger sized plant can produce at a lower cost per unit of output, these large production units lack "flexibility". Precisely what is meant by this term is not often spelt out. But here is offered one potential feature in connection with the steel industry: blast furnaces, their system downtime for relines and their limited variability of output. System dynamics as a tool for policy evaluation can, moreover, take into account both the revenue/market consequences of plant inflexibility as well as the cost of production aspects developed in the following section.

3.4.3 The costing of blast furnace and other operations

There is little doubt that money is the appropriate metric to employ in policy evaluations of technology in the steel industry. The evidence in the literature, particularly from Bryer et al (1982), confirms what might be intuitively expected: that strategic planning has involved the consideration of various options which have all been reduced to a financial measure. Not only that but *discounted* money values are adopted for the evaluations. This is entirely expected in view of the long term nature of most strategic planning. Accordingly, the model (reproduced in full as an appendix to this chapter) incorporates a financial sector which brings together under a common measure all the operational issues under consideration.

To declare such a laudable goal is one thing, but to unearth appropriate figures to employ in the model is very much another. Operating costs can be found in a number of books and published articles but they are invariably quite general, do not always indicate the capacity utilisation being achieved and do not declare either the blast furnace size assumed or the overall plant output.

Inescapably, artificial financial data have had to be employed. Nevertheless, the internal consistency of the numbers used was held relative to the proportions of cost allocated to the various processes and also to the proportions as between fixed and variable costs. Furthermore, the unit price figure (per ingot tonne) was chosen such that it was simultaneously in line with recent quoted prices and yielded a reasonable break even point for the hypothetical works under consideration which, it will be recalled, produces approximately three million ingot tonnes per annum. The derivation of all cost coefficients will now be given in detail.

The most up-to-date and comprehensive costing data was found in Barnett and Crandall (1986 p.120) and is based on U.S. experience. These authors cite all the relevant unit costs, in 1985 dollar terms, for a representative integrated steel mill operating at 90% of capacity and producing cold-rolled coil. The data sources are calculations by those authors based on confidential figures. Table 3.1 shows the split as between fixed and variable costs assuming, as do Jones and Cockerill (1984), that labour costs are classified as fixed. Also shown are the cost per tonne figures attributed to each of the major stages of production in an integrated steel mill, from the heavy end right through to the cold finishing stage.

	Fixed Cost	HEAVY END		Variable Cost
	31.3	Coke Oven		65.1
	31.85	Blast Furnace		101.8
	19.7	BOS Furnace		67.75
	12.0	Ingot Caster		3.6
	15.8	Slab Mill		26.55
		FINISHING END		
	27.45	Hot Strip Mill		23.0
	58.7	Cold Finishing		41.9
Total	196.80		Total	329.70

Table 3.1 Allocation of unit production costs ($ per ton) for a typical integrated steel mill (from Barnett & Crandall, 1986)

It can be seen that the following approximate proportionate allocation of unit costs prevails.

Fixed Costs:	Heavy End	56%	Finishing End	44%
Variable Costs:	Heavy End	80%	Finishing End	20%
Heavy End:	Fixed Costs	30%	Variable Costs	70%
Finishing End:	Fixed Costs	57%	Variable Costs	43%
Total Unit Costs :	Fixed	37.4%	Variable	62.6%

Assuming that the total cost (£) of output rises linearly with output, a pair of cost equations which satisfy the above proportions are:

$y = 152.03E6 + 118.58\ x$ Heavy End
and
$y = 120.1E6 + 30.41\ x$ Finishing End

$y = 272.13E6 + 148.99\ x$ Total

x = throughput per annum

The above assumes that the plant is operating at 90% of its capacity, which is 2.88 million tonnes × 1.15 × 0.9 = 2.98 million tonnes. The 15% increase accounts for upward variations which can be achieved at the heavy end by altering the blast furnace burden (handled by the Burden Efficiency Factor in the model). This flat-out capacity at the heavy end can furthermore be accommodated by the finishing end, where output can be increased by up to 20% (handled by the Order Backlog Factor in the model). These potential variations are represented in the model by table functions and have been described in an earlier section.

For the heavy end, costs are

152.03E6 + 118.58 (2.98E6) ≃ £505.4E6.

This is £51.02 per tonne (fixed), £118.58 (variable) and £169.6 (total).

For the finishing end the equivalent costs are

120.1E6 + 30.41 (2.98E6) ≃ £210.7E6 .

This is £40.3 per tonne (fixed), £30.41 (variable) and £70.7 (total).

Fixed costs per tonne can be seen to be allocated with 56% to the heavy end and 44% to the finishing end, as required. For variable costs the figures are 80% to the heavy end and 20% to the finishing end, again as required.

Further, the heavy end has 51.02/169.6 × 100 per cent of unit fixed costs which is the required 30% with 40.3/70.7 × 100 per cent of unit variable costs for the finishing end, which also meets the required 57% of the total.

Finally, the total unit fixed cost of 51.02 + 40.3 = £91.32 per tonne is very close to the required 37.4% of total overall unit costs.

Variable costs are 118.58 + 30.41 = £148.99 or nearly 62.6% of the total.

If a revenue per ingot tonne of £250 is assumed then the break-even point for the plant is ≃ 2.69 million tonnes throughput or 81% of its flat-out capacity. This is depicted in the static break-even graph below (figure 3.16).

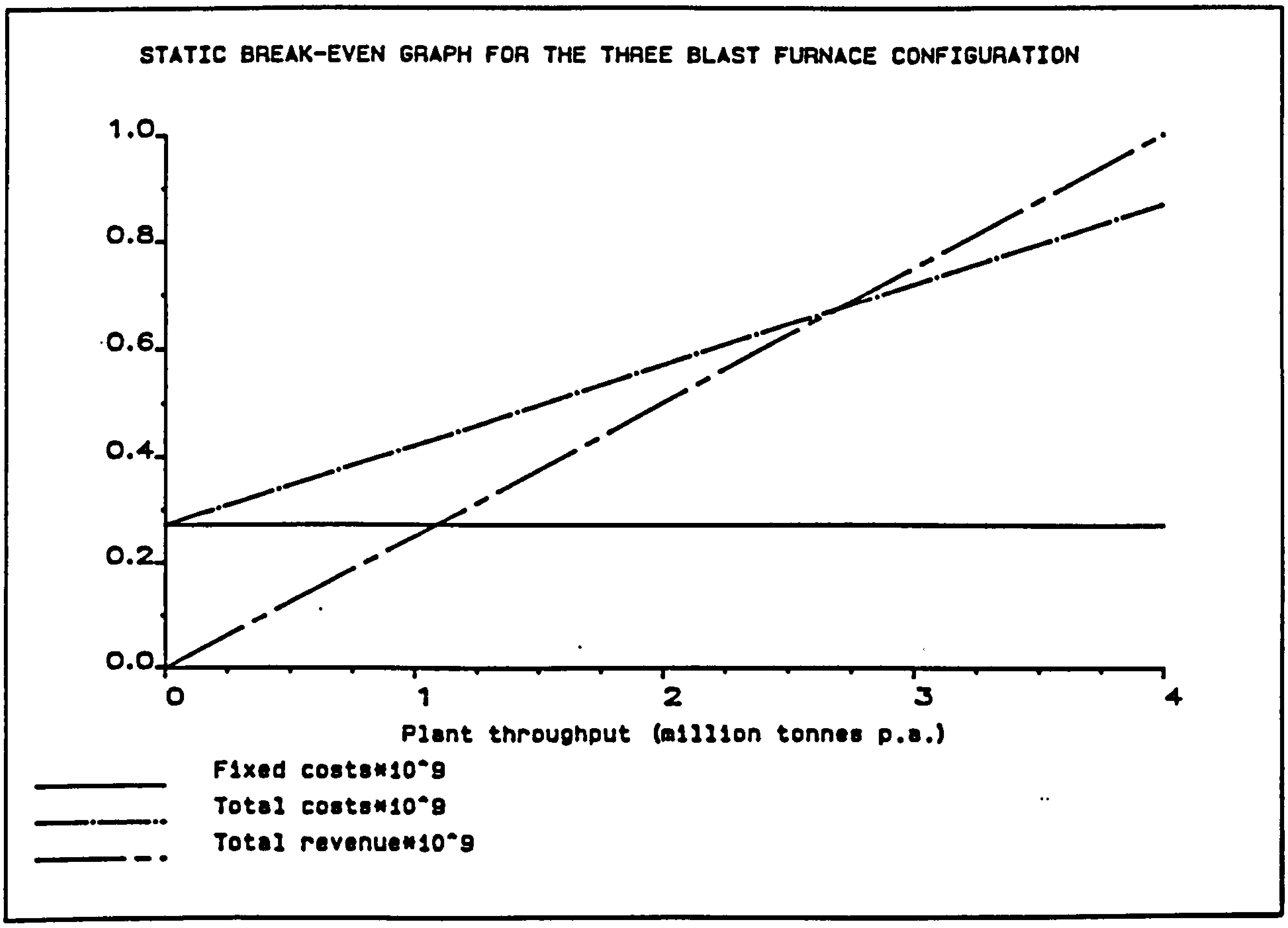

Figure 3.16 Static break-even graph for the 3 blast furnace works with assumed cost and revenue figures

Having explained the derivation of the cost coefficients for a three blast furnace configuration, it is now necessary to turn to the five (smaller) blast furnace configuration and repeat the exercise. This is not carried out ab initio but rather by adjusting the fixed cost coefficient associated with the heavy end for the (existing) three blast furnace configuration. It is assumed that unit variable costs at the heavy end and both fixed and variable costs at the finishing end are unchanged by the size of the blast furnaces installed. Overall output is the same as before.

From table 3.1 it can be seen that the blast furnaces and coke ovens account for 57% of the heavy end fixed costs per ton. Thus £86.66 million of the assumed £152.03 million fixed costs can be thought of as representing three blast furnaces and associated coke ovens in the model. This is £28.89 million per furnace. Assuming each furnace is operating at 90% of capacity (as before) its throughput per annum is

$960000 \times 1.15 \times 0.9 = 993600$ tonnes

yielding a cost per tonne of £29.07.

The size of a blast furnace is governed by its hearth diameter and so to find the increase in fixed cost per tonne from furnaces averaging 960,000 tonnes per annum to those averaging 576,000 tonnes per annum it is necessary to make an assumption about the relationship between hearth diameter and achievable annual output. The influential Battelle Institute (1977, p.181) have published some German data which are graphed in figure 3.17.

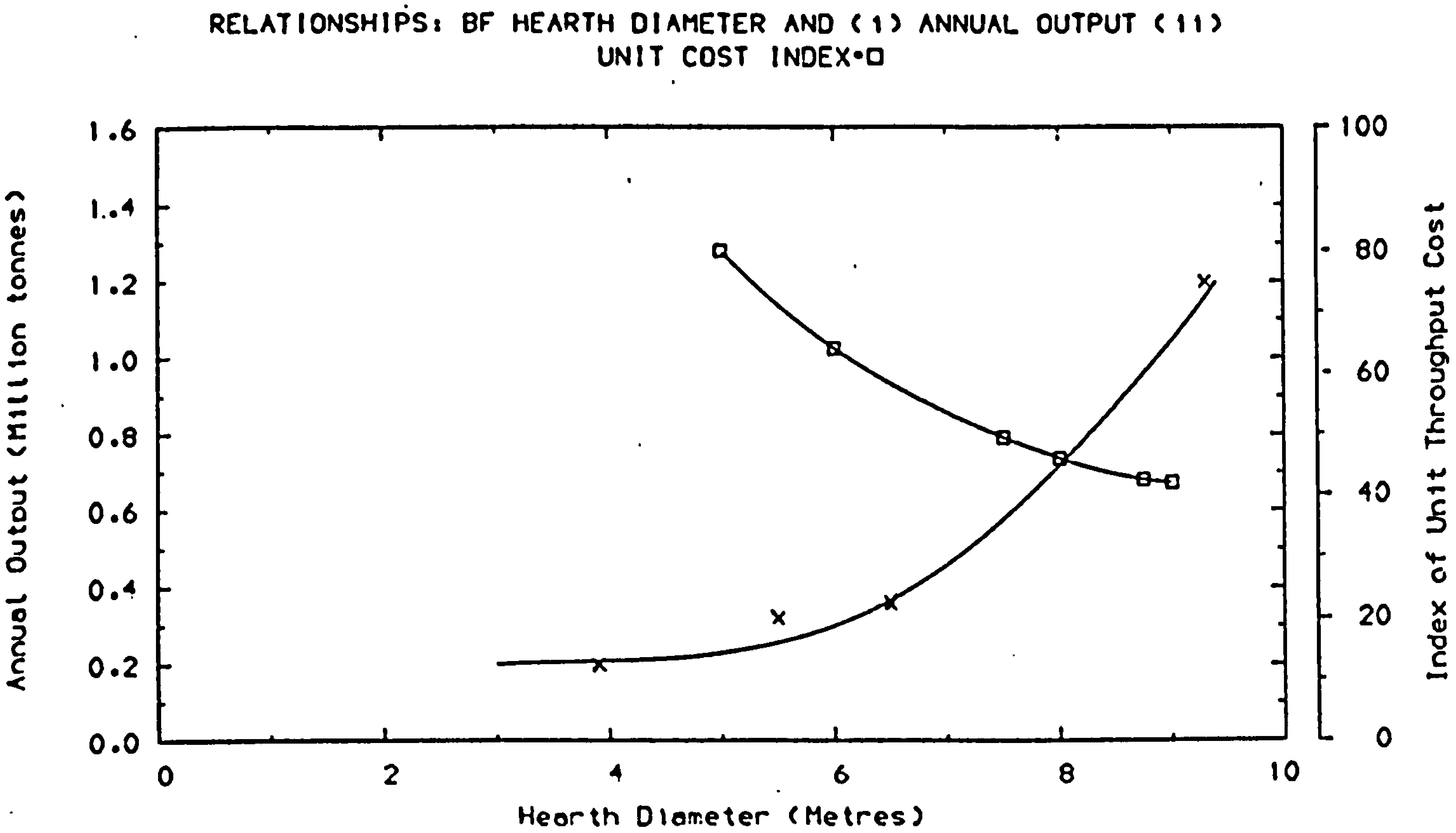

Figure 3.17 Relationship between blast furnace hearth diameter to (i) average annual output and (ii) an index of operating costs

The curve was fitted to the data by eye. An output of 576,000 tonnes per annum comes from a furnace of hearth diameter 7.5 metres and an output of 960,000 tonnes per annum from one of 8.75 metres diameter. Also shown in figure 3.17 are some additional data from Battelle (1977, p.182) which yield an estimated increase in operating costs of 16% between a 7.5 metre and an 8.75 metre furnace. This, then, represents the supposed diseconomies of smaller scale plants.

Returning to the derivation of the revised fixed costs for the smaller blast furnaces it is now possible to gross up the cost per tonne figure for the larger blast furnace and so obtain an estimate of the same appropriate to a smaller furnace. This gives 29.07 × 1.16 = £33.72 per tonne. Recall that total output is

2.88E6 × 1.15 × 0.9 = 2.98 million tonnes

at 90% of capacity. Hence the revised total fixed cost is

2.98E6 × £33.72 = £100.51 million.

This is an increase of

100.51E6 - 86.66E6 = £13.85 million. The two linear cost equations for the five blast furnace configuration are now given below.

y = 165.88E6 + 118.58 x	Heavy End
and	
y = 120.1E6 + 30.41 x	Finishing End (unchanged)
y = 285.98E6 + 148.99 x	Total

x = throughput per annum

With revenue per ingot tonne kept at £250 the above equations mean that the plant now breaks even at an annual throughput of 2.83 million tonnes or 140,000 tonnes per annum more than in the three blast furnace configuration. Break-even moves to 85.4% of capacity.

Stockholding costs are also included in the overall financial performance measures. Costs are added in to cover the holding of semi-finished steel and allocated steel. In each case an average monthly stock figure is obtained by adding together two months holdings and dividing by two. This average stock figure is then SAMPLEd each month (using the DYSMAP2 SAMPLE function) and multiplied by the cost of holding stock, assumed to be 15% per annum (applied at a monthly rate) of the unit value of the stock. Assumed unit values are £100 for semi-finished steel and £200 for allocated stock (at the finishing end). Relative to operating costs (fixed and variable), stockholding costs are a small component of total costs.

3.4.4 Configurations of three and five blast furnaces: financial comparisons

Having derived the relevant cost data it is now possible to conduct simulation explorations using financial performance measures. Where discounted costs and revenues are used, the discount rate is set to 15%. The B.S.C. used 16% in their strategy planning calculations according to Bryer et al (1982).

Figure 3.18 shows the annual profit with a three blast furnace configuration for each of the ten years of the 120 month simulation. Profit is calculated here, as it would be in a set of annual accounts, by cumulating revenues and costs over twelve months and then calculating the difference. At the end of each year the variables handling the cumulative data have to be reset to zero to allow the cumulations for the following year to commence.

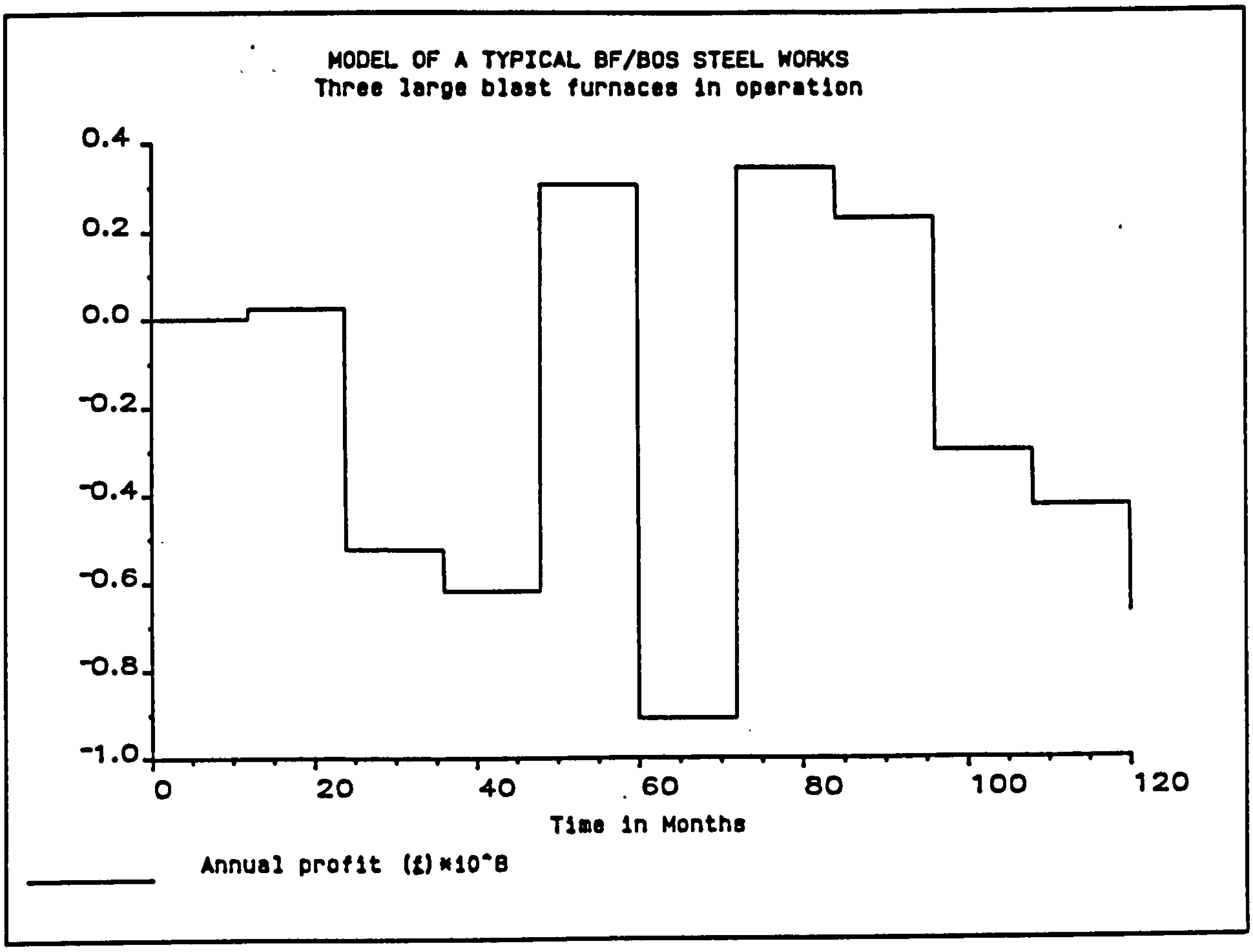

Figure 3.18 Annual profit from a three blast furnace configuration

Lurches between profitability and significant losses, so characteristic of a manufacturing business involving relatively high fixed costs and operating in the region of the break even point, are captured in the model.

Figure 3.19 depicts the annual profits reported by the British Steel Corporation (now British Steel plc) from 1967/68 to 1988/89. The marked swings are again apparent. For instance, in 1972-73 B.S.C. turned a £12 million trading loss into a £45 million profit. Between 1974/75 and 1975/76 a profit of £144 million became a loss of £159 million. In 1985/86 a £91 million trading profit was reported when the year before a loss of £64 million had been posted.

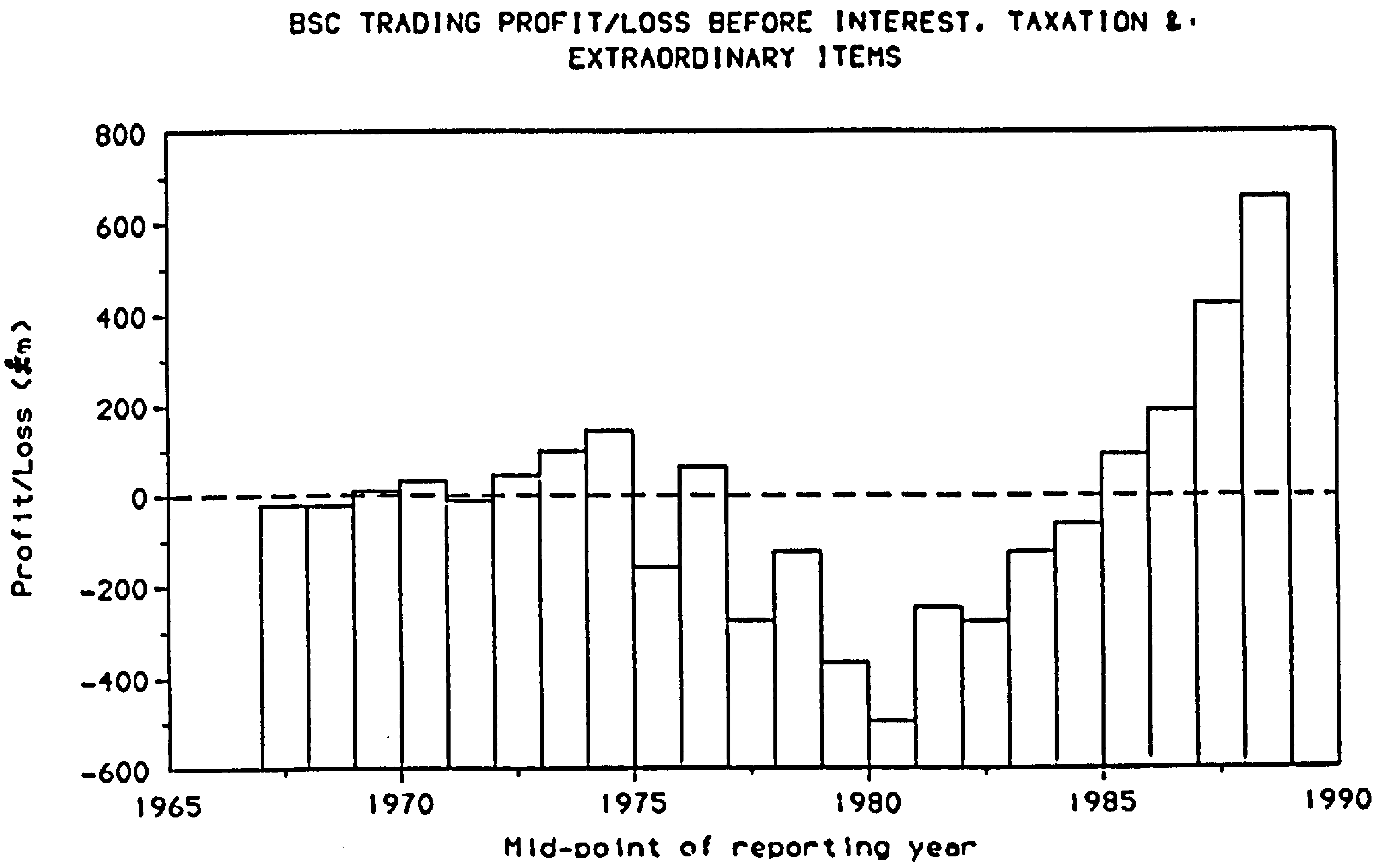

Figure 3.19 B.S.C. (British Steel plc) financial results before interest, taxation and extraordinary items

While figure 3.16 gives a picture of the break even point in a static framework, it is perhaps appropriate now to show how the main financial variables behave in the dynamic situation where customer demand is cyclical. Figure 3.20 is, in effect, a dynamic break even graph. It shows how revenue compares to total cost when running the model with three blast furnaces. Clearly, on those occasions when total revenue fails to cover total costs a loss is the outcome. This is clearly the case in the second, third, fifth and ninth years, for example. It is not difficult to envisage a slump in demand so severe that even fixed costs are not covered. In such an eventuality a firm making steel would be in very serious financial trouble.

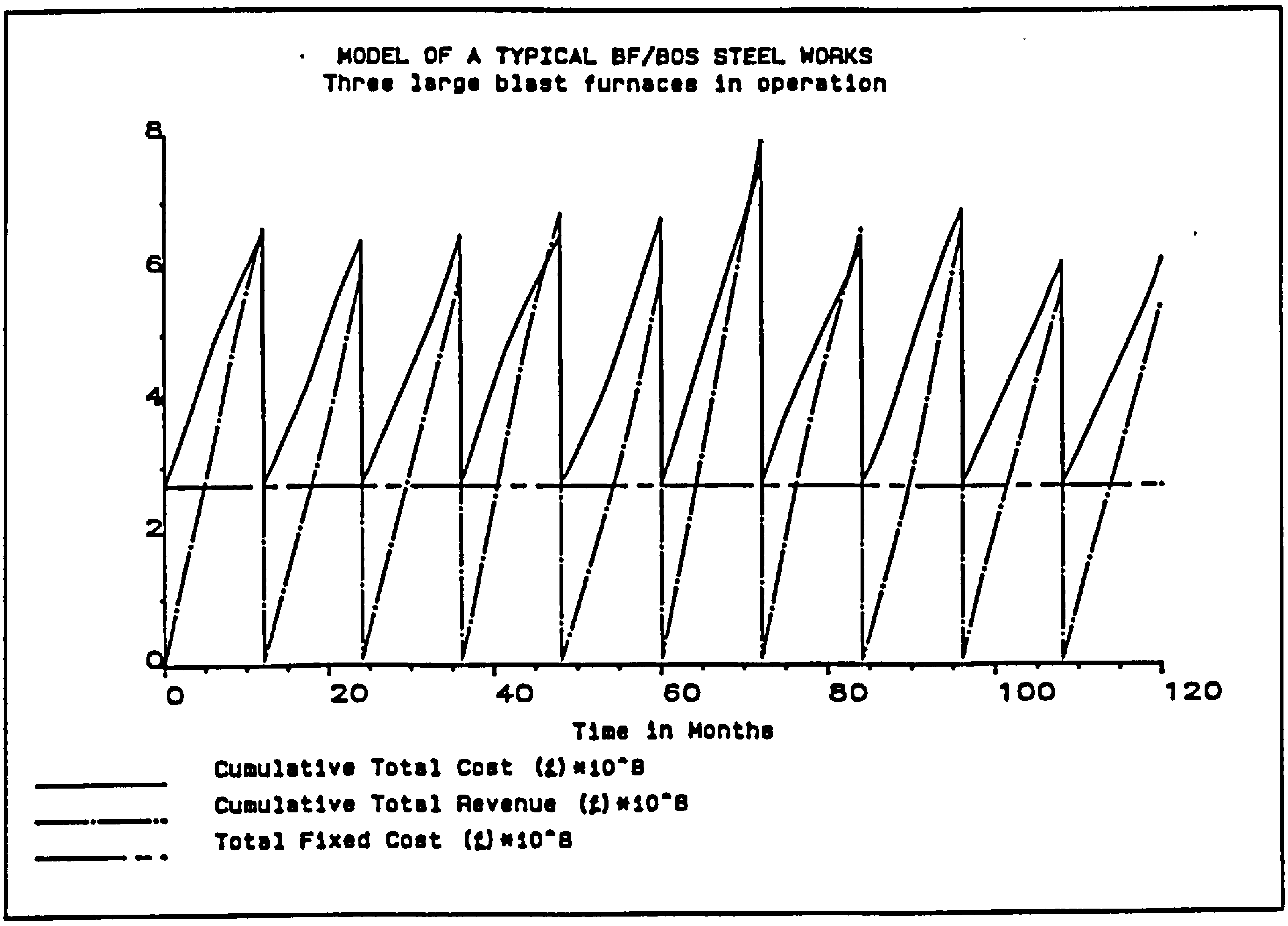

Figure 3.20 The behaviour of costs and revenue for the three blast furnace model when demand includes a business cycle

Having depicted the results from the model when a configuration of three blast furnaces are used, it is now possible to offer comparative financial scenarios in the situation where, instead, five smaller blast furnaces are employed. Demand is kept exactly the same as with the three blast furnace runs. Figure 3.21 shows the cumulative discounted profit, over the ten year run, for each configuration.

Recalling figure 3.18 it is not surprising that *for both options* a significant loss is revealed over the ten year period, but in terms of a financial *comparison* the supposedly less economic configuration is superior.

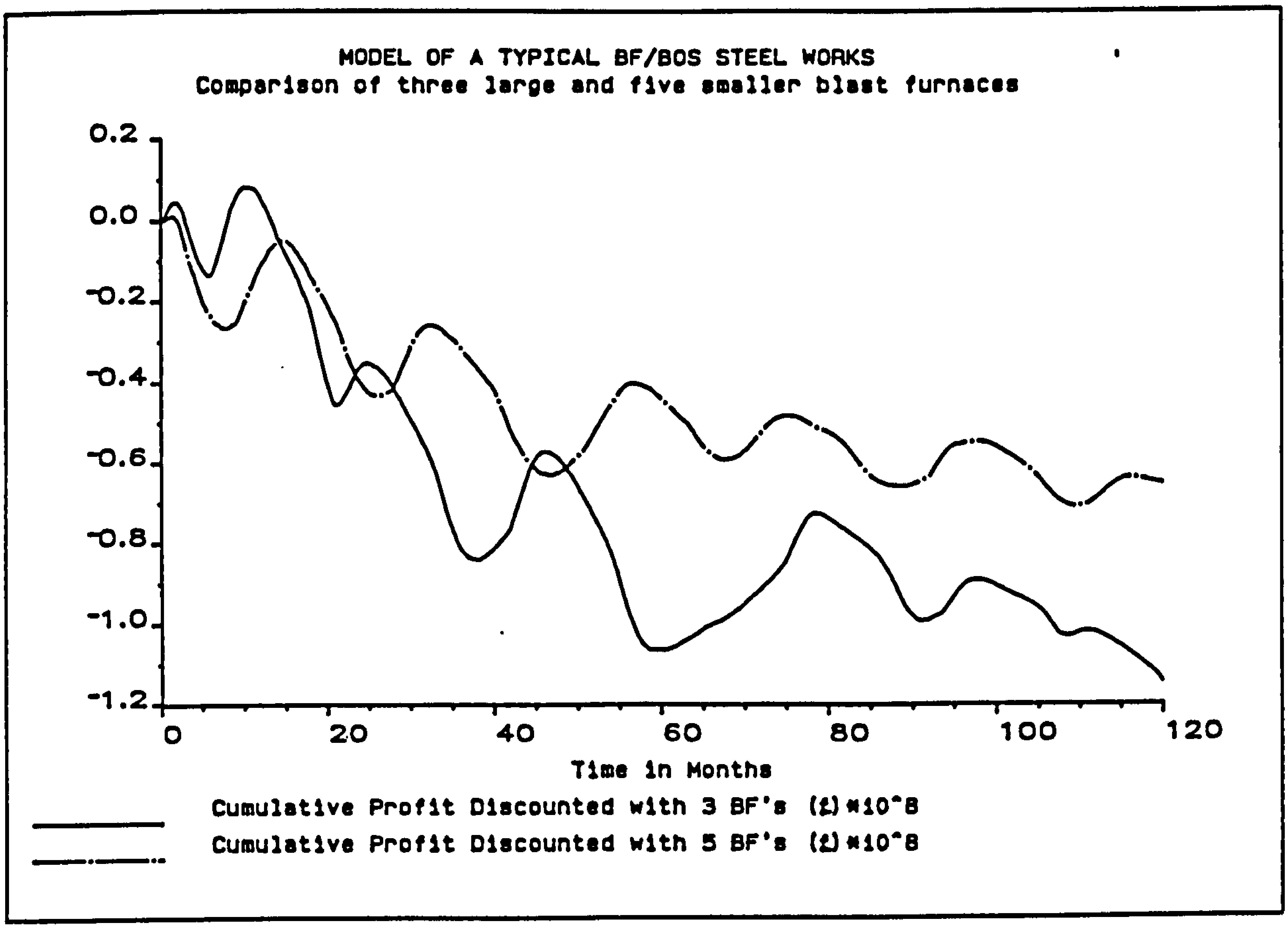

Figure 3.21 Comparative scenario in terms of cumulative discounted profit for configurations of two different blast furnace sizes

To uncover the reason for this result it is necessary to look at the two components of the profit equation -- costs and revenues, figures 3.22 and 3.23 respectively. Figure 3.22 reveals that the configuration of larger blast furnaces is indeed the cheapest. The economies of scale are clearly available and utilised.

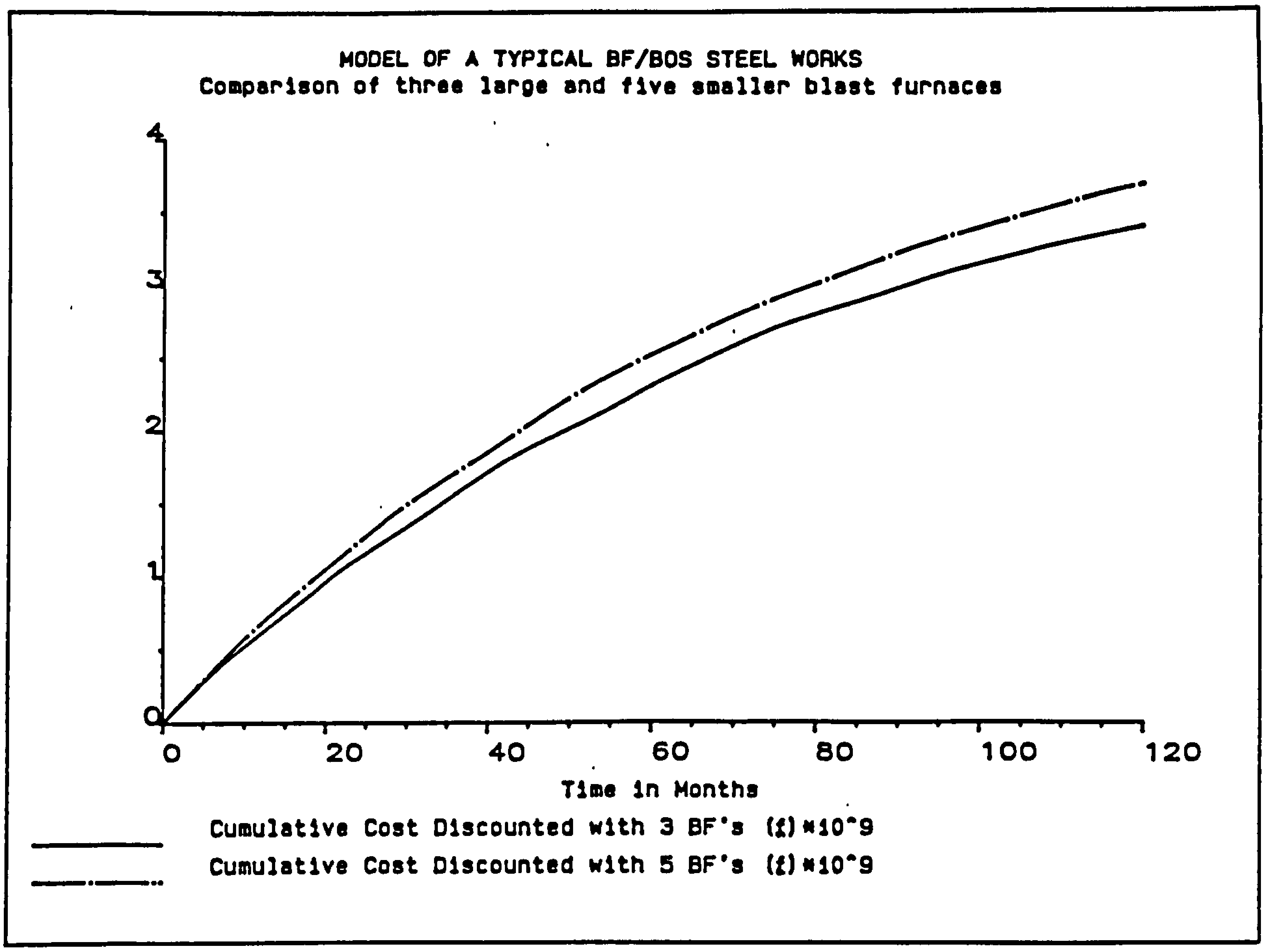

Figure 3.22 Cumulative costs discounted under the three and five blast furnace configurations

However, the picture is reversed when the revenue side of the equation is examined (figure 3.23). This is the nub of the issue. Although the five blast furnace operation is more expensive to operate, it is more flexible. Less business is lost abroad because lead times do not extend so far consequent on supply shortfalls due to relines. The gap between discounted revenue is wider in favour of the five blast furnace configuration than the gap between discounted cost is in favour of the three blast furnace configuration.

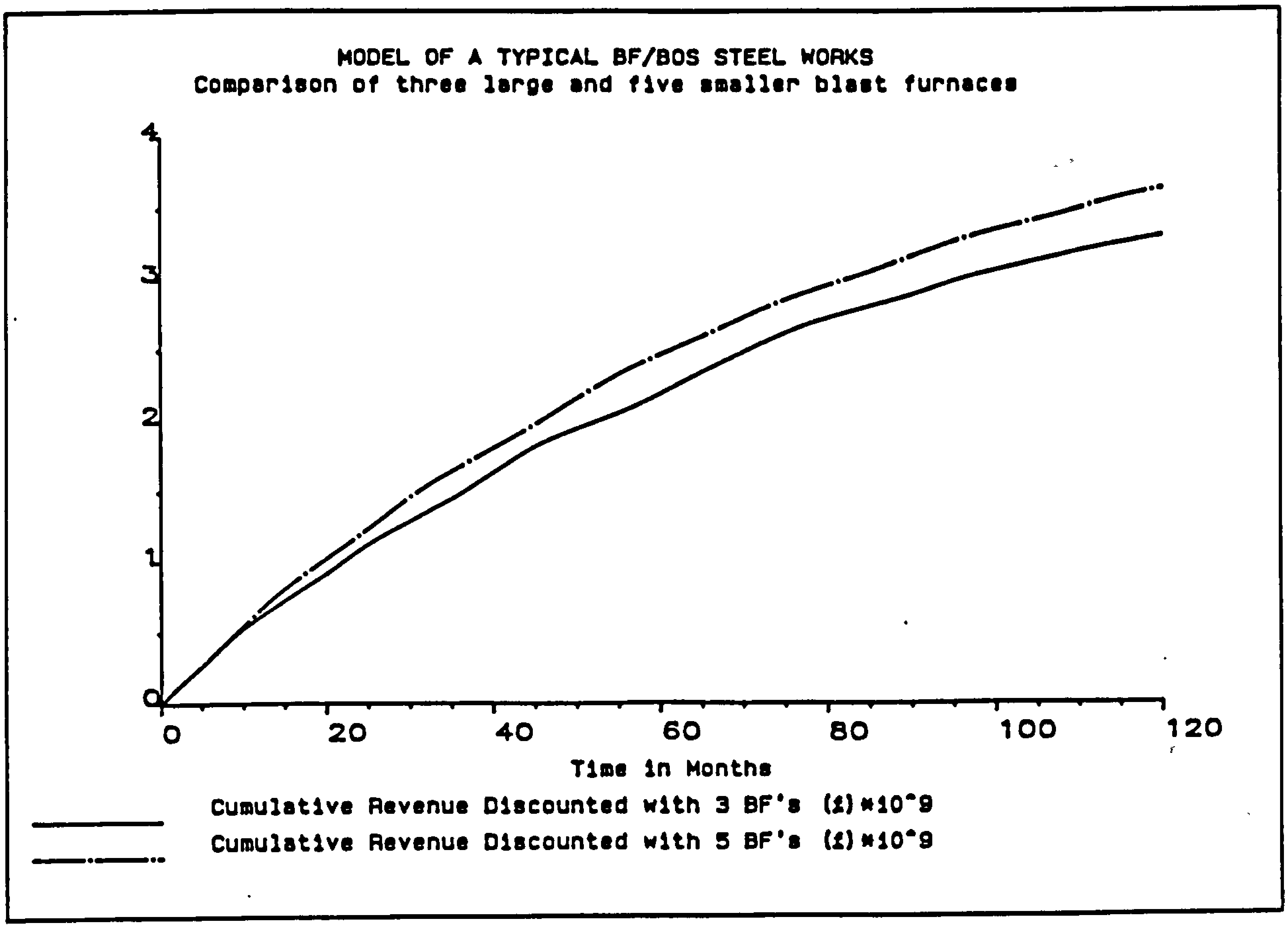

Figure 3.23 Cumulative revenue discounted under the three and five blast furnace configurations

It can be seen, therefore, that the graph of a comparison of the delivery lead time, presented earlier in figure 3.15, and which favoured the configuration of smaller furnaces, is a major determinant of the improved profitability (smaller losses) evidenced in their operation. Less revenue is lost to foreign competitors if order backlogs and lead times are better managed. Economies of scale might exist but these economies cannot be put to effective use if it implies a productive set-up which cannot cope in strong market conditions, leading to an adverse customer reaction. The revenue as well as the cost side of the equation needs to be considered. Tomlinson, Buzacott and Tsuji may be hinting at this when they say (1982):

> *"In fact, the more that one studies a real problem (of scale), the more the dynamics seem to gather in importance, and the more one becomes aware that an optimum based on static information may be local in time, and extremely dangerous."*

Figure 3.24 merely reflects the unit cost differences between the two configurations. It shows a scatter of points, one point for each year in the simulation, of the output cost per tonne actually achieved in that year. Each locus of points creates a curve reflecting economies attained through more effective capacity utilisation for a given scale. A curve of this shape is commonly seen in economics textbooks. Shifting to a smaller scale of plant causes a transfer to a different locus of cost per tonne points.

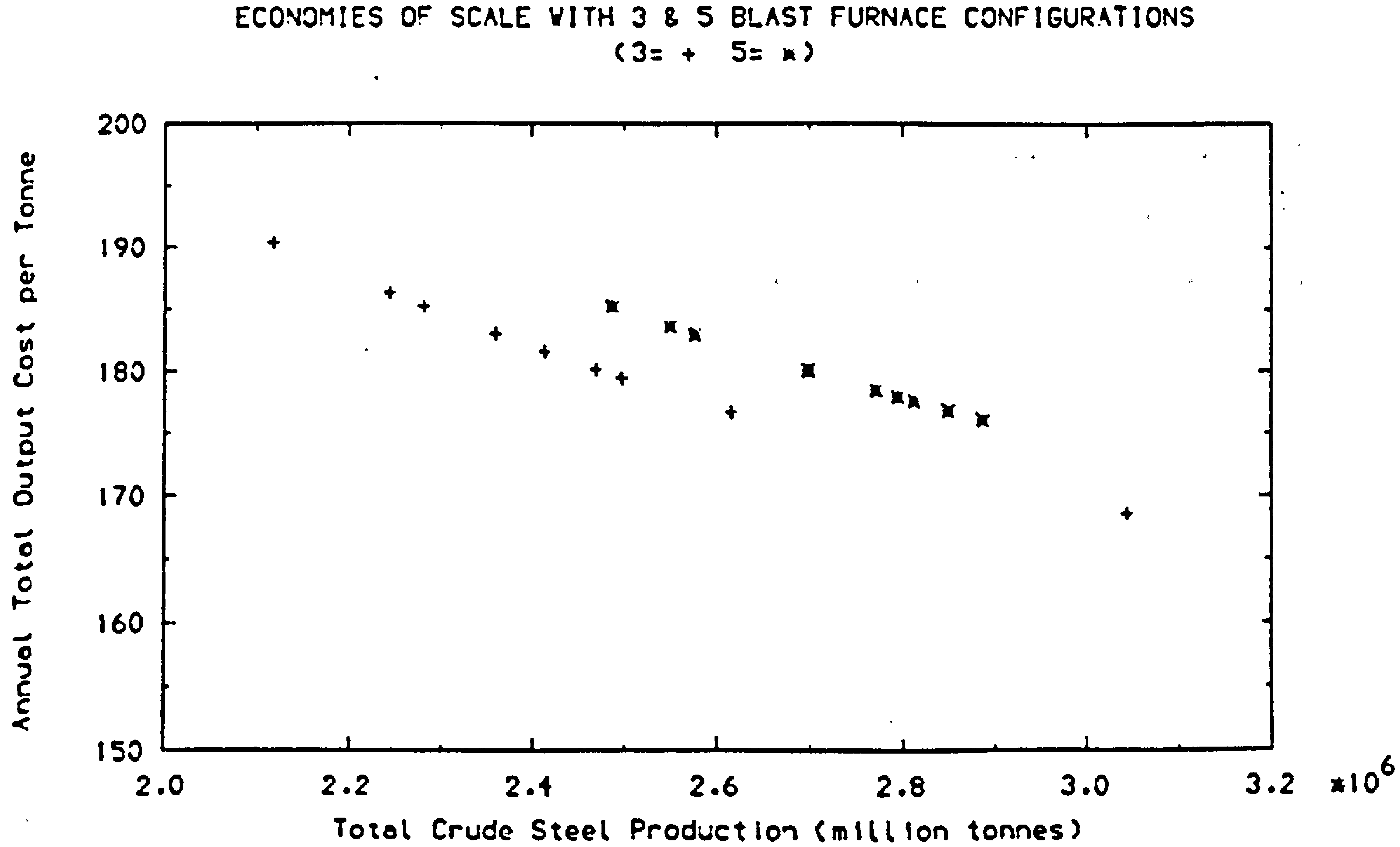

Figure 3.24 Output cost per tonne figures achieved over the ten year simulation for each configuration of blast furnaces

To reinforce the argument in favour of the smaller furnaces it is worth pointing out that, in costing the five furnace operation, the amounts for coke ovens were included in the sum to which a loading factor of 16% was applied. If the figures for coke ovens are excluded, on the grounds that they will operate to supply five furnaces in exactly the same way as they operate to supply three with an identical total throughput, then the increase in fixed costs for the smaller furnaces is not as great. The break even point is consequently lower and the above results would favour the small furnace operation even more. The scatter of points between the two configurations in figure 3.24 would be even closer together.

A sensitivity test concerning the mean demand has been conducted on this model. In place of a mean demand of 240,000 tonnes per month, a figure of 200,000 tonnes was used. The cyclical component is left unchanged but the mean level around which the oscillations are occurring is now reduced by nearly 17%. The result for the lower mean demand is graphed in figure 3.25 where the cumulative discounted profit is shown for the three and the five blast furnace configurations.

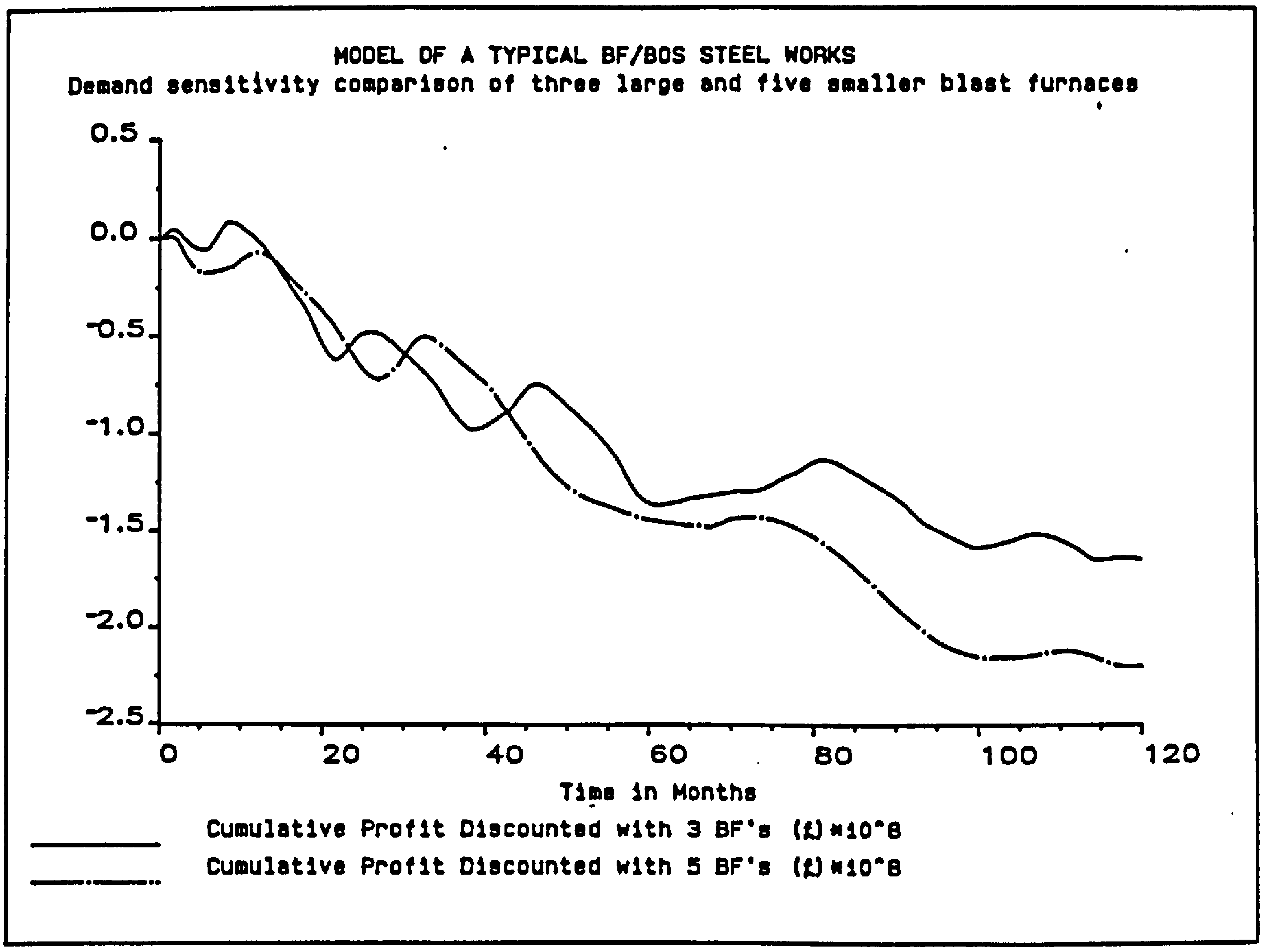

Figure 3.25 Cumulative discounted profit for configurations of two different blast furnace sizes when mean demand is reduced to 200,000 tonnes p.a.

The result is quite interesting. Because demand is reduced, the works can now more easily cope. Blast furnace relines are not as critical. With the higher demand scenario, relines lost business by extending lead times and the cheaper (large) blast furnace configuration resulted in significant lost revenue, to such an extent that it emerged as the least profitable arrangement. Here the situation is reversed. There is less pressure on capacity and although the five furnace configuration still manages the greatest revenue, the lower output costs of the larger furnaces are such that they outweigh any disadvantages on the revenue side and the result is that the three furnace configuration yields the smallest discounted loss and becomes the preferred configuration. The smaller furnaces are always the worst for cumulative costs discounted and best for cumulative revenue discounted but what matters are the relative sizes of the discrepancies in each case.

Of course, the *absolute* profit or loss values change markedly arising from the lower average demand. This reflects the point made earlier that industries with high fixed costs of production require consistently strong throughput in order to remain profitable. For the three furnace operation the cumulative discounted loss rises from £115 million to £166 million consequent on demand being reduced to 200,000 tonnes per month. For the five furnace operation, with higher fixed costs, the cumulative loss discounted rises from £65 million to £221 million.

It is worth reflecting on these results in terms of their implications for policy. There is no doubt that unit output costs can be reduced by increasing the scale of the operation as represented here by blast furnace hearth diameter. However, unless a margin of throughput capacity over average demand is tolerated, larger furnaces will lead to rapid extensions of the lead time in times of sharply increased customer demand, to such an extent that their ex ante economies of scale are wiped out. The narrower is the gap between capacity and average demand the more economies of scale are turned on their head: a smaller scale operation may be more profitable.

These experiments with the model may have had an input to the debate concerning strategic policy in the UK steel industry in the late 1970's and early 1980's. Over this period (as is documented in some detail by Bryer et al (1982)) the British Steel Corporation closed the Consett and Corby steel works and the heavy end at Shotton works. All were described as possessing plant on too small a scale to be profitable. B.S.C. were to concentrate production on five main steelworks in the UK where large-scale operation would secure extremely low unit costs per tonne of output. To this end plant improvements were to take place at these five major works. Port Talbot, for instance, would have the benefit (sic) of a large new blast furnace. It would cope with the output of three smaller ones at that site and these small furnaces would, in consequence, be de-commissioned.

Juxtaposed against this action by the British Steel Corporation stands the strategic initiative taken by Kaiser Steel in the U.S.A. in 1978. With the rapid growth in steel demand in 1973-74 optimism flourished and Kaiser steel built a new basic oxygen facility capable of producing 2.8 million tons of crude steel per year and a continuous caster that could produce 700,000 tons of slabs annually. The facilities, which came on-stream in 1978 and which cost $240 million, were closed in 1983. Demand had not proved strong enough to make the plant profitable. The entire plant was subsequently sold for $110 million. Only the finishing end has been used by the new owners to roll slabs imported from abroad.

3.4.5 A configuration including Electric Arc Furnaces

Over the last three decades the electric arc furnace technology in steelmaking has grown such that by 1985 it represented around 30% of total crude steel output in the U.S.A., 27% in the UK and 45% in Italy (Aylen, 1989). Quite simply it represents the 'new' technology for making steel and is now on the verge of being a major competitor to the BF/BOS system even for the production of slabs (Barnett and Crandall, 1986).

An electric arc furnace offers operational, financial and technological advantages over the BF/BOS process. Although inherently smaller in scale (a typical electric furnace yields around 500,000 tonnes of crude steel per annum) it has shown to be a significant competitor to the blast furnace and basic oxygen converter found in large integrated plants. An electric arc furnace uses steel scrap and, therefore, the generation of pig iron (carried out by a blast furnace) is not necessary. It is probably true to say, overall, the choice between the blast furnace and electric arc process routes, *at any one time*, depends on an interplay between costs of coking coal and iron ore on the one hand and steel scrap and power on the other.

Operationally, the electric furnace offers advantages because it does not require an extensive period for relining of refractory materials. Regular maintenance can be performed over the weekend (International Iron and Steel Institute, 1983). Indeed, developments in water-cooled sidewalls have reduced the amount of refractory materials used in a modern electric furnace. Also, it is capable of being stopped and started in response to the prevailing level of demand. As Aylen notes (1989) it is relatively easy for an arc melting shop to step down from 20 to 10 shifts a week and thereby save some manning costs. This is in sharp contrast to a blast furnace which, as has been mentioned earlier, operates continuously once it has been fired.

On the financial side there is no doubt at all that an electric furnace is capable of producing steel at a lower capital cost per tonne. In times of high inflation this is reinforced by the average construction time, between 1 and 2 years for a 'mini-mill' (the type of steelmaking operation within which the electric arc furnace is central) and possibly up to 4 years for the first stage of an integrated steelworks (Case Clearing House, 1975b).

Aylen (1989) summarises the difference between an integrated works and a mini-mill using electric arc steelmaking by stating that oxygen steelmaking is a high capital cost, low operating cost technique with high fixed costs but low and stable marginal costs whereas electric arc steelmaking from scrap involves low initial capital costs and high and volatile operating costs: electric furnaces are a low fixed cost but high marginal cost route.

Whether electric furnaces are a higher marginal cost option depends on the relative costs of their inputs compared to the inputs required by a blast furnace operation. Barnett and Crandall (1986) appear to dispute Aylen's claim. Although they have included both fixed and variable cost elements, their calculations reveal a lower cost per ton for the production of cold-rolled coil in a new mini-mill than in either an existing or brand new works utilising the blast furnace/BOS technology. Their figures are reproduced in table 3.2.

	$ per ton
New Integrated Steel Mill	495.05
Representative Integrated Steel Mill	445.45
New Steel Mini-mill	398.00

Table 3.2 Cost of Producing Cold-Rolled coil in three different works configurations each operating at 90% of capacity in 1985 (Barnett and Crandall, 1986)

Because the electric arc furnace is a new steelmaking technology it continues to benefit from advances in this technology. The unit size of such plant is small and so renewal tends to be faster than with an integrated works. As pointed out by Aylen (1989), the enormous sunk costs of an integrated steelworks are a 'barrier to exit' causing renewal to be a much more slow moving process. However, with each successive renewal of an electric furnace-based steel making facility, management can gain the productivity advantages imbued in the current versions which incorporate the latest technological advances.

For instance, Ultra-High Power (UHP) electric furnaces have appeared which yield long arcs and markedly reduce electrode consumption, particularly when melting scrap. Systems involving such furnaces normally now incorporate micro-processors and powerful computers to monitor and control the on-going process in a technical sense. Water cooled linings to reduce reliance on refractories (which need more maintenance) have already been mentioned. Secondary steelmaking is much more commonplace. In this arrangement the arc furnace itself can be optimised for *melting* the charge while the *refining* processes are carried out in a second (steelmaking) vessel. This, incidentally, also allows a wider range of product types to be produced — far wider than would be found in a single integrated works.

All of these technological advances in electric steelmaking have combined to yield the improvements in furnace performance documented by Barnett and Crandall (1986, p.57).

Criterion	1965	1975	1985
Tap-to-Tap time (hours)	10	5	1.5
Electrode use (lbs per ton)	14	12	9
Electricity use (kw hours per ton)	550	525	520
Labour use (man-hours per ton)	2.9	1.75	0.9

Table 3.3 Electric Arc Furnace performance improvements over 20 years arising from technological advances (Barnett and Crandall, 1986)

Because the electric arc technology is still developing, it can be expected that additional improvements will take place yielding further significant competitive advantages arising from reductions in the unit output cost. Indeed, Barnett and Crandall (1986) believed that in 1985 in the U.S.A. the electric arc process route was on the verge of being competitive with an integrated works for the production of slabs, the forerunners of coil and sheet products, hitherto thought capable of being produced *only* in an integrated works.

With many significant advantages offered in favour of electric arc steelmaking, it begs the question of why this technology has hardly been seen in UK steelmaking operating under the control of the British Steel Corporation (now British Steel plc). It is necessary to go back to the Annual Report and Accounts for 1976/77 before mention is made of plans to construct a new electric arc plant: one was to be built at Shelton (Stoke-on-Trent) incorporating a single ultra-high powered arc and would "represent the application of the latest technology to this process". The cost was put at £22 million. In general, it seems that B.S.C. never considered the possibility of giving electric arc based steel production a more prominent role in their affairs. The electric arc process route was relegated to a role solely in the production of specialist engineering steels and never in more mainstream activities, despite the growing evidence, particularly from America, that the transition to such activities was now feasible.

This doubtless reflects the 'Heritage' and 'Development' strategies discussed earlier, which both emphasised the benefits of economies of scale and the expansion of large integrated works at coastal sites. The emphasis on large scale operations may have been an acceptable 'world view' at one time, but given Barnett and Crandall's assertion that electric arc based plants are now becoming competitive even for the production of slabs, it would appear that a careful reconsideration of policy is called for.

While the demolition of an entire integrated works and its replacement by an electric arc based production facility is hardly a serious strategic consideration, the possibility of replacing a single blast furnace with a number of electric arc furnaces feeding a continuous casting plant (a mixed steelworks option) is surely worth contemplating. Such an option may seem somewhat iconoclastic to those in the industry and be summarily dismissed in consequence. Nonetheless it does have the advantage that, insofar as a BOS converter vessel uses steel scrap as well as molten iron, a supply of scrap to any BF/BOS works is already in place. If there are gluts and shortages in the availability of scrap, utilisation of two production technologies which differ in their extent of scrap requirements must offer operational advantages to the works management.

Accordingly, the model described above has been amended to reflect a situation where one of the three large blast furnaces (producing 85,000 tonnes of crude steel equivalent, per month) is replaced by two electric arc furnaces (producing 42,500 tonnes per month each). This means that the 'mix' of steel produced is, in round terms, one-third electric arc and two-thirds blast furnace/basic oxygen furnace.

Running an electric arc furnace as opposed to a blast furnace means there are operational differences which can be reflected in amendments to the influence diagram of the system presented previously (Figure 3.2, p.148). The notion of required semi-finished steel production can be introduced. This represents the production needed to keep the average months of orders on hand and the semi stockholdings equal to the desired amounts. It is true that under the blast furnace technology option links between orders on hand/semis stocks and crude steel production exist but they operate only insofar as changes in burden content introduce some degree of flexibility into the system. The main managerial control, of cutting out a blast furnace altogether when demand is depressed, is an 'all or nothing' action which is often left too late anyway.

Now, with electric arc furnaces available, it is possible to vary the output of crude steel over a much wider range and the degree of control made available for matching output to demand is that much closer in consequence. The two large blast furnaces and associated basic oxygen furnaces can be loaded to the maximum since, if operating below capacity, a large increase in the unit cost of production will result arising from the high fixed costs. The electric furnaces can then be used to respond to the imbalance (negative or positive) between crude steel supply and customer demand.

In figure 3.26 is shown a fragment of the influence diagram developed previously. This partial diagram depicts the revisions surrounding crude steel production in the amended model. For instance, it is not always necessary to have both electric furnaces operating if demand is depressed. In any event with much lower fixed costs their break-even point is significantly lower than that for a basic oxygen works.

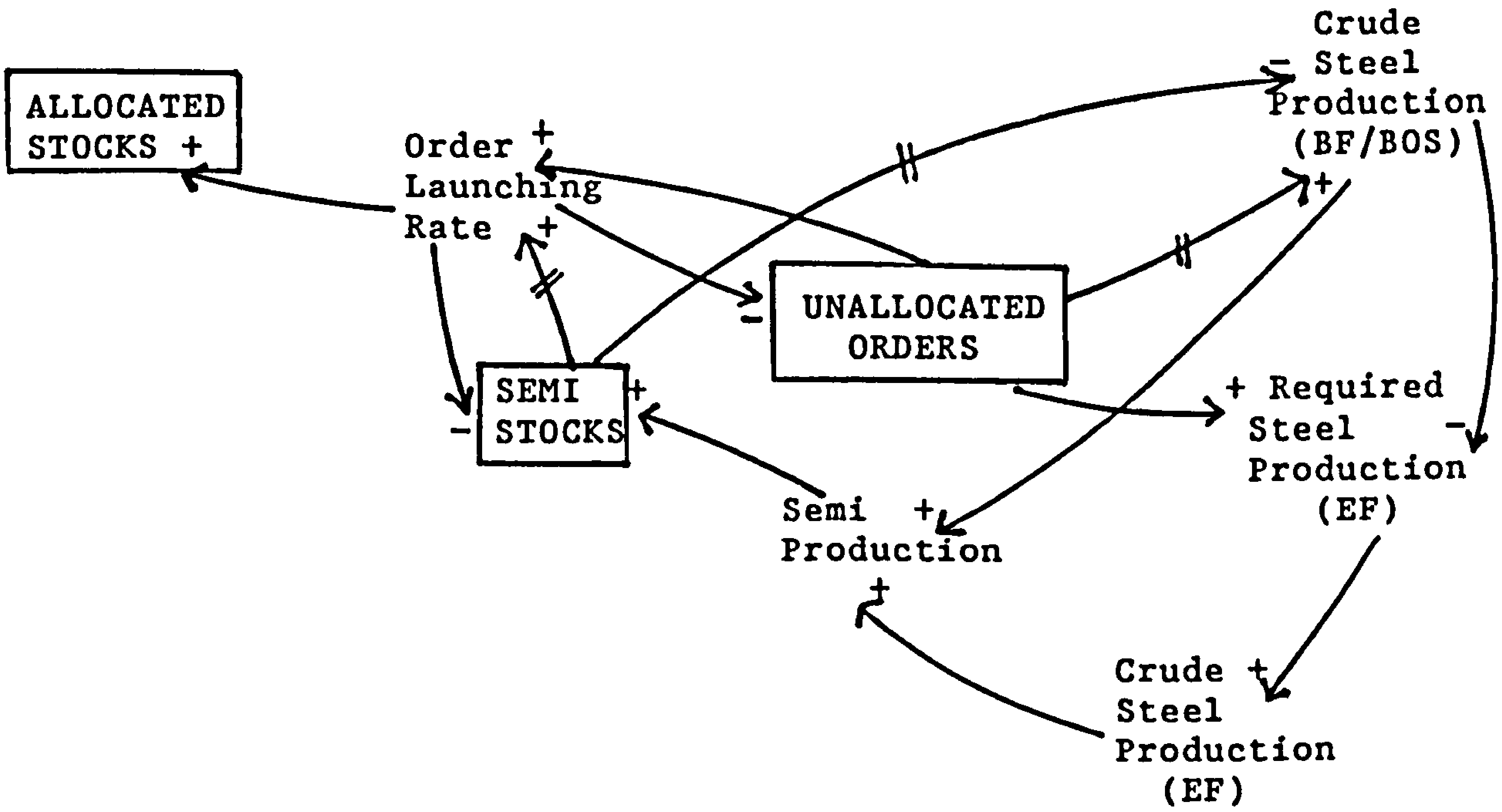

Figure 3.26 Partial influence diagram showing the revisions consequent on use of electric arc furnaces

Of particular importance is the link between unallocated orders and required steel production from the electric furnaces. As the level of unallocated orders moves up and down, the required steel production can move with it. In the case of blast furnace technology, however, the link works only one way, signified by the two short lines across the arrow connecting unallocated orders with crude steel production from the blast furnaces. Here, if unallocated orders rise, blast furnace production can respond only to the extent that the quality of burden can be adjusted upwards (and hence the driving rate of the furnace similarly). But if there is a fall in unallocated orders, the output from the furnace cannot suddenly be cut back. It may eventually be blown out prematurely, but that would be a top-level decision and as much assurance as possible would be sought in advance that the downturn was not merely a short-term phenomenon.

This is all reflected in figure 3.27 where it can be seen that, under the mixed technology scenario, semi production holds up around the first 20 months and between the 70th and 85th months when blast furnaces go out for relining. Availability of steel is maintained and as a result there is less of a reaction from the market to the supply situation. As is also shown in figure 3.27 the delivery lead time is somewhat lower during these crucial periods.

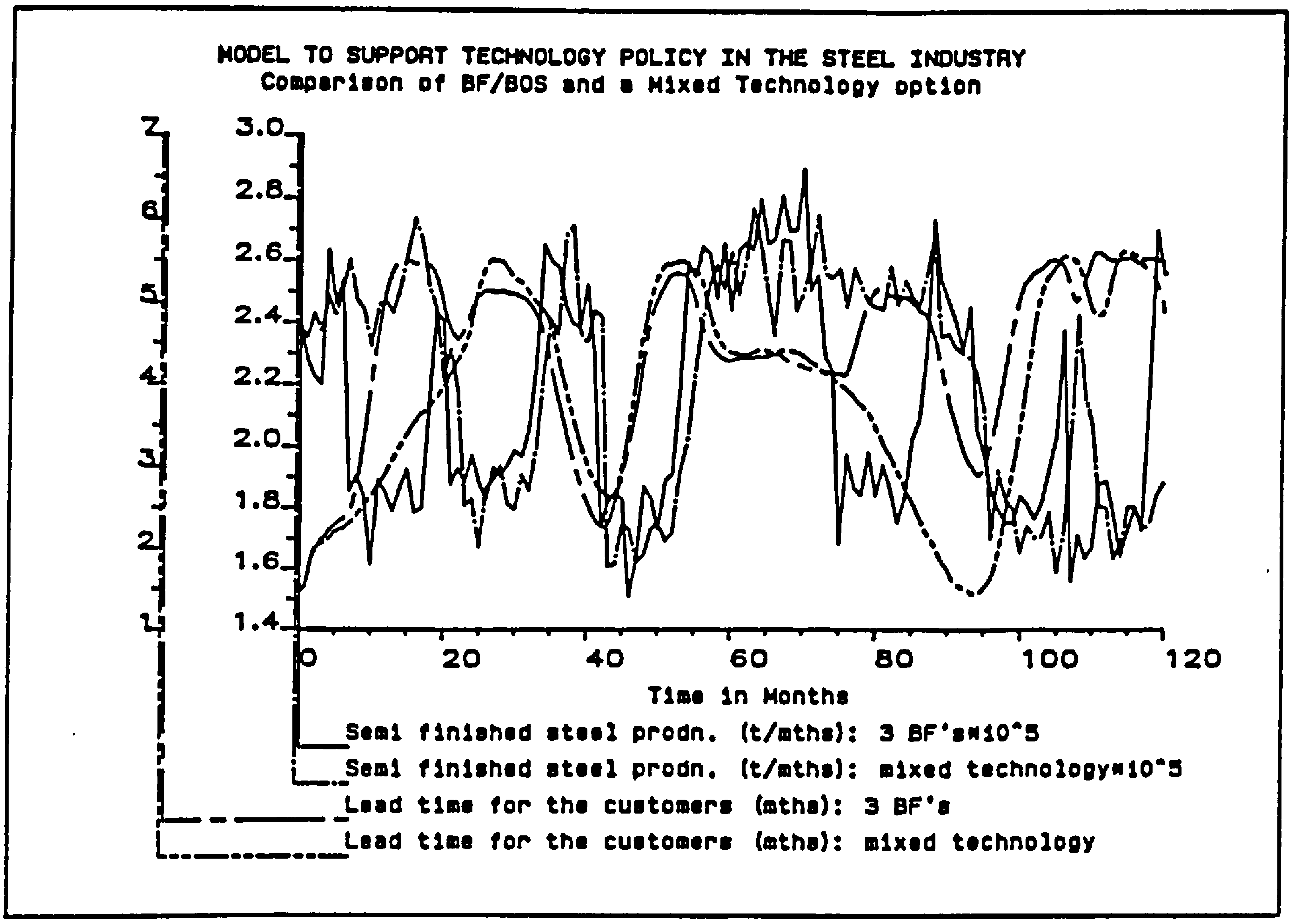

Figure 3.27 Production of semi-finished steel and delivery lead times under (i) a BF/BOS configuration and (ii) a configuration including electric arc furnaces

Sensitivity tests involving reducing the mean annual demand to 160,000 tonnes per month (a one-third reduction) show that the blast furnace configuration is then more able to cope with demand, despite the relines, and lead times do not rise in comparison with the mixed technology option. Nonetheless, a new set of problems then emerges for the blast furnace option. Low demand means poor capacity utilisation (see figure 3.28) and, unless an entire furnace is mothballed for some considerable time, a large build-up of semi-finished steel stocks takes place. Both these eventualities have cost implications which are weighted against the blast furnace option and in favour of the electric arc technology.

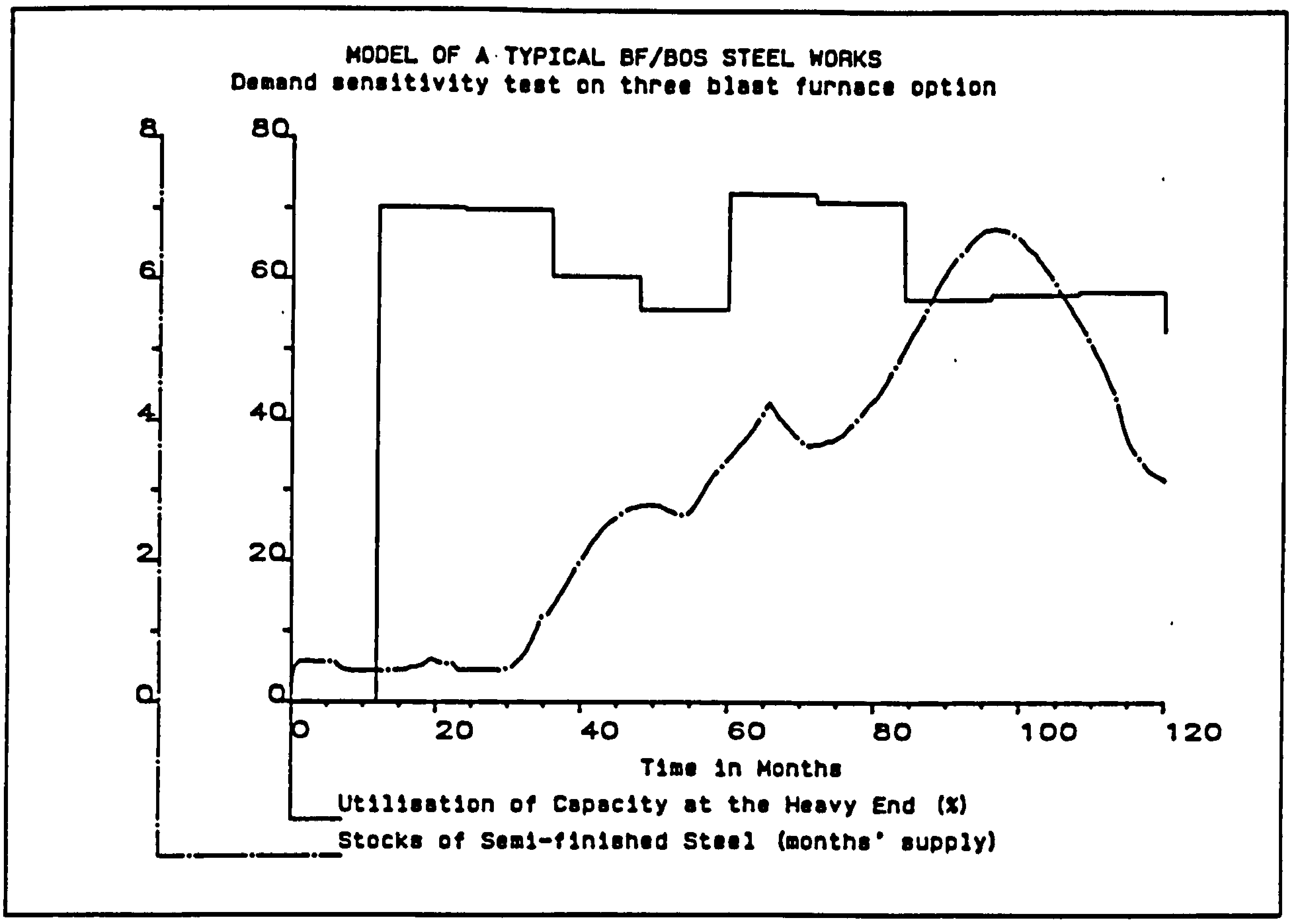

Figure 3.28 Heavy-end capacity utilisation and stocks of semi-finished steel (months' supply) when monthly average demand is reduced to 160,000 tonnes (blast furnace option)

3.4.6 The Costing of Electric Arc Furnace Operations

In order to make financial comparisons between configurations involving blast furnaces with facilities including electric arc furnaces it is necessary to revise the costings developed earlier. As with the calculations for the smaller blast furnaces, the figures for the electric arc furnaces are derived by making appropriate adjustments to the cost data used for the three large blast furnaces.

Once again the costings adopted are based on U.S.A. data in 1985 and supplied by Barnett and Crandall (1986, p.124). They give representative cost per ton figures for a new steel mini-mill (incorporating electric arc furnaces), producing cold-rolled coil and operating at 90% of output. As before, the figures published are split into the various processes involved.

The production technology mix being modelled involves the replacement of one of the blast furnaces by two electric arc furnaces. In terms of the original fixed costs, therefore, only those for the blast furnace and associated coke ovens need to be considered. Those for the BOS furnaces, slabbing and ingot mills will be untouched as these facilities will still be required by the remaining two blast furnaces. On the other hand, when considering variable costs a completely new set of figures are required for the electric arc process route feeding a new continuous casting plant. None of the existing heavy end processes will be used by the new facility.

Table 3.4 shows the costs, in dollars per ton, for an electric arc furnace and an associated continuous casting plant.

	Fixed Cost			Variable Cost
	20.4	Electric Furnace		135.0
	18.15	Continuous Casting Plant		3.5
Total	38.55		Total	138.5

Table 3.4 Allocation of unit production costs ($ per ton) for the heavy end of a typical mini-mill (from Barnett & Crandall, 1986)

Compared to the variable cost for a blast furnace shown earlier in table 3.1 ($101.8 per ton) it can be seen why an electric arc furnace is said by some to possess a penalty in terms of marginal costs.

Because the electric arc furnace and concast plant is new, it will attract much higher interest and depreciation charges than will an existing integrated works. Barnett and Crandall put this at $82.15 per ton for an entire new mini-mill. To extract from this that portion relating to the melting shop and concast plant alone it was necessary to use that proportion which fixed costs in these particular shops bear to the total of all fixed costs in a new mini-mill, some 37%. In the absence of a split of the $82.15 per ton this approach was thought to be the most reasonable one to adopt. The total fixed cost per ton is now $38.55 + (0.37 × 82.15) = $68.95.

Compared to the blast furnace costing in table 3.1, $68.95 per ton is 9% higher than the corresponding blast furnace plus coke oven fixed cost per ton of $63.15. Of the total heavy end fixed costs for the three blast furnace configuration assumed in the model (£152.03 million) blast furnaces plus coke ovens account for 63.15/110.65 = 57 per cent. ($110.65 per ton was the total heavy end fixed cost, detailed in table 3.1, for the BF/BOS technology option.) Hence, the fixed cost for *each* furnace is

((£152.03E6 × 0.57)/3) = £28.89E6.

This result is then grossed up by 9% to yield a fixed cost for the electric arc furnace operation of £31.49E6, representing an increase in fixed costs of £2,600,000 annually. £28.89E6 is also the amount by which the original total fixed cost of £152.03E6 is reduced, leaving £123.14 as representing fixed costs for the remaining two blast furnaces and associated plant not involved with the electric arc operation.

Turning now to the variable costs, it will be recalled that total variable costs per ton for the original blast furnace operation were \$264.8 (table 3.1). The figure of \$138.5 (from table 3.4) is 52.3% of the original total variable costs. Thus, the revised variable cost figure used in the model is:

118.58 × 0.523 = £62.02.

The revised linear cost equations are, therefore:

y = 123.14E6 + 118.58 x	Heavy End - BF/BOS operation
y = 31.49E6 + 62.02 x	Heavy End - Electric Arc operation
and	
y = 120.1E6 + 30.41 x	Finishing End (unchanged)

x = throughput per annum

3.4.7 Financial comparisons between the blast furnace and mixed technology options

Having established the appropriate changes to the cost equations it is now possible to review some of the results when the model is run incorporating the new cost coefficients. Figure 3.29 shows that the mixed technology option of electric arc furnaces operating side-by-side with blast furnaces is a much more profitable operational strategy than to rely on the large blast furnace option alone.

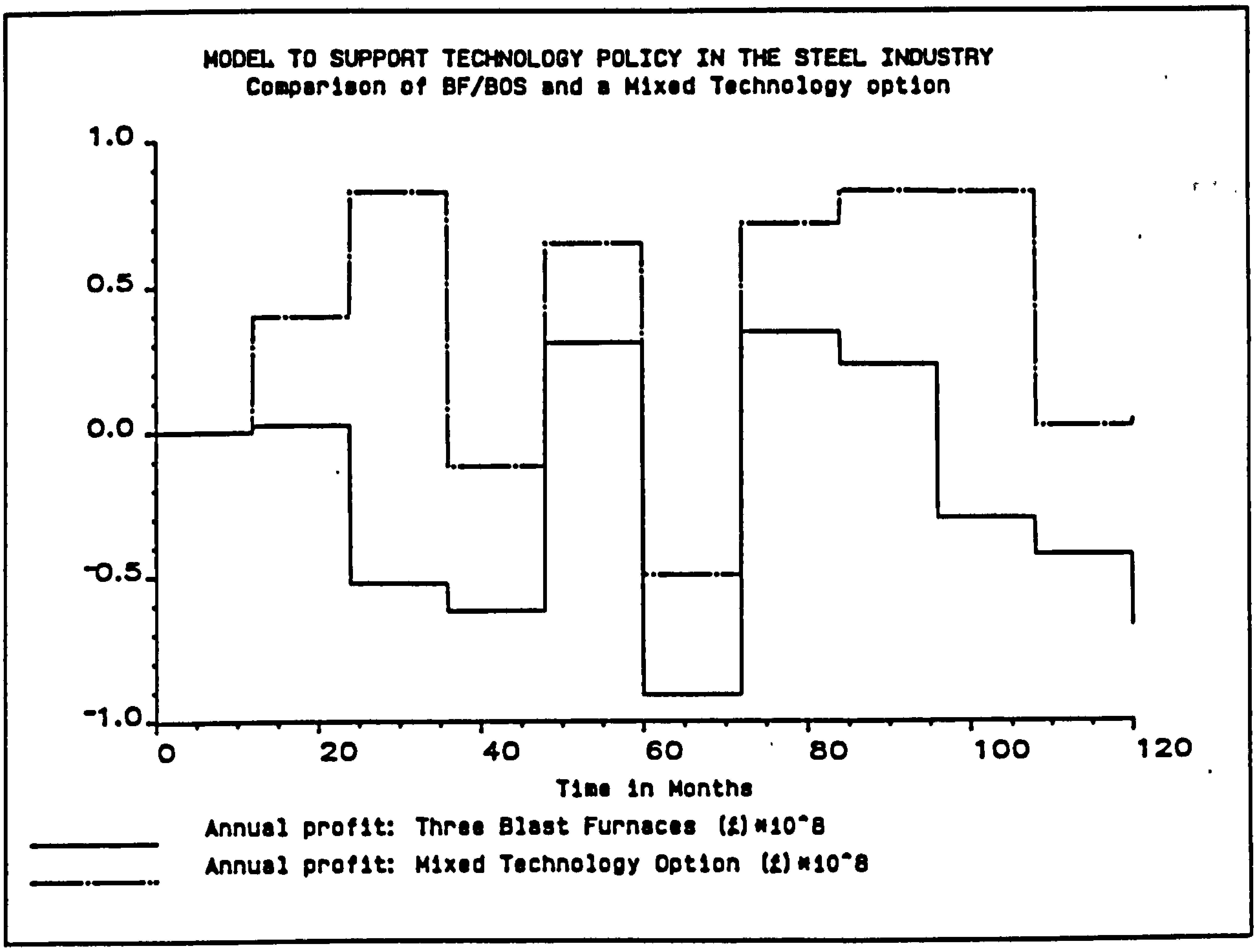

Figure 3.29 Annual profit comparison between (i) large blast furnace option and (ii) a mixed technology option

The profit advantage shown by the mixed technology option is perhaps not surprising from the cost point of view when the variable cost used for each electric arc furnace is so much lower than that for the blast furnace. However, there is also a revenue advantage for the mixed option because the presence of the electric furnaces means that steel availability is maintained during the crucial reline periods for the blast furnaces. Thus, the mixed technology option is capable of delivering a double benefit: a lower cost operation together with a capability to avoid market reactions consequent on what would otherwise be production 'pauses'.

It will be recalled from the earlier comparisons between three and five blast furnaces that the latter could offer only a single benefit. Revenue held up because a smaller proportion of total steel production was lost during re-line periods but costs were still somewhat higher because the smaller blast furnace option was, by definition, a higher cost option. However, the mixed technology option additionally offers a cost as well as a revenue advantage.

Sensitivity runs conducted on the mean demand reveal that the mixed technology option is still the preferred one. While both options show a cumulative loss in DCF terms when demand is reduced to as low as 160,000 tonnes per month, the mixed technology option is the smaller loss (see table 3.5). At this level of demand, the blast furnace option suffers cost loadings arising from poor capacity utilisation and high stocks. During the period of maximum holding (around the 96th month in the simulation) the cost of stockholding of semi-finished steel is running at £2 million per month.

	Cumulative profit (loss) discounted over 10 years, £million
Demand 200E3 per month Mixed Technology option	52.459
Demand 200E3 per month Blast Furnaces only option	(165.962)
Demand 160E3 per month Mixed Technology option	(243.215)
Demand 160E3 per month Blast Furnaces only option	(430.268)

Table 3.5 Effect of demand sensitivity tests on cumulative profit (loss) discounted for the two configurations

In view of the difficulties, mentioned earlier, of unearthing reliable cost data split between the heavy and finishing ends; between fixed and variable costs; and taking account of the size and number of production units at a works, it would not be appropriate to undertake sensitivity tests on demand alone. Sensitivity tests on the cost coefficients are also essential.

Unless the data used for parameter values is known to possess a high degree of integrity, any policy model should be subject to such tests on relevant parameters. Accordingly, in addition to the demand sensitivity tests, similar explorations have been conducted on both the variable and fixed cost coefficients employed in the mixed technology model.

The results for changes in the variable cost per tonne, with demand at 240,000 tonnes per month, are shown in figure 3.30.

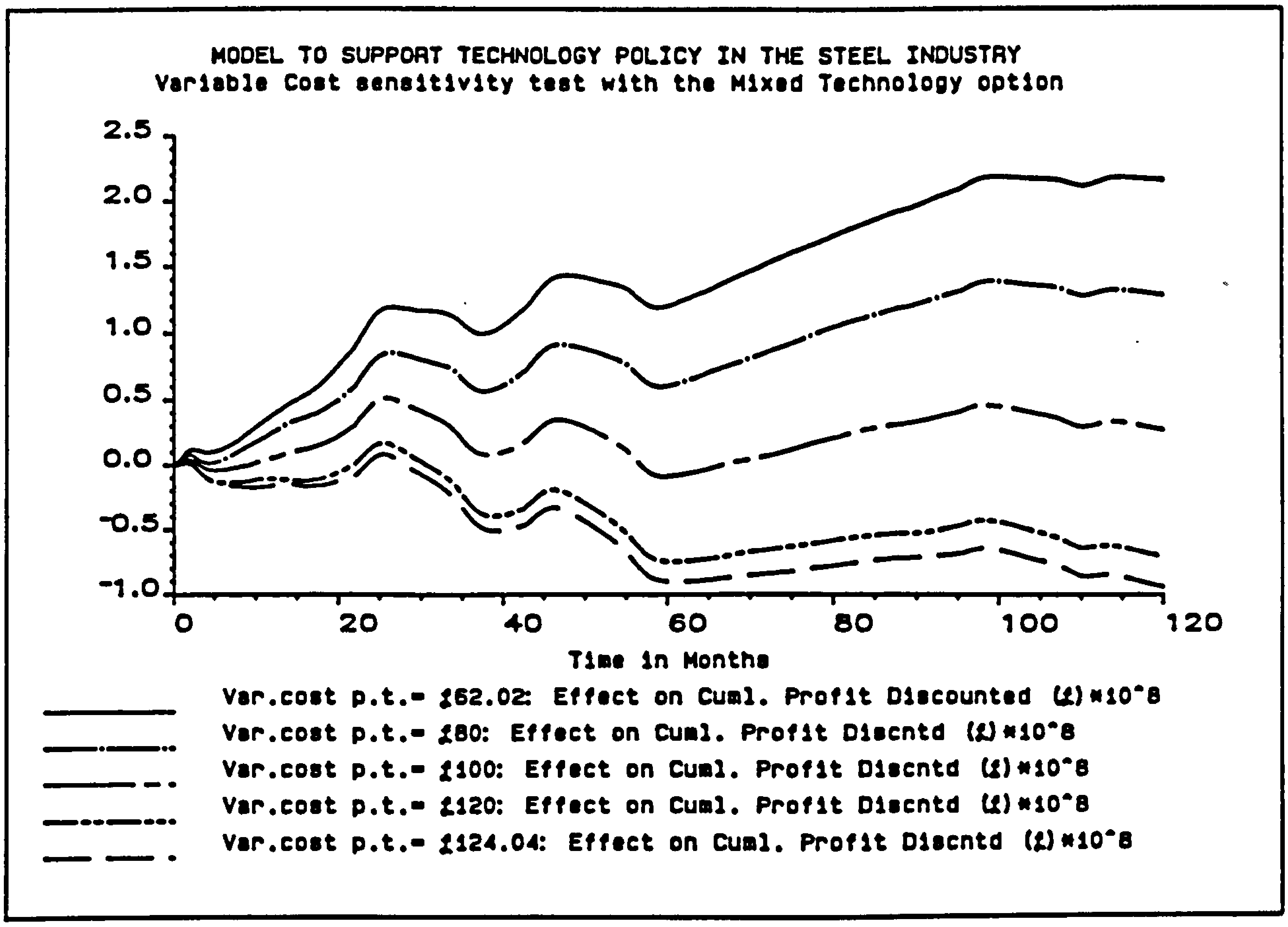

Figure 3.30 Sensitivity analysis on cumulative profit discounted with respect to the variable cost per tonne

It can be seen that even a doubling of the variable cost per tonne leaves the mixed technology option as the preferred one. Between a variable cost per tonne of £100 and £120 the cumulative discounted profit turns into a loss but on no occasion, over the range of possibilities considered, is the mixed technology option inferior to the option involving blast furnaces only. A variable cost per tonne of £124.04 would imply a huge leap in scrap and/or power prices making the electric arc process route extremely expensive when compared to the blast furnace/basic oxygen system route, assuming that no similar upward movement occurs in the prices of iron ore or coking coal. In fact, at £124.04, the variable cost per tonne is higher than the one assumed for the blast furnaces (£118.58).

Results for sensitivity runs incorporating a lower mean demand as well as changes in the variable cost coefficient are given in table 3.6.

Variable cost per tonne £	Demand 200,000 tonnes/month	Demand 160,000 tonnes/month
62.02	52.459	(243.215)
80	(21.908)	(283.540)
100	(102.308)	(323.290)
120	(183.771)	(366.370)
124.04	(201.442)	(375.982)
Blast Furnaces only	(165.962)	(430.268)

Table 3.6 Cumulative discounted profit (loss), £million, for a range of variable costs and two different mean demand levels

The blast furnace option is not the worst case with mean demand set at 200,000 tonnes per month. This is mainly because annual total finishing end costs are higher with the mixed technology option. Being a more flexible option, electric furnaces can be brought in or out more often. In some years a higher throughput passes through the finishing end as a result and this pushes up total finishing end costs. On the other hand, the blast furnace option results in one being blown out prematurely because of market conditions, saving variable costs both at the heavy and finishing ends. An additional reason for the result is that the mixed technology option does not secure the revenue advantage over and above the blast furnace option. The latter can now more easily cope with market demand, leakages to imports are not as severe as with a higher demand and the two configurations secure much the same cumulative revenue discounted.

A similar sensitivity exercise has been conducted for the fixed costs also, with the results being given in table 3.7.

Fixed cost per annum £m.	Demand 240,000 tonnes/month	Demand 200,000 tonnes/month	Demand 160,000 tonnes/month
31.49	215.451	52.459	(243.215)
40	173.164	7.048	(289.740)
55	93.931	(69.935)	(364.366)
70	18.014	(148.337)	(444.119)
80	(37.266)	(200.856)	(495.924)
Blast Furnaces only	(114.664)	(165.962)	(430.268)

Table 3.7 Cumulative discounted profit (loss) £m. for a range of fixed costs and three different mean demand levels

The fixed costs considered show that in excess of a doubling of the annual figure would be needed before the mixed technology option became inferior to the option involving blast furnace technology only. Overall, the results lend support to the view that the choice of the mixed technology option is fairly robust with respect to reasonable variations in costs.

3.5 Discussion

Clearly there is considerable interest in the choice of heavy end technology for use in steelmaking. Similarly, there is debate about the extent to which economies of scale operate in the steel industry. By means of the policy model described above it is possible that, for the first time, a tool is available which can simultaneously handle the financial, operational and marketing aspects of these unresolved matters. It is a new tool used in this particular context. Certainly, system dynamics has been applied in the steel industry previously but not specifically for the chosen purpose accorded this model.

That such a model might be welcomed by those associated with the industry (either managers or academics) is a distinct possibility. Some of the authors previously cited mention factors such as 'flexibility' quite regularly but, in the opinion of the present author, no one has yet been able to explicitly quantify even one aspect of this important consideration when evaluating competing technologies. Consider the comments of Jones and Cockerill (1984).

> *"To acquire the potential benefits of scale, demand must grow in line with capacity so that plants and firms can operate at, or near, full capacity. The recession in the industry has meant that this has not been possible and in such circumstances large-scale units can suffer severe cost penalties because of their inevitable inflexibility. It can be costly and difficult to run complex equipment at rates well below those for which it was designed.*

> *Plants using smaller-scale technology may be more appropriate and efficient in these conditions. Older plants with small if out-dated equipment can cope better with demand fluctuations. More significantly in steel, overhead costs may be reduced and flexibility increased by building small-scale plants using electric arc furnaces. This development has meant that units with annual capacities of one million tons or less can be commercially viable in many industrialised markets."*

Cartwright (1972) writing some twelve years earlier seems reconciled to never being able to fully articulate the role of this intangible factor. He says:

> *"There comes a point, which is ill-defined, where the increase in profitability from making a very large plant still larger is quite small, and may be offset by unquantifiable disadvantages such as loss of flexibility".*

It is to be hoped that the policy model offered above provides some food for thought to British Steel executives as they ponder the strategic direction of the firm in the 1990's. In terms of its scope, the model is not devoid of criticism. It describes the operations of a single works when British Steel possesses five major steelmaking plants. The effects of blast furnace relines may be mitigated in the context of the operations of an entire firm because semis may be transferred from one works to another in an attempt to equalise supply availability. On the other hand it may be the orders themselves which are transferred. Provided a similar product capability is available at works 'B', works 'A' may transfer customer orders to works 'B' in times of strong customer demand. But as the model and the history of UK steel in the mid-1970's has shown, it is precisely when demand is strong that the effects of blast furnace relines are most damaging to customer confidence.

The components of steel demand are probably closely related. It is true that upturns in demand will be felt by works making sheet and strip before those making bar, rod and plate but not separated enough to allow significant inter-works transfers of orders. In any case transfers from a works making flat products to one producing general steels is almost certainly an impossibility by reason of the differing rolling and finishing facilities.

Within a broad product grouping the only ways to cope with a large blast furnace undergoing relining would be either to ensure that this happened at a low point in the steel demand cycle or to consciously work with a margin of spare capacity so as to ensure the effects on output were negligible. However, the economics of large integrated steelworks require a high capacity utilisation in order to break even. If spare capacity is needed, then it is best made available by using a mixed technology option the same (or similar) to the configuration modelled above.

When all things are considered the preferred option must be, if integrated works are to be the sole choice for the production configuration, to reline during a demand downturn. This carries grave risks should the upturn in the steel demand cycle come more suddenly than expected or if a blast furnace, put on an extended campaign in order to maintain product availability during a high demand phase and to be 'blown out' as soon as this passes, creates so many engineering problems that its output is negligible.

Irrespective of the reline problem, the lack of a capability to adjust output in an integrated works in response to changes in demand (coarse tuning as opposed to fine tuning) must present severe problems at the tactical level for the production planners and directly contribute to the supply lags which Blake (1965) attempted to analyse with his econometric model. In turn, these supply lags are responsible for the adverse market reaction identified by Carnell (1974) and underscored by the model reported above. This reaction is exacerbated by the role of the steel stockholders standing as they do between producers and consumers.

Far from this study being presented as the last word on the matters which it addresses, it is probably true to say that it represents the first words written which describe a method allowing controlled comparisons between choices in technology policy. Further work along these lines would be both welcome and timely. Because a system dynamics model is able to quantify a factor (flexibility) which industrial economists often mention but seem unable to explicitly accommodate in policy analyses, it is possible that a new line of inquiry might be opened up into the evaluation of economies of scale and production technology choices in industry.

REFERENCES FOR CHAPTER 3 AND STEEL INDUSTRY SELECT BIBLIOGRAPHY

H ABROMEIT (1986) *"British Steel: an Industry between the State and the Private Sector"*, Berg Publishers, Leamington Spa.

W ADAMS and J B DIRLAM (1966) "Big Steel, Invention and Innovation", *Quarterly Journal of Economics*, 80, 167-189.

G ANANDALIGAM (1987) "Process Modelling under Uncertainty: Simulation Analysis of Indian Steel", *Jnl. Op. Res. Soc.*, 38, 115-125.

G ANANDALIGAM and D BHATTACHARYA (1985) "Process Modelling and Industrial Energy Use in Developing Countries -- The Steel Industry in India", *Omega*, 13, 295-306.

J M AYLEN (1982) "Plant Size and Efficiency in the Steel Industry: an International Comparison", *Nat. Inst. Econ. Rev.*, 100, 65-76.

J M AYLEN (1988) "Privatisation of the British Steel Corporation", *Fiscal Studies*, 9, 1-25.

J M AYLEN (1989) *"Choice of Process Route in Steelmaking".* Unpublished paper presented at the 3rd European Electric Steel Congress, Bournemouth.

D F BALL and A W PEARSON (1976) "The Future Size of Process Plant", *Long Range Planning*, 8, 18-28.

D F BARNETT and R W CRANDALL (1986) *"Up from the ashes: the rise of the steel minimill in the United States"*, Brookings Institution, Washington.

D F BARNETT and L SCHORSCH (1983) *"Steel: Upheaval in a basic Industry"*, Ballinger, Mass.

BATTELLE INSTITUTE (1977) *"Scale Advantages of Equipment in the Iron and Steel Industry"*, Stockholm.

C BLAKE (1965) "Supply Lags and Demand Acceleration in the UK Steel Market", *Scottish Journal of Political Economy*, 12, 62-80.

J S BOSWELL (1983) *"Business Policies in the Making: Three Steel Companies Compared"*, George Allen and Unwin, London.

M G BOYLAN (1975) *"Economies of Scale in the Steel Industry: the Case of US blast furnaces"*, Praeger, New York.

M G BOYLAN (1980) "Evaluating Input Changes in a Given Facility - Iron Making", *Omega*, 8, 517-531.

BRITISH IRON AND STEEL FEDERATION (1966) "The Steel Industry: the Stage I Report of the Development Co-ordinating Committee, London.

BRITISH STEEL CORPORATION (1972) *"Making Steel",* London.

R A BRYER, T J BRIGNALL and A R MAUNDERS (1982) *"Accounting for British Steel: a financial analysis of the failure of the BSC 1967-80 and who was to blame",* Gower Press, Aldershot.

J A BUZACOTT, M F CANTLEY, V N GLAGOLEV and R C TOMLINSON (Eds.) (1982) *"Scale in Production Systems",* Pergamon, Oxford.

M F CANTLEY and V N GLAGOLEV (1978) *"Problems of Scale - the Case for IIASA Research",* Research Memorandum 78-47, International Institute of Applied Systems Analysis, Austria.

P E CARNELL (1974) *"Studies in the Use of Industrial Dynamics Models in the B.S.C."* Unpublished PhD thesis, University of Aston.

W F CARTWRIGHT (1971) "The Economic Survival of the Blast Furnace", *Journal of the Iron and Steel Institute,* 209, 89-95.

W F CARTWRIGHT (1972) "The Place of Mini-Steelworks in the World" *Journal of the Iron and Steel Institute,* 210, 221-228.

CASE CLEARING HOUSE (1972) *"British Steel Corporation",* Case No. 672-080-1.

CASE CLEARING HOUSE (1975a) *"The Making of Steel: a Process Note",* Case No. 675-006-5.

CASE CLEARING HOUSE (1975b) *"Note on Mini-Mill Steelmaking",* Case No. 675-005-5.

A CHELIUSTKIN (1975) *"Systems Analysis applied to Hot Strip Production",* Research Memorandum 75-46, International Institute of Applied Systems Analysis, Austria.

A COCKERILL (1974) *"The Steel Industry - International Comparisons of Industrial Structure and Performance",* Cambridge University Press, Cambridge.

A COCKERILL (1975) "Strategy: Steel", *Management Today,* November, 44-49.

B C DANGERFIELD and O VAPENIKOVA (1987) *"DYSMAP2 User Manual",* University of Salford.

A De GEUS (1988) "Planning as Learning", *Harvard Business Review,* 66, 70-74.

D R DILLEY and D L McBRIDE (1967) "Oxygen Steelmaking: Fact vs. Folklore", *Iron and Steel Engineer,* 44, 131-152.

I DISLEY (1990) "OR in British Steel", *OR Insight,* 3, 7-8.

S EILON, B GOLD and J SOESAN (1976) *"Applied Productivity Analysis for Industry",* Pergamon, Oxford.

FINANCIAL TIMES (1988) *British Steel - Prospectus,* 25 November.

J W FORRESTER (1961) *"Industrial Dynamics"*, M.I.T. Press, Cambridge, U.S.A.

W K V GALE (1967) *"The British Iron and Steel Industry"*, David and Charles, Newton Abbott.

B GOLD (1974) "Evaluating Scale Economies: The Case of Japanese Blast Furnaces", *Jnl. Ind. Econ.*, 23, 1-18.

B GOLD (1979) *"Productivity, Technology and Capital"*, Lexington Books, Mass.

B GOLD (1982) "Revising Prevailing Approaches to Evaluating Scale Economies in Industry" in J A BUZACOTT, M F CANTLEY, V N GLAGOLEV and R C TOMLINSON (Eds.) *"Scale in Production Systems"*, Pergamon, Oxford.

B GOLD, W S PIERCE and G ROSEGGER (1970) "Diffusion of Major Technological Innovations in US Iron and Steel Manufacturing", *Jnl. Ind. Econ.*, 18, 218-241.

B GOLD, G ROSEGGER and M G BOYLAN (1980) *"Evaluating Technological Innovations"*, Lexington Books, Mass.

L G GOLLOP (1965) "The Steel Industry" in C M BERNERS-LEE (Ed.) *"Models for Decision"*, English Universities Press, London.

J GRIEVE-SMITH (1984) *"Strategic Planning in the Nationalised Industries"*, MacMillan, London.

D W HEAL (1974) *"The Steel Industry in Post-War Britain"*, David and Charles, Newton Abbott.

HMSO (1973) *"British Steel Corporation: Ten Year Development Strategy"*, Cmnd. 5226.

HMSO (1975) *"B.S.C. Organisation Review 1975"*, House of Commons Paper No. 604, Session 1974-75, 6 August.

HMSO (1978) *"British Steel Corporation: the Road to Viability"*, Cmnd. 7149.

W T HOGAN (1972) *"The 1970's: Critical Years for Steel"*, Lexington Books, Mass.

I R HOOS (1972) *"Systems Analysis in Public Policy"*, University of California Press.

INTERNATIONAL IRON AND STEEL INSTITUTE (1983) *"The Electric Arc Furnace"*, Committee on Technology, Brussels.

INTERNATIONAL IRON AND STEEL INSTITUTE (1983) *"Steel and the Automotive Sector"*, Committee on Economic Studies, Brussels.

G A JAGERS and W R HUISJES (1986) "Production planning in rolling mills", in C B TILANUS, O B DeGANS and J K LENSTRA (Eds.) *"Quantitative Methods in Management: Case Studies of Failures and Successes"*, Wiley, Chichester.

P S JOHNSON (Ed.) (1979) *"The Structure of British Industry"*, Crosby Lockwood Staples, London.

T T JONES and A COCKERILL (1984) *"Structure and Performance of Industries"*, Philip Allan, Oxford.

B S KEELING and A E G WRIGHT (1964) *"The Development of the Modern British Steel Industry"*, Longmans, London.

P T KNIGHT and G S MADALLA (1967) "International Diffusion of Technical Change - A Case Study of the Oxygen Steel Making Process", *Economic Journal*, 77, 531-558.

R KUMAR (1983) "Perspective Planning Model of a Steel Plant based on System Dynamics Principles", *Dynamica*, 9, 74-83.

R KUMAR and P VRAT (1989) *"Using Computer Models in Corporate Planning"*, Long Range Planning, 22, 114-120.

R D LANGMAN and T H HARRIS (1975) "What future is there in the UK for the electric arc furnace?", *Ironmaking and Steelmaking*, 4, 253-261.

A H LECKIE and A J MORRIS (1968) "The Effect of Plant and Works Scale on Costs in the Iron and Steel Industry", *Journal of the Iron and Steel Institute*, 206, p442.

I LEFKOWITZ and A CHELIUSTKIN (Eds.) (1976) *"Integrated Systems Control in the Steel Industry"*, International Institute of Applied Systems Analysis, Austria.

I MacGREGOR (1982) "Managing the British Steel Corporation", *European Management Journal*, v. 1.

P H MORRIS (1974) *"Economic Planning in the B.S.C."* Unpublished paper presented at steel industry seminar, University of Liverpool.

N E D O (1986) *"Steel: the World Market and the UK Steel Industry"*, London.

B R NIJHAWAN, H F CLEERE and C POPOV (1974) "The Iron and Steel Industry and the developing countries", *Ironmaking and Steelmaking*, 1, 46-50.

R J NOORDMAN, A GILLEBAART and R SEEDER (1986) "OR in the (Dutch) Steel Industry" in C B TILANUS, O B DeGANS and J K LENSTRA (Eds.) *"Quantitative Methods in Management: Case Studies of Failures and Successes"*, Wiley, Chichester.

OECD (1980) *"Steel in the 80's"*, OECD Symposium, Paris.

C F PRATTEN (1971) *"Economies of Scale in Manufacturing Industry"*, Cambridge University Press, London.

C PRATTEN and R M DEAN - in collaboration with A Silberston (1965) *"The Economies of Large-scale Production in British Industry - an Introductory Study"*, Occasional Paper No. 3, Cambridge University Press, London.

G ROSEGGER (1980) "Comparing a New Technology with its Predecessor: Steel Making", *Omega*, 8, 533-543.

C K ROWLEY (1971) *"Steel and Public Policy"*, McGraw Hill, London.

M RUSSELL (1984) "Scale's True Economies", *Management Today*, May, 82-84.

C S RUSSELL and W J VAUGHAN (1976) *"Steel Production: Processes, Products and Residuals"*, Johns Hopkins University Press, Baltimore.

L L SCHORSCH (1987) "Lessons from the Steel Crisis", *McKinsey Quarterly*, 3, 2-21.

M L SHRIKANT (1974) "Economic, financial and technical considerations in the choice of mini-steelplant by developing nations", *Ironmaking and Steelmaking*, 2, 78-84.

D SURGUCHOV (Ed.) (1977) *"Computer Applications in the Steel Industry"*, International Institute of Applied Systems Analysis, Austria.

D W SUTTON and P A COATES (1981) "On-Line Mixture Calculation System for Stainless Steel Production by BSC Stainless: the Least Through Cost Mix System (LTCM)", *Jnl. Op. Res. Soc.*, 32, 165-169.

R TAYLOR (1982) "British Steel's Melt Down", *Management Today*, September, 50-57.

R C TOMLINSON, J A BUZACOTT and K TSUJI (1982) "Concluding Remarks" in J A BUZACOTT, M F CANTLEY, V N GLAGOLEV and R C TOMLINSON (Eds.) *"Scale in Production Systems"*, Pergamon, Oxford.

J VAIZEY (1974) *"The History of British Steel"*, Weidenfeld and Nicolson, London.

L VINELL (1973) *"Business Cycles and Steel Markets"*, Beckmans, Stockholm.

K WARREN (1970) *"The British Iron and Steel Industry since 1840: an economic geography"*, Bell and Sons, London.

D WATERSTONE (1975) Address to *Steel International '75* Conference, *Modern Purchasing*, June, 26-27.

LISTING OF THE THREE BLAST FURNACE MODEL

```
* MODEL OF TYPICAL BF/BOS STEEL WORKS
NOTE
NOTE
NOTE  ORDER BACKLOG AND ORDERS BOOKED(SHORT TERM)
NOTE
NOTE  ORDER BACKLOG AND DELIVERY RATE EFFECT ON LEAD TIME
NOTE
NOTE  ORDER BACKLOG AND DELIVERY RATE
NOTE
NOTE  ORDER BACKLOG, DELIVERY LEAD TIME AND IMPORTS
NOTE
NOTE
L COBG.K=COBG.J+DT*(OPLH.JK-DR.JK)
N COBG=NOLR*MUNON+ADR*FPLT
SEED 0.5
A OPL.K=SWITCH(OPLI,OPLI+NORMRN(MOPL.K,SDOPL),TIME.K)*OVBF.K
C OPLI=240E3
C SDOPL=10E3
A MOPL.K=AMP*SIN(PI*2*TIME.K/PERD)
C AMP=48E3
C PERD=48
C PI=3.141592654
R OPLH.KL=OPL.K*(1-FOPLA.K)
L UNALLO.K=UNALLO.J+DT*(OPLH.JK-OLR.JK)
N UNALLO=360E3
R OLR.KL=NOLR*OBGF.K*SEMSF.K
N OLR=NOLR
C NOLR=240E3
A SOLR.K=SMOOTH(OLR.JK,TSOL)
C TSOL=2
L ALLOCS.K=ALLOCS.J+DT*(OLR.JK-DR.JK)
N ALLOCS=FPLT*ADR
A MUNO.K=UNALLO.K/NOLR
A MUNOR.K=MUNO.K/MUNON
C MUNON=0.5
A OBGF.K=TABHL(OBGFT,MUNOR.K,0,2,0.2)
T OBGFT=0/0.223/0.447/0.65/0.84/1/1.107/1.171/1.193/1.198/1.2
R DR.KL=DELAY3(OLR.JK,FPLT)
C FPLT=1
A ADR.K=SMOOTH(DR.JK,DRAT)
C DRAT=3
A OVBF.K=TABHL(OVBFT,DLTPC.K,3,5,0.5)
T OVBFT=1/1.06/1.16/1.194/1.2
A DLTPC.K=COBG.K/ADR.K
L COL.K=COL.J+DT*(OLR.JK-RZCOL.JK)
N COL=0
R RZCOL.KL=PULSE(COL.K/DT,12,12)
A ANNTOL.K=SAMPLE(COL.K,12,0)
S UFE.K=(ANNTOL.K/(NOLR*12*1.2))*100
NOTE
NOTE
NOTE  SEMI STOCKS AND ORDERS LAUNCHED  -- NEGATIVE LOOP
```

```
NOTE
NOTE
L SEMS.K=SEMS.J+DT*(SEMP.JK-OLR.JK)
N SEMS=MSEMSN*SOLR
C MSEMSN=0.25
A SEMSF.K=TABHL(SEMSFT,MSEMS.K,0,1,0.2)
T SEMSFT=0/0.07/0.5/0.845/0.94/1
A SEMSR.K=MSEMS.K/MSEMSN
A MSEMS.K=SEMS.K/NOLR
NOTE
NOTE  PRODUCTION
NOTE
R SEMP.KL=PF1.K+PF2.K+PF3.K
S UHE.K=(ANNTSEMP.K/(2.88E6*1.15))*100
A NFB.K=SWITCH(F1OUT,F1IN,PF1.K)+SWITCH(F2OUT,F2IN,PF2.K)+
X SWITCH(F3OUT,F3IN,PF3.K)
C F1IN=1
C F1OUT=0
C F2IN=1
C F2OUT=0
C F3IN=1
C F3OUT=0
C TRLF=3.5
A MOH.K=UNALLO.K/SOLR.K+ALLOCS.K/ADR.K
A AVMOH.K=DLINF3(MOH.K,TRCMOH)
C TRCMOH=3
A BEF.K=NCLIP(1.15,PBEF.K,6,(NTF-MALLF.K)/AMTPF,MUNO.K,2)
A PBEF.K=TABHL(PBEFT,MUNO.K,1,6,1)
T PBEFT=1/1.005/1.035/1.088/1.135/1.15
A FSCMC.K=NCLIP(0,10E6,1.5,AVMOH.K,SEMSR.K,1.5)
A MF1F2.K=MAX(CPF1.K,CPF2.K)
A MALLF.K=MAX(MF1F2.K,CPF3.K)
T PFFT=0.05/0.07/0.11/0.185/0.28/0.39/0.53/0.705/0.875/0.97/1
T REFECT=0.6/0.72/0.82/0.9/0.95/0.98/1
C NTF=5E6
C AMTPF=80E3
C PNDEC=1
NOTE
NOTE
NOTE  LONG DELIVERY DELAYS LEADING TO IMPORTS OF STEEL
NOTE
NOTE
R OIMS.KL=FOPLA.K*OPL.K
A FOPLA.K=TABHL(FOPLAT,DLTPC.K,3,6,0.5)
T FOPLAT=0/0.0375/0.0913/0.175/0.2875/0.45/1
R IMS.KL=DELAY3(OIMS.JK,DSOIMS)
C DSOIMS=3
NOTE
NOTE
NOTE  COSTS & PROFIT
NOTE
NOTE
R REVR.KL=DELAY3(DR.JK,PAYDEL)*RPIT
N DR=NOLR
C RPIT=250
C PAYDEL=2
L CREV.K=CREV.J+DT*(REVR.JK-RZCREV.JK)
N CREV=0
R RZCREV.KL=PULSE(CREV.K/DT,12,12)
R COSTSEMP.KL=SEMP.KL*VCPTHE
```

```
C VCPTHE=118.58
R COSTD.KL=DR.KL*VCPTFE
C VCPTFE=30.41
L CCOSTHE.K=CCOSTHE.J+DT*(COSTSEMP.JK-RZCCOSTHE.JK)
N CCOSTHE=FCHE
C FCHE=152.03E6
R RZCCOSTHE.KL=PULSE((CCOSTHE.K-FCHE)/DT,12,12)
L CCOSTFE.K=CCOSTFE.J+DT*(COSTD.JK-RZCCOSTFE.JK)
N CCOSTFE=FCFE
C FCFE=120.1E6
R RZCCOSTFE.KL=PULSE((CCOSTFE.K-FCFE)/DT,12,12)
A PREVSEMS.K=SAMPLE(SEMS.K,1,60E3)
A AVSEMS.K=(PREVSEMS.K+SEMS.K)/2
A CHSEMS.K=SAMPLE(AVSEMS.K,1,60E3)*CHSEMSPM.K
A CHSEMSPM.K=0.15*SUCSEMS/12
C SUCSEMS=100
A PREVALCS.K=SAMPLE(ALLOCS.K,1,240E3)
A AVALCS.K=(PREVALCS.K+ALLOCS.K)/2
A CHALCS.K=SAMPLE(AVALCS.K,1,60E3)*CHALCSPM.K
A CHALCSPM.K=0.15*SUCALCS/12
C SUCALCS=200
L CCHALCS.K=CCHALCS.J+DT*(CHALCS.J-RZCCHALCS.JK)
N CCHALCS=0
R RZCCHALCS.KL=PULSE(CCHALCS.K/DT,12,12)
L CCHSEMS.K=CCHSEMS.J+DT*(CHSEMS.J-RZCCHSEMS.JK)
N CCHSEMS=0
R RZCCHSEMS.KL=PULSE(CCHSEMS.K/DT,12,12)
A CTCOST.K=CCOSTHE.K+CCOSTFE.K+CCHSEMS.K+CCHALCS.K
A CPROF.K=CREV.K-CTCOST.K
A ANNPROF.K=SAMPLE(CPROF.K,12,0)
A TFC.K=FCHE+FCFE
L CD.K=CD.J+DT*(DR.JK-RZCD.JK)
N CD=0
R RZCD.KL=PULSE(CD.K/DT,12,12)
L CSEMP.K=CSEMP.J+DT*(SEMP.JK-RZCSEMP.JK)
N CSEMP=0
R RZCSEMP.KL=PULSE(CSEMP.K/DT,12,12)
A CPT.K=RATIO(CCOSTHE.K,CSEMP.K)
S ANNCPT.K=SAMPLE(CPT.K,12,0)
A ANNTSEMP.K=SAMPLE(CSEMP.K,12,0)
NOTE
NOTE
NOTE  DCF EQUATIONS
NOTE
NOTE
C R=0.15
L CUMRDIS.K=CUMRDIS.J+DT*(REVR.JK/(1+R/12)**TIME.J)
N CUMRDIS=0
A TFCPM.K=(FCHE+FCFE)/12
L CUMCDIS.K=CUMCDIS.J+DT*((TFCPM.J+COSTD.JK+COSTSEMP.JK+CHSEMS.J
X +CHALCS.J)/(1+R/12)**TIME.J)
N CUMCDIS=0
S CUMPROFDIS.K=CUMRDIS.K-CUMCDIS.K
NOTE
NOTE  EQUATIONS FOR FURNACE 1
NOTE
A PF1.K=CLIP(PF1EC.K,PF1N.K,6,(NTF-CPF1.K)/MNPF1)
A PF1EC.K=SWITCH(MNPF1,CLIP(0,NORMRN(MNPF1,SDPF1)*REFE1C.K,CPF1.K,
X MXTF1.K),TIME.K)
A REFE1C.K=TABHL(REFECT,(NTF-CPF1.K)/MNPF1,0,6,1)
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A PF1N.K=SWITCH(MNPF1,CLIP(0,NORMRN(MNPF1,SDPF1)*PFF1.K*BEF.K,
X CPF1.K,MXTF1.K),TIME.K)
C MNPF1=75E3
C SDPF1=5773.5
L CPF1.K=CPF1.J+DT*(PF1.J+ADDRPIC1.JK-RZCPF1.JK)
N CPF1=3.4E6
R ADDRPIC1.KL=NCLIP(10E6/DT,0,TPICF1.K,0,MXTF1.K,CPF1.K)
A TPICF1.K=CPF1.K-MALLF.K-FSCMC.K
A HTMF1.K=SAMPLE(TIME.K,IVLF1.K,0)
A IVLF1.K=CLIP(LENGTH,DT,CPF1.K,MXTF1.K)
R RZCPF1.KL=NCLIP(PULSE(CPF1.K/DT,TIME.K,DT),0,TIME.K,
X (HTMF1.K+TRLF-DT),FSCMC.K,1)
A MPF1.K=CPF1.K/MNPF1
A PFF1.K=TABHL(PFFT,MPF1.K,0,2,0.2)
A MXTF1.K=NTF+EXTF1.K*SWEXTF1.K
A EXTF1.K=CLIP(0,1E6,CPF1.K,NTF)
A SWEXTF1.K=NCLIP(1,0,AVMOH.K,4,CTDECF1.K,(NTF-CPF1.K))
A CTDECF1.K=(MNPF1+3*SDPF1)*PNDEC
NOTE
NOTE  EQUATIONS FOR FURNACE 2
NOTE
A PF2.K=CLIP(PF2EC.K,PF2N.K,6,(NTF-CPF2.K)/MNPF2)
A PF2EC.K=SWITCH(MNPF2,CLIP(0,NORMRN(MNPF2,SDPF2)*REFE2C.K,CPF2.K,
X MXTF2.K),TIME.K)
A REFE2C.K=TABHL(REFECT,(NTF-CPF2.K)/MNPF2,0,6,1)
A PF2N.K=SWITCH(MNPF2,CLIP(0,NORMRN(MNPF2,SDPF2)*PFF2.K*BEF.K,
X CPF2.K,MXTF2.K),TIME.K)
C MNPF2=80E3
C SDPF2=5773.5
L CPF2.K=CPF2.J+DT*(PF2.J+ADDRPIC2.JK-RZCPF2.JK)
N CPF2=4.6E6
R ADDRPIC2.KL=NCLIP(10E6/DT,0,TPICF2.K,0,MXTF2.K,CPF2.K)
A TPICF2.K=CPF2.K-MALLF.K-FSCMC.K
A HTMF2.K=SAMPLE(TIME.K,IVLF2.K,0)
A IVLF2.K=CLIP(LENGTH,DT,CPF2.K,MXTF2.K)
R RZCPF2.KL=NCLIP(PULSE(CPF2.K/DT,TIME.K,DT),0,TIME.K,
X (HTMF2.K+TRLF-DT),FSCMC.K,1)
A MPF2.K=CPF2.K/MNPF2
A PFF2.K=TABHL(PFFT,MPF2.K,0,2,0.2)
A MXTF2.K=NTF+EXTF2.K*SWEXTF2.K
A EXTF2.K=CLIP(0,1E6,CPF2.K,NTF)
A SWEXTF2.K=NCLIP(1,0,AVMOH.K,4,CTDECF2.K,(NTF-CPF2.K))
A CTDECF2.K=(MNPF2+3*SDPF2)*PNDEC
NOTE
NOTE  EQUATIONS FOR FURNACE 3
NOTE
A PF3.K=CLIP(PF3EC.K,PF3N.K,6,(NTF-CPF3.K)/MNPF3)
A PF3EC.K=SWITCH(MNPF3,CLIP(0,NORMRN(MNPF3,SDPF3)*REFE3C.K,CPF3.K,
X MXTF3.K),TIME.K)
A REFE3C.K=TABHL(REFECT,(NTF-CPF3.K)/MNPF3,0,6,1)
A PF3N.K=SWITCH(MNPF3,CLIP(0,NORMRN(MNPF3,SDPF3)*PFF3.K*BEF.K,
X CPF3.K,MXTF3.K),TIME.K)
C MNPF3=85E3
C SDPF3=5773.5
L CPF3.K=CPF3.J+DT*(PF3.J+ADDRPIC3.JK-RZCPF3.JK)
N CPF3=1.2E6
R ADDRPIC3.KL=NCLIP(10E6/DT,0,TPICF3.K,0,MXTF3.K,CPF3.K)
A TPICF3.K=CPF3.K-MALLF.K-FSCMC.K
A HTMF3.K=SAMPLE(TIME.K,IVLF3.K,0)
A IVLF3.K=CLIP(LENGTH,DT,CPF3.K,MXTF3.K)
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R RZCPF3.KL=NCLIP(PULSE(CPF3.K/DT,TIME.K,DT),0,TIME.K,
X (HTMF3.K+TRLF-DT),FSCMC.K,1)
A MPF3.K=CPF3.K/MNPF3
A PFF3.K=TABHL(PFFT,MPF3.K,0,2,0.2)
A MXTF3.K=NTF+EXTF3.K*SWEXTF3.K
A EXTF3.K=CLIP(0,1E6,CPF3.K,NTF)
A SWEXTF3.K=NCLIP(1,0,AVMOH.K,4,CTDECF3.K,(NTF-CPF3.K))
A CTDECF3.K=(MNPF3+3*SDPF3)*PNDEC
NOTE
NOTE
NOTE  OUTPUT CONTROL STATEMENTS
NOTE
NOTE
C DT=0.125
C LENGTH=120
C PRTPER=4
PRINT 1)ALLOCS,UNALLO,COBG,OLR/2)DR,ADR,SOLR/3)SEMS,SEMP,MOH,MUNOR
PRINT 4)COBG,DLTPC
PRINT 5)CUMPROFDIS
NOTE
NOTE
NOTE  DEFINITIONS OF VARIABLE NAMES
NOTE
NOTE  T= TONNES             MTHS= MONTHS      PS=POUNDS STERLING
NOTE  BF= BLAST FURNACES    YRS= YEARS
NOTE
NOTE
D ADDRPIC1=(T/MTHS) ADDITIONAL RATE FOR PREMATURE INTERRUPTION OF
* B.F. 1 CAMPAIGN
D ADDRPIC2=(T/MTHS) ADDITIONAL RATE FOR PREMATURE INTERRUPTION OF
* B.F. 2 CAMPAIGN
D ADDRPIC3=(T/MTHS) ADDITIONAL RATE FOR PREMATURE INTERRUPTION OF
* B.F. 3 CAMPAIGN
D ADR=(T/MTHS) AVERAGE DELIVERY RATE
D ALLOCS=(T) ALLOCATED STOCK
D AMP=(T/MTHS) AMPLITUDE OF SINE WAVE
D AMTPF=(T/MTHS) AVERAGE MONTHLY THROUGHPUT PER FURNACE
D ANNCPT=(PS/T) ANNUAL COST PER TONNE
D ANNPROF=(PS) ANNUAL PROFIT
D ANNTOL=(T) ANNUAL TOTAL OF ORDERS LAUNCHED
D ANNTSEMP=(T) ANNUAL TOTAL SEMI PRODUCTION
D AVALCS=(T) AVERAGE ALLOCATED STOCK
D AVSEMS=(T) AVERAGE SEMI STOCK
D AVMOH=(MTHS) AVERAGE MONTHS' OF ORDERS ON HAND
D BEF=(1) BURDEN EFFICIENCY FACTOR
D CCHALCS=(PS) CUMULATIVE COST OF HOLDING ALLOCATED STOCK
D CCHSEMS=(PS) CUMULATIVE COST OF HOLDING SEMI STOCK
D CCOSTHE=(PS) CUMULATIVE COST AT THE HEAVY END
D CCOSTFE=(PS) CUMULATIVE COST AT THE FINISHING END
D CD=(T) CUMULATIVE DELIVERIES
D CHALCS=(PS/MTHS) COST OF HOLDING ALLOCATED STOCK
D CHALCSPM=(PS/(T*MTHS)) COST OF HOLDING ALLOCATED STOCK PER MONTH
* PER UNIT
D CHSEMS=(PS/MTHS) COST OF HOLDING SEMI STOCK
D CHSEMSPM=(PS/(T*MTHS)) COST OF HOLDING SEMI STOCK PER MONTH
* PER UNIT
D COBG=(T) CUSTOMER ORDER BACKLOG
D COL=(T) CUMULATIVE ORDERS LAUNCHED
D COSTD=(PS/MTH) COST OF DELIVERIES
D COSTSEMP=(PS/MTHS) COST OF SEMI PRODUCTION
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D CPF1=(T) CUMULATIVE PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
* FURNACE NO. 1
D CPF2=(T) CUMULATIVE PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
* FURNACE NO. 2
D CPF3=(T) CUMULATIVE PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
* FURNACE NO. 3
D CPROF=(PS) CUMULATIVE PROFIT
D CPT=(PS/T) COST PER TONNE
D CREV=(PS) CUMULATIVE REVENUE
D CSEMP=(T) CUMULATIVE SEMI PRODUCTION
D CTCOST=(PS) CUMULATIVE TOTAL COST
D CTDECF1=(T) CRITICAL THRESHOLD FOR DECISION ON EXTENDING B.F. 1
* CAMPAIGN
D CTDECF2=(T) CRITICAL THRESHOLD FOR DECISION ON EXTENDING B.F. 2
* CAMPAIGN
D CTDECF3=(T) CRITICAL THRESHOLD FOR DECISION ON EXTENDING B.F. 3
* CAMPAIGN
D CUMCDIS=(PS) CUMULATIVE COSTS DISCOUNTED
D CUMPROFDIS=(PS) CUMULATIVE PROFIT DISCOUNTED
D CUMRDIS=(PS) CUMULATIVE REVENUE DISCOUNTED
D DLTPC=(MTHS) DELIVERY LEAD TIME PERCEIVED BY THE CUSTOMER
D DR=(T/MTHS) DELIVERY RATE
D DRAT=(MTHS) DELIVERY RATE AVERAGING TIME
D DSOIMS=(MTHS) DELAY IN SATISFYING ORDERS FOR IMPORTED STEEL
D DT=(MTHS) SOLUTION INTERVAL
D EXTF1=(T/MTHS) EXTRA THROUGHPUT OF B.F. 1 (IN ADVANCE OF RELINE)
D EXTF2=(T/MTHS) EXTRA THROUGHPUT OF B.F. 2 (IN ADVANCE OF RELINE)
D EXTF3=(T/MTHS) EXTRA THROUGHPUT OF B.F. 3 (IN ADVANCE OF RELINE)
D F1IN=(BF) BLAST FURNACE NO. 1 IN BLAST
D F1OUT=(BF) BLAST FURNACE NO. 1 OUT OF BLAST
D F2IN=(BF) BLAST FURNACE NO. 2 IN BLAST
D F2OUT=(BF) BLAST FURNACE NO. 2 OUT OF BLAST
D F3IN=(BF) BLAST FURNACE NO. 3 IN BLAST
D F3OUT=(BF) BLAST FURNACE NO. 3 OUT OF BLAST
D FCHE=(PS) FIXED COSTS AT THE HEAVY END
D FCFE=(PS) FIXED COSTS AT THE FINISHING END
D FOPLA=(1) FRACTION OF ORDERS PLACED ABROAD
D FOPLAT=(1) FRACTION OF ORDERS PLACED ABROAD -- TABLE OF VALUES
D FPLT=(MTHS) FINISHING PROCESSES LEAD TIME
D FSCMC=(T) FACTOR FOR SUSPENSION OF CAMPAIGN DUE TO MARKET
* CONDITIONS
D HTMF1=(MTHS) HELD (I.E. FROZEN) TIME FOR BLAST FURNACE NO. 1
D HTMF2=(MTHS) HELD (I.E. FROZEN) TIME FOR BLAST FURNACE NO. 2
D HTMF3=(MTHS) HELD (I.E. FROZEN) TIME FOR BLAST FURNACE NO. 3
D IMS=(T/MTHS) IMPORTS OF STEEL
D IVLF1=(MTHS) INTERVAL OVER WHICH FROZEN TIME IS HELD FOR BLAST
* FURNACE NO. 1
D IVLF2=(MTHS) INTERVAL OVER WHICH FROZEN TIME IS HELD FOR BLAST
* FURNACE NO. 2
D IVLF3=(MTHS) INTERVAL OVER WHICH FROZEN TIME IS HELD FOR BLAST
* FURNACE NO. 3
D LENGTH=(MTHS) LENGTH OF THE SIMULATION RUN
D MF1F2=(T) MAXIMUM CUMULATIVE THROUGHPUT BETWEEN B.F. 1 AND B.F. 2
D MALLF=(T) MAXIMUM CUMULATIVE THROUGHPUT OVER ALL BLAST FURNACES
D MNPF1=(T/MTHS) MEAN PRODUCTION FOR BLAST FURNACE NO. 1
D MNPF2=(T/MTHS) MEAN PRODUCTION FOR BLAST FURNACE NO. 2
D MNPF3=(T/MTHS) MEAN PRODUCTION FOR BLAST FURNACE NO. 3
D MOH=(MTHS) MONTHS' OF ORDERS ON HAND
D MOPL=(T/MTHS) MEAN OF ORDERS PLACED
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D MPF1=(MTHS) MONTHS' OF PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
* FURNACE NO. 1
D MPF2=(MTHS) MONTHS' OF PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
* FURNACE NO. 2
D MPF3=(MTHS) MONTHS' OF PRODUCTION (IN CURRENT CAMPAIGN) BY BLAST
* FURNACE NO. 3
D MSEMS=(MTHS) MONTHS' OF SEMI STOCKS
D MSEMSN=(MTHS) MONTHS' OF SEMI STOCKS NORMALLY
D MUNO=(MTHS) MONTHS' OF UNALLOCATED ORDERS
D MUNON=(MTHS) MONTHS OF UNALLOCATED ORDERS NORMALLY
D MUNOR=(1) MONTHS' OF UNALLOCATED ORDERS RATIO
D MXTF1=(T) MAXIMUM THROUGHPUT BY BLAST FURNACE NO. 1
* (BEFORE RELINE REQUIRED)
D MXTF2=(T) MAXIMUM THROUGHPUT BY BLAST FURNACE NO. 2
* (BEFORE RELINE REQUIRED)
D MXTF3=(T) MAXIMUM THROUGHPUT BY BLAST FURNACE NO. 3
* (BEFORE RELINE REQUIRED)
D NFB=(BF) NUMBER OF BLAST FURNACES IN BLAST
D NOLR=(T/MTHS) NORMAL ORDER LAUNCHING RATE
D NTF=(T) NORMAL THROUGHPUT OF BLAST FURNACE (BEFORE RELINE
* REQUIRED)
D OBGF=(1) ORDER BACKLOG FACTOR
D OBGFT=(1) ORDER BACKLOG FACTOR -- TABLE OF VALUES
D OIMS=(T/MTHS) ORDERS FOR IMPORTED STEEL
D OLR=(T/MTHS) ORDER LAUNCHING RATE
D OPL=(T/MTHS) ORDERS PLACED
D OPLH=(T/MTHS) ORDERS PLACED AT HOME
D OPLI=(T/MTHS) ORDERS PLACED INITIALLY
D OVBF=(1) OVER-BOOKING FACTOR
D OVBFT=(1) OVER-BOOKING FACTOR -- TABLE OF VALUES
D PAYDEL=(MTHS) PAYMENT DELAY FROM CUSTOMERS
D PBEF=(1) POTENTIAL BURDEN EFFICIENCY FACTOR
D PBEFT=(1) POTENTIAL BURDEN EFFICIENCY FACTOR -- TABLE OF VALUES
D PERD=(MTHS) PERIODICITY OF SINE WAVE
D PF1=(T/MTHS) PRODUCTION OF CRUDE STEEL FROM BLAST FURNACE NO. 1
D PF1EC=(T/MTHS) PRODUCTION FOR B.F. 1 AT END OF CAMPAIGN LIFE
D PF1N=(T/MTHS) PRODUCTION OF CRUDE STEEL FROM BLAST FURNACE NO. 1
* NORMALLY
D PF2=(T/MTHS) PRODUCTION OF CRUDE STEEL FROM BLAST FURNACE NO. 2
D PF2EC=(T/MTHS) PRODUCTION FOR B.F. 2 AT END OF CAMPAIGN LIFE
D PF2N=(T/MTHS) PRODUCTION OF CRUDE STEEL FROM BLAST FURNACE NO. 2
* NORMALLY
D PF3=(T/MTHS) PRODUCTION OF CRUDE STEEL FROM BLAST FURNACE NO. 3
D PF3EC=(T/MTHS) PRODUCTION FOR B.F. 3 AT END OF CAMPAIGN LIFE
D PF3N=(T/MTHS) PRODUCTION OF CRUDE STEEL FROM BLAST FURNACE NO. 3
* NORMALLY
D PFF1=(1) PRODUCTION BUILD-UP FACTOR FOR BLAST FURNACE NO. 1
D PFF2=(1) PRODUCTION BUILD-UP FACTOR FOR BLAST FURNACE NO. 2
D PFF3=(1) PRODUCTION BUILD-UP FACTOR FOR BLAST FURNACE NO. 3
D PFFT=(1) PRODUCTION BUILD-UP FACTOR FOR BLAST FURNACES AFTER
* RELINING -- TABLE OF VALUES
D PI=(1) DIMENSIONLESS CONSTANT
D PNDEC=(MTHS) PRIOR NOTICE FOR DECISION ON EXTENDING A B.F.
* CAMPAIGN
D PREVALCS=(T) PREVIOUS VALUE OF ALLOCATED STOCK
D PREVSEMS=(T) PREVIOUS VALUE OF SEMI STOCK
D PRTPER=(MTHS) PRINTING INTERVAL
D R=(1/YRS) DISCOUNT FACTOR
D REFE1C=(1) REDUCED EFFICIENCY FACTOR AT END OF B.F. 1'S CAMPAIGN
D REFE2C=(1) REDUCED EFFICIENCY FACTOR AT END OF B.F. 2'S CAMPAIGN
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D REFE3C=(1) REDUCED EFFICIENCY FACTOR AT END OF B.F. 3’S CAMPAIGN
D REFECT=(1) REDUCED EFFICIENCY FACTOR AT END OF A B.F. CAMPAIGN --
* TABLE OF VALUES
D REVR=(PS/MTHS) REVENUE RECEIVED
D RPIT=(PS/T) REVENUE PER INGOT TONNE
D RZCCHALCS=(PS/MTHS) RE-ZERO CUMULATIVE COST OF HOLDING ALLOCATED
* STOCK
D RZCCHSEMS=(PS/MTHS) RE-ZERO CUMULATIVE COST OF HOLDING SEMI STOCK
D RZCCOSTHE=(PS/MTHS) RE-ZERO CUMULATIVE COST AT THE HEAVY END
D RZCCOSTFE=(PS/MTHS) RE-ZERO CUMULATIVE COST AT THE FINISHING END
D RZCD=(T/MTHS) RE-ZERO CUMULATIVE DELIVERIES
D RZCOL=(T) RE-ZERO CUMULATIVE ORDERS LAUNCHED
D RZCPF1=(T/MTHS) RE-ZERO CUMULATIVE PRODUCTION FOR BLAST FURNACE
* NO. 1
D RZCPF2=(T/MTHS) RE-ZERO CUMULATIVE PRODUCTION FOR BLAST FURNACE
* NO. 2
D RZCPF3=(T/MTHS) RE-ZERO CUMULATIVE PRODUCTION FOR BLAST FURNACE
* NO. 3
D RZCREV=(PS/MTHS) RE-ZERO CUMULATIVE REVENUE
D RZCSEMP=(T/MTHS) RE-ZERO CUMULATIVE SEMI PRODUCTION
D SDOPL=(T/MTHS) STANDARD DEVIATION OF ORDERS PLACED
D SDPF1=(T/MTHS) STANDARD DEVIATION OF PRODUCTION FOR BLAST
* FURNACE NO. 1
D SDPF2=(T/MTHS) STANDARD DEVIATION OF PRODUCTION FOR BLAST
* FURNACE NO. 2
D SDPF3=(T/MTHS) STANDARD DEVIATION OF PRODUCTION FOR BLAST
* FURNACE NO. 3
D SEMP=(T/MTHS) SEMI PRODUCTION
D SEMS=(T) SEMI STOCKS
D SEMSF=(1) SEMI STOCKS FACTOR
D SEMSFT=(1) SEMI STOCKS FACTOR -- TABLE OF VALUES
D SEMSR=(1) SEMI STOCKS RATIO
D SOLR=(T/MTHS) SMOOTHED ORDER LAUNCHING RATE
D SUCALCS=(PS/T) STANDARD UNIT COST OF ALLOCATED STOCK
D SUCSEMS=(PS/T) STANDARD UNIT COST OF SEMI STOCK
D SWEXTF1=(1) SWITCH TO CONTROL EXTRA THROUGHPUT FOR B.F. 1
D SWEXTF2=(1) SWITCH TO CONTROL EXTRA THROUGHPUT FOR B.F. 2
D SWEXTF3=(1) SWITCH TO CONTROL EXTRA THROUGHPUT FOR B.F. 3
D TFC=(PS) TOTAL FIXED COSTS
D TFCPM=(PS/MTHS) TOTAL FIXED COSTS PER MONTH
D TIME=(MTHS) SIMULATED TIME
D TPICF1=(T) TEST FACTOR FOR PREMATURE INTERRUPTION OF CAMPAIGN
* IN B.F. 1
D TPICF2=(T) TEST FACTOR FOR PREMATURE INTERRUPTION OF CAMPAIGN
* IN B.F. 2
D TPICF3=(T) TEST FACTOR FOR PREMATURE INTERRUPTION OF CAMPAIGN
* IN B.F. 3
D TRCMOH=(MTHS) TIME TO RECOGNISE CHANGES IN MONTHS’ OF ORDERS
* ON HAND
D TRLF=(MTHS) TIME TO RELINE A BLAST FURNACE
D TSOL=(MTHS) TIME FOR SMOOTHING ORDERS LAUNCHED
D UFE=(1) UTILISATION OF CAPACITY AT FINISHING END
D UHE=(1) UTILISATION OF CAPACITY AT HEAVY END
D UNALLO=(T) UNALLOCATED ORDERS
D VCPTFE=(PS/T) VARIABLE COST PER TONNE AT THE FINISHING END
D VCPTHE=(PS/T) VARIABLE COST PER TONNE AT THE HEAVY END
RUN BASE RUN: NOISE + CYCLE (AMP= 48E3) + 3 BLAST FURNACES
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ADDITIONAL STATEMENTS FOR THE FIVE BLAST FURNACE MODEL

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NOTE
NOTE
NOTE    These statements must follow on from the three
NOTE    blast furnace model
NOTE
NOTE
SEED 0.5
C MNPF1=55E3
C SDPF1=4472.14
N CPF1=3.4E6
C MNPF2=50E3
C SDPF2=4472.14
N CPF2=4.6E6
C MNPF3=50E3
C SDPF3=4472.14
N CPF3=1.2E6
A MF1F3.K=MAX(MF1F2.K,CPF3.K)
A MF1F4.K=MAX(MF1F3.K,CPF4.K)
A MALLF.K=MAX(MF1F4.K,CPF5.K)
R SLP.KL=PF1.K+PF2.K+PF3.K+PF4.K+PF5.K
S UHE.K=SMOOTH(SEMP.JK,TSSEMP)/((MNPF1+MNPF2+MNPF3+MNPF4+MNPF5)
X *1.15)*100
A NFB.K=SWITCH(F1OUT,F1IN,PF1.K)+SWITCH(F2OUT,F2IN,PF2.K)+
X SWITCH(F3OUT,F3IN,PF3.K)+SWITCH(F4OUT,F4IN,PF4.K)+
X SWITCH(F5OUT,F5IN,PF5.K)
C F4OUT=0
C F4IN=1
C F5OUT=0
C F5IN=1
C AMTPF=48E3
NOTE
NOTE  COSTS & PROFIT
NOTE
C FCHE=165.88E6
NOTE
NOTE  EQUATIONS FOR FURNACE 4
NOTE
A PF4.K=CLIP(PF4EC.K,PF4N.K,6,(NTF-CPF4.K)/MNPF4)
A PF4EC.K=SWITCH(MNPF4,CLIP(0,NORMRN(MNPF4,SDPF4)*REFE4C.K,CPF4.K,
X MXTF4.K),TIME.K)
A REFE4C.K=TABHL(REFECT,(NTF-CPF4.K)/MNPF4,0,6,1)
A PF4N.K=SWITCH(MNPF4,CLIP(0,NORMRN(MNPF4,SDPF4)*PFF4.K*BEF.K,
X CPF4.K,MXTF4.K),TIME.K)
C MNPF4=40E3
C SDPF4=4472.14
L CPF4.K=CPF4.J+DT*(PF4.J+ADDRPIC4.JK-RZCPF4.JK)
N CPF4=2.8E6
R ADDRPIC4.KL=NCLIP(10E6/DT,0,TPICF4.K,0,MXTF4.K,CPF4.K)
A TPICF4.K=CPF4.K-MALLF.K-FSCMC.K
A HTMF4.K=SAMPLE(TIME.K,IVLF4.K,0)
A IVLF4.K=CLIP(LENGTH,DT,CPF4.K,MXTF4.K)
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R RZCPF4.KL=NCLIP(PULSE(CPF4.K/DT,TIME.K,DT),0,TIME.K,
X (HTMF4.K+TRLF-DT),FSCMC.K,1)
A MPF4.K=CPF4.K/MNPF4
A PFF4.K=TABHL(PFFT,MPF4.K,0,2,0.2)
A MXTF4.K=NTF+EXTF4.K*SWEXTF4.K
A EXTF4.K=CLIP(0,1E6,CPF4.K,NTF)
A SWEXTF4.K=NCLIP(1,0,AVMOH.K,4,CTDECF4.K,(NTF-CPF4.K))
A CTDECF4.K=(MNPF4+3*SDPF4)*PNDEC
NOTE
NOTE  EQUATIONS FOR FURNACE 5
NOTE
A PF5.K=CLIP(PF5EC.K,PF5N.K,6,(NTF-CPF5.K)/MNPF5)
A PF5EC.K=SWITCH(MNPF5,CLIP(0,NORMRN(MNPF5,SDPF5)*REFE5C.K,CPF5.K,
X MXTF5.K),TIME.K)
A REFE5C.K=TABHL(REFECT,(NTF-CPF5.K)/MNPF5,0,6,1)
A PF5N.K=SWITCH(MNPF5,CLIP(0,NORMRN(MNPF5,SDPF5)*PFF5.K*BEF.K,
X CPF5.K,MXTF5.K),TIME.K)
C MNPF5=45E3
C SDPF5=4472.14
L CPF5.K=CPF5.J+DT*(PF5.J+ADDRPIC5.JK-RZCPF5.JK)
N CPF5=0.5E6
R ADDRPIC5.KL=NCLIP(10E6/DT,0,TPICF5.K,0,MXTF5.K,CPF5.K)
A TPICF5.K=CPF5.K-MALLF.K-FSCMC.K
A HTMF5.K=SAMPLE(TIME.K,IVLF5.K,0)
A IVLF5.K=CLIP(LENGTH,DT,CPF5.K,MXTF5.K)
R RZCPF5.KL=NCLIP(PULSE(CPF5.K/DT,TIME.K,DT),0,TIME.K,
X (HTMF5.K+TRLF-DT),FSCMC.K,1)
A MPF5.K=CPF5.K/MNPF5
A PFF5.K=TABHL(PFFT,MPF5.K,0,2,0.2)
A MXTF5.K=NTF+EXTF5.K*SWEXTF5.K
A EXTF5.K=CLIP(0,1E6,CPF5.K,NTF)
A SWEXTF5.K=NCLIP(1,0,AVMOH.K,4,CTDECF5.K,(NTF-CPF5.K))
A CTDECF5.K=(MNPF5+3*SDPF5)*PNDEC
RUN ORDERS BOOKED = NOISE + CYCLE + 5 BLAST FURNACES OPERATING
```

ADDITIONAL STATEMENTS FOR THE MIXED TECHNOLOGY MODEL

```
NOTE
NOTE
NOTE    These statements must follow directly after the three
NOTE    blast furnace model
NOTE
NOTE
SEED 0.5
NOTE
NOTE
NOTE  PRODUCTION
NOTE
NOTE
R SEMP.KL=SEMPBF.KL+SEMPEF.KL
R SEMPBF.KL=PF1.K+PF3.K
L CSEMPBF.K=CSEMPBF.J+DT*(SEMPBF.JK-RZCSEMPBF.JK)
N CSEMPBF=0
R RZCSEMPBF.KL=PULSE(CSEMPBF.K/DT,12,12)
A ANNTSEMPBF.K=SAMPLE(CSEMPBF.K,12,0)
S UHE.K=(ANNTSEMP.K/(((MNPF1+MNPF3)*12*1.15)+(NEFP*MPEF*12)))*100
S UEF.K=(ANNTSEMPEF.K/((NEFP*MPEF)*12))*100
S UBF.K=(ANNTSEMPBF.K/((MNPF1+MNPF2)*12*1.15))*100
A MALLF.K=MAX(CPF1.K,CPF3.K)
A NFB.K=SWITCH(F1OUT,F1IN,PF1.K)+SWITCH(F3OUT,F3IN,PF3.K)
NOTE
NOTE
NOTE  ELECTRIC FURNACES
NOTE
NOTE
L CSEMPEF.K=CSEMPEF.J+DT*(SEMPEF.JK-RZCSEMPEF.JK)
N CSEMPEF=0
R RZCSEMPEF.KL=PULSE(CSEMPEF.K/DT,12,12)
A ANNTSEMPEF.K=SAMPLE(CSEMPEF.K,12,0)
A RSEMPEF.K=MAX((UNALLO.K-NOLR*MUNON)/DPEF-(PF1.K+PF3.K),0)
C DPEF=1
R SEMPEF.KL=SWITCH(0,NORMRN(MIN(RSEMPEF.K,NSEMPEF.K),SDPEF.K),
X RSEMPEF.K)
A NSEMPEF.K=CLIP(MPEF,NEFP*MPEF,MPEF,RSEMPEF.K)
A NEFOP.K=SWITCH(0,CLIP(1,NEFP,MPEF,RSEMPEF.K),RSEMPEF.K)
C NEFP=2
C MPEF=40E3
A SDPEF.K=CLIP(0,CLIP(5773.5,4082.5,MPEF,RSEMPEF.K),18E3,RSEMPEF.K)
NOTE
NOTE
NOTE  COSTS & PROFIT
NOTE
NOTE
R COSTSEMP.KL=COSTSEMPHE.K+COSTSEMPEF.K
A COSTSEMPHE.K=(PF1.K+PF3.K)*VCPTHE
A COSTSEMPEF.K=SEMPEF.KL*VCPTEF
C VCPTEF=62.02
L CCOSTEF.K=CCOSTEF.J+DT*(COSTSEMPEF.J-RZCCOSTEF.JK)
N CCOSTEF=FCEF
```

```
C FCEF=31.49E6
R RZCCOSTEF.KL=PULSE((CCOSTEF.K-FCEF)/DT,12,12)
L CCOSTHE.K=CCOSTHE.J+DT*(COSTSEMPHE.J-RZCCOSTHE.JK)
N CCOSTHE=FCHE
C FCHE=123.14E6
A CTCOST.K=CCOSTHE.K+CCOSTEF.K+CCOSTFE.K+CCHSEMS.K+CCHALCS.K
A TFC.K=FCHE+FCEF+FCFE
A TFCPM.K=(FCHE+FCEF+FCFE)/12
NOTE
NOTE
NOTE  DEFINITION STATEMENTS
NOTE
NOTE  EF= ELECTRIC FURNACES
NOTE
NOTE
D ANNTSEMPBF=(T) ANNUAL TOTAL SEMI PRODUCTION FROM BLAST FURNACES
D ANNTSEMPEF=(T) ANNUAL TOTAL SEMI PRODUCTION FROM ELECTRIC FURNACES
D CCOSTEF=(PS) CUMULATIVE COST AT ELECTRIC FURNACES
D CSEMPBF=(T) CUMULATIVE SEMI PRODUCTION FROM BLAST FURNACES
D CSEMPEF=(T) CUMULATIVE SEMI PRODUCTION FROM ELECTRIC FURNACES
D COSTSEMPEF=(PS/MTHS) COST OF SEMI PRODUCTION FROM ELECTRIC
* FURNACES
D COSTSEMPHE=(PS/MTHS) COST OF SEMI PRODUCTION AT THE HEAVY END
D DPEF=(MTHS) DELAY IN PRODUCTION FROM ELECTRIC FURNACES
D FCEF=(PS) FIXED COSTS AT ELECTRIC FURNACES
D MPEF=(T/MTHS) MEAN PRODUCTION FROM ELECTRIC FURNACES
D NEFOP=(EF) NUMBER OF ELECTRIC FURNACES OPERATING
D NEFP=(EF) NUMBER OF ELECTRIC FURNACES AT THE PLANT
D NSEMPEF=(T/(EF*MTHS)) NORMAL SEMI PRODUCTION FROM ELECTRIC
* FURNACES
D SDPEF=(T/MTHS) STANDARD DEVIATION OF PRODUCTION FROM AN
* ELECTRIC FURNACE
D SEMPEF=(T/MTHS) SEMI PRODUCTION FROM ELECTRIC FURNACES
D RSEMPEF=(T/MTHS) REQUIRED SEMI PRODUCTION FROM ELECTRIC FURNACES
D RZCCOSTEF=(PS/MTHS) RE-ZERO CUMULATIVE COST AT ELECTRIC FURNACES
D RZCSEMPBF=(T/MTHS) RE-ZERO CUMULATIVE SEMI PRODUCTION FROM
* BLAST FURNACES
D RZCSEMPEF=(T/MTHS) RE-ZERO CUMULATIVE SEMI PRODUCTION FROM
* ELECTRIC FURNACES
D UBF=(1) UTILISATION OF CAPACITY: BLAST FURNACES
D UEF=(1) UTILISATION OF CAPACITY: ELECTRIC FURNACES
D VCPTEF=(PS/T) VARIABLE COST PER TON AT ELECTRIC FURNACES
RUN TWO ELECTRIC FURNACES IN PLACE OF SECOND BLAST FURNACE
```

4 A MODEL TO SUPPORT PUBLIC POLICY IN RESPECT OF THE AIDS EPIDEMIC

4.1 Introduction

The AIDS pandemic has been described as the greatest threat posed to world health in the twentieth century. Unknown prior to 1981, its spread since then has been relentless such that by 1st December 1988 (World AIDS Day) 129,385 persons worldwide were reported to the World Health Organisation (WHO) as exhibiting symptoms of the Acquired Immune Deficiency Syndrome (AIDS). Of this total, in excess of 77,000 were attributed to the USA alone. WHO estimate that, because of under-reporting, the true figure for worldwide cases is likely to be between 250,000 and 300,000. In the United Kingdom up to the end of 1988 there were 1982 reported cases of whom 1059 had died. The onset of clinical AIDS leads ultimately to death: there is no known cure, nor is one likely to be found in the forseeable future.

In the face of such startling and depressing statistics it is incumbent on the world's scientific community to respond in terms of enhancing understanding about the epidemiology of this new disease, projecting its spread and evaluating alternative strategies for containing that spread. To a great extent this has happened. The author is aware of over twenty separate groups or individuals engaged worldwide in modelling the spread of AIDS and that of its aetiological agent, the Human Immunodeficiency Virus (HIV). Symposia on AIDS modelling held in both Europe (Jager and Ruitenberg, 1988) and the United States (Institute of Medicine, 1988) have resulted in the publication either of summary reports of the overall proceedings or all individually contributed papers.

In the U.K. a number of studies have already been published. Within these, the work of a group of researchers at Imperial College is particularly prominent. Professor Roy Anderson and his colleagues have, between them, produced over a dozen articles devoted to various aspects of the transmission dynamics of HIV. Along with R. M. May of Princeton University, Anderson has described the development of a deterministic mathematical model which underpins most of the group's work (Anderson, Medley, May and Johnson, 1986; May and Anderson, 1987; May and Anderson, 1988). Latterly, detailed aspects of this model have been expounded by Blythe and Anderson (1988a; 1988b) while Medley et al (1987; 1988a; 1988b) have concentrated attention on successive analyses of what data exists to enable the parameters of the distribution of the incubation period of AIDS to be determined. Professor Sir David Cox, who has contributed to the work on the incubation time distribution, was also the Chairman of a working party set up by the government in March 1988 and charged with the task of determining a best estimate of new cases of AIDS over the next five years. This group reported their conclusions in what has become known as the 'Cox Report' (Department of Health and the Welsh Office, 1988). Subsequently, the study was updated with the group re-convening under the chairmanship of Nicholas Day and their report, including amended projections by risk group, was published earlier this year, becoming known as the 'Day Report' (Public Health Laboratory Service, 1990).

Other work in the U.K. includes a study by Knox (1986) reporting the development of a steady-state analysis of the epidemic using a model categorised for specific risk groups adopting specific sexual practices, whilst Wilkie (1988) describes a model he has created for use as a planning tool by the Institute of Actuaries on behalf of U.K. Life Offices. As would be expected the output from this model contains a lot of age-related detail. Griffiths et al (1990a; 1990b) have conducted AIDS research using a variety of techniques from statistical extrapolation to sophisticated mathematical and simulation modelling. Finally, purely data-driven studies have been carried out (McEvoy and Tillett, 1985; Healy and Tillett, 1988). These involve fitting a curve to the existing data on new AIDS cases and extrapolating the fitted curve. Providing the projection is not done for more than a few years ahead, this kind of statistical analysis is perfectly acceptable. A critical overview of modelling work published by November 1987, primarily relating to the U.K. and Western Europe, is given by Isham (1988). In addition, a bibliograhy on AIDS modelling, incorporating an assessment of some of the entries, is now available (Withers, 1988).

In the crescendo of scientific responses to this immense human problem the voice of the operational research community has not so far been heard. Yet with a rich tradition of success in improving organisational decision making it might be expected that O.R. would be well placed to contribute to the debate surrounding this vital issue of public policy. But here perhaps is the nub of the issue: the distinction between policy making and decision making, a distinction which was stressed in chapter 1.

Operational Research has not traditionally ventured far towards strategic issues in planning, preferring instead to concentrate on its strengths in dealing with operational and tactical matters (Eilon, 1989). But it is policies, *not decisions*, which determine the success or failure of organisations, industries and governments. Poor strategic policy can never be overcome by enlightened tactical decisions no matter how sophisticated are the tools involved in the decision making process. If a trend is now evident that O.R. is moving away from an algorithmic approach and towards a systems approach then this should be nurtured and encouraged since the process of analysing strategic issues is furthered by adopting a systemic orientation. This chapter, describing a systems model of the processes underpinning the epidemiology of HIV/AIDS, should therefore be seen not only as a contribution to the international debate on the AIDS pandemic but also as a statement of the ability of the O.R. community to orientate itself towards policy issues that lie in the glare of the public eye.

Studies of the epidemiology of infectious diseases have not previously figured in the system dynamics literature save for some simple examples included in textbooks. Yet the epidemiology of any disease is an aggregated dynamic process of the sort which is well-suited to the system dynamics modelling approach. Moreover, the shift from running such models on mainframe computers to running them on personal computers, which has been a feature only of the last three or four years, has consolidated the advantages possessed by system dynamics for the creation and presentation of models of disease spread. Such models are now capable of playing a vital public policy support role for national and regional health planners and administrators.

Epidemiology concerns subject matter at the interface between medical science, biological science and statistics and epidemiological studies readily recognise the contribution made by mathematical modelling (Bailey, 1975). But this recognition does not yet appear to embrace computer simulation. Certainly the mathematical modellers often need to employ numerical methods to solve their complex non-linear differential equations but this is as near as they venture towards harnessing computer simulation in their work. It is argued below that this is not far enough. Adoption of what has been termed a "blue collar" approach (Clark, 1988) may lack the purity sought by some but it does offer a number of advantages which demystify the modelling process in the eyes of the client. This is a strength which deserves to be recognised.

The system dynamics software adopted for this study, DYSMAP2 (Dangerfield and Vapenikova, 1987), incorporates an *Interactive Command Processor* environment which goes some way towards providing the mode of user interface which possesses the greatest hope of harnessing client interest and involvement. From this environment it is possible, using simple commands, to form and display different types of plot (with or without user defined scales); to change existing model equations or add new ones as a prelude to a further simulation run; and be reminded of the list of runs so far carried out as well as the original equations in the model.

The software produces high resolution colour graph plots on screen as a major component of model output. In this way it exhibits a high degree of portability whilst allowing the ease of output assimilation which a graph plot provides. In particular, the ability to plot a graph for one variable alongside the same variable from another simulation run (comparison plots or co-plots as they are called) ensures that those interested in the model's output can rapidly digest the effects of either policy or parameter changes. In the case of the latter this is of special importance, for it is an accepted facet of AIDS epidemiology that few of the crucial parameters relating to its transmission are known with certainty. A review of this aspect is provided by Anderson and May (1988). Additionally, the provision of scatter plots is useful in that they allow the plot of one variable against any other in the model. Thus it is possible to assess the growth of HIV prevalence against numbers of cumulative clinical cases of AIDS, for instance. Examples of graph plots from various model simulations are included in the sections on results given below.

Over the last three years or so, significant new knowledge has been uncovered about the processes which determine the spread of HIV. This knowledge has been gleaned from empirical studies in epidemiology, virology and sociology. The model described in this chapter (Dangerfield and Roberts, 1989; Roberts and Dangerfield, 1989; Roberts and Dangerfield, 1990a; Roberts and Dangerfield, 1990b) has the purpose of offering a means of understanding the epidemiology of HIV/AIDS in the UK homosexual community initially, and is designed for the role of providing a policy support tool in that it can be seen as stimulating debate on the strategic response to this extremely serious problem of public health. The model incorporates this new knowledge via the following features, all relevant to the course of the AIDS epidemic -- heterogeneity in sexual activity, a variable infectivity profile over the long incubation period of the virus and a change in sexual behaviour.

Heterogeneity refers to the phenomenon whereby a subset of the susceptible population are seen to be more intensively engaged in high risk behaviours than are other susceptible persons in the same risk group. The variable infectivity profile derives from a number of studies pointing towards the possibility that there is a burst of infectivity shortly after initial infection with HIV, followed by a long period of virtually zero infectivity before this starts to climb again in a third phase as the symptoms of clinical AIDS appear. Finally, significant reductions in the number of different sexual partners taken by male homosexuals -- currently the group accounting for the largest number of AIDS cases in the UK -- have been reported from more than one empirical investigation.

4.2 Purpose, Structure and Parameters of the model

The purpose of the model is to provide a policy support tool which can be used as a component in the debate concerning the management of the epidemic; as a means of obtaining increased understanding of HIV transmission dynamics; and as a way of judging the efficacy of various intervention strategies.

Whilst many of the published mathematical models of AIDS epidemiology are technically impressive, they have been put together in a vacuum insofar as they attempt to relate to potential clients. This is where the system dynamics method should exhibit its strengths, since it is essential that the model's interface with those who are engaged in national and regional planning for the management of the epidemic is such that it facilitates debate, ultimately sustaining the model in its role as a policy support tool. The interface should be a feature of the overall modelling effort, not merely an afterthought or something which has been totally ignored.

Although projections *are* possible, the model is not primarily intended to possess a forecasting role. Rather it examines the progress of the epidemic in an at-risk cohort of one million male homosexuals, allowing the investigator to easily compare the relative epidemiological consequences of crucial virological and behavioural aspects of the infection. One million males is equivalent to 6.8% of the sexually active male population between the ages of 16 and 56 years. Little has been reported about attempts to assess the extent of male homosexuality in the U.K. In 1978 Belsey and Adler described a large study of genito-urinary clinic attendees (Belsey and Adler, 1978). They found that 9% of male patients were homosexual. Because other studies have established that homosexuals change their partners far more frequently than heterosexuals (see below), it may be expected that homosexuals would be disproportionately represented in surveys of clinic attendees. Hence 9% must be regarded as an upper limit for the proportion in the population as a whole, but what figure below 9% is appropriate for the true proportion of homosexuals in the population must at present remain a matter of conjecture.

Male homosexuals accounted for some 84% of all U.K. cases reported to the Communicable Disease Surveillance Centre (CDSC) by the end of 1987. They also make up the major risk group in both the United States and Europe as a whole, although the proportions there lie between 60% and 70% of reported cases because of the relative size of the risk group arising from intravenous drug abuse (between 20% and 25% in the U.S.A. and Europe as a whole, but only 7% of cases in the U.K. up to the end of 1987).

4.2.1 Influence and Flow Diagrams

The influence diagram shown in figure 4.1 depicts the four main feedback loops to be found in the model. With the exception of the replacement of "deaths" by "immunity" in loop 4, or the addition of an adjacent fifth loop to allow for *either* deaths or immunity, the epidemiology of most diseases is characterised by the loops shown in figure 4.1 (with appropriate time constants). The possibility of transfer to an immune state unfortunately just does not exist with AIDS. There have been no reports of anyone making a full and complete recovery after having been diagnosed as presenting with symptoms of clinical AIDS.

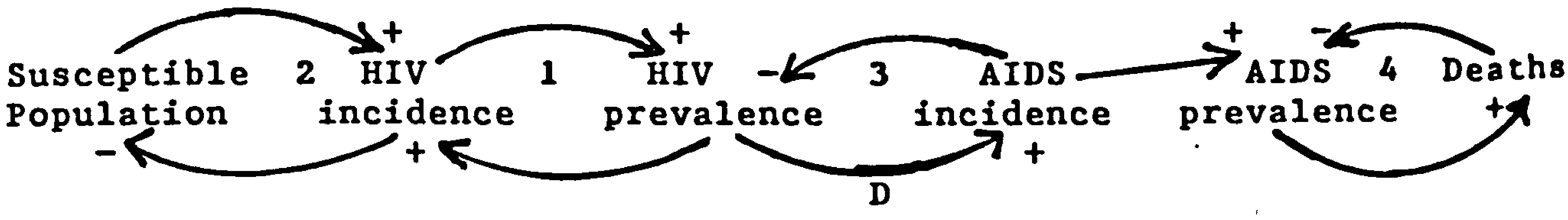

Figure 4.1 Influence diagram for the model

Loop 1 is dominant initially. This merely shows a positive loop in which newly-infected persons pass on the infection by adding to the HIV population, or HIV prevalence to use the correct epidemiological term. Loop 2 reflects the way in which the declining pool of susceptibles implies a saturation effect in the progress of the disease. Finally, loop 3 demonstrates how the emergence of numbers of people with clinical AIDS is also constraining the system's ability to spread HIV, although the link between HIV prevalence and AIDS incidence masks the lengthy incubation period of the virus (signified by the 'D' on the arrow) and the extent to which people infected with HIV ultimately convert to clinical AIDS. Whereas a mere two years ago the proportion of HIV-infecteds who progressed to clinical AIDS was estimated to be as low as 0.3 it is now believed to be nearer 0.9, with many experts resigned to accepting that it will ultimately prove to be 1.0 .

Loop 1 reflects what epidemiologists call the 'basic reproductive rate of infection'. This is quantifiable and equivalent to the loop gain. If the gain around this loop is > 1.0 then an epidemic is inevitable. Reducing the gain to ≤ 1.0 is indicative of the concomitant parameter changes which clinicians and health educationists would have to see in order to bring the epidemic under control.

Of the four gain elements in this loop (which have to be multiplied together in order to calculate the open loop gain), three are to be found in the equation for the infection rate of HIV. They are the Mean Number of Different sexual Partners (MNDP) taken by each infected individual, the Probability of Infection Per Partner (PIPP) and the Susceptible Population Ratio (SPR) which is the proportion of the at-risk population still uninfected. The fourth gain element is simultaneously a delay constant; the average length of time that individuals remain infectious. This is synonymous with the length of time an individual is incubating the virus (save for a short latency period immediately following initial invasion of the virus) for which current estimates suggest 8 years (Medley, Anderson, Cox & Billard, 1988a).

In the early stages of infection the operation of loop 1 continues unchecked with initial open loop gain values probably in excess of 7.0 (in this model it is 8.4). Ultimately, however, the declining pool of susceptible individuals reduces SPR sufficiently below 1.0 to cause the intensity of the epidemic to abate. HIV incidence peaks and then declines as a consequence. Yet the task facing health educationists in the initial stage of the spread of the disease is starkly clear. If the incubation period of the virus is indeed 8 years, the values of MNDP and PIPP have, between them, to be reduced by a factor in excess of eight in order to bring the epidemic under control.

The flow diagram at figure 4.2 shows the various states or compartments which characterise the stages of the clinical evolution of the syndrome, leading ultimately to death once the invasion of the body's immune system by HIV is sufficient to compromise it to such an extent that the patient develops an opportunistic infection which proves to be incurable. Although flows such as recruits to the susceptible class and deaths from other causes (background mortality) could be explicitly included in the model, their absence derives from the difficulty of their specification. Published models which incorporate these flows have so far merely assigned them arbitrarily constant rates. Their inclusion is implicit of such models adopting a quasi-forecasting role which is not the intention here. Exploratory runs with recruitment and background mortality have demonstrated that the results obtained from the analyses reported below are not materially affected by the incorporation of such additional features.

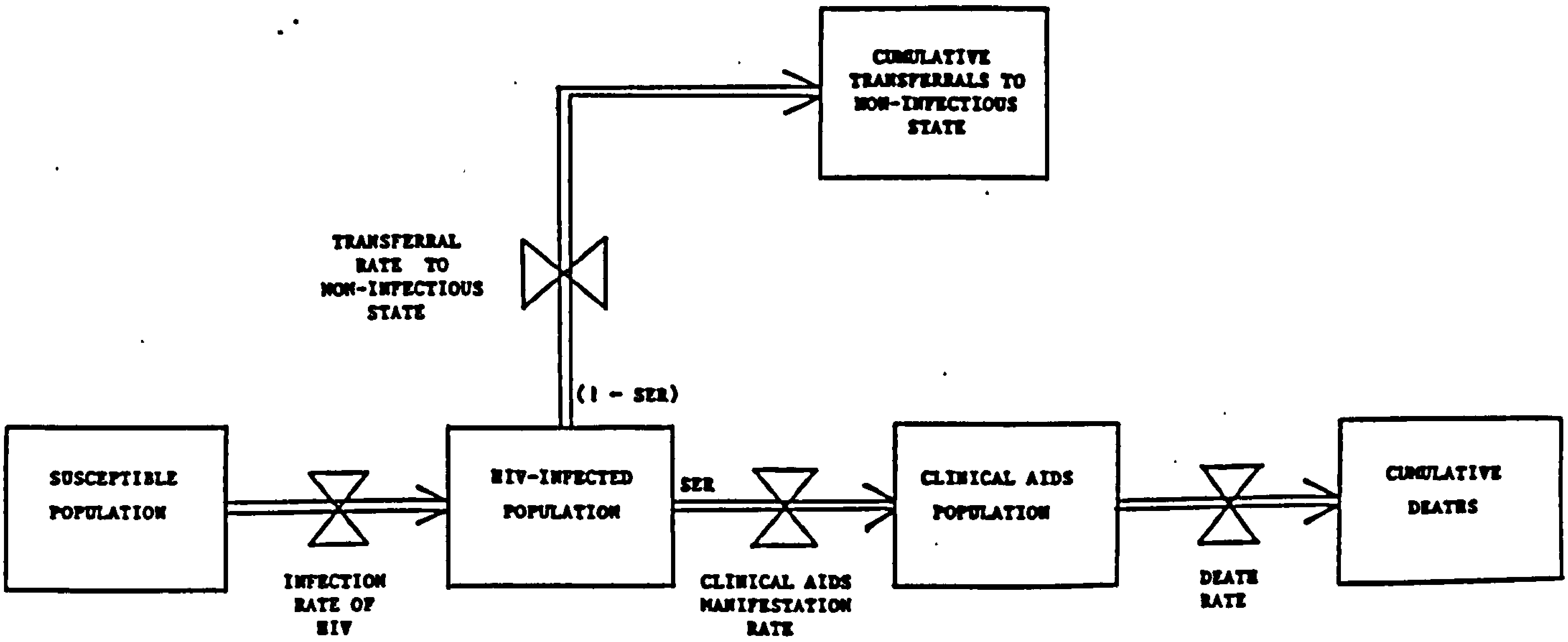

Figure 4.2 Flow diagram of the model

4.2.2 Varying parameter values

The split in the flows emerging from the HIV population in figure 4.2 is indicative of the possibility that not all people who become infected with the virus will ultimately exhibit symptoms conforming to the clinical definition of AIDS. The model incorporates a value of 0.7 for the parameter, named the Symptoms Emergence Ratio (SER), which handles this feature. This choice of value may well prove to be rather an underestimate, although variations in this parameter (as with any other) are easily handled and the resultant effects on the shape of the epidemic displayed.

The ability to examine easily the effects on the epidemic of changes in key parameter values is clearly critical since so much uncertainty presently surrounds their magnitudes (Anderson and May, 1988). Below is illustrated the effect on the clinical AIDS population of increasing the proportion of the HIV-infecteds contracting AIDS, beyond the value of 0.7 assumed in the base model. Later, in section 4.2.4, the effect of increasing the average survival time beyond one year is shown.

The proportion of the HIV-infecteds contracting AIDS is modelled by the Symptoms Emergence Ratio and figure 4.3 shows the effect on the clinical AIDS population of increasing SER from 0.7 to 1.0 in steps of 0.1 . The changes do not affect the timing of the peak of the epidemic but of course affect its relative size.

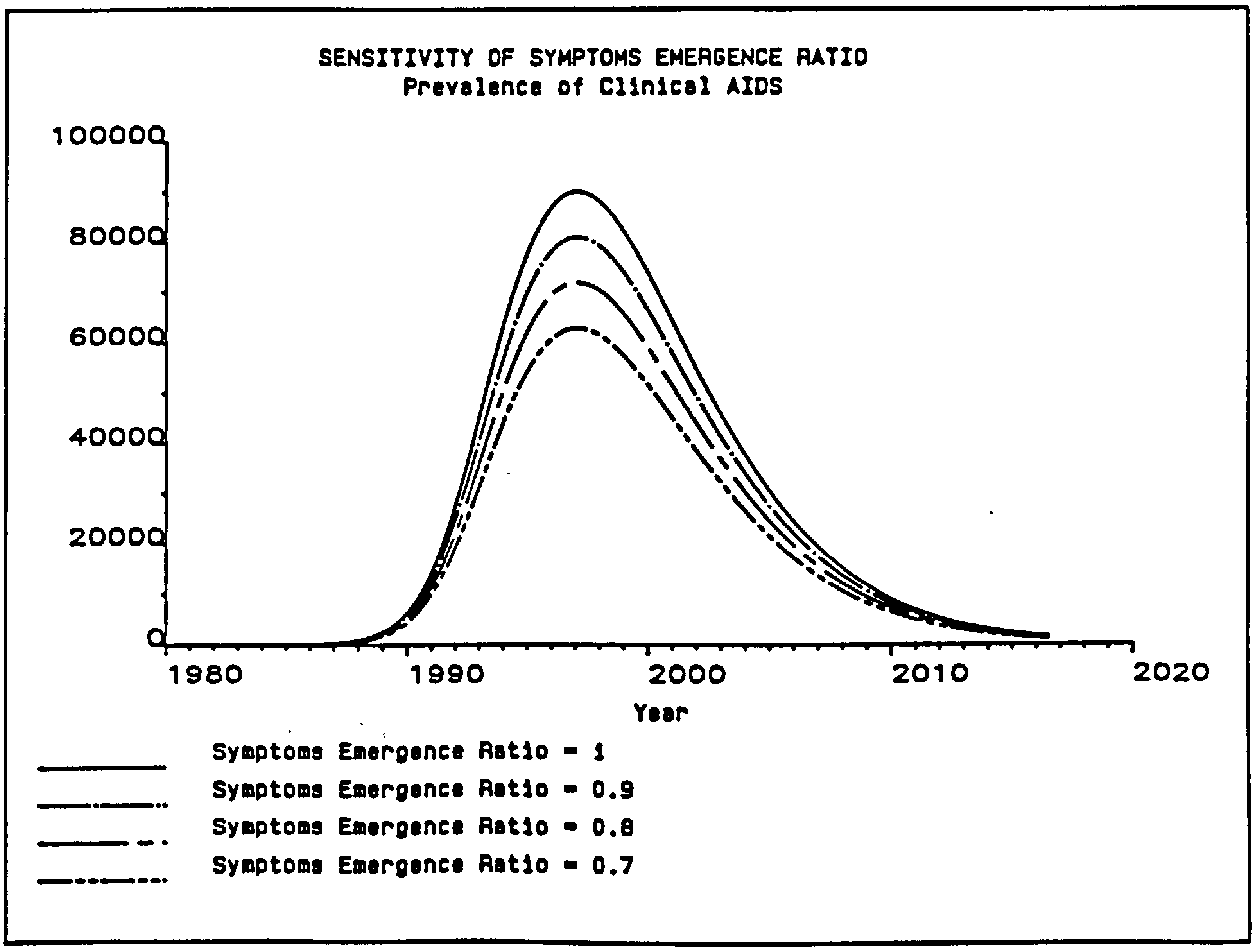

Figure 4.3 Effect of variations in the Symptoms Emergence Ratio on the prevalence of Clinical AIDS (Base model)

4.2.3 Infection Rate equation

The equation describing the rate of infection with HIV per unit time (IRHIV) "drives" the model and is set out below. New infections are assumed to be proportional to the number of HIV-infecteds, their average number of different sexual partners per year, the average probability of infection per sexual partner and the proportion of susceptible people in the at-risk population. The equation gives the total amount of susceptibles who become infected each simulated time step (1/16 th of a year), having regard to both the chances of them not being already infected and of the host actually passing the infection on. The absence of the variable describing those with clinical AIDS, the Clinical Aids Population (CAP), in the infection rate equation arises from the assumption made, in common with most other authors, that those with clinical symptoms of AIDS do not contribute to further infection.

```
IRHIV=HIVPOP*MNDP*SPR*PIPP
```

where

IRHIV = Infection Rate of HIV (persons per year)

HIVPOP= HIV POPulation (persons)

MNDP = Mean Number of Different Partners per year (persons per year per person)

SPR = Susceptible Population Ratio (dimensionless)

PIPP = Probability of Infection Per Partner (dimensionless)

The equation for SPR, the Susceptible Population Ratio, is

SPR=SP/(ETPAR-CCC)

where

SP = Susceptible Population (persons)

ETPAR = Estimated Total Population At Risk (persons)

CCC = Cumulative Clinical Cases (persons)

All model equations are required to balance dimensionally and this is automatically checked by the software employed.

Some models of AIDS epidemiology (Hyman and Stanley, 1988) incorporate not an average Probability of Infection Per Partner (PIPP) but instead employ a probability of infection per contact (sexual act). A consequence of this is that the estimated number of sexual acts per partner has also to be incorporated as a parameter. Our preference for the average probability of infection per partner derives from data analysed by Peterman et al (1988) which shows that there is very little correlation between the transmission of HIV to spouses of persons infected via blood transfusion and their frequency of sexual intercourse.

In order to determine reasonable values for MNDP, PIPP and the other important parameter, the Mean Incubation Period of the Virus (MIPV), it is necessary to utilise the results of both clinical and social survey data in addition to the time series data of reported cases of AIDS in the United Kingdom. None of these parameters have been measured with a high degree of confidence and the value of PIPP is the most uncertain. A formula for the doubling time (in years) of the spread of infection is derived by Anderson et al (1986). Using the notation adopted above:

$$t_d = (\ln 2)*MIPV/(PIPP*MNDP*MIPV-1)$$

Given that the doubling time in the data on cumulative cases has been (until quite recently) of the order of 9 months and the average incubation time for HIV is thought to be 8 years (Medley et al, 1988), this must mean that the product of PIPP and MNDP is just above 1.0 . A value for MNDP of 10.5 is incorporated following a major social survey conducted by the British Market Research Bureau (BMRB, 1987) on behalf of the government, with the purpose of evaluating the public education campaign on AIDS. In turn, this must mean that the average probability of infection ≃ 0.1, a figure within the range for this probability calculated by Grant et al (1987) using direct methods. Consequently 0.1 is the value employed in the homogeneous sexual mixing model, the results from which are described below.

It is interesting to note that the recently reported near doubling of the numbers of heterosexual cases of AIDS must, if the above formula is used, mean that the product of MNDP and PIPP is 0.8. There are those who consider that the value for PIPP for susceptibles engaging in heterosexual sexual practices with an infected partner is likely to be lower than for those engaging in homosexual practices and, if this assumption is correct, it must mean that there is a reasonable degree of heterogeneity in the number of sexual partners per unit time in the heterosexual population. A large scale survey of sexual behaviour in the UK, currently in the field, will hopefully shed some light on the extent of this heterogeneity. As an epidemiological concept, heterogeneity is discussed in section 4.3 below.

4.2.4 Incubation and Survival Distributions

The two probability distributions included in the model are now considered. Firstly, the incubation time distribution is examined. Subsequently, consideration is given to that for the survival time of a patient consequent on a diagnosis of clinical AIDS. The incubation time is defined as the time period from initial invasion of HIV until symptoms of an opportunistic infection, which allows a diagnosis of AIDS, are manifested. However, within this extremely long period of time there is a short latency period. Following a primary infection there is a period of some six weeks, on average, before an individual produces antibodies to HIV which can be detected by one of the standard tests now employed. The latency period prior to the point of seroconversion, as it is known, is not thought important enough to warrant specific inclusion in a model which simulates the progress of the epidemic over forty years. The model assumes, therefore, that infected people are capable of infecting others *immediately*, once they themselves have been exposed to HIV.

The incubation period - and in particular the mean incubation time - has a crucial effect on the course of the epidemic. It is, therefore, not surprising that considerable attention has been focussed on an appropriate probability distribution. The Centres for Disease Control in the U.S.A. have provided one of the most widely analysed data sets, specifically on transfusion-associated cases, which by the end of the first quarter of 1989 numbered some 1469 usable adult cases. The use of data on transfusion cases to fit an incubation distribution is not without its problems. There will always be a reason for giving someone a blood transfusion and it may well be that the underlying health of transfusion recipients is, on average, not as strong as that of a member of any of the major risk groups who are exposed to an inoculum of HIV. Further, and this applies to any data purporting to pinpoint the (historical) date of infection in an individual, it is not possible to retain 100% of the data sample because some transfusion infected people will die from other (unrelated) causes before they manifest symptoms of clinical AIDS.

The most intractable difficulty in dealing with the transfusion dataset is inescapable: the data are truncated. Observations from the right hand tail of the distribution are disproportionately low at present and it will be many years before enough data has been amassed to be absolutely sure of the values of the parameters and the appropriate probability distribution. Additional distortions to the data stem from the fact that in the U.S.A. blood used for tranfusion was routinely screened for traces of HIV as from March 1985 and, in the two years prior to that, donors had been withholding their normal offerings because of increasing knowledge about the threat of AIDS and its principal modes of transmission. Consequently, a much lower incidence of infective transfusions can be expected from persons with transfusion dates beyond the first quarter of 1985 and a declining incidence in the two years prior to that.

Statistical analyses have been conducted on the transfusion data by Medley et al (1987; 1988a; 1988b) and these have been parametric in character. They have explored both an exponential and a linear increase in the incidence of infective transfusions and used the resultant values, along with a postulated probability distribution, to calculate the expected numbers of AIDS diagnoses arising at various time points j which have emanated from initial infection at given base dates i, such that $i \leq j$. They take point (1,1) as January 1978 and produce a triangular matrix of observed and expected monthly values of AIDS incidence. The calculations derive from a log-likelihood model which is maximised so as to simultaneously determine the parameters of the equation for incidence of infective transfusions as well as the expected numbers of diagnoses.

Two probability distributions were evaluated: Weibull and Gamma. The former produced a mean value of 8.23 years in keeping with other estimates. The mean for the Gamma distribution was found to be very high at 27.2 years although a subsequent analysis by Anderson and Medley (1988) produced means of 7.66 years (Weibull) and 14.33 (Gamma). Because the Gamma distribution has a longer right-hand tail it should be expected, in cases where the data are right censored, to produce a higher mean than does the Weibull.

A graphical comparison between the three cumulative distribution functions, parameterised according to the results given by Medley et al, is shown at figure 4.4 along with the Erlang type 3 distribution (μ= 8 yr) which is the one employed in the model. The Erlang is a Gamma distribution with the value of the shape parameter an integer number greater than zero. Two of the plots are from the initial (1987) analysis -- Weibull and Gamma -- and one is from the Anderson and Medley (1988) analysis -- Gamma -- on the assumption that only the scale parameter has changed since the initial analysis. (The full details of the revised fitted distribution have not yet been published; only the latest figure for the mean has been revealed.) From the comparison it is clear that there is a reasonably close approximation between the cumulative distribution function for the Erlang type 3 and the Weibull posited by Medley et al.

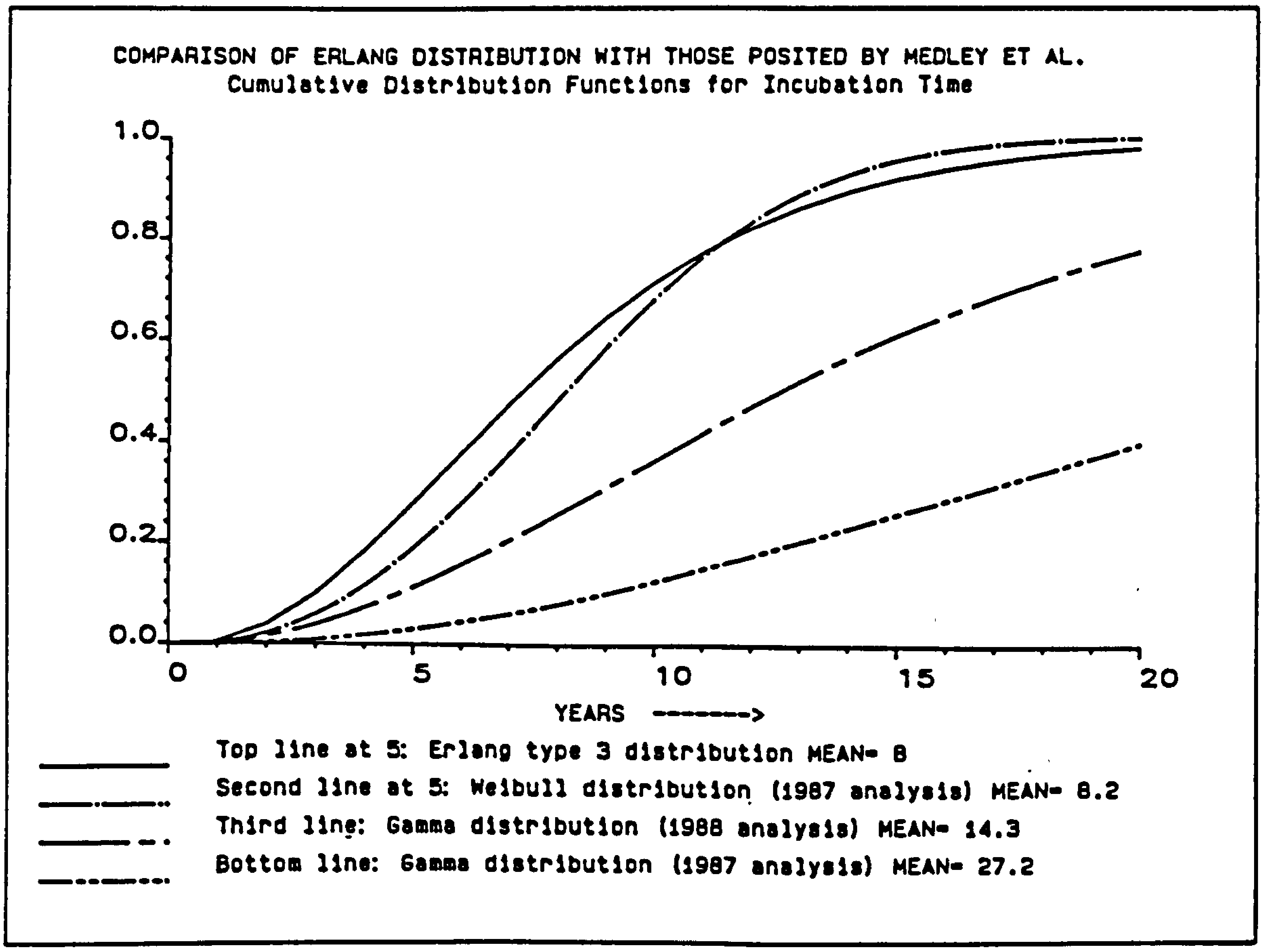

Figure 4.4 Comparison of the c.d.f's from analysis of the transfusion dataset by Medley et al with the Erlang used in the model

It would be extremely unwise, given the data presently available, to claim that either the Weibull or the Gamma (Erlang) distribution is appropriate to the exclusion of the other. Indeed, further investigation using the Lognormal or

Gompertz distributions may well prove to show an adequate fit to the available data.

Consideration of the type of distribution to employ is often related to its hazard function. This is formally defined as

$$h(x) = f(x)/(1-F(x)) \quad (\text{for } F(x) < 1)$$

where $f(x)$ and $F(x)$ are, respectively, the p.d.f. and c.d.f. of X and it is commonly used in survival analysis. In the present context it describes the fractional instantaneous rate of conversion to clinical AIDS for the remainder of a cohort who have been incubating HIV since a known common point in the past. One attraction of the Weibull distribution to the epidemiologists is that its hazard function is of a fairly simple mathematical form; it increases as some power of time. This, it is argued, is in line with the biological phenomenon of continuous and progressive compromise of the immune system characteristic of the development of AIDS.

The hazard function of the Erlang is mathematically more complicated than that of the Weibull which militates against its use in analytical studies. Nevertheless, for order 2 or above, it increases at a decreasing rate and so is not inappropriate for modelling progressive compromise of the immune system. Indeed, two authors who evaluated the effects on the epidemic of various candidates for the probability distribution of the incubation time conclude: "A low order Erlang distribution seems most likely to give a reasonably accurate approximation" (Blythe and Anderson, 1988a).

Figure 4.5 shows the Erlang type 3 distribution used in the model, together with its hazard function. The mean was set at 8 years in line with the findings referred to above. It is portrayed in a way which should aid understanding. It shows the rate of conversion to clinical AIDS of 100 individuals exposed to HIV infection at time t=0.

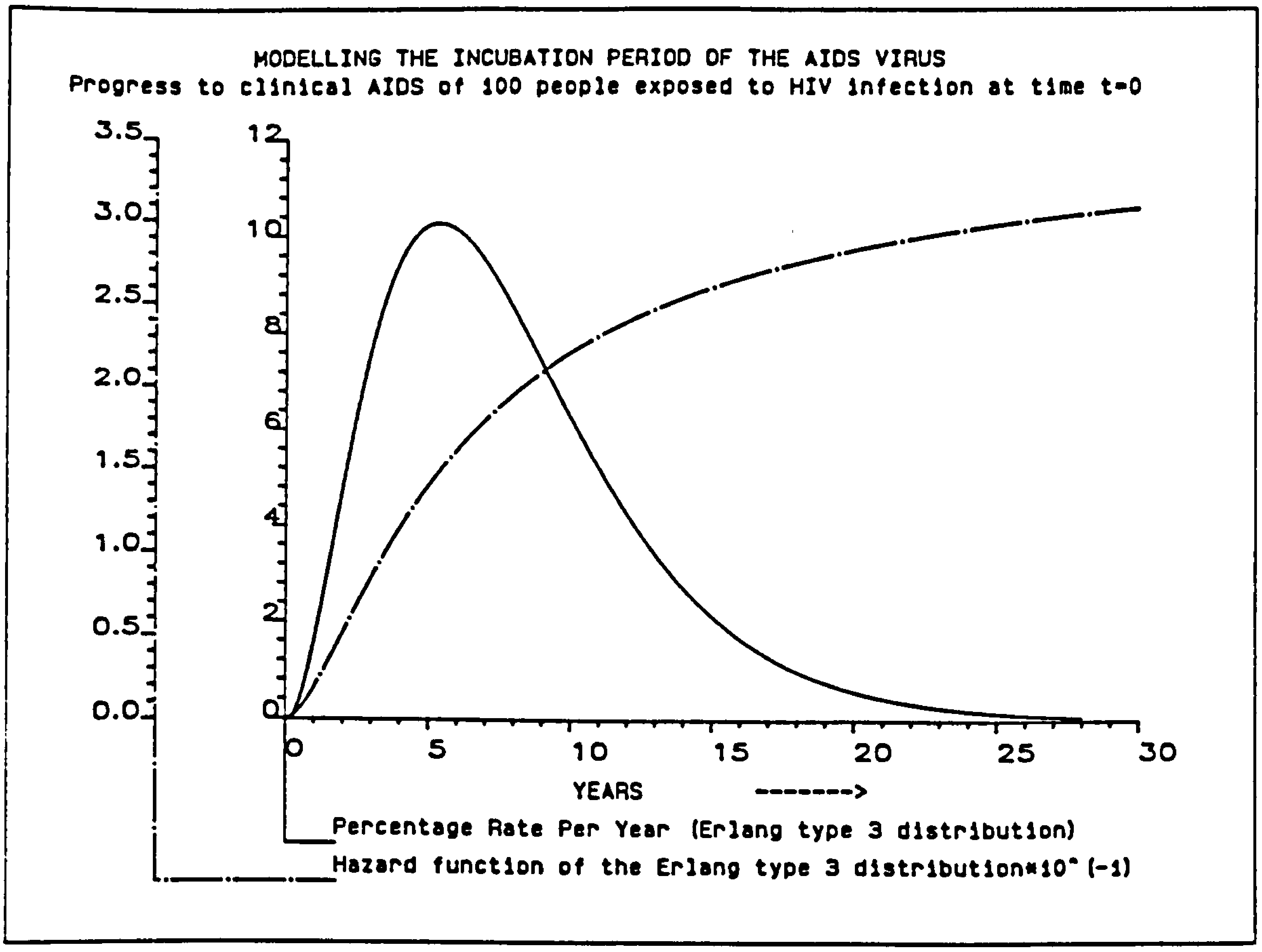

Figure 4.5 Incubation time of HIV for 100 people based on an Erlang type 3 distribution (μ=8 yr), together with its associated hazard function

The Erlang type 3 distribution, equivalent to a third order delay (DELAY3) in system dynamics models, should be familiar to operational researchers as it is commonly employed in queueing models to represent n-stage service processes where the time for each stage is taken to be a negative exponential distribution. In fact, an Erlang type 1 distribution is a negative exponential, so a third-order Erlang is merely the distribution achieved by cascading together three negative exponential distributions. There is intrinsic merit in employing the Erlang, arising from recent evidence (Pedersen et al, 1987; Burger et al, 1986) that the progression from initial HIV infection to clinical AIDS can be viewed as comprising three separate stages. Not one of the other distributions under consideration has the property that it can be disaggregated in this way.

Following on from the incubation distribution it is appropriate to consider the probability distribution of survival time. Studies in the U.K. of the survival time of patients after diagnosis of clinical AIDS have been carried out by Reeves and Overton (1988) and Reeves (1988). A two parameter exponential is proposed on the basis of analysis of the latest data

$$S(t) = 0.9198 \exp(-0.0669t)$$

where $S(t)$ is the probability of surviving $>t$ months.

This function reflects a positive probability of instantaneous deaths (zero survival time) for which $p = 0.0802$. Hence there is both a mean and a conditional mean survival time. The latter is 14.9 months; the overall mean is $(1-0.0802)/0.0669 =$ 13.7 months. In figure 4.6 is employed a negative exponential distribution of survival time (equivalent to a first order delay, DELAY1, in system dynamics) with a mean of 12 months which accords with the results from Reeves (1988) especially since some of the cases used in her analysis were administered zidovudine which can be expected to improve average survival time (Reeves, 1989). Under an assumption of a one year mean survival time, 35.6% survive for over 1 year, 12.7% survive over 2 years and 4.5% over 3 years.

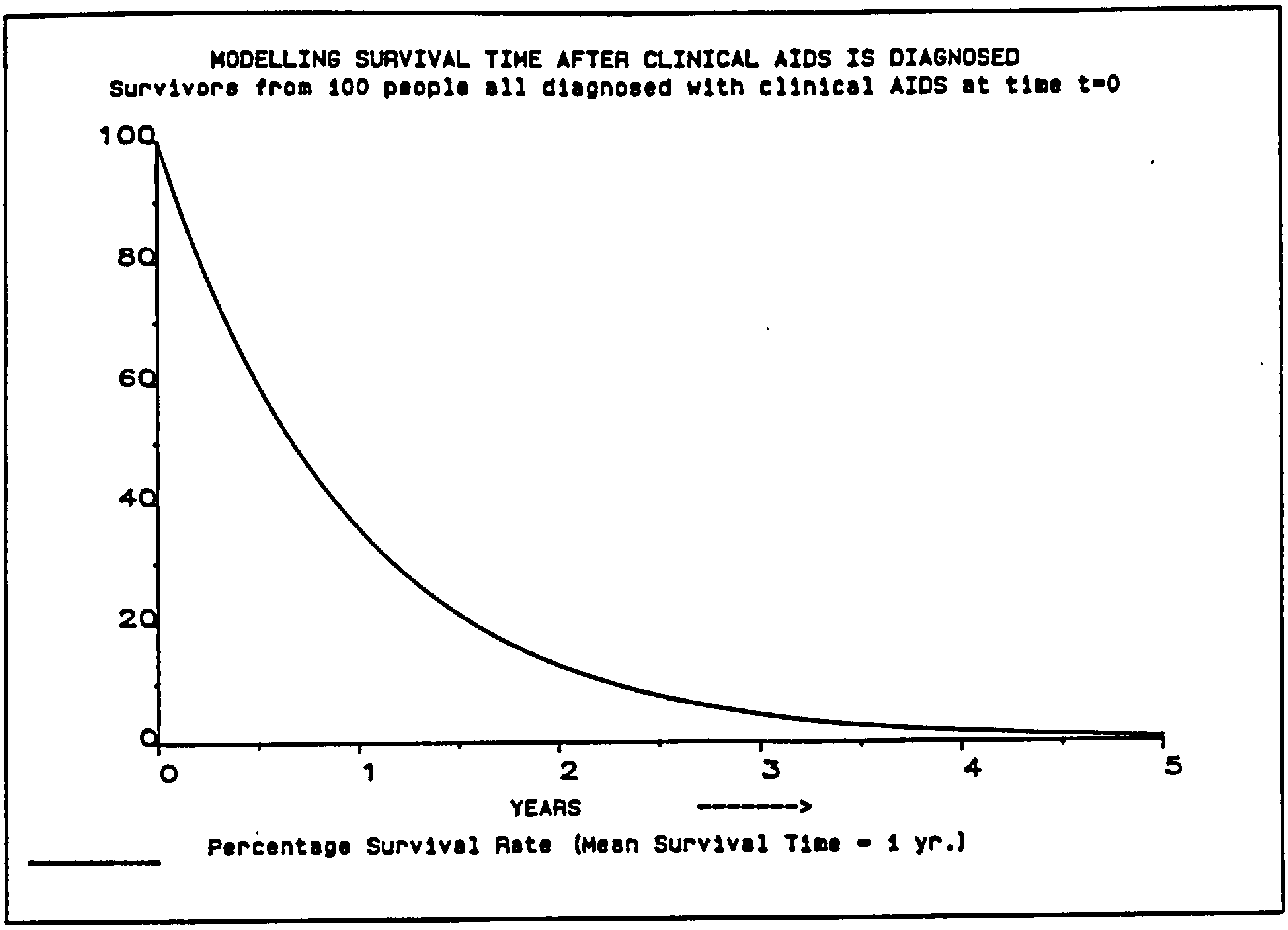

Figure 4.6 Assumed distribution of survival time: mean = 1 yr.

The consequence of administering drugs like zidovudine is to increase the average survival time and the simulated outcome, using the base model, for the Clinical Aids Population (CAP) is shown in figure 4.7 for various hypothetical increases in this average beyond the value of one year. Clearly the widespread administration of drugs like zidovudine in anti-viral therapy has potentially important implications for bed occupancy and hospital/community care resources for AIDS patients generally. Those responsible for making these resources available would be ill-advised to ignore such implications.

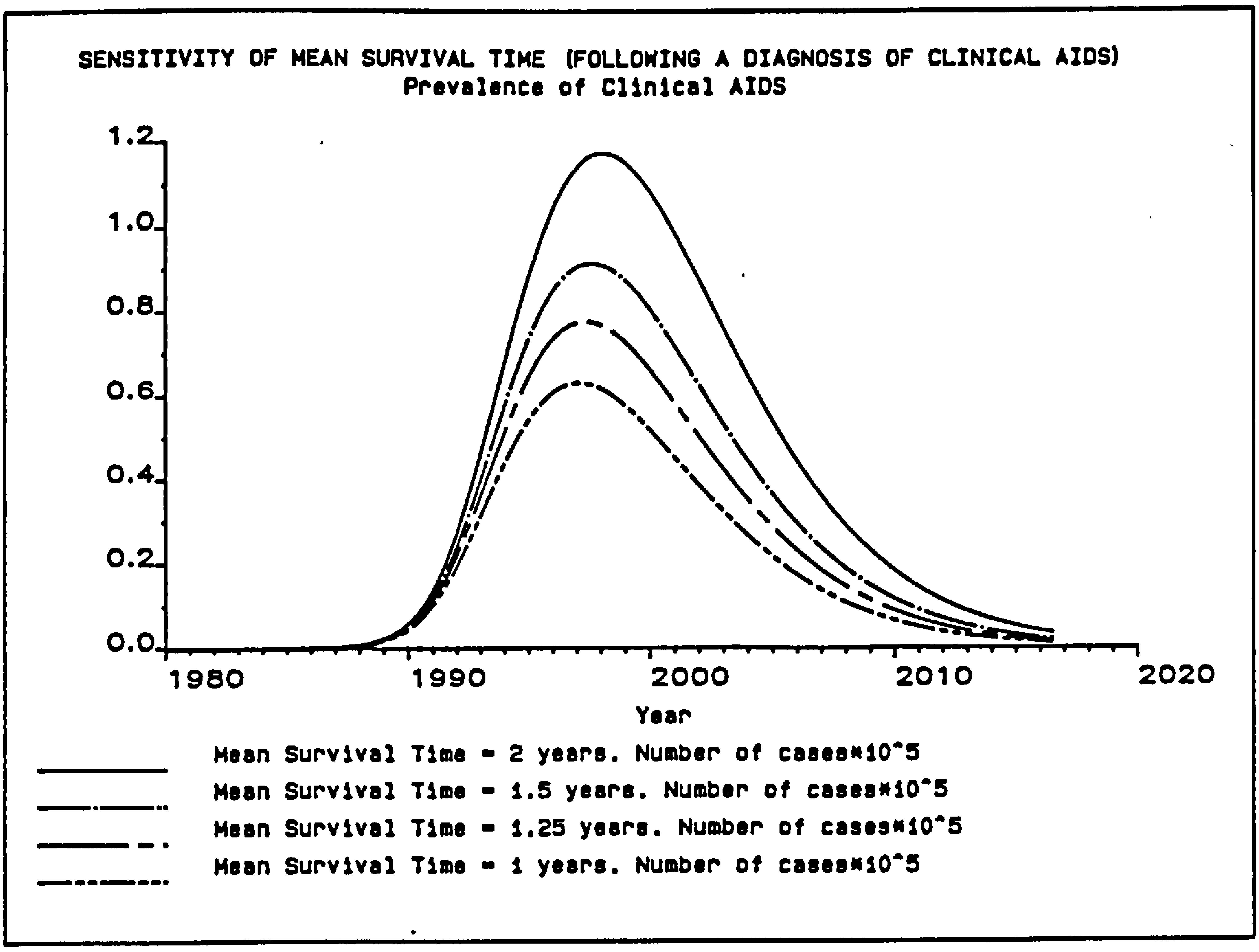

Figure 4.7 Effect of increasing survival time on the Clinical AIDS Population (Base model)

4.3 Base model scenarios concerning anti-viral therapy

The effects of two possible interventions based on anti-viral therapy are now explored: a vaccine for seronegative members of the at-risk population; and a drug to reduce infectivity for seropositive members of the at-risk population. It would seem possible that a drug to reduce infectivity may be produced earlier than a vaccine (Hall, 1987).

Figure 4.8 shows the effect of one realisation of these two possible interventions — a vaccine introduced in 1992, possibly an optimistic eventuality, and a drug to reduce infectivity by 50% introduced in 1990. There are obvious difficulties — both practical and ethical — in identifying the qualifying recipients of either a vaccine or a drug to reduce infectivity. Hence this simulation, which assumes all qualifying members are identified, produces an optimistic scenario of the impact of either intervention. Further explorations with the vaccine option have shown that there will come a point in time when a vaccine will be too late to affect the size of the epidemic in the homosexual population.

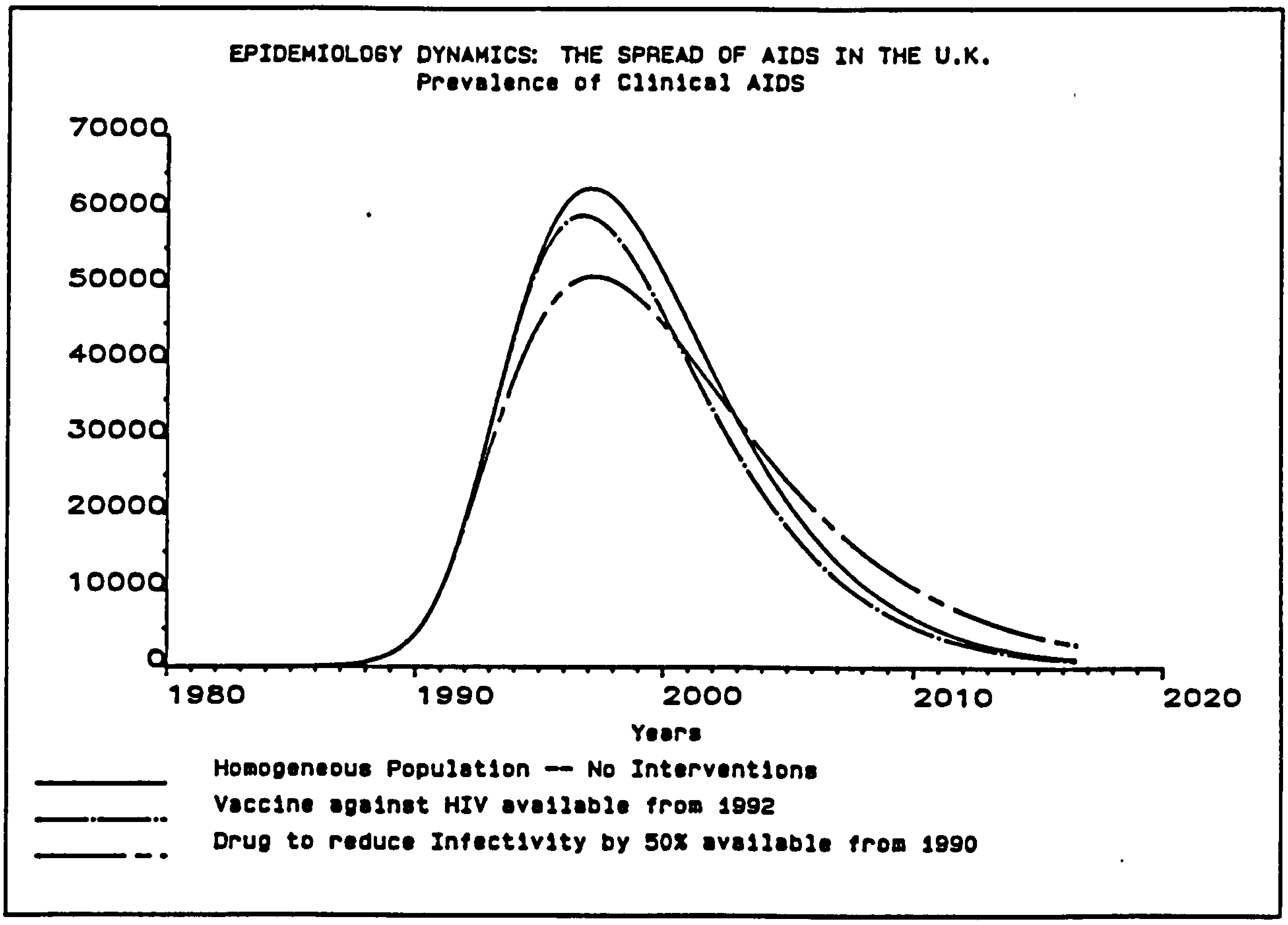

Figure 4.8 Scenarios showing the effect of two possible anti-viral therapies (Base model)

4.4 Heterogeneity in Sexual Mixing

Published data on the frequency distribution of claimed partner change rates by male homosexuals are consistent in reporting a large variance usually very much larger than the mean. This is the case with data from both sides of the Atlantic. It is clear that this risk group has a much higher frequency of partner change than does the young sexually active heterosexual risk group. Taken together with the adoption of very high risk sexual practices (such as unprotected anal intercourse) which increase the probability of viral transmission, this explains the initial preponderance of AIDS cases in the male homosexual risk group.

Winkelstein et al (1987) reported an average of 10.8 partners per year in 1984 from his study of homosexual/bisexual men in San Francisco. However, 27% claimed to have had more than 10 partners per year. This non-uniformity of partner change is further supported by evidence from the survey undertaken by the British Market Research Bureau for the government (BMRB, 1987). This survey revealed from the results at the first wave of interviews (February 1986) that, while a total of 27% of the sample claimed 0, 1 or 2 different sexual partners in the past year, 15% claimed in excess of 11 (including 6 respondents in the 41-50 category and 2 in the 51-75 category).

It is clear, therefore, that any credible model of the spread of AIDS within the U.K. homosexual population should incorporate this heterogeneity in sexual mixing. In such models one factor influencing the force of the infection is what is termed the *'effective'* mean number of contacts. This is defined as the mean + (variance/mean) and it is necessary in order to properly account for the right-hand tail of the overall sexual activity distribution (May and Anderson, 1987). In the homogeneous mixing model the variance is zero and hence the effective mean is simply the mean itself.

Heterogeneity is incorporated into the model by disaggregating the susceptible population into separate strata each with their own mean number of different partners. This has been done to, as far as possible, mirror the variance in the data reported by BMRB which cannot, of itself, be calculated because of the way the data is presented. This separation is such that interaction between members of the different strata can take place. Mixing is programmed to happen in proportion to the product of the size of the group and its number of potential sexual partners per year (proportionate mixing).

The crude disaggregation of the at risk cohort of one million homosexual males was done such that 30% had 1 partner yr^{-1}, 50% 6 different partners yr^{-1} and 20% 36 different partners yr^{-1}. The overall mean was 10.5 partners yr^{-1}, in accordance with the overall sample average (at wave 1 of four 'waves' of interviews) reported in the BMRB survey, and the variance was 167.25 giving a variance to mean ratio of 15.9 . For epidemiological purposes, this split gives an effective mean of 26.4 .

In this enhanced model in order to properly contain the product of the Mean Number of Different Partners (MNDP) and the Probability of Infection Per Partner (PIPP) (multiplied together in the infection rate equation) to a value of 1.0, a revised value of 0.04 was substituted for PIPP. Retaining PIPP at 0.1 causes a very rapid take off of the epidemic, totally inconsistent with the currently available time series data. In this way the model has reinforced the view that the maximum value of the product of the effective MNDP and PIPP cannot be much above 1.0 .

4.5 Sensitivity tests on the incubation time distribution

Having introduced the concept of heterogeneity it is worth returning to the incubation time distribution. As already noted, this is an important component of any model of AIDS epidemiology. Results of sensitivity tests performed on the incubation time distribution are reported, restricting consideration to the more complex heterogeneous mixing model only. A change in the particular distribution employed is considered and, in addition, the effects of variations in its first two moments are assessed.

Figure 4.9 below shows a comparison of the Clinical AIDS Manifestation Rate (incidence of AIDS) resulting from a negative exponential distribution of incubation time (DELAY1) and an Erlang type 3 distribution (DELAY3). The two density functions involved are shown in figure 4.10 and are quite dissimilar, as are the respective hazard functions (not shown). With the negative exponential the hazard function is constant and for the Erlang type 3 it is increasing at a decreasing rate.

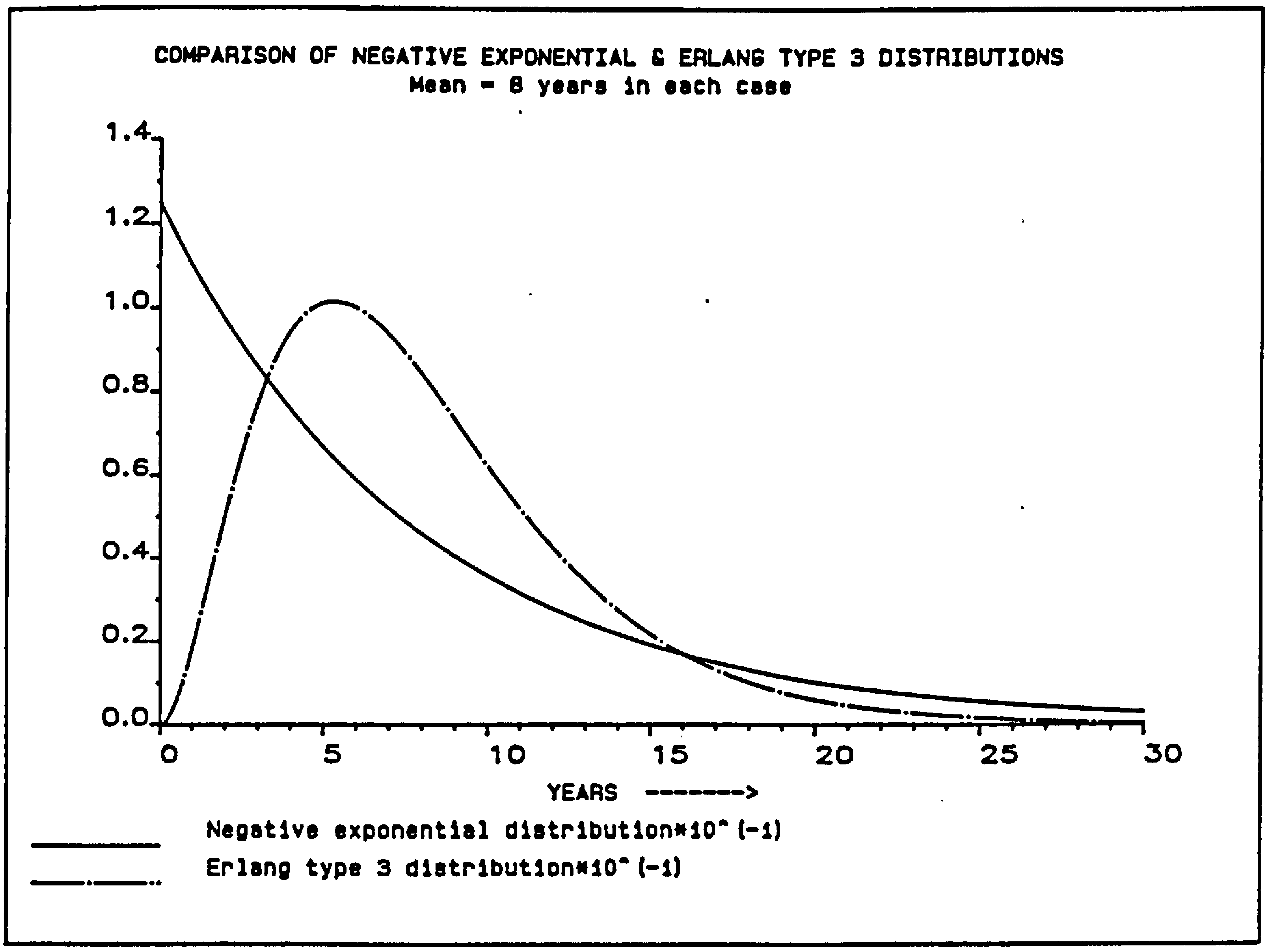

Figure 4.9 Density functions for Exponential & Erlang distributions

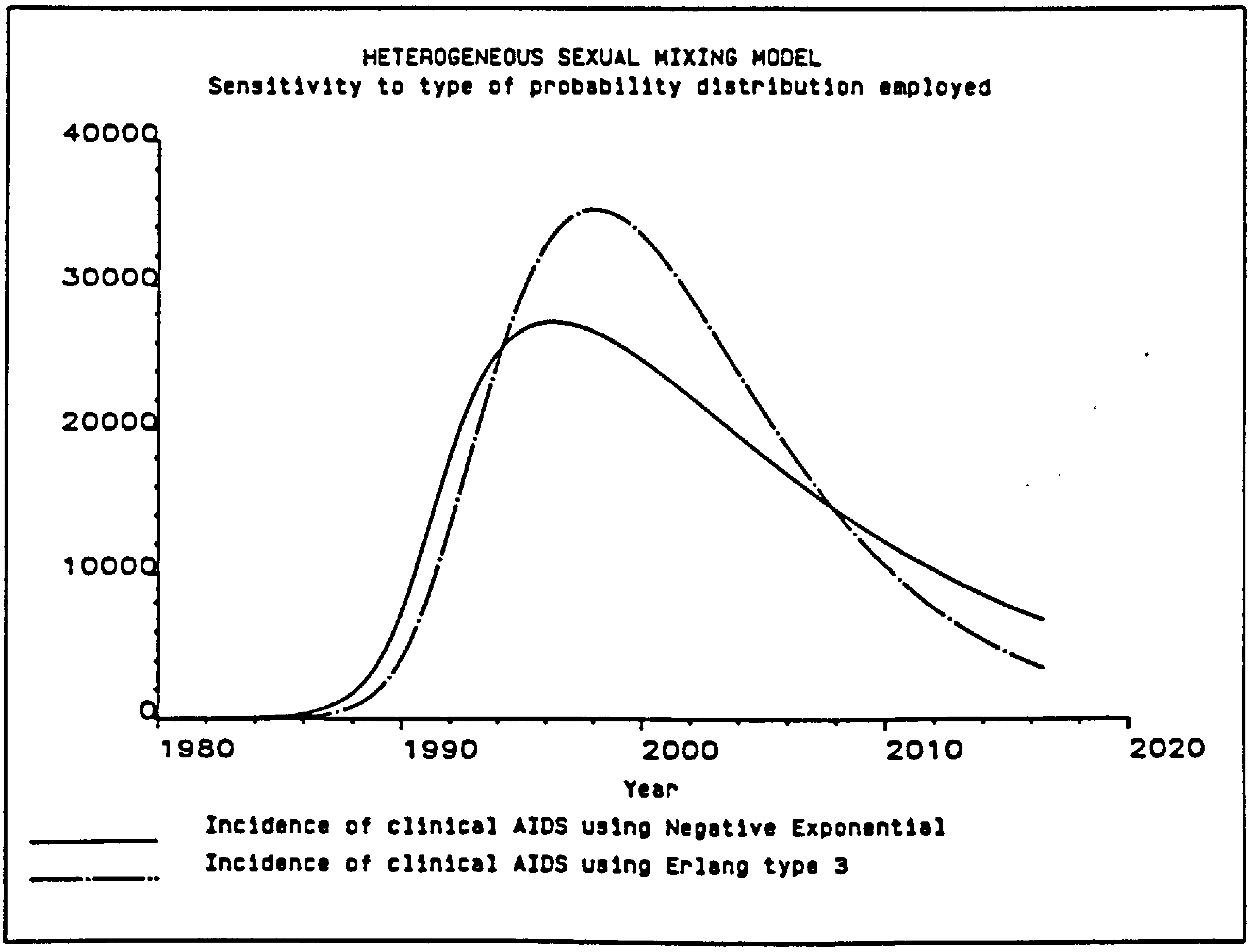

Figure 4.10 Incidence of new AIDS cases arising from the two chosen distributions

What is clear from the output graph is that the Erlang distribution produces an epidemic which is more clustered around the period of peak incidence in 1998. With the negative exponential distribution used for the incubation time the epidemic takes off more quickly but after reaching a peak its decline is noticeably slower than with the Erlang.

Although an Erlang type 3 distribution with a mean of 8 years has been employed in the model, it may well turn out that the mean incubation time is significantly different from this figure. Already a study using estimated seroconversion data from homosexuals in San Francisco has reported a mean nearer 11 years (Bacchetti and Moss, 1989). Since the DYSMAP2 software (Dangerfield and Vapenikova, 1987) easily allows changes in the mean incubation time, it is possible to readily see the effects of such a change on the course of the epidemic. Figure 4.11 depicts the results from variations in the mean value for the incubation time. The incidence of new AIDS cases is plotted for four different mean incubation times. As can readily be seen, the smaller is the mean the more severe but less prolonged is the epidemic. This is because those infected are progressing to AIDS more quickly. They are therefore around for a shorter period and hence are infecting fewer susceptibles.

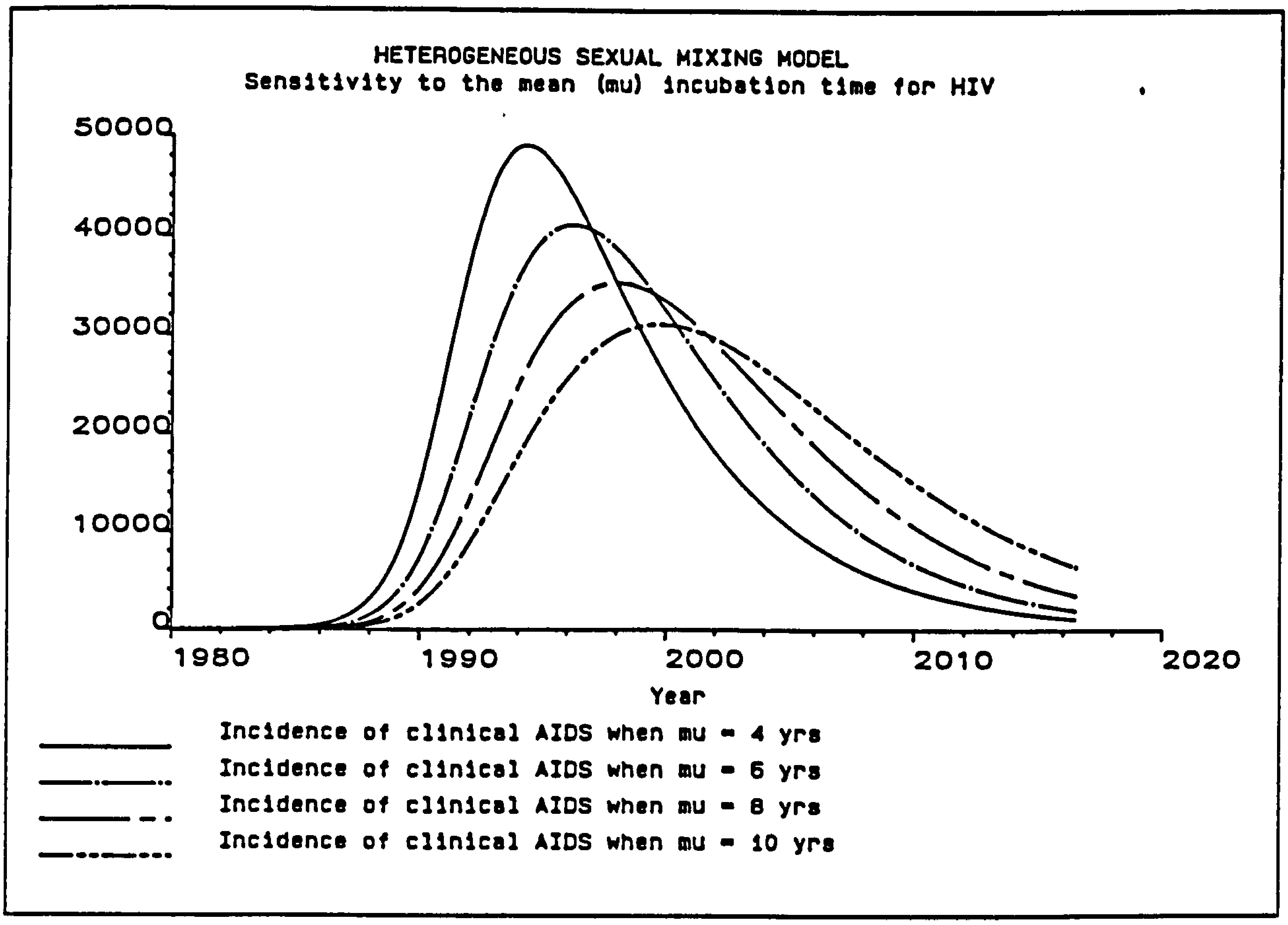

Figure 4.11 Sensitivity of incidence of new AIDS cases to variations in the mean incubation time (Erlang type 3 distribution)

As a further addition to the sensitivity testing, Table 4.1 indicates specific cumulative percentages for conversion to clinical AIDS for incubation times of 8, 9 and 11 years when using an Erlang type 3 distribution. (The percentages are of the proportion of infecteds who eventually progress to clinical AIDS.) On the basis of current evidence it would seem more likely that the mean incubation time might turn out to be greater than 8 years rather than less.

Mean incubation period (Years)	Cumulative Percentage converting to clinical AIDS after (Years)									
	1	2	4	6	7	8	9	10	12	15
8	0.6	4.0	19.0	38.9	48.6	57.6	65.4	72.2	82.6	91.9
9	0.5	3.0	14.9	32.2	41.1	49.7	57.6	64.6	76.1	87.5
11	0.3	1.8	9.7	22.5	29.8	37.1	44.3	51.2	63.4	77.4

Table 4.1 Cumulative percentage converting to clinical AIDS for three different mean incubation periods (Erlang type 3 distribution)

Finally, whilst discussing the ease with which sensitivity tests on the mean can be accomplished, it is also the case that experiments can be carried out which explore alterations in the variance. The variance of an Erlang distribution is related to its mean by

$$\sigma^2 = \mu^2/c$$

where μ = the overall mean

and c = the order of the distribution (shape parameter)

Hence changes in the variance for a fixed mean can be obtained by changing c. Thus with a mean of 8 years by rerunning the model using 3rd, 6th and 9th order delays (equivalent to Erlang type 3, 6 and 9 distributions respectively) it is possible to alter the variance from 21.3 to 10.67 to 7.1 . Figure 4.12 shows the effects of these changes in the variance.

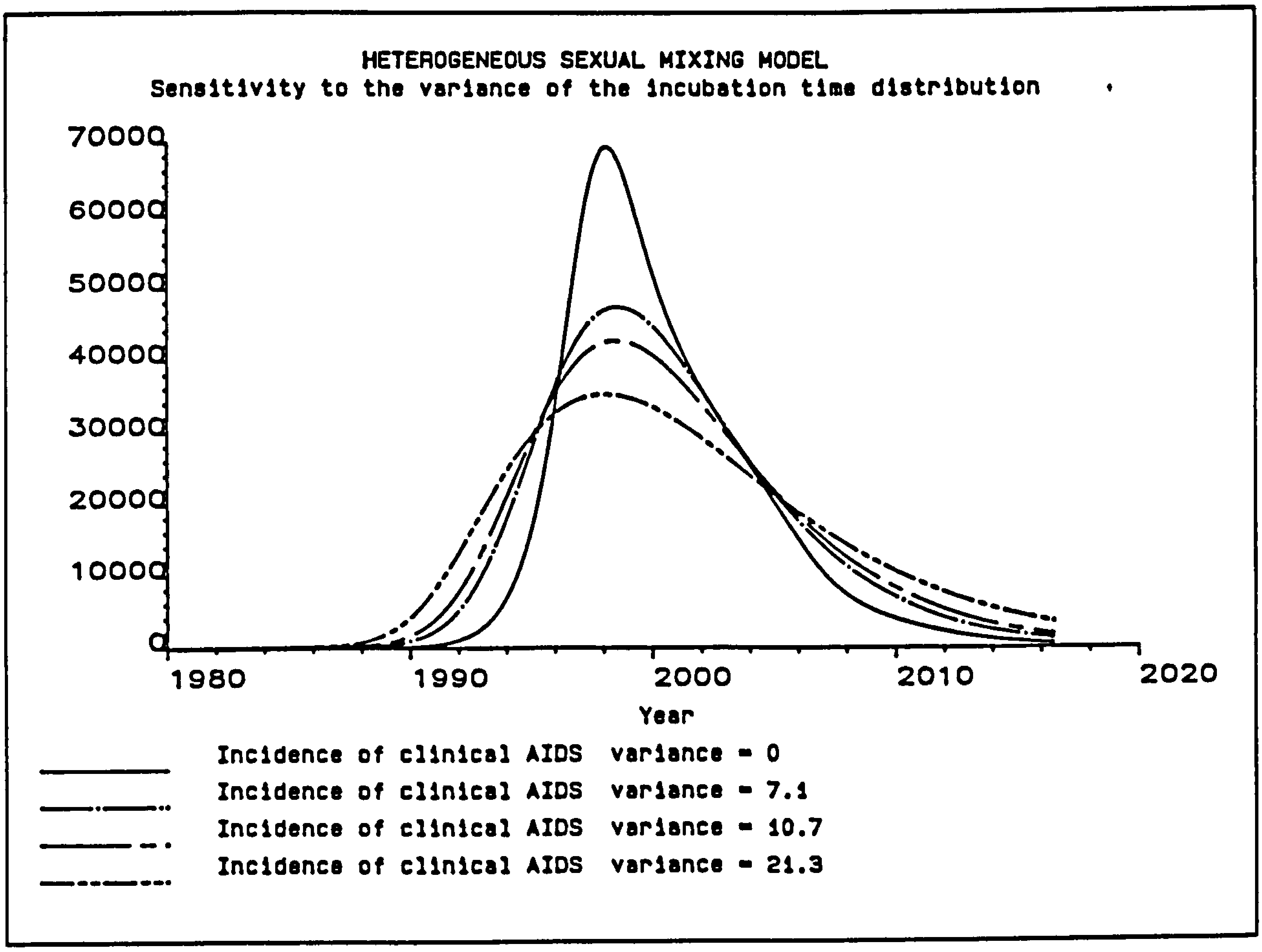

Figure 4.12 Sensitivity of incidence of new AIDS cases to changes in the variance of the incubation time distribution (Erlang)

It can be seen that the smaller is the variance the higher and later is the peak of the epidemic. Also shown on the graph is the result of an infinite order delay (pipeline delay). This produces a variance of zero and so merely shifts the HIV incidence curve (not shown) 8 years to the right. At least one early model of AIDS spread incorporated a fixed incubation time for all infecteds (Pickering et al, 1986).

4.6 Structural results from the models

Some important structural results from the models are now examined, beginning with the effects of heterogeneity in sexual mixing on the course of the epidemic. Figure 4.13 shows a comparison plot (co-plot) where the graphs on the plot, reading from the top, show the prevalence of clinical AIDS for, repectively, the homogeneous and heterogeneous profiles of the sexually active population.

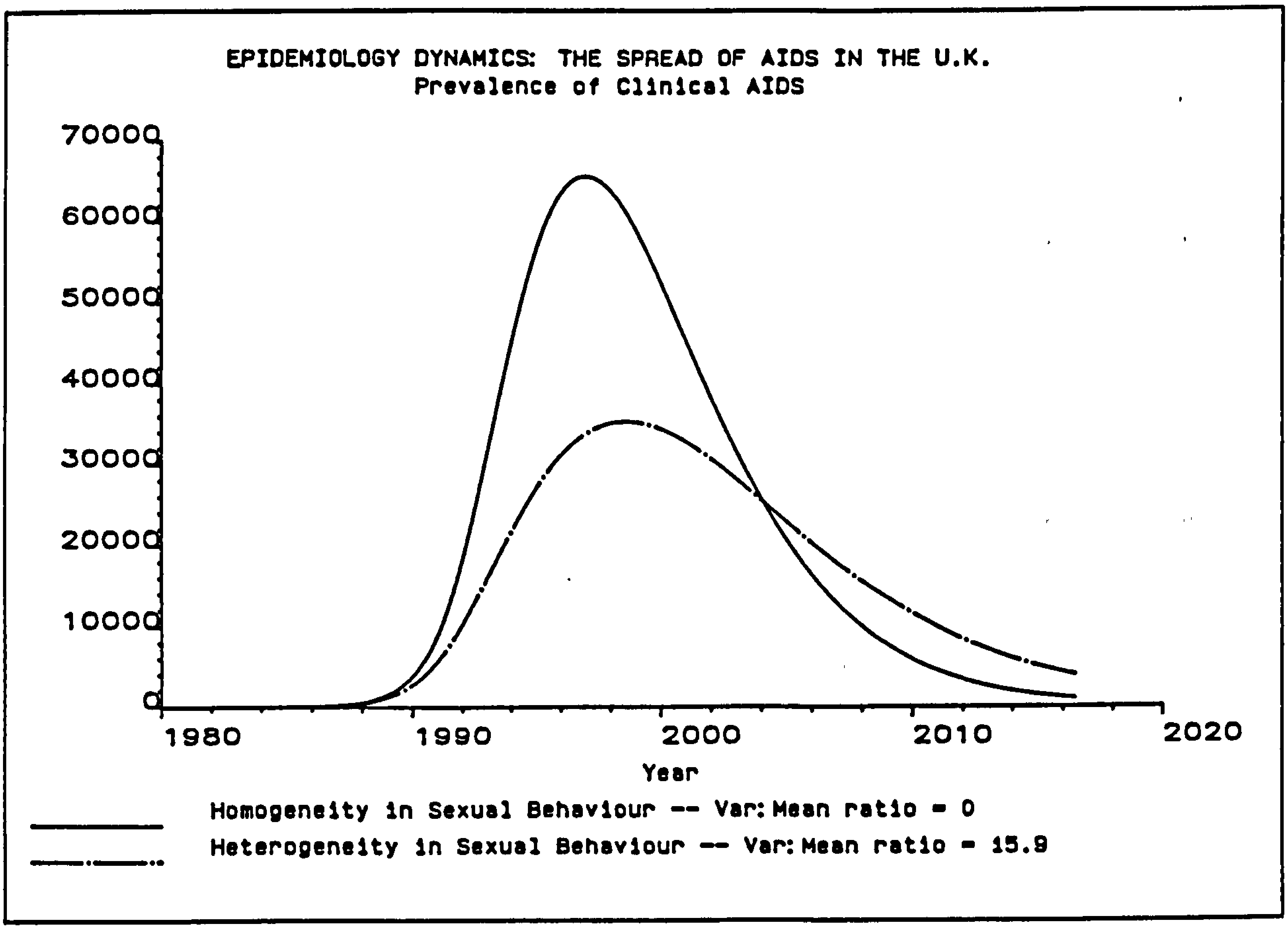

Figure 4.13 AIDS prevalence arising from the homogeneous and heterogeneous sexual mixing models

The effect of heterogeneity in the number of sexual partners is clearly encouraging for those who have to tackle the consequences of this epidemic. Peak prevalence of the disease is delayed by some three years and the overall intensity of the epidemic is lessened. Although not shown, the proportion ultimately infected falls from 100% down to 76%. As noted elsewhere (May and Anderson, 1987) these results are the consequence of the more sexually active individuals being removed from the system relatively quickly and thereby not contributing to the spread of the disease. The greater the degree of heterogeneity in the susceptible population the less severe is the overall epidemic.

Figure 4.14 below gives an insight into the effects of heterogeneity by showing the spread of the infection across all three sexual strata. The epidemic is initiated half way through 1976 (which gives a good fit to known AIDS cases up to end-1988) by introducing one infected individual into the most active sexual class (stratum 3). Because of the mixing between classes the infection is eventually spread across all the sexual activity groups, although the least sexually active group takes seven years longer than the most active group to reach peak incidence of AIDS. Also, the highly active group are responsible for the greatest incidence of AIDS cases only up until 1994 after which point the moderately active group take over and then remain the largest contributor for the rest of the simulation.

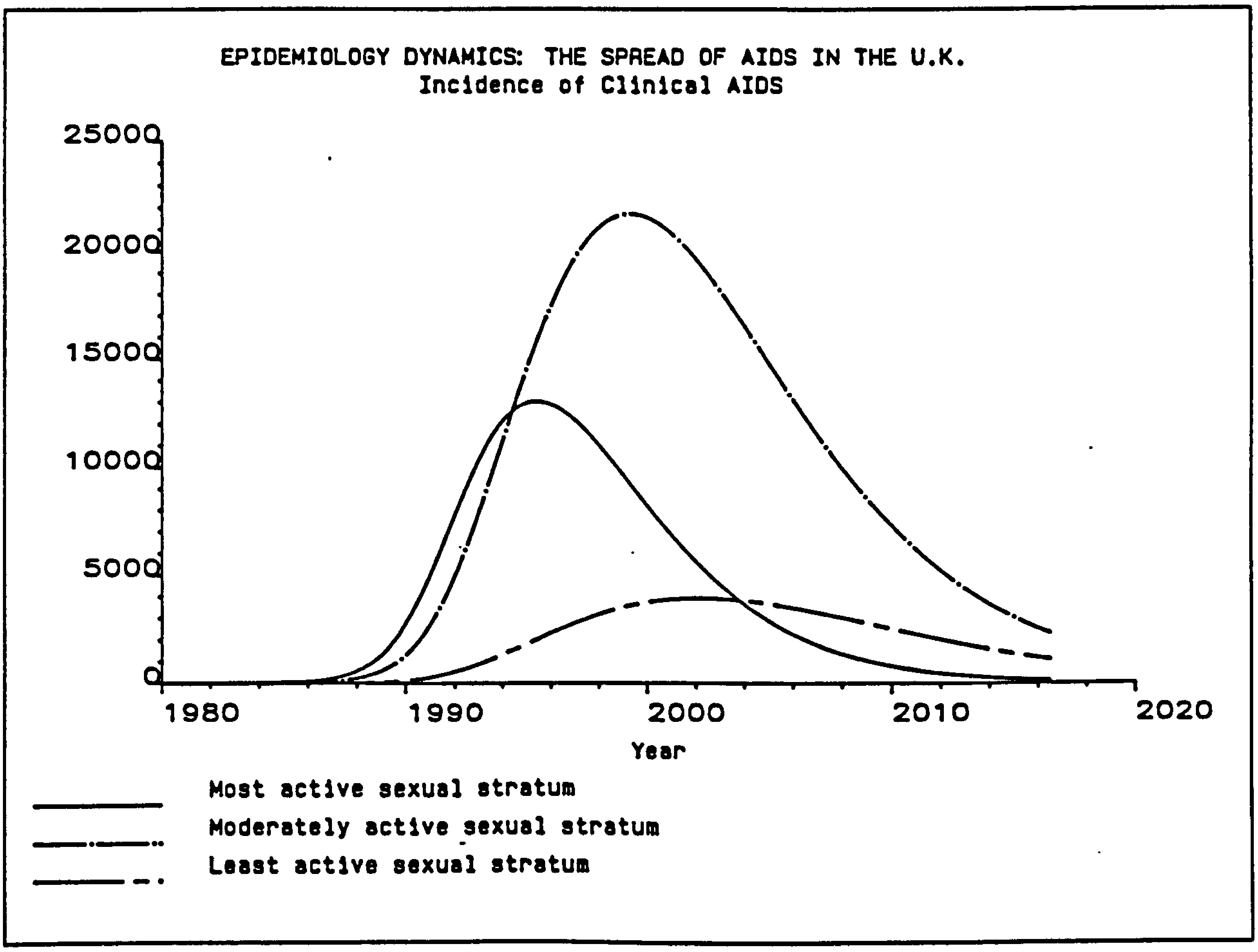

Figure 4.14 AIDS incidence in the three sexual strata of the heterogeneous mixing model

It is clear from the BMRB survey and other subsequent studies

(Evans et al, 1989; van Griensven, 1989) that the male homosexual population has undergone a significant change in sexual behaviour, clearly in response to the effects of the epidemic. For instance, the BMRB survey disclosed that, over the period February 1986 to February 1987, the average number of sexual partners per year taken by a sample of male homosexuals had fallen, over the four 'waves' of interviews, as follows: 10.49, 8.7, 7.1 and 4.8 .

Assuming this trend reflects changes in the whole of the male homosexual population, this data was incorporated by allowing the Mean Number of Different Partners (MNDP) to vary, tracking as closely as possible the reported trend from February 1986 and then remaining at 4.8 new partners annually from early in 1987. (There may, of course, be further reductions after this point.) The variance of the data consequently diminished over the period involved with the variance to mean ratio falling from 15.9 at wave 1 to 6.5 at wave 4. Figure 4.15 shows a co-plot from a run which superimposes this changing behaviour onto the heterogeneous sexual mixing model.

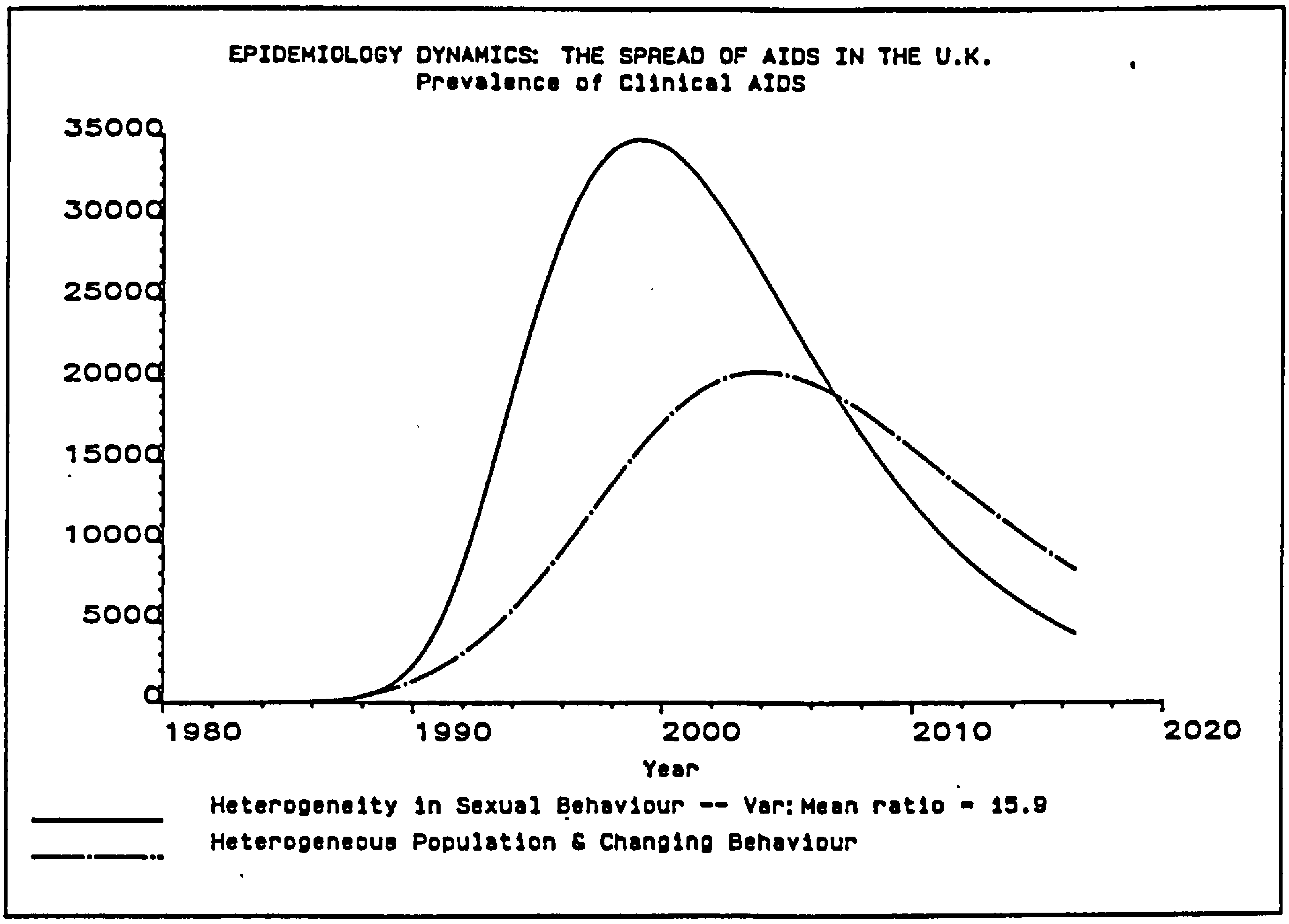

Figure 4.15 Projection of the effects of changing sexual behaviour reported in the government sponsored BMRB survey

The incorporation of changing behaviour has startling effects. The peak prevalence of the disease is pushed towards the middle of the first decade after the millenium and the proportion ultimately infected falls to 57%. Such a result confirms the sense of the message conveyed by many authorities about the need for at-risk individuals to voluntarily control the type and frequency of those sexual practices which clearly contribute towards the spread of HIV infection.

The data on changing behaviour were obtained from four waves of interviews in gay bars and incorporated sample sizes the lowest and highest of which were 156 (at wave 1) and 298 (at wave 2), respectively. Coxon (1986) questions the reliability of attempting to elicit from male homosexuals their number of different partners, citing, from his own studies, discrepancies between estimates given by respondents and sexual diaries which they were required to submit at periodic intervals. He is particularly sceptical of data obtained from attendees at clinics who have been presented with pre-supplied intervals for the estimated number of partners. Whether the data from the government sponsored survey are reliable remains to be seen, but at the present time they are the most comprehensive available and the inquiry does possess the merit that respondents were questioned at their normal social haunts and not in a clinical situation.

One interesting factor which might confound the observed changed behaviour by male homosexuals is that, in a system of heterogeneous mixing, the overall mean number of different partners will, over time, fall anyway. This arises from the fact that the stratum with the most rapid frequency of partner change is lost from the system most quickly, leaving the remainder who will have a lower overall mean number of different partners. In the model the equations below capture this particular situation.

$$\mathrm{OMNDP} = \mathrm{TSHIVA}/\sum(\mathrm{ETPAR}_i-\mathrm{CCC}_i)$$

$$\mathrm{TSHIVA} = \sum(\mathrm{ETPAR}_i-\mathrm{CCC}_i)*\mathrm{MNDP}_i$$

where

OMNDP = Overall Mean Number of Different Partners

TSHIVA = Total Susceptible and HIV Activity

ETPAR = Estimated Total Population At Risk

CCC = Cumulative Clinical Cases

MNDP = Mean Number of Different Partners

However, figure 4.16 clearly shows that there is no danger of this phenomenon confounding the results from the BMRB survey because the changing behaviour occurs well in advance of 'natural' changes happening in the system. In figure 4.16 the plot from the homogeneous mixing model is also shown for comparison. Obviously with homogeneous mixing the effective mean number of different partners remains a constant.

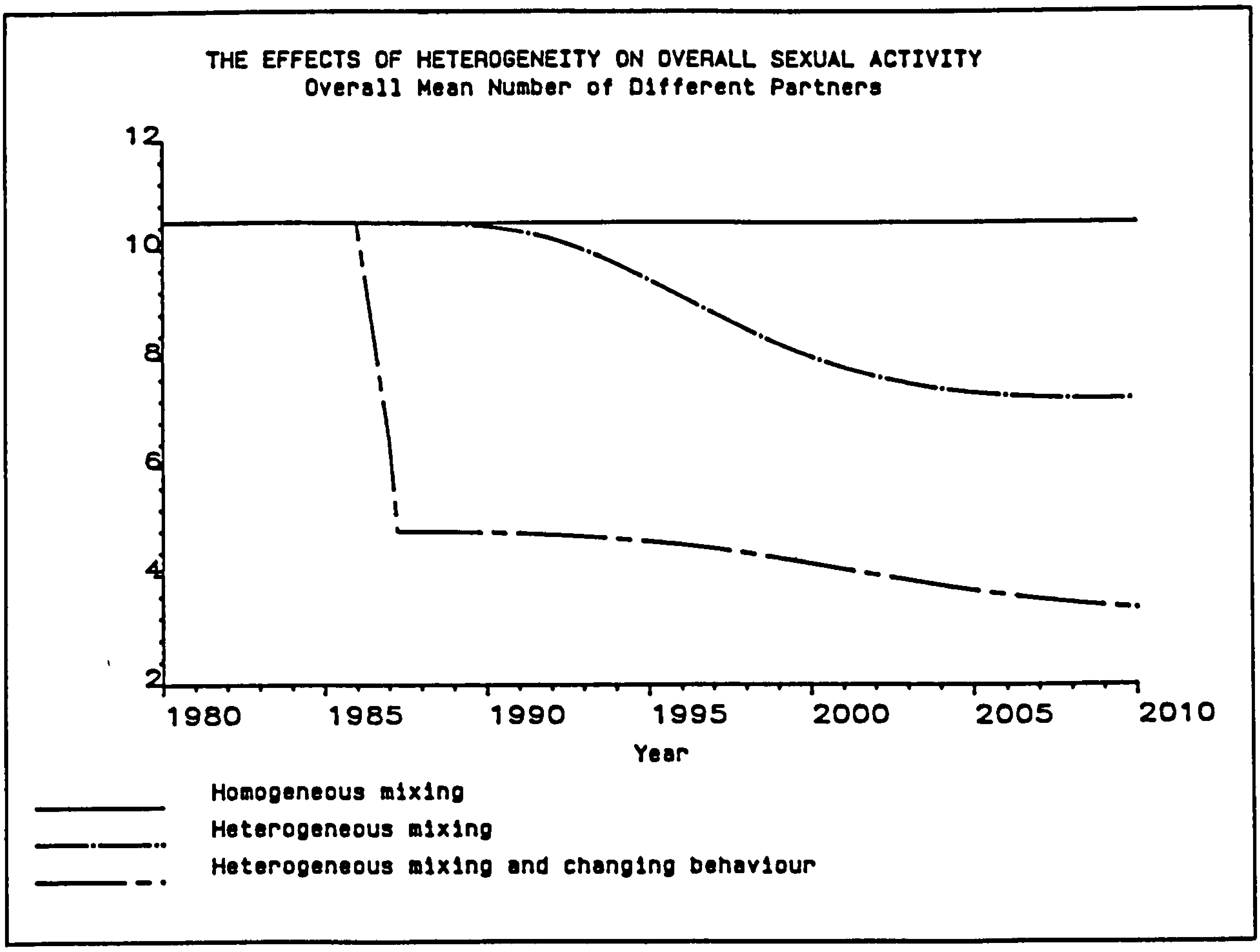

Figure 4.16 Plot of Overall Mean Number of Different Partners for (i) homogeneous (ii) heterogeneous and (iii) heterogeneous + changing behaviour models

4.6.1 Results from incorporating variable infectivity

In the base model it was assumed that the infectious period was equal to the incubation period and, moreover, that the probability of infection was constant throughout. However, it now seems that a constant infectivity profile is unlikely. Infectivity may be related to the amount of antigenaemia (free virus) in the circulatory system of an infected individual.

That is, the greater the antigenaemia the more infectious the individual.

Studies indicate that the level of antigenaemia goes up in the first few weeks after infection and then goes down as antibody response occurs, remaining at very low levels for years (Pedersen, Nielsen, Vestergaard et al, 1987; Burger et al, 1986). As the immune system collapses in the year or so before AIDS develops, antigenaemia counts return to high levels. Figure 4.17 illustrates the possible antigenaemia levels -- and hence the infectivity profile -- during an assumed eight year incubation period. This variable infectivity profile is modelled using three cascaded first order delays with mean delay times of 1, 6 and 1 years respectively.

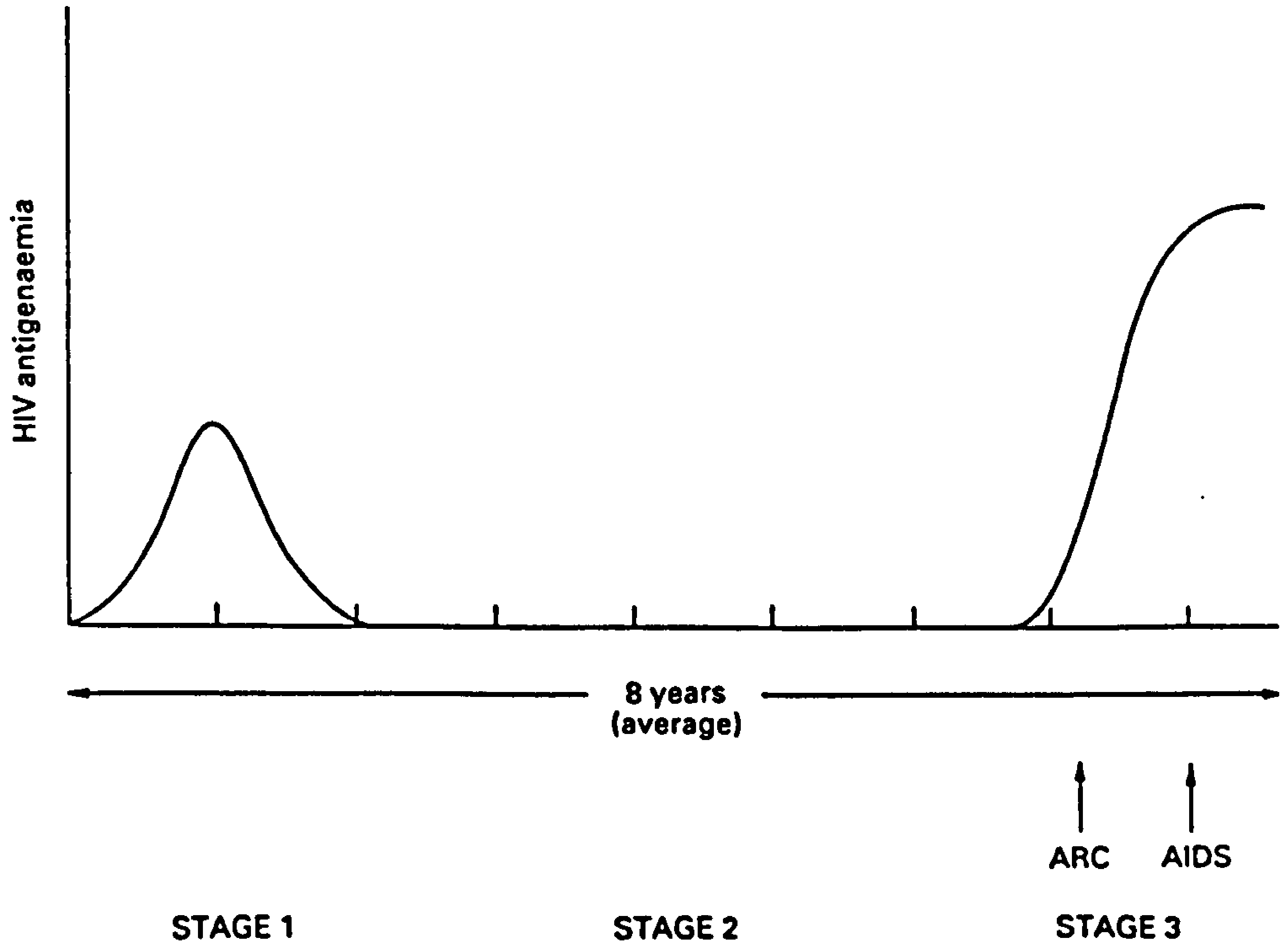

Figure 4.17 Assumed infectivity profile over the incubation period

During the first year the Probability of Infection Per Partner

(PIPP1) was set at 0.06, during the middle six years (PIPP2) at zero and during the last year (PIPP3) at 0.12 . Figure 4.18 shows the effect on the prevalence of AIDS of incorporating this variable profile into the heterogeneous sexual activity model. Its effect once again is to lessen the size of the epidemic.

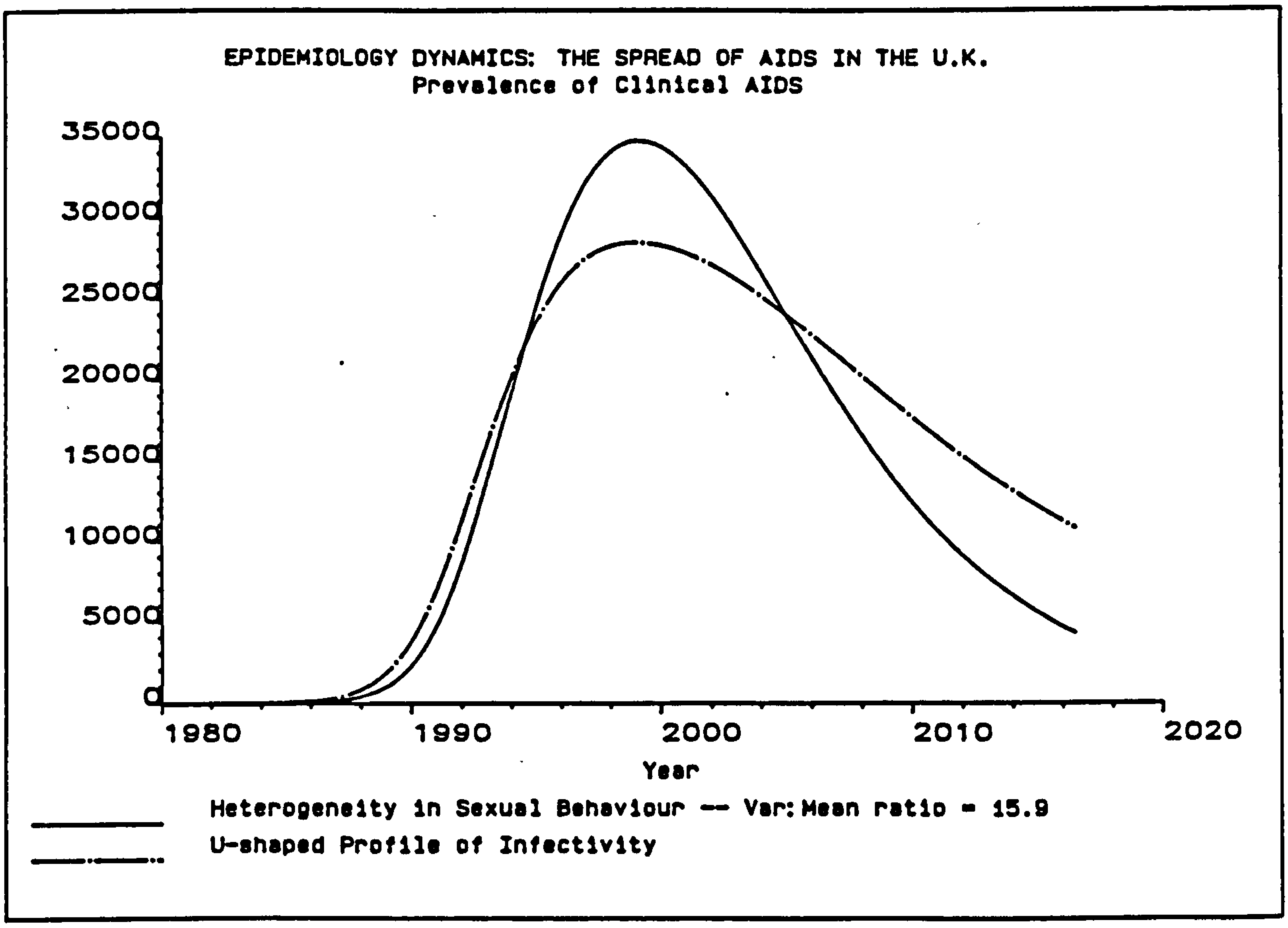

Figure 4.18 Comparison between the effects of (i) heterogeneity and (ii) heterogeneity and variable infectivity on the prevalence of clinical AIDS

Since the probabilities of infection at the beginning and at the end of the incubation period are highly uncertain, sensitivity tests have been performed. Figures 4.19 and 4.20 illustrate the effect of changes in these two parameters, PIPP1 and PIPP3. It can be seen that variations in PIPP1 have a much greater impact on the course of the epidemic than do changes of twice the amount made to PIPP3. On both graphs the flat profile of infectivity plot is included for comparison purposes.

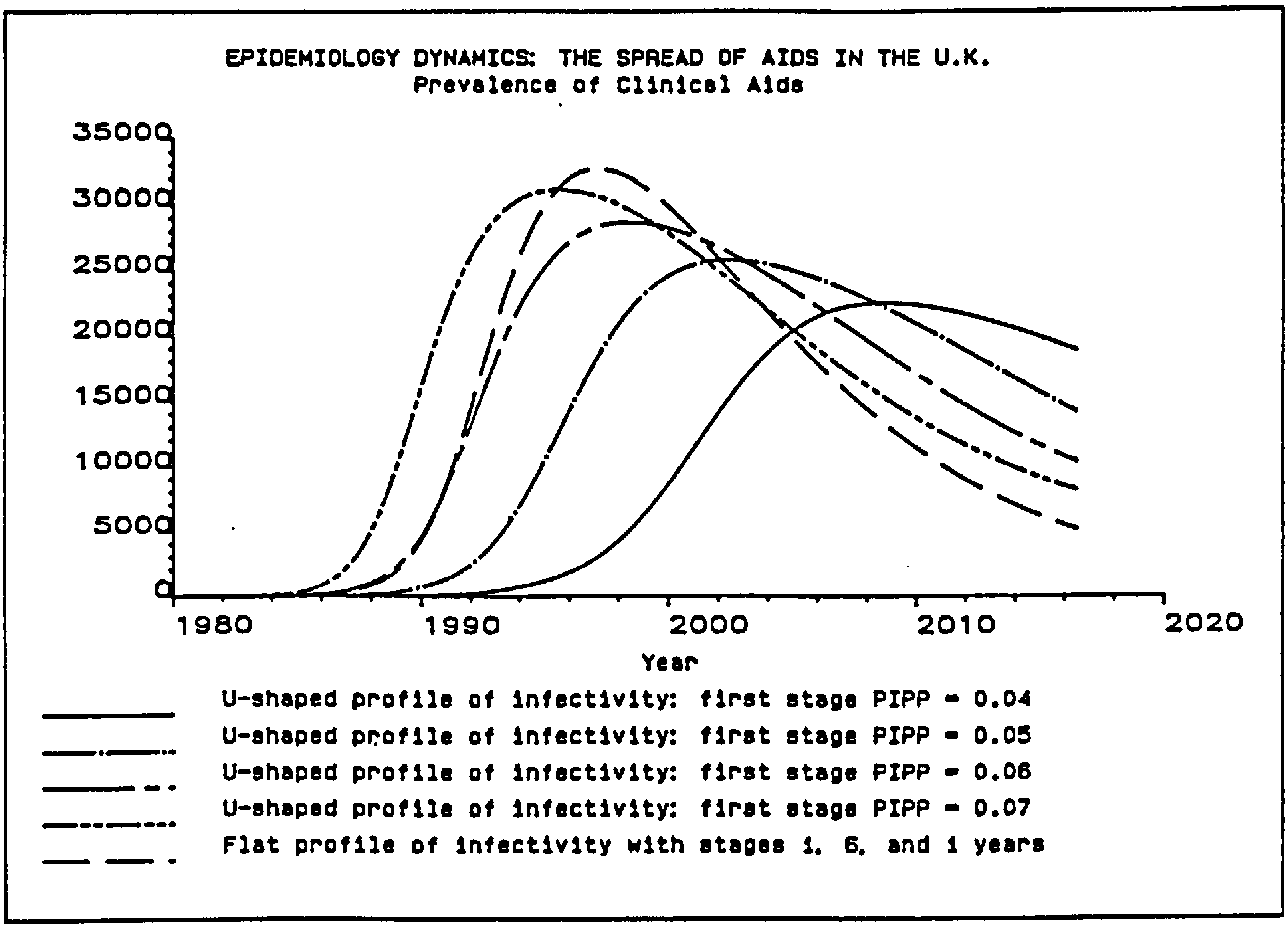

Figure 4.19 Effect of variations in the first stage of infectiousness on the prevalence of clinical AIDS

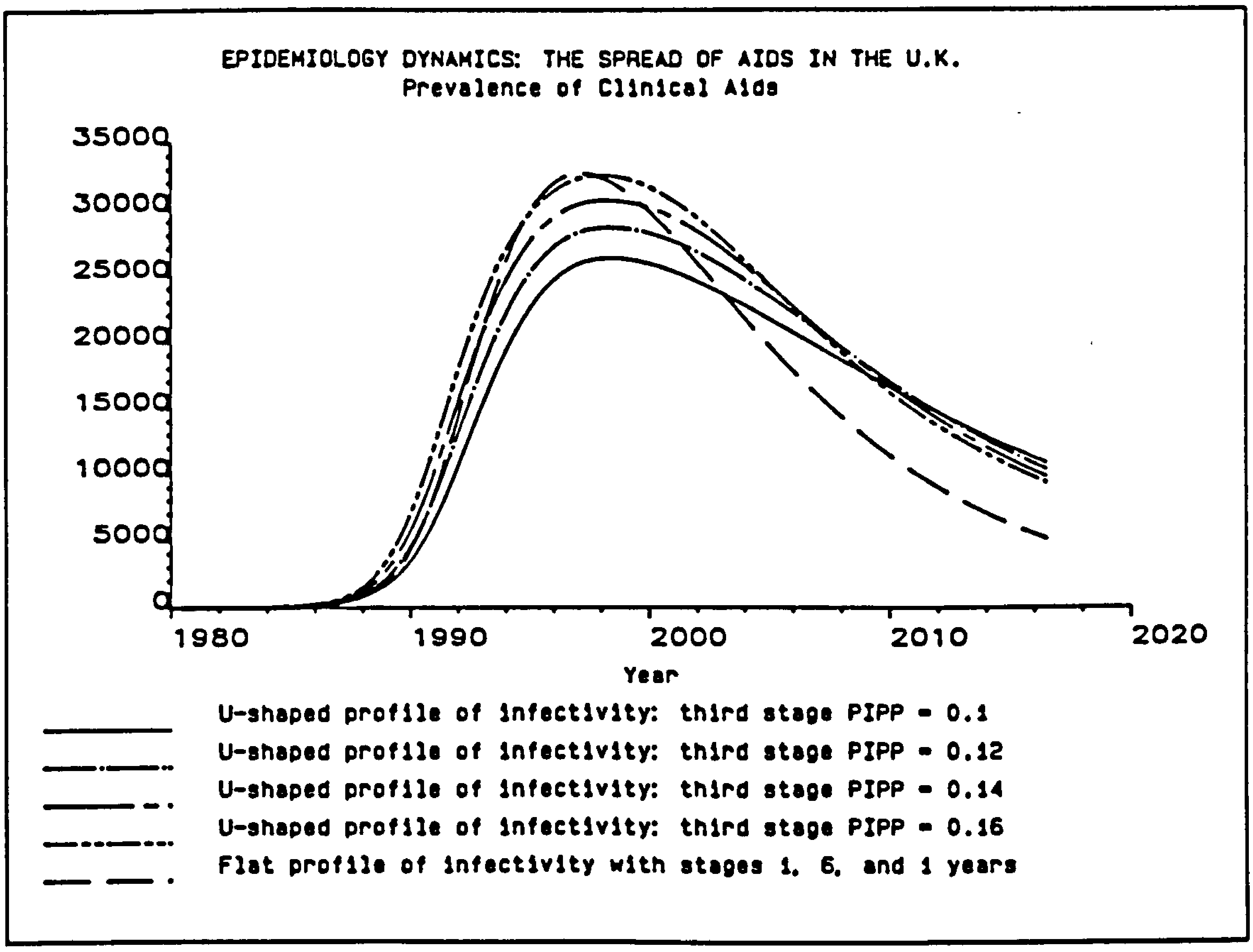

Figure 4.20 Effect of variations in the second stage of infectiousness on the prevalence of clinical AIDS

The implications of this result are twofold; for the virologists it is necessary to concentrate on assessing infectivity during this first stage of infectiousness shortly after initial invasion of the virus; and for the health educationists it is imperative that they succeed in their desire to persuade those people, whose behaviour puts them at risk of infection, to adopt safe sexual practices. The earlier in the course of the epidemic that this message is heeded, the greater is the benefit.

This result could also provide an input into the debate surrounding a recent policy announcement that, in addition to patients with clinical AIDS, HIV-infecteds would also be treated with the drug zidovudine (AZT). There may be those who think that the administration of zidovudine to this new group of patients will have epidemiological as well as prophylactic benefits. But as the result indicates, a major determinant of the progress of the epidemic is risky behaviours in the early stages of infectivity. At that time a newly-infected person may experience nothing more than a short acute illness which goes unremarked. Therefore, even if zidovudine also reduces infectivity, early identification of those individuals to whom its administration would be of epidemiological benefit is going to prove extremely difficult.

4.7 Results from an Optimisation experiment

In this section a parameter optimisation experiment is conducted in order to extract, from the quarterly time series data on cumulative reported cases of AIDS, as much as could be gained on behalf of a model incorporating heterogeneity in sexual activity and variable infectivity over the distributed incubation period. The concepts and tools of system dynamics optimisation have been developed for nearly a decade now by Keloharju (1976, 1981). Latterly they have been expounded in papers by Coyle (1985), Keloharju and Wolstenholme (1988, 1989) and Wolstenholme and Al-Alusi (1987).

Up until now the data-driven (curve fitting) approach to modelling the epidemic has existed in isolation from the transmission modelling approach. The latter reflects the actual processes going on but takes notice of externally generated data only insofar as parameter values are supported by empirical surveys and/or clinical case reports. However, by using the optimisation software it is possible to harness the information obtainable from time series data on the epidemic with the construction of a causal model.

The software tool associated with the use of system dynamics optimisation is an enhanced version of the mainframe DYSMAP package and is called DYSMOD (Dynamic Systems Modeller Optimiser and Developer), (Luostarinen, 1982). Up until 1990 this software was available only on Hewlett Packard minicomputers but it has recently been ported to an 80386-based PC environment (DYSMOD/386). DYSMOD includes a heuristic search routine devised by Buffa and Taubert (1972) which explores the multi-dimensional response surface created, through the range of variability of those parameters in the model not held fixed, with respect to an objective function. This function is either maximised or minimised.

DYSMOD is an implementation of a range of powerful system dynamics optimisation facilities. Of these, only the simplest, namely straightforward estimation of (constant) parameters, has been utilised in the experiment reported. For any optimisation, the user must formulate, using the DYSMAP language syntax, the necessary objective function to be included in the model along with all the other equations. An objective function was formulated which represented the sum of squared deviations of the simulated from the actual quarterly time series values for cumulative clinical cases of AIDS, from 1982 up to the end of the second quarter of 1988. A range for each of the six parameters chosen for optimisation was also specified, these being the Mean Number of Different Partners in each of three sexual activity groups, the Symptoms Emergence Ratio and the Probability of Infection Per Partner for each of stages 1 and 3 in the three-stage variable infectivity profile. All other parameters were held fixed.

The results showed the best fit Mean Number of Different Partners in each group to be 0.72, 4.66 and 27.90 compared with the values previously used (estimated from data provided from the government sponsored survey) of 1, 6 and 36. The Symptoms Emergence Ratio came out at 1.0, confirming the most pessimistic of all opinions on this feature and the Probability of Infection Per Partner in stages 1 and 3 as 0.071 and 0.149 respectively. Although the third stage infectivity is estimated at over twice that of the first stage, its influence on the magnitude of the overall epidemic is slight as compared with that of the first stage PIPP. (This feature has already been commented upon in the previous section.) A plot of the actual and simulated series, arising from running the model with the optimised parameter values to the end of 1988 Q2, is shown in figure 4.21 .

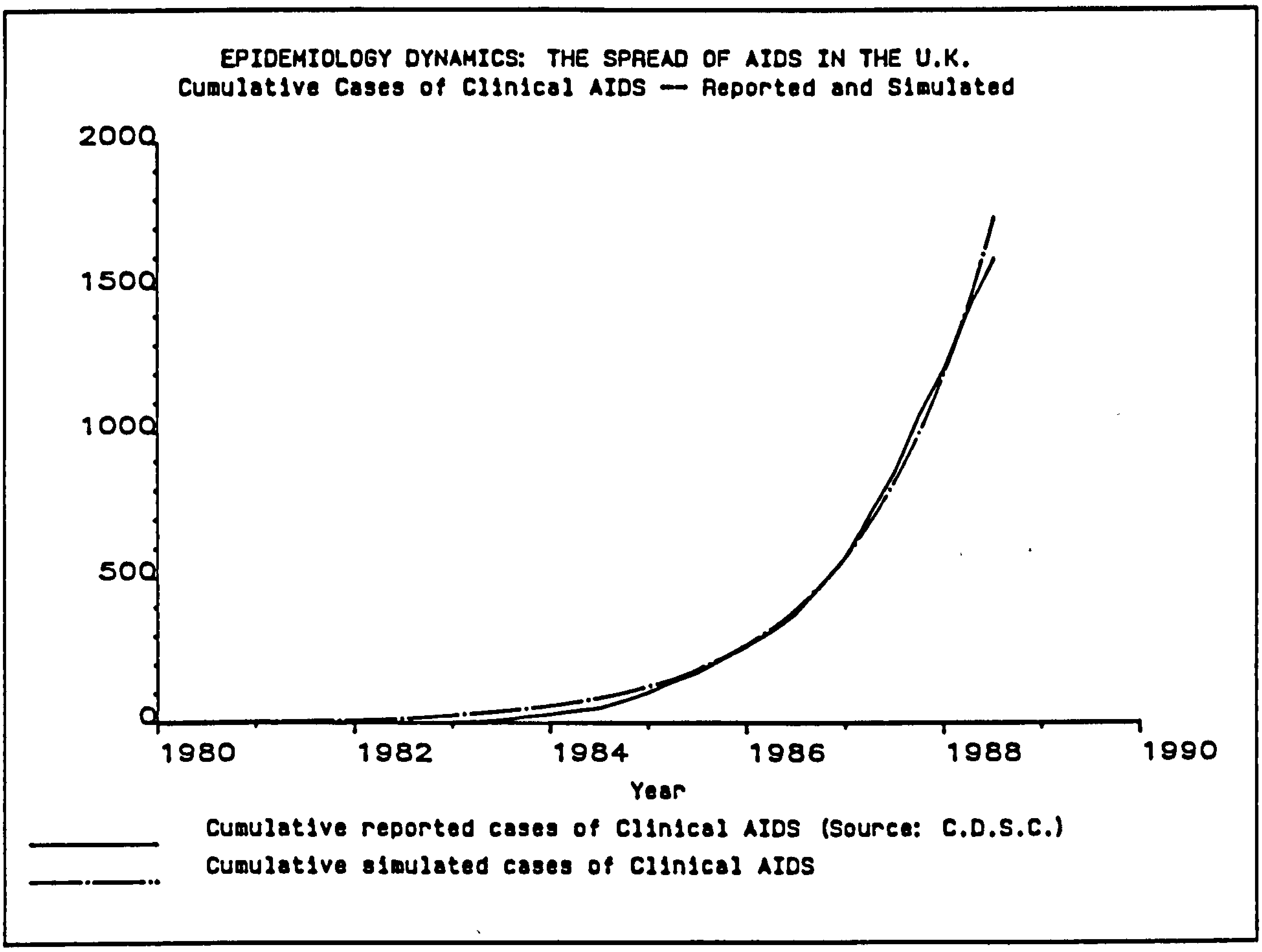

Figure 4.21 Comparison of actual and simulated cumulative cases of AIDS following the optimisation experiment

With such a good fit to the actual data it is worthwhile examining the figures produced for HIV prevalence at, say, end-1987. This is the 'base of the iceberg' phenomenon; the number of people HIV-infected but who have not yet shown symptoms of clinical AIDS. Reading the value, firstly, directly from the model variable for HIV prevalence and, secondly, using a multiplication factor which adjusts for whether the simulated cumulative clinical cases of AIDS are above or below the actual, gives a range between 18,800 and 19,100 rounded to the nearest hundred. The government appointed committee of experts, chaired by Professor Sir David Cox, has investigated ways of attempting a five year prediction for new AIDS cases (to assist in health care planning). Their report (Department of Health and the Welsh Office, 1988) puts a figure for HIV prevalence in homosexuals at end-1987 in the range 13,000 to 30,000.

4.8 The Relationship between HIV prevalence and reported cases of AIDS

Finding the relationship between the prevalence of the human immunodeficiency virus (HIV) and observed cases with clinical symptoms of the acquired immunodeficiency syndrome (AIDS) was the main preoccupation of contributors to the Cox Report. A recent American article by Salzberg and Dolins (1989) has claimed that the relationship is constant. This is something of an oversimplification.

With the model described above, it is trivial to compute the ratio of HIV prevalence to cases of AIDS over the course of the epidemic. In figure 4.22 below a plot of this ratio is presented and it can be seen that the relationship is forward falling with just a short period when the ratio remains fairly constant. The changes in the rate of fall of the curve reflect the changing nature of the relationship between the respective proportionate rates of growth of HIV infectives and AIDS cases. After the period when both proportionate growth rates are almost the same, the number of new cases of AIDS starts to increase quite substantially, the proportionate growth rate of cumulative AIDS cases is much higher than that for HIV prevalence and thus the ratio declines.

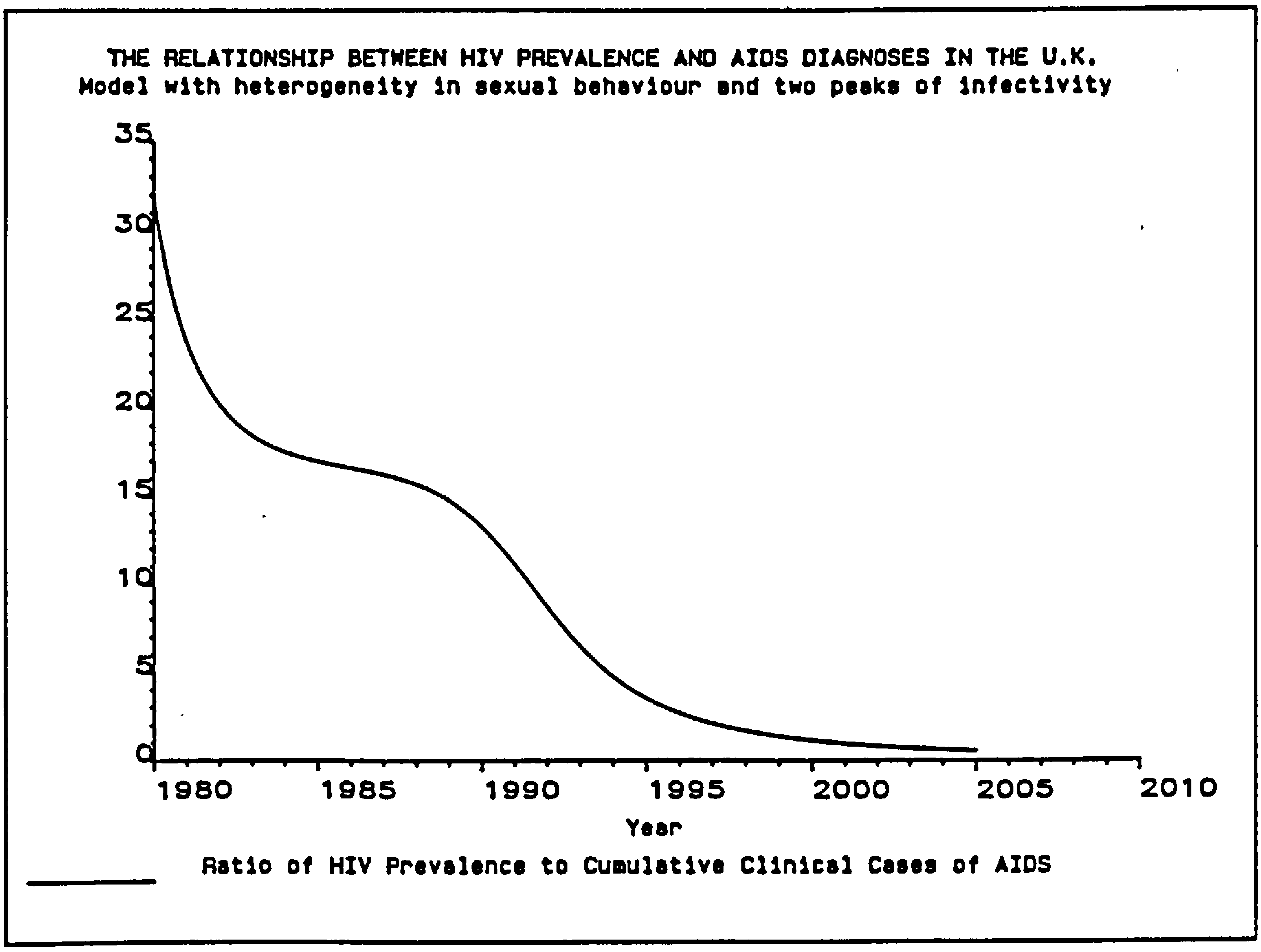

Figure 4.22 Plot of the ratio of HIV prevalence to cumulative clinical cases of AIDS

Although the precise values on the vertical axis in figure 4.22 are determined by the values of parameters and the assumptions in the model (and the ratio is not plotted prior to 1980 because not one AIDS case is generated before that date), the form of the curve is universal and will be an artefact of the AIDS epidemic in all countries which report one. Moreover, its overall shape is the same whether you take the ratio of HIV prevalence to AIDS incidence; to AIDS prevalence; to cumulative cases of AIDS (as illustrated above); or to AIDS incidence in the year following (as with Salzberg and Dolins).

4.9 Model Validation

With the approach adopted there is normally a much sharper external focus on model validation than is the case with other modelling methods. Why this should be so is not readily apparent, but nonetheless various validation tests have been performed on the model.

The scientific method espoused by Popper (1959) provides a backcloth to the entire range of tests capable of being applied: the model should not be 'obviously wrong'. The tests conducted covered the following:

(a) A mathematical check that the model neither gained or lost people during the execution of the simulation.

(b) A run of the heterogeneous model with all three strata having the same mean of 10.5 partners yr^{-1}. This produced an exact trace of the homogeneous model behaviour.

(c) A detailed assessment of all the numerical values chosen for the parameters.

(d) A comparison of the simulated output with the corresponding reported data up to the present time.

(e) An inspection of the maximum and minimum values of *all* the model variables. This is to check that the model, while perhaps generating reasonable values for the important output variables, is not being sustained by totally implausible values for the supporting variables. This check revealed that all variables' values were satisfactory.

Of the above, points (a) and (c) warrant further explanation.

A checksum equation was formulated in order to satisfy test (a) above. This took the following form:

CHECK=ETPAR-(SP+HIVPOP+CTNIS+CAP+CD)

where

ETPAR = Estimated Total Population At-Risk

SP = Susceptible Population

HIVPOP = HIV infected POPulation

CTNIS = Cumulative Transferrals to Non-Infectious State

CAP = Clinical Aids Population

CD = Cumulative Deaths

Clearly its value should be zero at all times and indeed the numerical results for this variable showed that it was zero or (at most) approximately equal to $|1.2\times10^{-10}|$. The software employed operates in double precision arithmetic throughout and so the calculated values for the CHECK variable are highly computationally accurate despite the fact that a differencing operation between some reasonably large numbers is being carried out.

In respect of (c) it can be stated categorically that the estimates of parameter values used in the model were drawn from the published literature. In the section above *all* the sources have been identified. Because the model is not characterised by a level of detail which goes down to the separation of individual risk groups and type of sexual activity, the extent of the necessity for parameter values is constrained. Models which incorporate great detail compound the difficulty involved in obtaining reliable parameter estimates and in any case detailed models are not necessarily justified in the light of the needs of those people who are planning for the epidemic.

4.10 Conclusion

If the foregoing has demonstrated that system dynamics has a role to play in epidemiological modelling then it will have served its purpose. It is not the quarter which epidemiologists might have previously turned to in seeking help, but developments in the power of personal computers and in system dynamics simulation software have combined to ensure that the management scientist has a capability which should prove attractive to clinicians, epidemiologists and others who are in the front line for developing policies to cope with this major problem of public health. Written description of the models fails to convey the impact of this policy support tool in use. Runs take a matter of minutes on a PC/AT and, if one of the latest 32-bit personal computers is deployed, the 'run and plot' time is measured in seconds. For instance, using a 386-SX machine equipped with a maths co-processor, the most complex model, incorporating heterogeneity in sexual mixing and a variable infectivity profile, runs in 33 seconds.

The impact which the AIDS pandemic is having on the output of epidemiological models worldwide has much in common with the genesis of O.R. in wartime. The world is faced with an incipient problem of potentially horrendous proportions. It follows from this that there is insufficient time to be drawn into lengthy consideration of how comprehensive one model is compared to another or of the relative merits of analytical as opposed to simulation models; each approach has a contribution to make. The offering above stems from the view that analytical models may be mathematically exact but incur overheads in formulation time and, more so, in the time needed for their solution. They also impose a barrier to understanding for the clients, when what is needed is a means of endorsing a common vocabulary.

The heterogeneous sexual mixing model is complex without being detailed. Nevertheless, there are some who have attempted to incorporate into their models a degree of detail on sexual risk groups and practices which cannot be other than overambitious given current knowledge concerning the measurement of vital parameters. Attempts to construct very detailed models of HIV transmission inevitably put up the cost (and time) of the research as well as placing an unnecessarily heavy stress on model validation. The objective in devising this model was to create something which was: capable of handling the significant features of the HIV/AIDS epidemics which have been highlighted in the medical and scientific literature; ideal for rapid recomputation and illustration of the effects of parameter changes and, most of all, was reasonably transparent to non-modelling professionals. It is to be hoped that some movement towards achieving that goal has been accomplished.

The use of stochastic models of AIDS spread has its adherents. The approach adopted here does not, in fact, prohibit such explorations. DYSMAP2 has both normal and uniformly distributed random number functions, so it would be a simple task to impose stochasticity on the model and re-run it many times, producing the results in the form of frequency distributions as has been done by Bailey and Estreicher (1988). However, it is worth reiterating the main conclusion of Tan and Hsu (1989) from their experiments with some stochastic models. They found that, providing the numbers at risk are large enough, stochastic models merely produce an approximation to the underlying deterministic model.

Modelling the epidemic in the homosexual risk group is a necessary first step for the UK and many other countries where this group accounts for a significant proportion of total AIDS cases. However, it should be expected that such a model would eventually be augmented by further sectors incorporating drug users and non-monogamous sexually active heterosexuals, with linkages across all three groups. To attempt to achieve such a goal using mathematical modelling is daunting, because of the greater degree of interaction between the risk groups involved and the need to model the sexes separately. But by employing a system dynamics simulation approach there is a realistic hope of producing such an enhanced model. This could then, with appropriate parameter changes, be applied to the AIDS epidemic in any country of the world: it would be a generic model.

It is hardly surprising, therefore, that the model described above is regarded as a first step, albeit an important one, in supporting public policy on HIV and AIDS. It is intended subsequently to enlarge the model of spread in the homosexual population along the lines indicated in the previous paragraph. As a consequence of the research to date, together with any further enhancements, it is to be hoped that medical professionals and health planning staff will become convinced that system dynamics models are a helpful support tool for capturing those insights which will contribute cogently to debates on AIDS policy.

REFERENCES FOR CHAPTER 4

R M ANDERSON, G F MEDLEY, R M MAY and A M JOHNSON (1986) "A Preliminary Study of the Transmission Dynamics of the Human Immuno-deficiency Virus (HIV), the causative agent of AIDS", *IMA J. Math. Med. Biol.*, 3, 229-263.

R M ANDERSON and R M MAY (1988) "Epidemiological parameters of HIV Transmission", *Nature*, 333, 514-519.

R M ANDERSON and G F MEDLEY (1988) "Epidemiology of HIV infection and AIDS: incubation and infectious periods, survival and vertical transmission", *AIDS*, 2, 557-563.

P BACCHETTI and A R MOSS (1989) "Incubation Period of AIDS in San Francisco", *Nature*, 338, 251-253.

N T J BAILEY (1975) *"The Mathematical Theory of Infectious Diseases"*, Chapman and Hall, London.

N T J BAILEY and T J ESTREICHER (1988) "Implications of Stochastic Variations in HIV/AIDS Modelling". In *EC Workshop on Quantitative Analyses of AIDS - Abstracts*, pp 2-3, National Institute of Public Health and Environmental Protection, Bilthoven.

E M BELSEY and M W ADLER (1978) "A Study of STD Clinic Attenders in England and Wales", *Br. J. Vener. Dis.*, 57, 285-289.

S P BLYTHE and R M ANDERSON (1988a) "Distributed Incubation and Infectious Periods in Models of the Transmission Dynamics of the Human Immunodeficiency Virus (HIV)", *IMA J. Math. Med. Biol.*, 5, 1-19.

S P BLYTHE and R M ANDERSON (1988b) "Variable Infectiousness in HIV Transmission Models", *IMA J. Math. Med. Biol.*, 5, 181-200.

BRITISH MARKET RESEARCH BUREAU (1987) *"AIDS: Monitoring Response to the Public Health Campaign February 1986 - February 1987"*, H M S O, London.

E S BUFFA and W H TAUBERT (1972) *"Production - Inventory Systems: Planning and Control"*, Rev.Ed., R.D.Irwin, New York.

M BURGER et al. (1986) "Transmission of LAV/HTLVIII in sexual partners: seropositivity does not predict infectivity in all cases", *Am. J. Med.*, 81, 5-10.

R CLARK (1988) *"System Dynamics and Modelling"*, Operations Research Society of America.

A P M COXON (1986) *Project Sigma Working Paper*, 4, Social Research Unit, University College, Cardiff.

R G COYLE (1985) "The Use of Optimisation Methods for Policy Design in a System Dynamics model", *System Dynamics Review*, 1, 81-91.

B C DANGERFIELD and O VAPENIKOVA (1987) *"DYSMAP2 User Manual"*, University of Salford.

B C DANGERFIELD and C A ROBERTS (1989) "A Role for System Dynamics in Modelling the Spread of AIDS", *Transactions of the Institute of Measurement and Control*, 11, 187-195.

DEPARTMENT OF HEALTH AND THE WELSH OFFICE (1988) *"Short-term prediction of HIV Infection and AIDS in England and Wales"*, H M S O, London.

S EILON (1989) Editorial: "O.R. at the Top", *Omega*, 17, 1-8.

B A EVANS et al. (1989) "Trends in Sexual Behaviour and Risk Factors for HIV infection among homosexual men, 1984-7", *Br. Med. J.*, 298, 215-218.

R M GRANT, J A WILEY and W WINKELSTEIN (1987) "Infectivity of the Human Immunodeficiency Virus: Estimates from a Prospective Study of Homosexual Men", *J. Infect. Dis.*, 156, 189-193.

J D GRIFFITHS and K A WHEELER (1990a) "Modelling the Spread of AIDS". In *"Mathematics in Medicine and Biology"*, Oxford Univ.Press, (forthcoming).

J D GRIFFITHS, J WILLIAMS and K A WHEELER (1990b) "Modelling the Course of the AIDS epidemic". In *"O R Work in HIV/AIDS"*, B C DANGERFIELD and C A ROBERTS (Eds.), Operational Research Society, Birmingham.

M HALL (1987) Unpublished paper presented at *British Association for the Advancement of Science* Conference, Belfast.

M J R HEALY and H TILLETT (1988) "Short-term extrapolation of the AIDS epidemic", *J. R. Statist. Soc. A*, 151, 50-61.

J M HYMAN and E A STANLEY (1988) "Using Mathematical Models to Understand the AIDS Epidemic", *Math. Biosci.*, 90, 415-473.

INSTITUTE OF MEDICINE (1988) *"Approaches to Modelling Disease Spread and Impact"*, National Academy Press, Washington D.C.

V ISHAM (1988) "Mathematical Modelling of the Transmission Dynamics of HIV infection and AIDS: a Review", *J. R. Statist. Soc. A*, 151, 5-30.

J C JAGER and E J RUITENBERG (Eds.) (1988) *"Statistical Analysis and Mathematical Modelling of AIDS"*, Oxford University Press, Oxford.

R KELOHARJU (1976) "Multi Objective Decision Models in System Dynamics", *Dynamica*, 3, 3-13.

R KELOHARJU (1981) *"Relativity Dynamics"*, Helsinki School of Economics, Helsinki.

R KELOHARJU and E F WOLSTENHOLME (1988) "The Basic Concepts of System Dynamics Optimisation", *Systems Practice*, 1, 65-86.

R KELOHARJU and E F WOLSTENHOLME (1989) "A Case Study in System Dynamics Optimisation", *J. Opl. Res. Soc.*, 40, 221-230.

E G KNOX (1986) "A Transmission model for AIDS", *Eur. J. Epidemiol.*, 2, 165-177.

A LUOSTARINEN (1982) *"DYSMOD User's Manual"*, Helsinki School of Economics, Helsinki.

M McEVOY and H TILLETT (1985) "Some Problems in the prediction of future numbers of cases of the Acquired Immunodeficiency Syndrome in the U.K." *Lancet*, ii, 541-542.

R M MAY and R M ANDERSON (1987) "Transmission Dynamics of HIV infection", *Nature*, 326, 137-142.

R M MAY and R M ANDERSON (1988) "The Transmission Dynamics of human immunodeficiency virus (HIV)", *Phil. Trans. R. Soc. Lond. B*, 321, 565-607.

G F MEDLEY, R M ANDERSON, D R COX and L BILLARD (1987) "Incubation Period of AIDS in patients infected via blood transfusion", *Nature*, 328, 719-721.

G F MEDLEY, L BILLARD, D R COX and R M ANDERSON (1988a) "The Distribution of the Incubation period for the Acquired Immunodeficiency Syndrome (AIDS)", *Proc. R. Soc. Lond. B*, 233, 367-377.

G F MEDLEY, R M ANDERSON, D R COX and L BILLARD (1988b) "Estimating the incubation period for AIDS patients", *Nature*, 333, 505.

C PEDERSEN, C M NIELSEN, B F VESTERGAARD et al. (1987) "Temporal Relation of Antigenaemia and loss of antibodies to core antigens to development of clinical disease of HIV infection", *Br. Med. J.*, 295, 567-569.

T A PETERMAN et al (1988) "Risk of HIV Transmission from heterosexual adults with transfusion associated infections", *J. Am. Med. Ass.*, 259, 55-63.

J PICKERING et al. (1986) "Modelling the Incidence of Acquired Immunodeficiency Syndrome (AIDS) in San Francisco, Los Angeles and New York. *Mathematical Modelling*", 7, 661-688.

K R POPPER (1959) *"The Logic of Scientific Discovery"*, Basic Books, New York.

PUBLIC HEALTH LABORATORY SERVICE (1990) *"Acquired Immune Deficiency Syndrome in England and Wales to end 1993: projections using data to end September 1989"*, Communicable Disease Surveillance Centre, London.

G K REEVES (1988) "The Overall Distribution of Survival Time for U.K. AIDS Patients. In *Short-term prediction of HIV Infection and AIDS in England and Wales"*, 80-81, H.M.S.O., London.

G K REEVES (1989) Personal communication.

G K REEVES and S E OVERTON (1988) "Preliminary Survival Analysis of U.K. AIDS data", *Lancet*, i, 880.

C A ROBERTS and B C DANGERFIELD (1989) "Understanding the Epidemiology of HIV Infection and AIDS: experiences with a System Dynamics model". In *Proceedings of the 3rd European Simulation Congress*, D MURRAY-SMITH, J STEPHENSON & R N ZOBEL Eds., Simulation Councils Inc., 241-247.

C A ROBERTS and B C DANGERFIELD (1990a) "Modelling the Epidemiological Consequences of HIV Infection and AIDS: a contribution from Operational Research", *Journal of the Operational Research Society*, 41, 273-289.

C A ROBERTS and B C DANGERFIELD (1990b) "A System Dynamics Modelling Framework for Understanding the Epidemiology of HIV/AIDS". In *"O R Work in HIV/AIDS"*, B C DANGERFIELD and C A ROBERTS (Eds.), Operational Research Society, Birmingham.

A M SALZBERG and S L DOLINS (1989) "The Relation between AIDS cases and HIV prevalence", *N. Engl. J. Med.* 320, 936.

W Y TAN and H HSU (1989) "Some Stochastic Models of AIDS Spread", *Statistics in Medicine*, 8, 121-136.

G J P Van GRIENSVEN et al. (1989) "Changes in Sexual Behaviour and the fall in incidence of HIV infection among homosexual men", *Br. Med. J.*, 298, 218-221.

A D WILKIE (1988) "An Actuarial Model for AIDS", *J. Inst. Act.*, 115, 839-853.

W WINKELSTEIN, D M LYMAN, N PADIAN et al. (1987) "Sexual Practices and risk of infection by HIV", *J. Am. Med. Ass.*, 257, 321-325.

C S WITHERS (1988) *"AIDS: References on Modelling - with Comments"*, Dept. of Scientific and Industrial Research, Wellington, New Zealand.

E F WOLSTENHOLME and A S Al-ALUSI (1987) "System Dynamics and Heuristic Optimisation in Defence Analysis", *System Dynamics Review*, 3, 102-115.

LISTING OF THE VARIABLE INFECTIVITY MODEL

```
* EPIDEMIOLOGY DYNAMICS: THE SPREAD OF AIDS IN THE U.K.
N TIME=STIME
C STIME=1976.5
C ETPAR=1E6
L SP1.K=SP1.J+DT*(-EIRHIV1.JK)
N SP1=ETP1AR-HIVPOP1IN
C ETP1AR=300E3
L SP2.K=SP2.J+DT*(-EIRHIV2.JK)
N SP2=ETP2AR-HIVPOP2IN
C ETP2AR=500E3
L SP3.K=SP3.J+DT*(-EIRHIV3.JK)
N SP3=ETP3AR-HIVPOP3IN
C ETP3AR=200E3
NOTE
NOTE
NOTE   Three stages of infectivity for sexual activity group 1
NOTE
NOTE
L HIVPOP1S1.K=HIVPOP1S1.J+DT*(EIRHIV1.JK-HIVS2MR1.JK-ETRNIS1.JK)
N HIVPOP1S1=HIVPOP1IN/3
C HIVPOP1IN=0
R HIVS2MR1.KL=DELAY1(EIRHIV1.JK,S1IT.K)
L HIVPOP1S2.K=HIVPOP1S2.J+DT*(HIVS2MR1.JK-HIVS3MR1.JK)
N HIVPOP1S2=HIVPOP1IN/3
R HIVS3MR1.KL=DELAY1(HIVS2MR1.JK,S2IT.K)
N HIVS2MR1=0
L HIVPOP1S3.K=HIVPOP1S3.J+DT*(HIVS3MR1.JK-ECAMR1.JK)
N HIVPOP1S3=HIVPOP1IN/3
A HIVPOP1.K=HIVPOP1S1.K+HIVPOP1S2.K+HIVPOP1S3.K
NOTE
NOTE
NOTE   Three stages of infectivity for sexual activity group 2
NOTE
NOTE
L HIVPOP2S1.K=HIVPOP2S1.J+DT*(EIRHIV2.JK-HIVS2MR2.JK-ETRNIS2.JK)
N HIVPOP2S1=HIVPOP2IN/3
C HIVPOP2IN=0
R HIVS2MR2.KL=DELAY1(EIRHIV2.JK,S1IT.K)
L HIVPOP2S2.K=HIVPOP2S2.J+DT*(HIVS2MR2.JK-HIVS3MR2.JK)
N HIVPOP2S2=HIVPOP2IN/3
R HIVS3MR2.KL=DELAY1(HIVS2MR2.JK,S2IT.K)
N HIVS2MR2=0
L HIVPOP2S3.K=HIVPOP2S3.J+DT*(HIVS3MR2.JK-ECAMR2.JK)
N HIVPOP2S3=HIVPOP2IN/3
A HIVPOP2.K=HIVPOP2S1.K+HIVPOP2S2.K+HIVPOP2S3.K
NOTE
NOTE
NOTE   Three stages of infectivity for sexual activity group 3
NOTE
NOTE
L HIVPOP3S1.K=HIVPOP3S1.J+DT*(EIRHIV3.JK-HIVS2MR3.JK-ETRNIS3.JK)
N HIVPOP3S1=HIVPOP3IN
```

```
C HIVPOP3IN=1
R HIVS2MR3.KL=DELAY1(EIRHIV3.JK,S1IT.K)
L HIVPOP3S2.K=HIVPOP3S2.J+DT*(HIVS2MR3.JK-HIVS3MR3.JK)
N HIVPOP3S2=0
R HIVS3MR3.KL=DELAY1(HIVS2MR3.JK,S2IT.K)
N HIVS2MR3=0
L HIVPOP3S3.K=HIVPOP3S3.J+DT*(HIVS3MR3.JK-ECAMR3.JK)
N HIVPOP3S3=0
A HIVPOP3.K=HIVPOP3S1.K+HIVPOP3S2.K+HIVPOP3S3.K
NOTE
NOTE   Below, the Sexual Activity Ratio is used to parcel out
NOTE   the AGGregate Infection Rate of HIV amongst the three
NOTE   strata. This produces an Effective Infection Rate of
NOTE   HIV for each of the strata.
NOTE
R EIRHIV1.KL=AGGIRHIV.KL*SAR1.K
R EIRHIV2.KL=AGGIRHIV.KL*SAR2.K
R EIRHIV3.KL=AGGIRHIV.KL*SAR3.K
A TSA.K=SP1.K*MNDP1.K+SP2.K*MNDP2.K+SP3.K*MNDP3.K
A SAR1.K=SP1.K*MNDP1.K/TSA.K
A SAR2.K=SP2.K*MNDP2.K/TSA.K
A SAR3.K=SP3.K*MNDP3.K/TSA.K
R AGGIRHIV.KL=IRHIV1.K+IRHIV2.K+IRHIV3.K
A IRHIV1.K=(HIVPOP1S1.K*PIPPS1+HIVPOP1S2.K*PIPPS2+HIVPOP1S3.K
X *PIPPS3)*MNDP1.K*SPR.K
A IRHIV2.K=(HIVPOP2S1.K*PIPPS1+HIVPOP2S2.K*PIPPS2+HIVPOP2S3.K
X *PIPPS3)*MNDP2.K*SPR.K
A IRHIV3.K=(HIVPOP3S1.K*PIPPS1+HIVPOP3S2.K*PIPPS2+HIVPOP3S3.K
X *PIPPS3)*MNDP3.K*SPR.K
A SPR.K=TSA.K/((ETP1AR-CCC1.K)*MNDP1.K+
X (ETP2AR-CCC2.K)*MNDP2.K+(ETP3AR-CCC3.K)*MNDP3.K)
L HIVPOP.K=HIVPOP.J+DT*(AGGIRHIV.JK-CAMR.JK-TRNIS.JK)
N HIVPOP=HIVPOP1IN+HIVPOP2IN+HIVPOP3IN
A MNDP1.K=1
A MNDP2.K=6
A MNDP3.K=36
C PIPPS1=0.0378
C PIPPS2=0.0378
C PIPPS3=0.0378
A S1IT.K=MIPV/3
A S2IT.K=MIPV/3
A S3IT.K=MIPV/3
L CCC1.K=CCC1.J+DT*ECAMR1.JK
N CCC1=0
L CCC2.K=CCC2.J+DT*ECAMR2.JK
N CCC2=0
L CCC3.K=CCC3.J+DT*ECAMR3.JK
N CCC3=0
NOTE
NOTE
NOTE   The third & final stage of infectivity: the transmission
NOTE   to clinical AIDS for each of sexual activity groups 1, 2
NOTE   and 3.
NOTE   Also, the transfer to a non-infectious state for each of
NOTE   the 3 groups.
NOTE
NOTE
R ECAMR1.KL=DELAY1(HIVS3MR1.JK,S3IT.K)*SER
N HIVS3MR1=0
R ETRNIS1.KL=DELAY3(EIRHIV1.JK,MTNIS)*(1-SER)
```

```
N EIRHIV1=0
R ECAMR2.KL=DELAY1(HIVS3MR2.JK,S3IT.K)*SER
N HIVS3MR2=0
R ETRNIS2.KL=DELAY3(EIRHIV2.JK,MTNIS)*(1-SER)
N EIRHIV2=0
R ECAMR3.KL=DELAY1(HIVS3MR3.JK,S3IT.K)*SER
N HIVS3MR3=0
R ETRNIS3.KL=DELAY3(EIRHIV3.JK,MTNIS)*(1-SER)
N EIRHIV3=0
C MIPV=8
C MTNIS=8
C SER=0.7
R CAMR.KL=ECAMR1.KL+ECAMR2.KL+ECAMR3.KL
R TRNIS.KL=ETRNIS1.KL+ETRNIS2.KL+ETRNIS3.KL
S PCINF.K=(ETPAR-SP.K)/ETPAR*100
A SP.K=SP1.K+SP2.K+SP3.K
N CAMR=0
R DR.KL=DELAY1(CAMR.JK,MST)
C MST=1
L CAP.K=CAP.J+DT*(CAMR.JK-DR.JK)
N CAP=0
L CD.K=CD.J+DT*DR.JK
N CD=0
L CCC.K=CCC.J+DT*CAMR.JK
N CCC=0
L CTNIS.K=CTNIS.J+DT*TRNIS.JK
N CTNIS=0
S RHIVCAP.K=RATIO(HIVPOP.K,CAP.K)
S RHIVCCC.K=RATIO(HIVPOP.K,CCC.K)
NOTE
NOTE ACTUAL REPORTED STATISTICS
NOTE
S RCUMC.K=TABHL(RCUMCT,TIME.K,1982,1989,0.25)
T RCUMCT='CUMC.ACT'  External file
S RCUMD.K=TABHL(RCUMDT,TIME.K,1982,1989,0.25)
T RCUMDT='CUMD.ACT'  External file
NOTE
NOTE CHECKSUM EQUATIONS
NOTE
A CHECK1.K=ETPAR-(SP.K+HIVPOP.K+CTNIS.K+CAP.K+CD.K)
A CHECK2.K=HIVPOP.K-(HIVPOP1.K+HIVPOP2.K+HIVPOP3.K)
NOTE
NOTE DEFINITION STATEMENTS
NOTE
D AGGIRHIV=(P/YRS) AGGregate Infection Rate with HIV
D CAMR=(P/YRS) Clinical Aids Manifestation Rate
D CAP=(P) Clinical Aids Population
D CCC=(P) Cumulative Clinical Cases
D CCC1=(P) Cumulative Clinical Cases stratum 1
D CCC2=(P) Cumulative Clinical Cases stratum 2
D CCC3=(P) Cumulative Clinical Cases stratum 3
D CD=(P) Cumulative Deaths
D CHECK1=(P) CHECKsum equation no. 1 -- should be zero
D CHECK2=(P) CHECKsum equation no. 2 -- should be zero
D CTNIS=(P) Cumulative Transferrals to a Non-Infectious State
D DR=(P/YRS) Death Rate
D DT=(YRS) simulation time step
D ECAMR1=(P/YRS) Effective Clinical Aids Manifestation Rate
* stratum 1
```

```
D ECAMR2=(P/YRS) Effective Clinical Aids Manifestation Rate
* stratum 2
D ECAMR3=(P/YRS) Effective Clinical Aids Manifestation Rate
* stratum 3
D EIRHIV1=(P/YRS) Effective Infection Rate of HIV in stratum 1
D EIRHIV2=(P/YRS) Effective Infection Rate of HIV in stratum 2
D EIRHIV3=(P/YRS) Effective Infection Rate of HIV in stratum 3
D ETPAR=(P) Estimated Total Population At Risk
D ETP1AR=(P) Estimated Total Population of stratum 1 At Risk
D ETP2AR=(P) Estimated Total Population of stratum 2 At Risk
D ETP3AR=(P) Estimated Total Population of stratum 3 At Risk
D ETRNIS1=(P/YRS) Effective Transfer Rate to Non-Infectious State
* stratum 1
D ETRNIS2=(P/YRS) Effective Transfer Rate to Non-Infectious State
* stratum 2
D ETRNIS3=(P/YRS) Effective Transfer Rate to Non-Infectious State
* stratum 3
D HIVPOP=(P) HIV-infected POPulation
D HIVPOP1=(P) HIV-infected POPulation of stratum 1
D HIVPOP2=(P) HIV-infected POPulation of stratum 2
D HIVPOP3=(P) HIV-infected POPulation of stratum 3
D HIVPOP1IN=(P) HIV-infected POPulation of stratum 1 INitially
D HIVPOP1S1=(P) HIV-infected POPulation of stratum 1 at
* Stage 1 infectivity
D HIVPOP1S2=(P) HIV-infected POPulation of stratum 1 at
* Stage 2 infectivity
D HIVPOP1S3=(P) HIV-infected POPulation of stratum 1 at
* Stage 3 infectivity
D HIVPOP2IN=(P) HIV-infected POPulation of stratum 2 INitially
D HIVPOP2S1=(P) HIV-infected POPulation of stratum 2 at
* Stage 1 infectivity
D HIVPOP2S2=(P) HIV-infected POPulation of stratum 2 at
* Stage 2 infectivity
D HIVPOP2S3=(P) HIV-infected POPulation of stratum 2 at
* Stage 3 infectivity
D HIVPOP3IN=(P) HIV-infected POPulation of stratum 3 INitially
D HIVPOP3S1=(P) HIV-infected POPulation of stratum 3 at
* Stage 1 infectivity
D HIVPOP3S2=(P) HIV-infected POPulation of stratum 3 at
* Stage 2 infectivity
D HIVPOP3S3=(P) HIV-infected POPulation of stratum 3 at
* Stage 3 infectivity
D HIVS2MR1=(P/YRS) HIV Stage 2 Manifestation Rate for stratum 1
D HIVS2MR2=(P/YRS) HIV Stage 2 Manifestation Rate for stratum 2
D HIVS2MR3=(P/YRS) HIV Stage 2 Manifestation Rate for stratum 3
D HIVS3MR1=(P/YRS) HIV Stage 3 Manifestation Rate for stratum 1
D HIVS3MR2=(P/YRS) HIV Stage 3 Manifestation Rate for stratum 2
D HIVS3MR3=(P/YRS) HIV Stage 3 Manifestation Rate for stratum 3
D IRHIV1=(P/YRS) Infection Rate of HIV in stratum 1
D IRHIV2=(P/YRS) Infection Rate of HIV in stratum 2
D IRHIV3=(P/YRS) Infection Rate of HIV in stratum 3
D LENGTH=(YRS) LENGTH (duration) of the simulation
D MIPV=(YRS) Mean Incubation Period of the Virus
D MNDP1=(P/(P*YRS)) Mean Number of Different Partners for
* stratum 1 members
D MNDP2=(P/(P*YRS)) Mean Number of Different Partners for
* stratum 2 members
D MNDP3=(P/(P*YRS)) Mean Number of Different Partners for
* stratum 3 members
D MST=(YRS) Mean Survival Time (after a diagnosis of clinical aids)
```

```
D MTNIS=(YRS) Mean Time for transfer to Non-Infectious State
D PCINF=(1) PerCentage of the total population INFected
D PIPPS1=(1) Probability of Infection Per Partner at
* Stage 1 infectivity
D PIPPS2=(1) Probability of Infection Per Partner at
* Stage 2 infectivity
D PIPPS3=(1) Probability of Infection Per Partner at
* Stage 3 infectivity
D PRTPER=(YRS) PRinTing PERiod (interval)
D RCUMC=(P) Reported CUMulative Cases
D RCUMCT=(P) Reported CUMulative Cases -- Table of values
D RCUMD=(P) Reported CUMulative Deaths
D RCUMDT=(P) Reported CUMulative Deaths -- Table of values
D RHIVCAP=(1) Ratio of HIV population to Clinical Aids Population
D RHIVCCC=(1) Ratio of HIV population to Cumulative Clinical Cases
D S1IT=(YRS) Stage 1 Infectiousness Time
D S2IT=(YRS) Stage 2 Infectiousness Time
D S3IT=(YRS) Stage 3 Infectiousness Time
D SAR1=(1) Sexual Activity Ratio stratum 1
D SAR2=(1) Sexual Activity Ratio stratum 2
D SAR3=(1) Sexual Activity Ratio stratum 3
D SER=(1) Symptoms Emergence Ratio
D SP=(P) Susceptible Population (in total)
D SP1=(P) Susceptible Population stratum 1
D SP2=(P) Susceptible Population stratum 2
D SP3=(P) Susceptible Population stratum 3
D SPR=(1) Susceptible Population Ratio
D STIME=(YRS) Start TIME for the simulation
D TIME=(YRS) simulated TIME  -------->
D TRNIS=(P/YRS) Transfer Rate (total) to Non-Infectious State
D TSA=(P/YRS) Total Susceptible Activity
NOTE
NOTE OUTPUT CONTROL
NOTE
NOTE A PRTPER.K=1-STEP(0.75,1986)+STEP(0.75,1989)
C PRTPER=1
C DT=0.0625
C LENGTH=40
PRINT SP,HIVPOP,CAMR,CAP,DR,CD,AGGIRHIV
PRINT 2)CHECK1,CHECK2/7)CCC,PCINF
RUN HETEROGENEITY + FLAT PROFILE OF INFECTIVITY WITH EQUAL STAGES
A S1IT.K=1
A S2IT.K=6
A S3IT.K=1
RUN HETEROGENEITY+FLAT PROFILE OF INFECTIVITY WITH STAGES 1:6:1 YRS
C PIPPS1=0.06
C PIPPS2=0
C PIPPS3=0.12
RUN U-SHAPED PROFILE OF INFECTIVITY
A MNDP1.K=TABHL(MNDPT1,TIME.K,1986,1987.25,0.25)
T MNDPT1=1/0.9/0.8/0.7/0.6/0.5
A MNDP2.K=TABHL(MNDPT2,TIME.K,1986,1987.25,0.25)
T MNDPT2=6/5.4/4.8/4.2/3.6/3
A MNDP3.K=TABHL(MNDPT3,TIME.K,1986,1987.25,0.25)
T MNDPT3=36/32.6/29.25/25.8/22.5/15.75
D MNDPT1=(P/(P*YRS)) Mean Number of Different Partners:
* Table of values for stratum 1
D MNDPT2=(P/(P*YRS)) Mean Number of Different Partners:
* Table of values for stratum 2
```

```
D MNDPT3=(P/(P*YRS)) Mean Number of Different Partners:
* Table of values for stratum 3
RUN U-SHAPED PROFILE OF INFECTIVITY & CHANGING BEHAVIOUR
```

5 MODELLING A CORPORATE COLLAPSE: THE CASE OF LAKER AIRWAYS

5.1 Introduction

On 5 February 1982 there occurred in the United Kingdom a company collapse which was of major economic significance in the aviation industry and which came accompanied by a certain amount of human suffering. On that day, Laker Airways crashed with, it is said, debts in excess of £200m. As a firm selling direct to the public, hardly anyone in the U.K. had not heard of Laker Airways which, despite considerable pressure from the rival national carriers and even obstructionist policies by governments, had grown to such an extent that it offered serious competition to the other larger airlines on the normally prosperous N. Atlantic route.

But its collapse hit many of the people who were benefitting from Laker's idea of making it possible to fly to popular destinations at extremely low prices. Besides those holding Skytrain (the name Laker gave to the operation) tickets which instantly became worthless, others suffered the disappointment of having their outbound flight cut short; a DC-10 routing up over Scotland before turning to head over the Atlantic was called back to Gatwick airport as was an Airbus full of holidaymakers half way to Tenerife.

For those interested in the design of business policy, particularly financial policy, this corporate failure is an admirable case study which exhibits important features. The purpose of the model described below is to extract some of these features by explaining what happened and why it happened. Laker need not have failed; there is no doubting that. Some causal effects on Laker's financial position were exogenous, being associated with the economic environment. Yet these influences could possibly have been accommodated had they not compounded the difficulties ensuing from his other policies, particularly the speed of growth of the firm.

The model below describes the essential features of what happened. It is not based on material gleaned from academic journals but rather from quality newspapers (Economist, 1982a-c; Guardian, 1982a-c; Observer, 1982), Extel Unquoted Companies Services (1982) and a book written in popular style by two journalists (Eglin and Ritchie, 1982). The need to resort to these sources was unavoidable; they were the only sources available which contained any detail on the reasons for the collapse. However, it is often the case that material contained in quality newspapers and business magazines embodies essential information which enables the analyst to put together a useful dynamic model.

After discussion of the model, comment is made on the utility of system dynamics for illustration of a real life case study on policy design and consideration is given to what Laker might have done to improve his position.

5.2 The Model

The purpose of the model does not extend to reproducing the published accounts and balance sheets with a high degree of accuracy, although relevant variables from the company reports are included. It is felt that in the working model such variables exhibit values not totally out of line with the accounts. In any case, the official accounts for the final two critical years of operations are not available. The firm crashed almost two months away from its 1981-82 year end and at that time the return for the 1980-81 financial year still had not been made. The last published return (for 1979-80) was made on 21 January 1981.

Figure 5.1 shows the influence diagram for the overall system of interest.

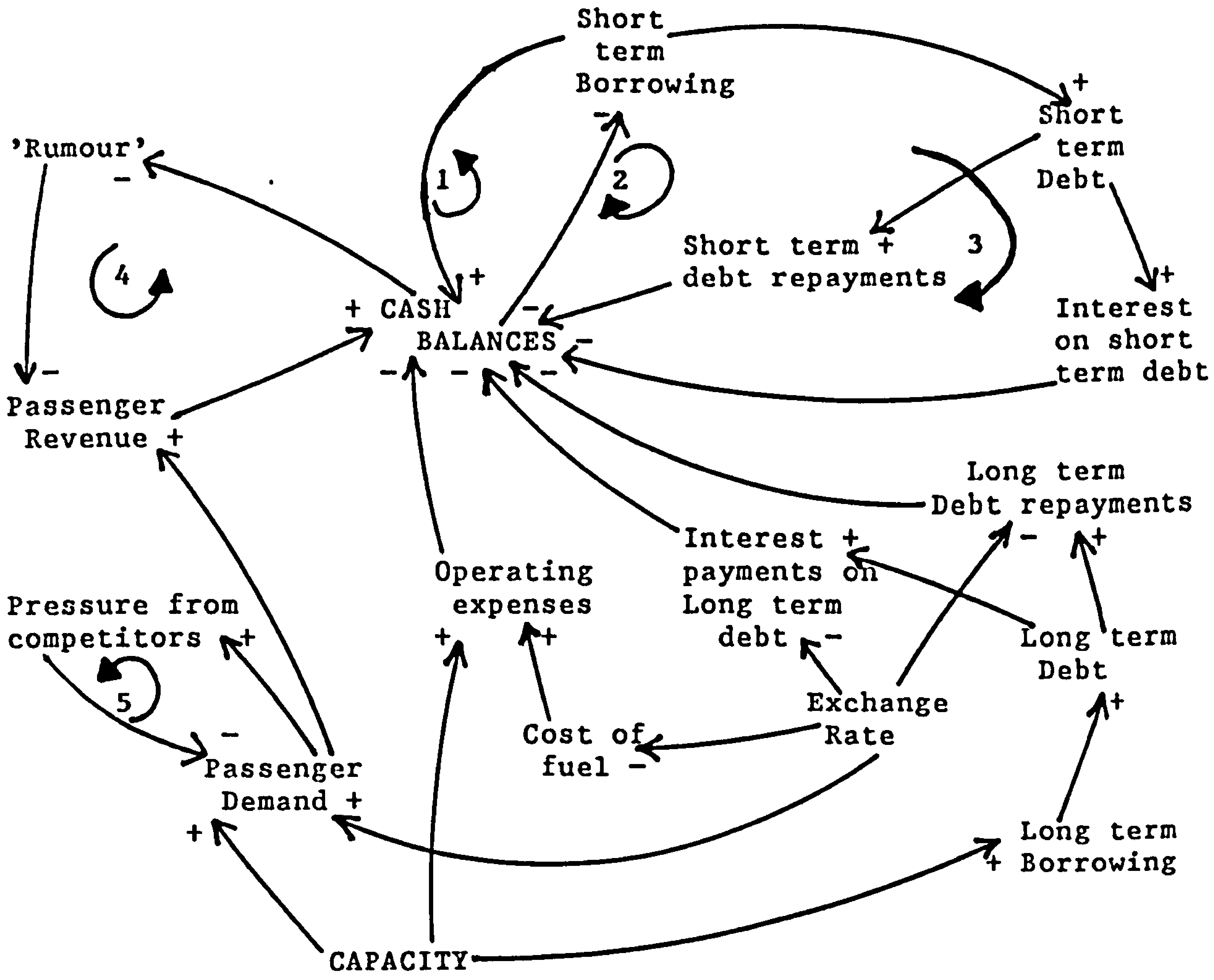

Figure 5.1 Influence diagram for the model

Capacity expansion drives the model. Laker expanded markedly over the years 1977-81 to become the fifth largest carrier on the transatlantic route. He did not exhibit a cautionary approach: with the low fares being charged he could fill his planes easily, especially during the peak Summer travel season.

He started with three wide-bodied DC-10's in 1977 and finished up owning around fifteen such jets including three European airbuses.

All of the new aircraft were financed by long term borrowing using the planes themselves as collateral. In the expansionary market at the time (and with the need to maintain the order books of national aircraft manufacturers) Laker found little trouble in persuading banks in America and Europe to lend him the money. However, these loans had to be repaid over ten years and during such a long period of time it is normal for an economic system to exhibit at least one, more probably two, cycles of activity (Lunt, 1975; Shearer, 1984). Laker did not survive the first downturn.

The diagram reflects the importance of the exchange rate to Laker. All his long term borrowing was denominated in dollars as were his fuel contracts. Thus the firm became progressively more exposed as the pound:dollar exchange rate fell steeply during 1981. This affected both repayments and interest on long term loans.

Loop 1 depicts how short term borrowing helped when cash became scarce, mainly during the final years of Laker's operations. But any form of borrowing involves repayments (loop 2) and interest (loop 3) and so is not something that can be thought of as the basis for a sound financial policy.

Loop 4 is a manifestation of a problem which any firm experiencing financial difficulties must dread, especially one like Laker which was providing a service to the public at large. It is the effect of rumour. In Laker's case, travel agents gradually became aware that they were dealing with an airline in a precarious position. Naturally, to protect their own and their client's interests they withheld revenue due to Laker until the very last minute. For Laker this extended delay in receiving revenue merely amplified his already weak financial position.

Travel agents had a role to play in the other feedback loop (loop 5) which was to have a major impact on Laker's ability to keep going; they could advise clients not to travel with Laker Airways. Not unnaturally, because of his spectacular growth (something like 50% per annum over four years), Laker came in for stiff competition from much larger carriers who were able to withstand offering cut price fares. Generally during 1981 the market for overseas travel was softening with increasing unemployment in the UK and a depreciating currency. The result was, for the first time Laker was operational on the UK - USA route, all the airlines were fighting over a diminishing market. The larger carriers started offering fares that matched or even undercut what Laker was charging. (Whether they did so in order to drive Laker out of business or in the spirit of free competition was the subject of a subsequent legal action by Laker.) His firm could not withstand this factor allied to the normal seasonal downturn and a Receiver was called in on 5 February 1982.

5.3 Results from the Model

Figure 5.2 illustrates the likely passenger demand experienced by Laker. Particularly during the Summer months it was up to available capacity. The fall off in demand in 1981-82 reflects the direct actions of competitors coupled with the more insidious effects of the fall in the pound against the dollar.

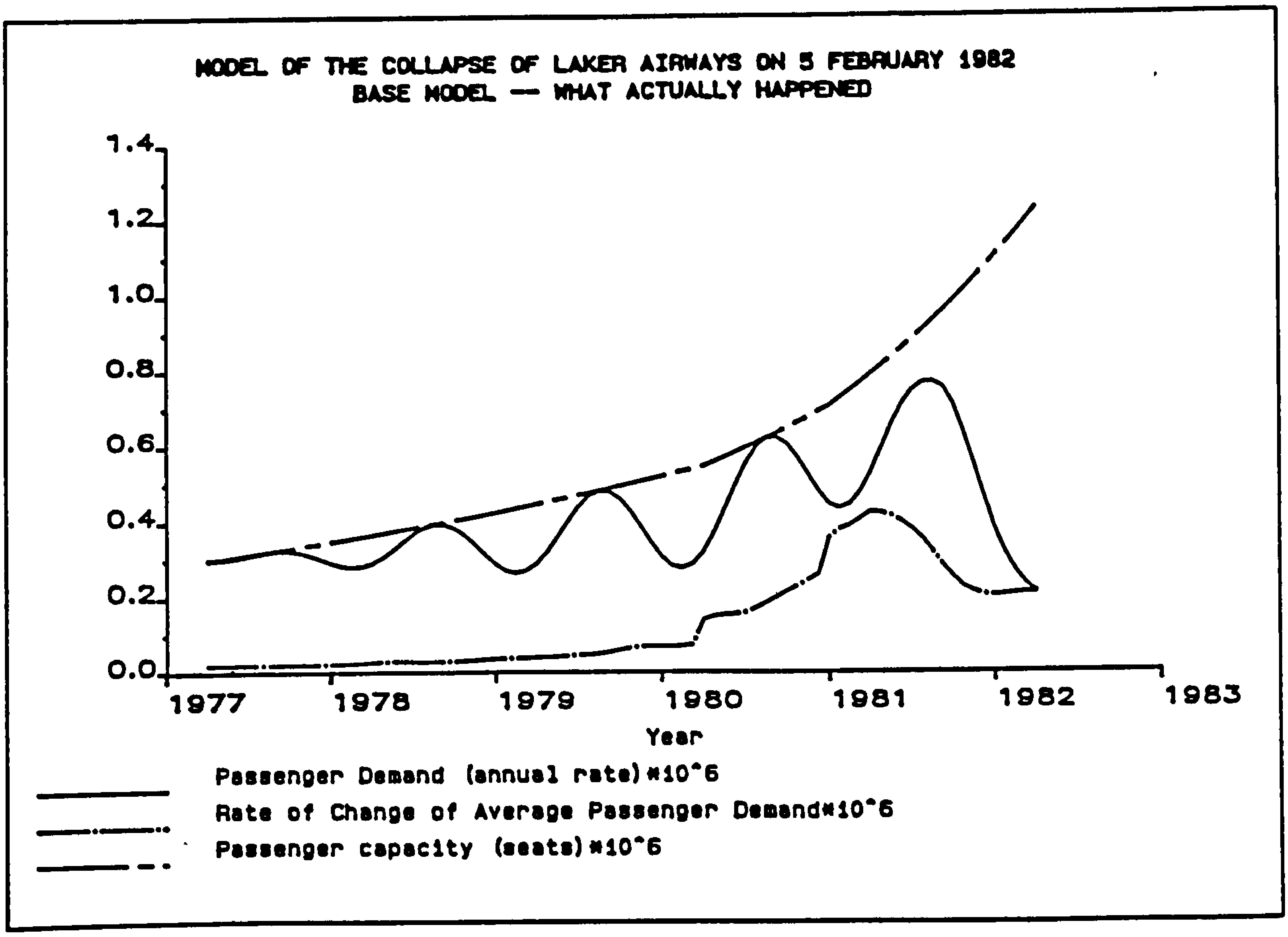

Figure 5.2 Passenger demand and capacity expansion

The effects of the slowdown in demand were obvious. Figure 5.3, depicting income and overall expenditure, shows a classic "twin squeeze" on company cash flow. As income was falling off (for the reasons outlined above and because travel agents were withholding payments due to Laker) expenditure was rising.

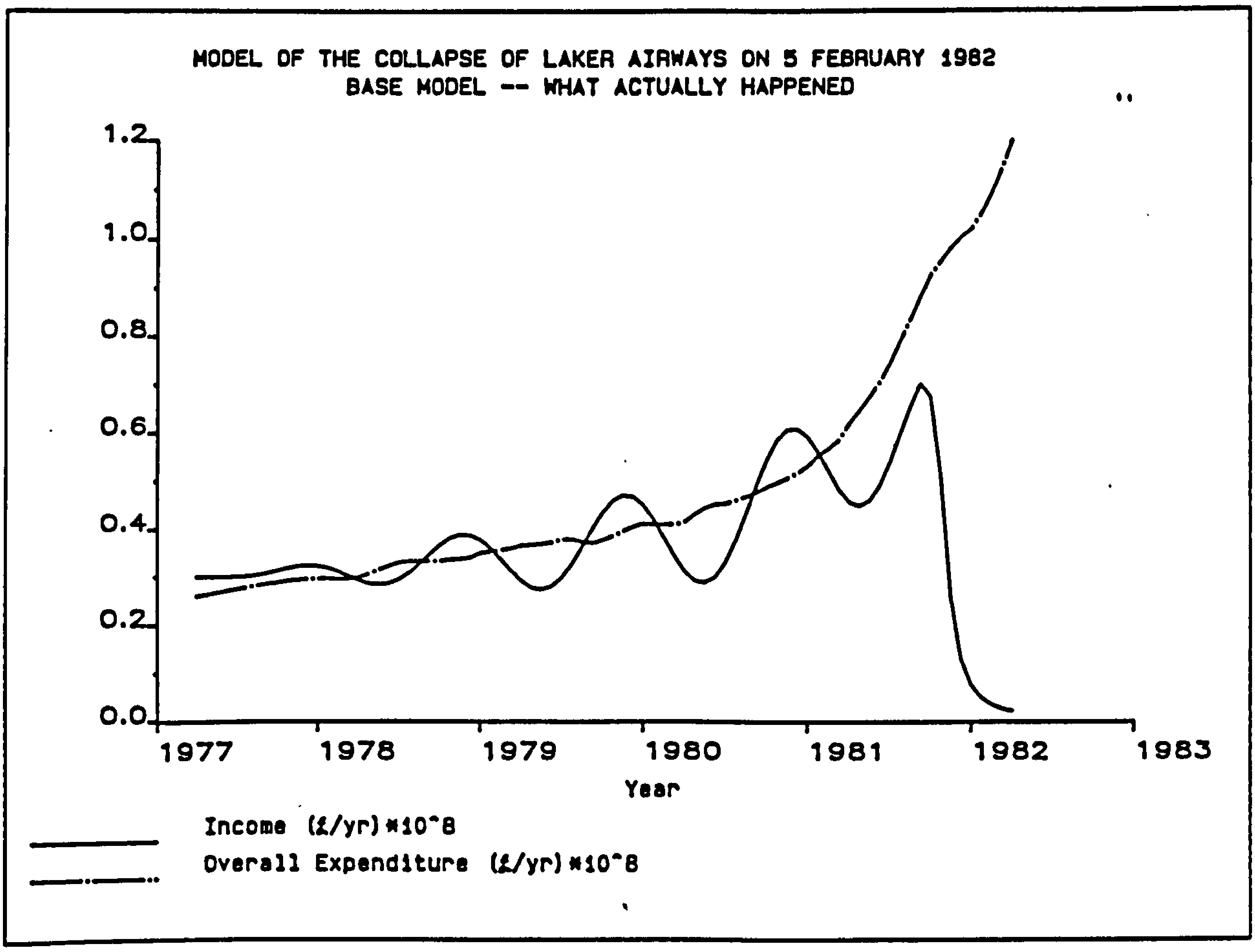

Figure 5.3 Laker's increasing expenditure simultaneous with decreasing income

Borrowing was being undertaken, in part, to sustain repayment of earlier debt. The rapid depreciation of sterling was pushing up both debt repayments and fuel costs denominated in dollars and a rise in bank Base Rate in late 1981 compounded the problems surrounding short term debt. The convolution of these two effects on the cash position of Laker Airways was alarming (figure 5.4).

An interesting topical analogy is with the (now frequent) drought situations in this country. The reason for the complete elimination of an inflow of water into the nation's reservoirs (cloudless skies) *is of itself* the reason why the outflow steps up. People take more frequent showers and desire to water their wilting garden lawns and flowers. In these circumstances, the intervening level variable (here literally the reservoir water level) can fall extremely rapidly. Hence the introduction of bans on the use of hosepipes.

The only difference between the situation Laker found itself in and the occurrence of a drought is that in the Laker case the causes of the increasing expenditure (cash outflow) were virtually simultaneously effecting a fall-off in revenue (cash inflow). In the drought situation the linkage is reversed; the falling inflow is simultaneously causing the rising outflow. However, the dramatic effect on the intervening level variable is the same.

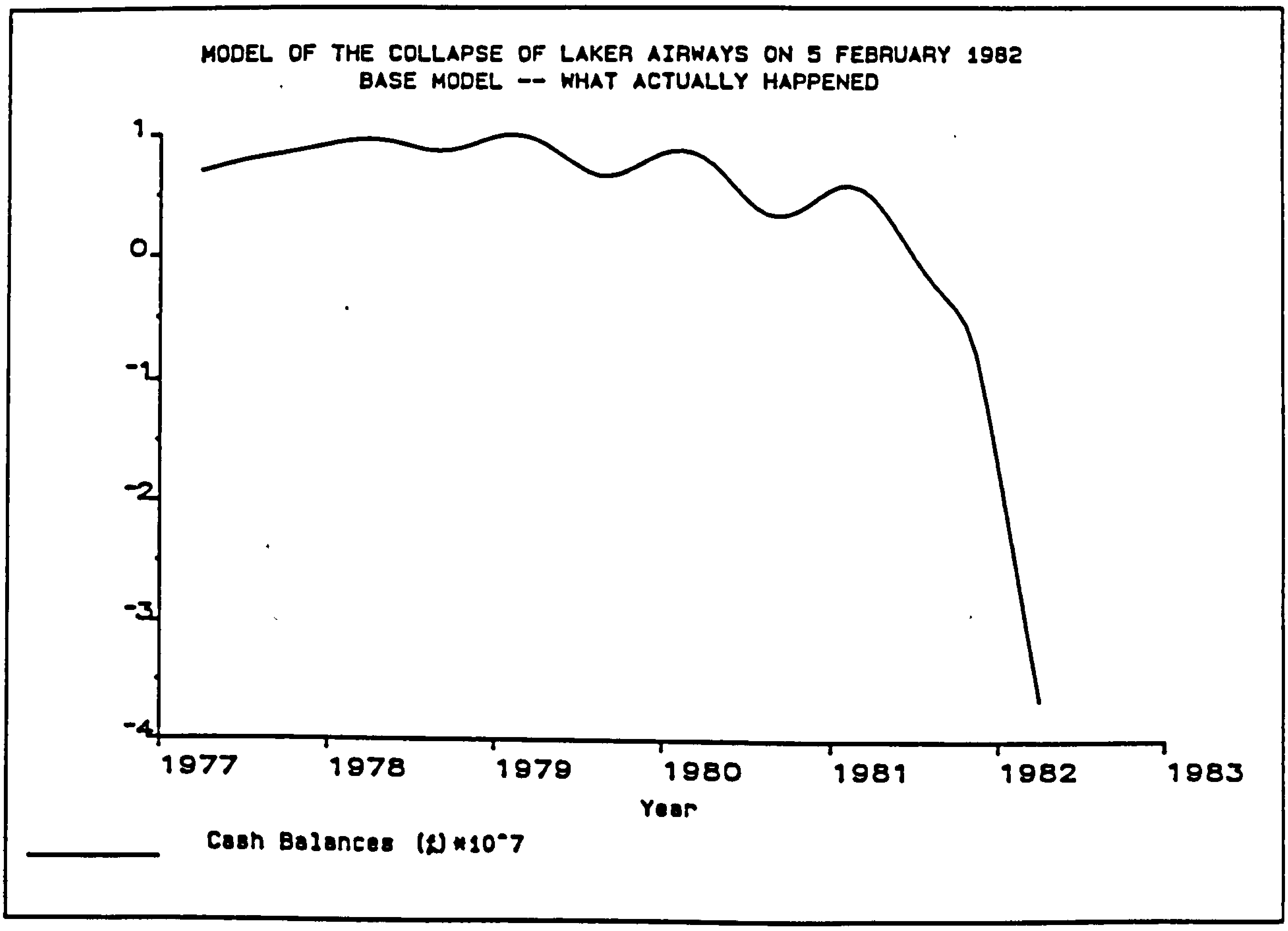

Figure 5.4 Laker's cash balances

5.4 The Model as a Teaching Tool

The case study is a popular tool for the teaching of business management. Pioneered at Harvard in the 1960's its use has spread worldwide. In the United Kingdom the Case Clearing House at Cranfield Institute of Technology holds many hundreds of cases which individual institutions can subscribe for. Few business schools eschew the use of case studies in courses on *Corporate Strategy* or *Business Policy*. A popular text associated with such courses is that by Christensen, Andrews and Bower (1987) now in its sixth edition. It was published originally in 1965.

Student groups typically spend several days studying the case material and then make a formal presentation to their tutor as to how they have analysed the 'scenario' they have been confronted with and, more pertinently, *what they would have done in the same situation.* It is at this point that the traditional case study approach loses its impact. There are no means of introducing a dynamic into the situation. Arguments about the effectiveness of the students' chosen course of action are hollow unless there is some way of putting hypotheses to the test.

With a computer simulation model those students are now at liberty to directly test out their chosen policies. This may transfer argument onto the adequacy of the model as a representation of the real life system. Nonetheless it is argued that this process, *of itself*, will improve their understanding of the complexities of business policy design far more potently than will a group discussion. Cognitive improvements in skills are of more substantial long term benefit.

It will also make the learning process more exciting. Apart from the vivid impact of the graphical results, a teaching tool is available which can be used to arbitrate on the various (possibly conflicting) policies coming out of the deliberations. There is now a better way of extracting relevant conclusions for policy design. The whole exercise is more fulfilling; more of a meaningful experience and less of an academic debate about what might have been.

This is not the first time that a system dynamics model has been formulated for the purpose of charting and evaluating a case study of a real-life organisation. Coincidentally, this earlier work also involved the rise and fall of a private corporation. In the 1970's Hall (1976) developed a system dynamics model reflecting a 20-year history of the old *Saturday Evening Post,* at one time one of the most profitable weekly magazines in the United States. After almost a decade of dwindling fortunes, it ceased publication in January 1969.

The Laker Airways case is obviously one which, primarily, has a strong financial undercurrent and it could be most profitably employed in the teaching of corporate financial policymaking. Laker induced his company into a financial condition sustainable only in a growing market. His chosen policy of rapid expansion based largely on borrowed money hemmed him in. It is perhaps a neat example of the concept of 'organisational origami' posited by Hall (1984). Laker's financial straightjacket might be included in a discussion of gearing ratios prefaced by consideration of material in Wright's book (1980) on financial management from which the following quote is extracted (p.156).

> *"...... Overborrowing ...... is not untypical of the business which is started on a shoestring by one or two individuals with no capital and partly explains their high failure rate. The years until profit retentions have considerably broadened their equity base are critical."*

Borrowing per se is not a poor policy. But continuous borrowing without consideration of possible vulnerability in a cyclical downturn is. Figures 5.5 and 5.6 show the effect of a policy of slower growth. In fact, this merely eliminates the spurts in Laker's borrowing which occurred in 1980 and 1981 when he purchased over ten new jets. The results suggest a containable situation and one that was likely to see the firm through the subsequent downturn.

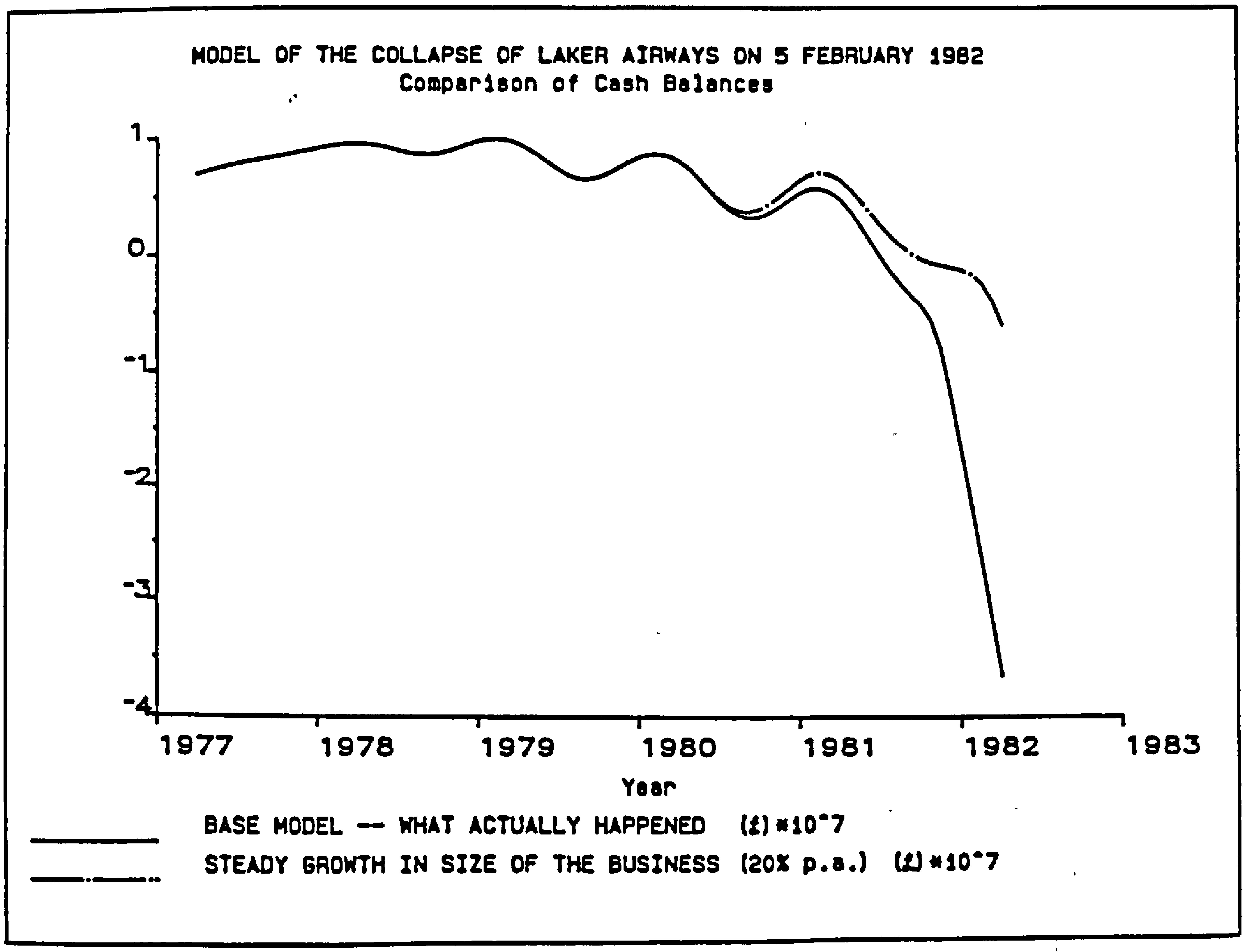

Figure 5.5 Comparison of cash balances under two rates of growth

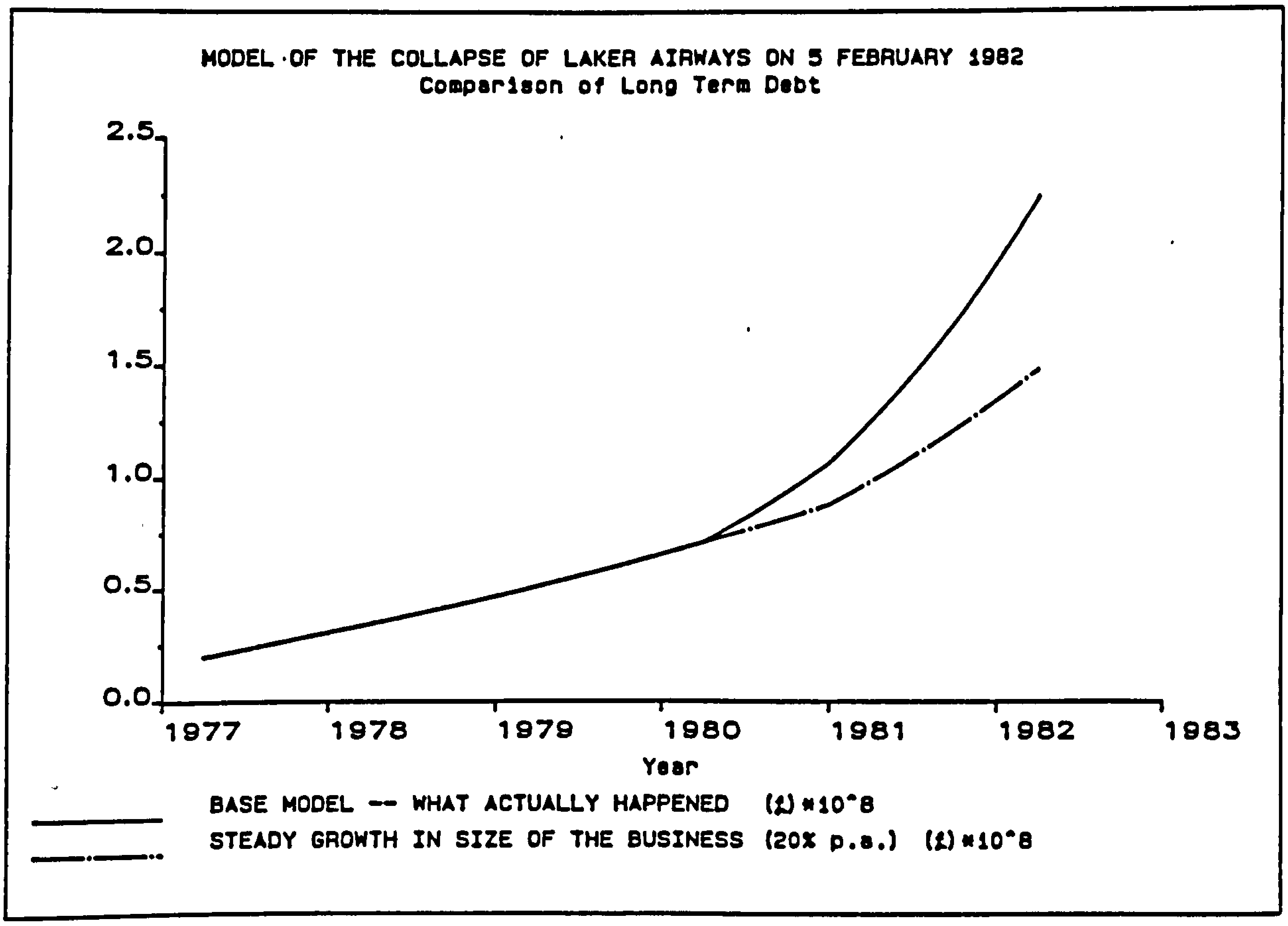

Figure 5.6 Comparison of long term debt under two rates of growth

In this context it is worth recording a recent comment by Richard Branson founder of Virgin Atlantic, another example of a small airline offering competitively priced tickets to popular destinations and which has emerged since Laker's demise. He stated:

> *"Airlines should be kept small and personal. We want no more than 10 major routes and a dozen 747 planes. If ever I get bigger, hold my head under cold water. I hope I have learnt from Laker's mistakes."*

Whether he has learnt from *all* of Laker's mistakes remains to be seen. Virgin Atlantic also has a significant amount of debt at the present time, just when the economic cycle is taking a turn for the worse.

An exogenous factor which was important for Laker's financial policy was the rate of exchange of the dollar to the pound. While this was high, Laker enjoyed the benefits of lower long term debt repayments and fuel costs. Figure 5.7 illustrates a situation that could never have happened. Here is shown the consequences for long term debt repayment of a constant rate of exchange of 2.2 dollars to the pound. For the student of financial policy though it offers a desirable method of projecting the comparative effect of anticipating using an average (as financial managers are apt to do) and anticipating by allowing for some dynamics around that average.

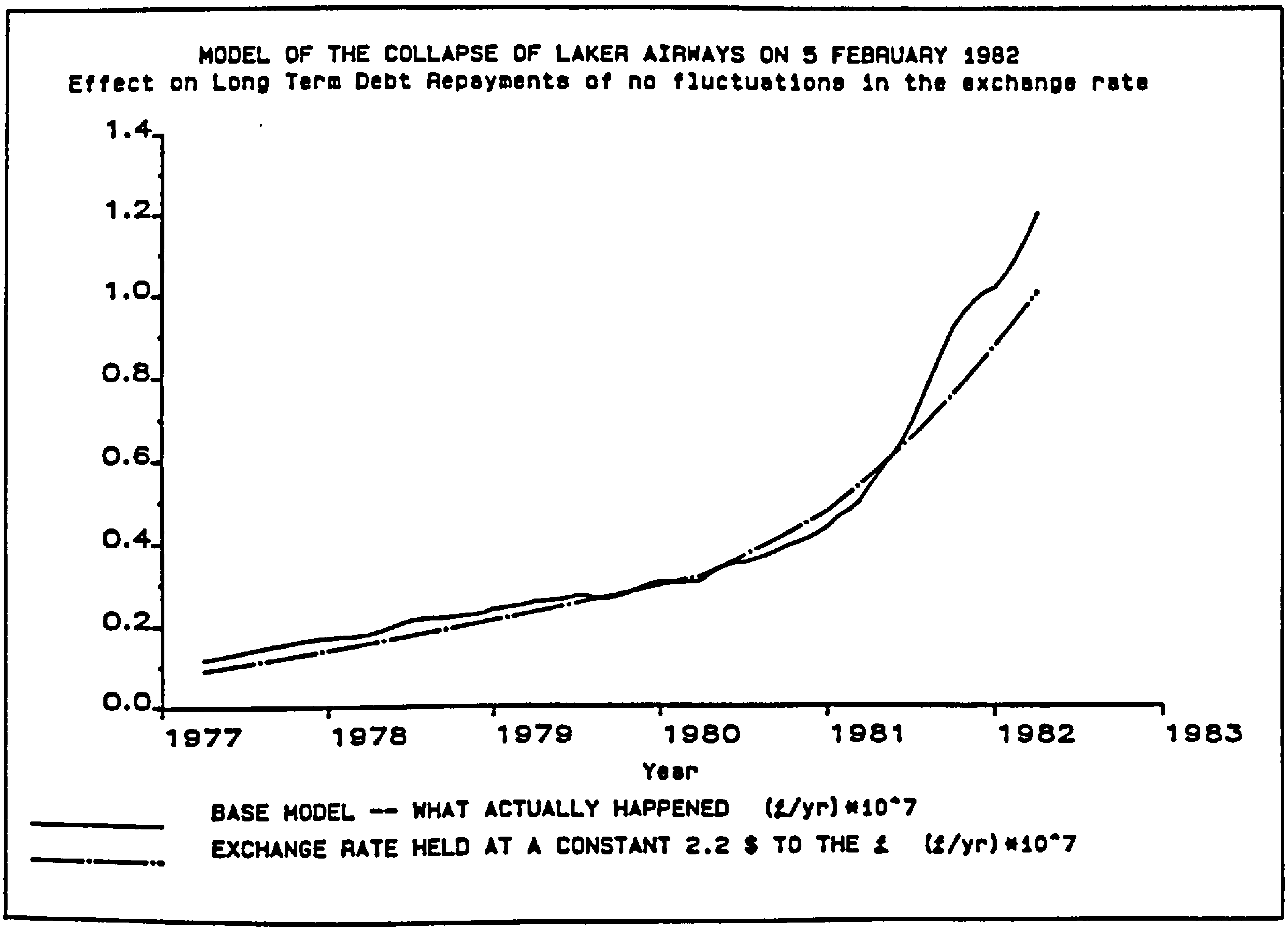

Figure 5.7 Long Term Debt Repayment under (i) actual and (ii) constant rates of exchange

Of course back in 1977 the Laker management would not have known the actual figures (plotted as a comparator in figure 5.7) but a number of plausible cycles around the assumed average could have been evaluated easily using the model and in this way a prudent value to specify for currency fluctuation reserves would have been available. Recognition of the timing of the previous exchange rate downturn (1976) might have indicated the need for substantial currency fluctuation reserves in the early 1980's. This possibility, of itself, ought to have cautioned the firm against an exposed debt structure around that time.

5.5 Conclusion

The foregoing has demonstrated the need to enhance the teaching of business policy by recourse to a model of a real life case study. While the traditional (reasoned discussion) case study approach has some merit, it does tend to perpetuate the distinctly non-quantitative approach to policy design which is quite widespread. Perhaps more models of this nature will help persuade those responsible for strategic policy that the computer really can help them animate their thinking.

REFERENCES FOR CHAPTER 5

C R CHRISTENSEN, K R ANDREWS and J L BOWER (1987) *"Business Policy: Text and Cases"*, 4th Edn., R D Irwin, Illinois.

ECONOMIST (1982a) *"The Laker Legacy"*, 13 February.

ECONOMIST (1982b) *"Sir Freddie's creditors join the used aircraft business"*, 13 February.

ECONOMIST (1982c) *"Little man's big debts"*, 13 February.

R EGLIN and B RITCHIE (1982) *"Fly Me I'm Freddie!"*, Futura Macdonald & Co., London.

EXTEL UNQUOTED COMPANIES SERVICE (1982) *Laker Airways (International) Ltd; LAA-Q 51*, updated to 10 February.

GUARDIAN (1982a) *"6,000 stranded as Laker crashes owing £210m"*, 6 February.

GUARDIAN (1982b) *"Banks and airlines fear 'domino' effect from Laker Airways crash"*, 6 February.

GUARDIAN (1982c) *"The Laker legend - and legacy"*, 6 February.

R I HALL (1976) "A System Pathology of an Organisation: the Rise and Fall of the old Saturday Evening Post", *Administrative Science Quarterly*, 21, 185-211.

R I HALL (1984) "The Natural Logic of Management Policy Making: its implications for the Survival of an Organisation", *Management Science*, 30, 905-927.

S T LUNT (1975) "Trade cycling in U.K. industry", *Measurement and Control*, 8, 152-156.

OBSERVER (1982) *"Laker's last standby"*, 7 February.

P R SHEARER (1984) "Cycles in business planning", *Transactions of the Institute of Measurement and Control*, 6, 27-32.

M G WRIGHT (1980) *"Financial Management"*, 2nd Edn., McGraw Hill, London.

LISTING OF THE MODEL

```
* MODEL OF THE COLLAPSE OF LAKER AIRWAYS ON 5 FEBRUARY 1982
NOTE
NOTE
NOTE  PASSENGER DEMAND
NOTE
NOTE
A P_DEM.K=(AVP_DEM.K+AMPSD.K*SIN(2*PI*(TIME.K-(STIME+PSLS))/SF))*
X MCOMP.K
C PI=3.141592654
C SF=1
C PSLS=0.125
A AMPSD.K=(PCAP.K-AVP_DEM.K)
L AVP_DEM.K=AVP_DEM.J+DT*RCAVP_DEM.JK
N AVP_DEM=300E3
R RCAVP_DEM.KL=AVP_DEM.K*PCAPGR.K*MEXCH.K
A MEXCH.K=TABLE(MEXCHT,PREXCH.K,1.5,2.5,0.125)
T MEXCHT=0.2/0.28/0.36/0.47/0.6/0.8/1.08/1.44/2
A PREXCH.K=SMOOTH(REXCH.K,TPCEXCH)
C TPCEXCH=0.25
A MCOMP.K=TABHL(MCOMPT,SPCAP.K,0.5E6,1.2E6,0.1E6)
T MCOMPT=1/1/0.93/0.78/0.51/0.29/0.15/0.13
A SPCAP.K=SMOOTH(PCAP.K,TCRLG)
C TCRLG=0.5
A REXCH.K=TABLE(REXCHT,TIME.K,1977.25,1982.25,1/12)
T REXCHT='EXCH.DAT'   External file
NOTE
NOTE
NOTE  PASSENGER CAPACITY
NOTE
NOTE
L PCAP.K=PCAP.J+DT*CAPEXP.JK
N PCAP=CAP_INIT
C CAP_INIT=300E3
R CAPEXP.KL=PCAP.K*PCAPGR.K
A PCAPGR.K=PCAPGR_INIT+STEP(ACAPGR1,TACAPGR1)+STEP(ACAPGR2,TACAPGR2)
C PCAPGR_INIT=0.2
CP ACAPGR1=0.15
C TACAPGR1=1980.25
CP ACAPGR2=0.1
C TACAPGR2=1981
S LF.K=P_DEM.K/PCAP.K
NOTE
NOTE
NOTE  CASH FLOWS & CASH BALANCES
NOTE
NOTE
L CB.K=CB.J+DT*(P_REV_RL.JK+STL.JK-INT_PAY.JK-LTDR_PND.JK-STDR.JK
X -OPEXP.JK)
N CB=7E6
S NCF.K=P_REV_RL.KL+STL.KL-INT_PAY.KL-LTDR_PND.KL-STDR.KL-OPEXP.KL
A P_REV.K=P_DEM.K*AVFARE
C AVFARE=100
```

```
R P_REV_RL.KL=DELAY3(P_REV.JK,PAY_DEL.K)
A PAY_DEL.K=TABXT(PAY_DELT,SCB.K,-3E6,1E6,1E6)
T PAY_DELT=1/0.46/0.3/0.25/0.25
A SCB.K=SMOOTH(CB.K,DRTLF)
C DRTLF=0.25
R OPEXP.KL=PCAP.K*OCPS.K
A OCPS.K=FCPS/REXCH.K+NFCPS
C FCPS=90
C NFCPS=25
S INCOME.K=P_REV_RL.KL
S EXPEND.K=INT_PAY.KL+LTDR_PND.KL+STDR.KL+OPEXP.KL
NOTE
NOTE
NOTE  LOANS & DEBT (LONG TERM AND SHORT TERM)
NOTE
NOTE
L LTDEBT.K=LTDEBT.J+DT*(LTL.JK-LTDR.JK)
N LTDEBT=20E6
R LTL.KL=CAPEXP.KL*CCWBA/AACWBA
A CCWBA.K=CCD
C CCD=45E6
C AACWBA=172500
R LTDR.KL=LTDEBT.K/RTLTDEBT
C RTLTDEBT=10
R LTDR_PND.KL=LTDEBT.K*(1/REXCH.K)/RTLTDEBT
R INT_PAY.KL=LTDEBT.K*IRLTDEBT/(100*REXCH.K)+STDEBT.K*IRSTDEBT.K/100
C IRLTDEBT=10.2
S GEAR_R.K=TOTDEBT.K/(EQUITY+RESERVES)
C EQUITY=5E6
C RESERVES=20E6
A IRSTDEBT.K=TABLE(IRSTDEBTT,TIME.K,1977.25,1982.25,1/12)
T IRSTDEBTT='INT.DAT'  External file
L STDEBT.K=STDEBT.J+DT*(STL.JK-STDR.JK)
N STDEBT=500E3
R STDR.KL=STDEBT.K/RTSTDEBT
C RTSTDEBT=2
R STL.KL=ABS(MIN(CB.K/TECD,ZEROSTL))
C TECD=1
C ZEROSTL=0
A TOTDEBT.K=LTDEBT.K/REXCH.K+STDEBT.K
NOTE
NOTE
NOTE  DEFINITION STATEMENTS
NOTE
NOTE   P = Passengers  (seats in the context of capacity)
NOTE
NOTE  PS = Pounds(£) Sterling
NOTE
NOTE   A = Aircraft
NOTE
D AACWBA=(P/(YR*A)) Average Annual Capacity of a Wide
* Bodied Aircraft
D ACAPGR1=(1/YR) Additional CAPacity Growth Rate phase 1
D ACAPGR2=(1/YR) Additional CAPacity Growth Rate phase 2
D AMPSD=(P/YR) AMPlitude of Seasonality in Demand
D AVFARE=(PS/P) AVerage FARE paid by passengers
D AVP_DEM=(P/YR) AVerage Passenger DEMand
D CAPEXP=(P/(YR*YR)) CAPacity EXPansion
D CAP_INIT=(P/YR) CAPacity INITially
D CB=(PS) Cash Balances
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D CCD=($/A) Capital Cost in Dollars
D CCWBA=($/A) Capital Cost of a Wide Bodied Aircraft
D DRTLF=(YR) Delay in Response by Travel trade to Laker's
* Financial position
D DT=(YR) simulation time step
D EQUITY=(PS) EQUITY held by the company
D EXPEND=(PS/YR) overall EXPENDiture
D FCPS=($/P) Fuel Cost Per Seat (passenger)
D GEAR_R=(1) GEARing Ratio
D INCOME=(PS/YR) overall INCOME
D INT_PAY=(PS/YR) INTerest PAYments
D IRLTDEBT=(1/YR) Interest Rate on Long Term DEBT
D IRSTDEBT=(1/YR) Interest Rate on Short Term DEBT
D IRSTDEBTT=(1/YR) Interest Rate on Short Term DEBT:
* Table of values
D LENGTH=(YR) duration of the simulation
D LF=(1) Load Factor
D LTDEBT=($) Long Term DEBT
D LTDR=($/YR) Long Term Debt Repayment
D LTDR_PND=(PS/YR) Long Term Debt Repayment in PouNDs
D LTL=($/YR) Long Term Lending
D MCOMP=(1) Multiplier from effect of actions of COMPetitors
D MCOMPT=(1) Multiplier from effect of actions of COMPetitors:
* Table of values
D MEXCH=(1) Multiplier from effect of EXCHange rate
D MEXCHT=(1) Multiplier from effect of EXCHange rate:
* Table of values
D NCF=(PS/YR) Net Cash Flow
D NFCPS=(PS/P) Non-Fuel Costs Per Seat (passenger)
D OCPS=(PS/P) Operating Cost Per Seat
D OPEXP=(PS/YR) OPerating EXPenditure
D PAY_DEL=(YR) PAYments DELay by travel trade
D PAY_DELT=(YR) PAYments DELay by travel trade: Table of values
D PCAP=(P/YR) Passenger CAPacity
D PCAPGR=(1/YR) Passenger CAPacity Growth Rate
D PCAPGR_INIT=(1/YR) Passenger CAPacity Growth Rate INITially
D P_DEM=(P/YR) Passenger DEMand
D PI=(1) dimensionless constant
D PREXCH=($/PS) Perceived Rate of EXCHange by travel customers
D P_REV=(PS/YR) Passenger REVenue
D P_REV_RL=(PS/YR) Passenger REVenue Received by Laker's bank
D PRTPER=(YR) PRinTing PERiod
D PSLS=(YR) Phase Shift for Laker's Seasonality
D RCAVP_DEM=(P/(YR*YR)) Rate of Change of AVerage Passenger DEMand
D RESERVES=(PS) RESERVES accumulated from previous profits
D REXCH=($/PS) Rate of EXCHange -- $ to £
D REXCHT=($/PS) Rate of EXCHange: Table of values
D RTLTDEBT=(YR) Repayment Term on Long Term DEBT
D RTSTDEBT=(YR) Repayment Term on Short Term DEBT
D SCB=(PS) Smoothed Cash Balances
D SF=(YR) Seasonality Factor
D SPCAP=(P/YR) Smoothed Passenger CAPacity
D STDEBT=(PS) Short Term DEBT
D STDR=(PS/YR) Short Term Debt Repayments
D STIME=(YR) Start TIME for the simulation
D STL=(PS/YR) Short Term Lending
D TACAPGR1=(YR) Time of Additional CAPacity Growth Rate phase 1
D TACAPGR2=(YR) Time of Additional CAPacity Growth Rate phase 2
D TCRLG=(YR) Time for Competitors to Respond to Laker's Growth
D TECD=(YR) Time to Eliminate Cash Deficit
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D TIME=(YR) years  ------->
D TOTDEBT=(PS) TOTal DEBT
D TPCEXCH=(YR) Time to Perceive Changes in the EXCHange rate
D ZEROSTL=(PS/YR) ZERO Short Term Lending
NOTE
NOTE
NOTE  OUTPUT CONTROL STATEMENTS
NOTE
NOTE
N TIME=STIME
C STIME=1977.25
C DT=0.0625
C LENGTH=5
C PRTPER=0.5
PRINT 1)P_DEM,AVP_DEM,RCAVP_DEM,AMPSD,LF
PRINT 2)MEXCH,MCOMP,REXCH,PREXCH,INCOME,EXPEND
PRINT 3)PCAP,SPCAP,CAPEXP,PCAPGR
PRINT 4)NCF,P_REV,STL,INT_PAY,LTDR_PND,OPEXP,STDR
PRINT 5)P_REV_RL,PAY_DEL,OPEXP,OCPS,CB,SCB
PRINT 6)LTDEBT,LTL,LTDR,LTDR_PND,GEAR_R
PRINT 7)IRSTDEBT,STDEBT,STL,TOTDEBT
RUN BASE MODEL -- WHAT ACTUALLY HAPPENED
C ACAPGR1=0
C ACAPGR2=0
RUN STEADY GROWTH AT 20% PER ANNUM
T REXCHT=61*2.2
RUN EXCHANGE RATE AT 2.2 DOLLARS TO THE POUND
```