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STUDIES OF THE USE OF
INDUSTRIAL DYNAMICS MODELS
IN THE BRITISH STEEL CORPORATION

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Summary

The research described was carried out for Strip Mills Division, British Steel Corporation. The work consisted of the application and analysis of the Industrial Dynamics method of continuous system simulation. The material and information feedback relationships within the Division and between itself and the market were simulated using different model structures and computer programs.

The study indicates that I.D. captures the essentials of modelling industrial feedback structures through the use of a consistent notation for describing and simulating socio-economic systems. It also suggests that to obtain useful results, the dynamic behaviour and its cause must be known prior to the model construction. I.D., however, offers a means of demonstrating the behaviour of these causal networks free of extraneous disturbances. It aids insight into the detailed causes, rather than the discovery of new forms or sources, of the dynamic behaviour. It permits an analysis of the sensitivity of the system to parameter or structural changes and can indicate the likely dynamic behaviour created by alternative procedures and policies.

The approach and notation of I.D. are discussed. Alternative Continuous System Simulation Languages, their development, limitations and computer requirements are compared with the I.D. compiler, DYNAMO. Many variables in the steel industry can take only discrete values and appear to be quantised. Quantisation and sampling of variables were built into a special purpose compiler for the study. The method and results are discussed.

The models constructed during the study are reviewed and two detailed case studies are analysed. A material flow process model of a steel works is shown to demonstrate production "waves" and process timing problems. A model of the Division - Market interface demonstrates the amplification of demand and the consequences of alternative marketing and counter cyclic stocking policies. It shows that by stockholding the Division could stabilise production and gain an export market of £5.6 m in a peak year.

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1. Introduction

The research involved the study of the approach known as "Industrial Dynamics". The title derives from J. W. Forrester's book Industrial Dynamics (1), which describes a method of simulating the dynamics of business systems. The method was novel at the time mainly because it provided a user oriented simulation language. It brought to management science a method which was both quantitative and visual for simulating the consequences of policy decisions.

1.1 Purpose of the Research

It was intended that the Industrial Dynamics approach be applied within the Corporation and that the cost and effort required be compared with the potential benefits. The following objectives of the study were set out in October 1969.

- . To demonstrate how a large scale (I.D.) model is constructed.
- . To analyse the application of I.D. models to planning and system design.

1.2 Industrial Dynamics - Definition

"Industrial Dynamics recognises a common systems base in the flow structure of all social-economic-industrial-political organisations. This perspective ties the segmented functional aspects of formal organisations into an integrated structure of varying rates of flow and responsively changing levels of accumulation. The flow paths involve all facets of organisational

resources - men, money, materials, orders and capital equipment - and the information and decision making network that links the other flows" (2).

The approach is based upon a descriptive notation and a continuous system simulation method utilising a special purpose simulation program; DYNAMO. The research group at M.I.T. where I.D. was developed, have been renamed the Systems Dynamics Group. In the last few years the applications have broadened into urban renewal (3), research and development (4), social services and ecology (5). The approach has become known as System Dynamics.

The thesis retains the term "Industrial Dynamics" to indicate the original intention of evaluating it in terms of its use in planning and policy decisions in industry, particularly the British Steel Corporation. It was not the intention to consider the non-industrial applications of the approach.

1.3 Organisation of the British Steel Corporation.

During the period of the research the organisation of the British Steel Corporation has changed. These changes created some difficulties with the research, particularly during the first, crucial, eighteen months. Senior Managers were absorbed with preparing facilities, developing procedures and establishing lines of communication and were less involved with the longer term analysis of capital investment, pricing or market dynamics.

Vesting date for the British Steel Corporation was 28th July, 1967. It was initially split into four main Groups; Midland, Northern and Tubes, Scottish and North-west, and South Wales (6). The research commenced in January 1970 for the South Wales Group which made flat rolled products; sheet steel for car bodies and tinsplate for cans, for example.

On 11th March, 1969 the Second Report on Organisation (7) proposed the formation of product divisions. In December 1969 the Third Report on Organisation (8) divided the Corporation into four steel making Divisions; General Steels, Special Steels, Tubes and Strip Mills. The South Wales Group became absorbed into Strip Mills Divisions when the divisional structure was implemented in March 1970. The research was continued for Strip Mills Management Services from March 1970.

1.4 Strip Mills Division - Organisation and Products.

In the 1972/73 financial year Strip Mills Division delivered 6.7 million tonnes of flat rolled steel to the home market and 1.6 million tonnes for export. In terms of crude steel production the Division produced 31% of the Corporation's total of 24 million tonnes. Ranked by the tonnage produced, Strip Mills Division is the second largest in the Corporation, producing virtually all the U.K. Sheet and Tinsplate delivered and employing 64,000 people. It includes the five main integrated steel works at Port Talbot, Llanwern,

Ebbw Vale (all in South Wales and previously forming the South Wales Group), Shotton (North Wales) and Ravenscraig (Scotland). It also includes the tinsplate works at Trostre and Velindre (South Wales).

Steel is made from iron ore, limestone and coal (as coke). The steel is cast as ingots which are reheated to a uniform temperature before rolling into slabs. The slabs are then hot rolled into coiled sheets. The sheet steel may take many routes. It may be sold or transferred to the tinsplate works. It may be cold reduced (cold rolled) or galvanised. Additionally it may be acid etched for cleaning (pickled), annealed or cut up.

1.5 Type of Models.

Prior to the commencement of the study some consideration was given to the type of models possible and for whom the study should be conducted. It was recognised that I.D. was not a procedure for simulating discrete items or events but had a continuous system formulation basis. Further it emphasised the significance of feedback systems incorporating both material and information flows and was unusual in providing a computer program which permitted and checked the validity of sets of interconnected (feedback) equations.

Forrester's claim that it was most useful for simulating the consequences, in broad terms, of policy decisions appeared to align with the few known applications at the time (9, 10, 11). It was agreed that the study

would be conducted at a senior management level and involve an assessment of new policies and procedures.

1.6 "Process" and "Policy" Models.

I.D. models demonstrate time varying behaviour created by control procedures and feedback relationships, whether deliberate or unintentional. The I.D. approach assumes two types of variable; Rates of flow and accumulated values (Levels). Figure 1 shows a simple I.D. feedback structure.

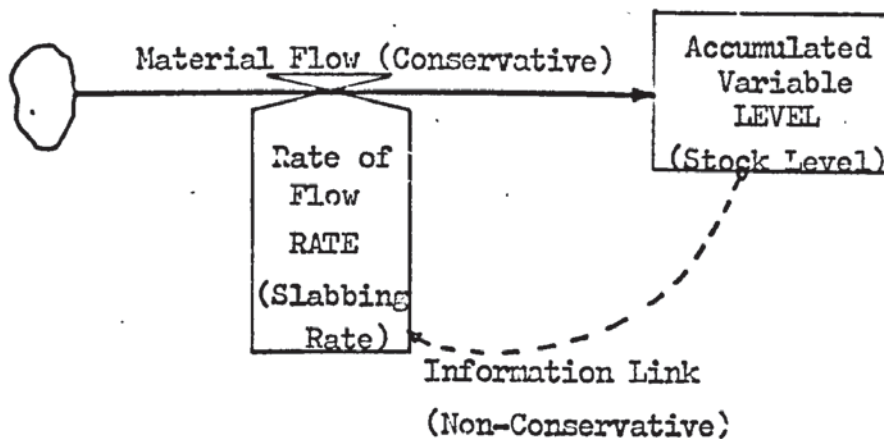


Figure 1 Basic I.D. Feedback Structure.

The integral or level variable (state of the system) and the rate of flow (action variable) are linked by two types of flow path; the conservative, material, flows (non-compressible) and the non-conservative, information (compressible) paths. I.D., therefore, simulates both the conservative (material) flow systems and the non-conservative (information) control procedures. The material and information paths in the

models are distinct and it was thought that they may themselves influence the type of dynamic behaviour created. Some I.D. models have concentrated on the material flow system using simple and usually local control procedures. Others, like Forrester's Corporate Growth Model (12, 13) simulate the major information and decision processes in the business.

The models created were deliberately classed as "Policy" (decision and information) and "Process" (Orders and Materials in the Production Flow System) models. There can be no clear boundary between these models but the distinction has been found to be more important than originally thought.

The "Process" models depend on the dynamic behaviour of a conservative flow process. Because the system is conservative, input rates and output rates cannot differ for long periods. The dynamic behaviour exhibited tends to be of short duration and not dramatic. The "Policy" models primarily use non-conservative networks with long time constants. These models are often able to sustain widely varying values that are capable of large oscillations or growth dynamics.

1.7 Structure of the Thesis.

The principles and notation of Industrial Dynamics are discussed in Chapter 2. The research method and the development of the models is outlined in Chapter 3 and two case studies are analysed in Chapters 4 and 5.

The computer programs and languages suitable for I.D. simulations and those used in the research are discussed in Chapter 6. Quantisation and sampling have been incorporated into a special purpose simulation package, the results of which are illustrated in Chapter 7. The conclusions regarding the costs, effort and potential benefits of the approach are included in Chapter 8.

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2. Principles, Methodology and Notation

This chapter reviews the principles, assumptions and recommended procedures for an I.D. study. It covers the type of problem that I.D. can address and includes discussions of the notation and problems of validation.

2.1 Principles of Industrial Dynamics

Relatively little has been said about the underlying assumptions or principles upon which I.D. is based. It has been claimed by Forrester (1) that I.D. incorporates a theory of systems. Furthermore much of I.D. material suggests that it is the theory of systems. It is therefore important to discover these principles and determine their generality and relevance to the analysis of industrial systems.

A source for material on the principles underlying Industrial Dynamics is Forrester's "Principles of Systems" (14). This book, written in 1968, has been reprinted and revised but is claimed to be a third of a complete book on the principles of system dynamics. Much of the book is hortatory and descriptive. Half of it is a work book and many of the "principles" relate directly to the continuous system simulation method used. Some of the "principles" relate the behaviour of first and second order continuous control systems; the time periods of exponential and simple oscillatory systems.

Of prime importance, however, are those principles which are fundamental to I.D. and distinguish it from other approaches. The principles identified below have been condensed from "Principles of Systems" (14), "Industrial Dynamics" (1), "Industrial Dynamics - After the First Decade" (15) and

"Modelling the Dynamic Processes of Corporate Growth" (12).

I.D. assumes:

- The use of dynamic simulation models
- Deterministic, identifiable structures
- Feedback structures causing dynamic behaviour
- A State-Space formulation
- A continuous variable formulation

2.1.1 Dynamic Simulation Method

I.D. assumes that time varying behaviour is of prime importance. It assumes that this behaviour cannot be reliably understood without the coding and execution of a dynamic model. Forrester (1) also states that the models will often produce unexpected behaviour giving an insight into the potential behaviour of the real system. It further assumes that the dynamic behaviour can be advantageously altered in the model and that these advantages can be transferred to the real system.

2.1.2 Deterministic Structures

I.D. assumes that there are causal relationships which can be analysed and modelled. The model cannot be created if the relationships are random or unknown. The relationships must additionally be quantifiable although it is claimed that the quantification need not be precise.

2.1.3 Feedback Structures

I.D. assumes that management should be concerned with behaviour created by feedback networks which may be within the organisation or outside it. Causes of the dynamic behaviour internal to the system description are assumed to be as important as externally induced perturbations.

2.1.4 State-Space Formulation

It is assumed that all industrial systems can be adequately simulated by assuming basic elements; rates of change and integral variables. The Rates of flow and the Levels or states of the system are the only necessary variables. The rates are connected to the levels by conservative, non-compressible flows. The levels are connected to the rates by compressible, non-conservative, information paths.

2.1.5 Continuous Variable Formulation

It is assumed that all variables can be treated as essentially continuous. Any variable may take an infinite number of values and should not change abruptly, with respect to one another or with time. It should be said that DYNAMO, the simulation program used to compile the I.D. models (16), permits some discontinuous functions and most I.D. simulations use some operators such as MIN, MAX or CLIP which abruptly limit the range of a variable. Extensive use of discontinuous or ill behaved functions is, however, contrary to the basic philosophy of I.D. It makes the simulation difficult because the integration method uses the Euler approximation (rectangular integration method) which needs a small iteration interval and extensive computer time.

2.1.6 Implications

The principles imply that the system is not restricted to a particular equation form other than that the equations are well-behaved. Non-linear equations and massed feedback networks are normal in I.D. models. The feedback networks imply that dynamic behaviour can be created internally without exogenous

variables. A closed boundary system can be constructed that will exhibit growth, oscillatory or more complex behaviour.

In this study, the main models were not entirely closed boundary models. The models were disturbed with external stimuli. This was useful at the validation stage because the response of the models could be compared with real system by introducing an input similar to that observed historically. Additionally, some of the hypothesised feedback loops in the steel consuming market were not adequately understood and were removed. In the Market Dynamics model the steel consumption was introduced as an exogenous variable.

In brief, I.D. assumes that new insights can be attained by modelling:

- . Feedback systems
- . Continuous variables
- . Rate-Level variables

If the problems considered exclude one of these requirements then I.D. is inappropriate. If there are no feedback structures which can be identified with the problem or if the variables are unquestionably discrete or if integral variables cannot be identified the I.D. approach is not appropriate.

2.2 Methodology

An essential part of Industrial Dynamics is the analytic method; the procedure for analysing a system and the creation of a model. Forrester presents a procedure for analysing business policies and industrial systems as a ten step check list (Industrial Dynamics, pg 13). This check list is similar to others concerned with systematising a project. These stages of

analysis were considered in depth in the study because it was felt that they were fundamental to the successful application of I.D. to real industrial systems. Forrester's checklist is given below with comments drawn from the research study.

"Identify the Problem"

If the problem is redefined, the boundary changes. Since the models incorporate feedback structures, a change in the problem normally implies the inclusion of a new set of feedback mechanisms. The dynamics created depend on the mechanisms modelled and therefore on the problem definition.

Two types of models were considered important in this study, the process flow or "simulation of the firm" type of model and the policy or "resource-acquisition" type of model. If the problems relate to process flows and control procedures the dynamics tend to be oscillatory and of short duration. If the models include capital investment, market development or research programs (resource acquisition) the models often simulate periods of ten to twenty years and exhibit growth characteristics. Selecting the problem means more than stabilising the objectives, it determines the type of data, the level of the people who should be involved and the means of validating the model.

"Isolate the factors that appear to interest to create the observed symptoms." ^{act}

This stage in an I.D. project seems to be fundamental to the whole process of creating an I.D. model. It is implied in a number of studies (11, 17) that the cause of the behaviour was reasonably well understood. In this study it appeared that it is

essential to understand the basic cause of the dynamic behaviour. If one cannot start from a basis of understanding the prime interactions causing the behaviour it appears there is little chance of being able to specify the detailed relationships in the form of equations or tabular data.

"Trace the cause-and-effect information-feedback loops ..."

"Formulate acceptable formal decision policies that describe how decisions result from the available information streams"

These two stages are highly related. Determining the decisions requires the determination of the information on which they are based and the actions taken. The problem arises, however, in attempting to simplify the decision process so that it can be stated in terms of a few simple equations and based on a few variables. The information channels and decisions have to be highly simplified and stated as continuously acting functions.

Simplification is common to all model building exercises but it creates problems of acceptance of the model, particularly for I.D. studies. It appears that it is important that those who will implement the results of an I.D. study should have some say in how the variables and decisions are to be aggregated if the models are to be acceptable.

"Construct a mathematical model ..."

In the study it was found that one of the few means of checking the feedback loops was to construct a flow diagram and attempt to get some discussion of how the variables were related. Ansoff and Slevin (18) have suggested that many companies may gain the greatest value from I.D. by terminating a study at the flow-chart stage. This appears contrary to the findings of this study.

It appears that I.D. is primarily a simulation method which requires that the behaviour and its causes are previously known. The construction of the model and its subsequent use helps refine this understanding, illustrates the sensitivity of the system to parameter and structural changes and aids the investigation of alternative policies and procedures.

"Generate the behaviour through time ..."

"Compare results ..."

The initial runs of the model took much longer than most I.D. reports suggest. Not because of errors in equation writing (syntax) but because feedback loops had been omitted. If the model is of a generalised system, as for example, Roberts' (4) R & D model and Urban Dynamics (3), the mechanisms can be hypothesised in a simple form and the model easily corrected and initialised.

An I.D. model that is based on a real system is time consuming to analyse, to initialise and to redesign. These models create a considerable volume of data; each variable is time varying and can be compared dynamically with other variables in the model and with the real system.

"Revise the model ..."

This stage inevitably forms part of the initialisation and comparison stages. In this study however it was found necessary to rewrite each of the main models. This was because the purpose of the models changed as the dynamics were viewed.

It appears that the change in viewpoint and model structure often occurs (17, 19). Consequently it is sensible to construct an initial model as an illustrative example demonstrating the

structure and type of behaviour. A second model should then be constructed to simulate the detailed problems identified.

"Redesign ..."

"Alter the real system ..."

These two stages are the intention of most Operational Research studies. In practice it is to be doubted whether most such studies are the sole cause of policy restatement nor in particular whether I.D. studies will be recognised as the prime motivation for major policy decisions.

I.D. studies demonstrate dynamic behaviour; of existing and proposed structures. A new policy can be simulated but it cannot be modelled in all its aspects. I.D. therefore tends to act in the role of other simulation methods, as support to a policy recommendation. It is particularly difficult therefore to use I.D. outside the "policy formulation group". These models need to be formulated and developed by those considering current policies and their redesign and with a knowledge of the Corporation's strategy.

In this study the conclusions reached and recommendations made are only likely to influence the general tide of opinion. It is unlikely that the results presented here have themselves caused Divisional or Corporate management to change major policies. It is apparent, however, that there is a greater awareness of plant and market dynamics and that they are recognised as having potentially internal causes. The behaviour of the market for example is more seriously treated as a feedback problem.

2.3 Notation

An important aspect of I.D. is the notation. Models are often described using the I.D. notation even when other Continuous System Simulation Languages have been used. A distinction must be made between the I.D. notation and the requirements of the DYNAMO compiler.

This discussion of the notation excludes those problems which are clearly concerned with the implementation of the notation in past and present versions of DYNAMO. However, DYNAMO was written specifically for I.D. simulations and is a measure of the consistency of the notation. It includes routines for checking that the models conform to the I.D. notation. The lack of generality in the DYNAMO compiler, however, is not a consequence of the notation but of the philosophical basis of I.D. that variables should be treated as essentially well-behaved.

The notation is used as:

- A Diagram Notation
- A Simulation Notation

The method is claimed to be user oriented. Apart from algebra the method does not require any specialised knowledge. Both the flowchart and the algebraic statements are closely related. For each diagram symbol there is a corresponding equation. The output from one equation to the next is shown diagrammatically by a connecting flowpath. The equations can be supplied to the simulation package in any order so that the sequence of equations can relate to their layout in a diagram.

The integration of the diagrammatic and statement formulations of the models is extremely important to the method. Analysing a feedback structure with only a list of statements is difficult. The I.D. diagrams allow an overall view of the model but permit the presentation of the essential details. Since each type of variable is represented by a separate symbol many of the relationships can be deduced from the diagram without reference to the equations.

The state/space formulation is common to all Continuous System Simulation Languages. The integrals (Levels) are the basis for the method; it being assumed that all recordable variables are based upon integrated values. The integrated variables are dependant only on Rates which are themselves only dependant on the integrals. In any causal chain rates and levels alternate. This alternation of the rates and levels is a direct consequence of the assumption that only integral variables are recordable.

The notation used for the simulation statements is checked thoroughly by the program recommended for I.D. simulations; DYNAMO. The compiler requires a strict adherence to the I.D. notation but is extensive in its checking of statements. It is far more thorough in its analysis than any other of the Continuous System Simulation Languages.

The notation is described briefly by Pugh (16) and in greater detail by Forrester (1).

2.3.1 Diagram Notation

The diagram notation recognises compressible and non-compressible networks. The conservative (non-compressible)

networks consist only of rates and levels plus sources and sinks. The non-conservative (compressible) networks are the information paths and link the level variables to the rates. Since the rate formulation can be quite complex they may be further subdivided into auxiliary variables.

Figure 2 summarises the diagrammatic symbols used by Forrester and in this thesis. In Industrial Dynamics, Forrester uses some additional symbols to represent a sub-structure of the model. These symbols tend to cloud the simplicity of the approach; they are discussed in Section 2.3.3.

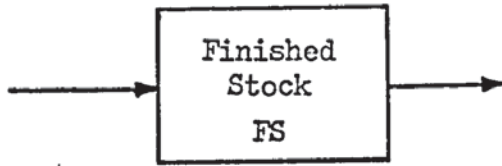
2.3.2 Simulation Statements

The simulation method assumes that variables are essentially continuous functions; continuous in time and with respect to one another. Each diagram symbol represents a rate, level or auxiliary which may be represented by a single equation. Each equation defines a single variable. All variables are single dimensioned quantities which implies that each variable can only have a single quality.

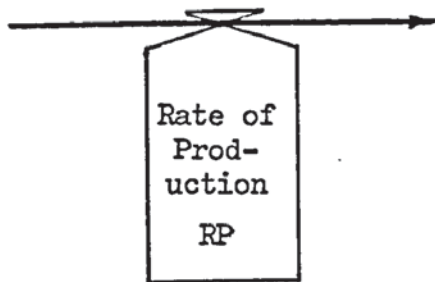
The simulation method computes the variables repeatedly. The independent variable, time, is incremented by small fixed steps before the equations are recomputed. The Industrial Dynamics notation incorporates a subscript notation into each variable name that reminds the user of the sequence and type of variable used. DYNAMO checks these subscripts, corrects them and warns the user.

All the equations are computed in each iteration. Level variables are computed from the previous iteration values of themselves and the rate variables. Auxiliary equations,

Diagram Notation



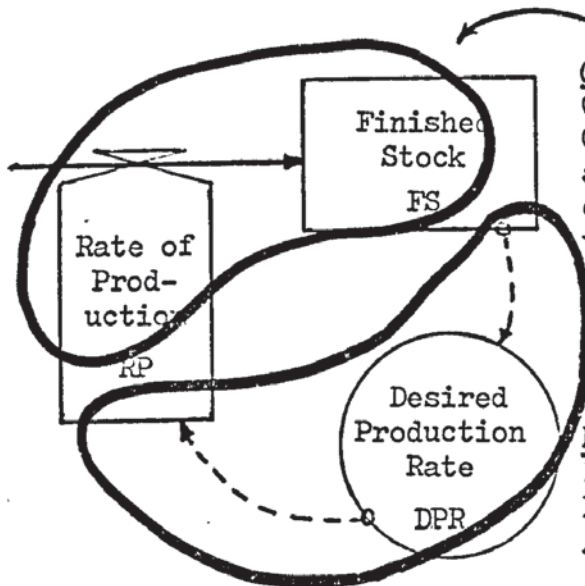
Level; Integral or accumulated variables. Only recordable variables in a system. Levels depend only on rates of flow.



Rate; Rate of flow or action. The only other fundamental element. Rates are based only on Levels.



Auxiliary; Conceptually part of the Rate formulation. A useful means of subdividing the Rate equations into manageable formulae. Auxiliary equations are based on Level and Auxiliary equations only.



Conservative System; Material, Orders, Money, Personnel and Capital Equipment. Each path alternates Rates and Levels and does not include Auxiliary variables.

Non-Conservative System; Information flow. Paths link Levels to Rates and may include Auxiliary variables.

Figure 2 I.D. Diagram Notation

conceptually part of the rate formulation, are suitably sequenced (by the simulation program) and computed from other current auxiliary variables and current level variables. Rates are based on the computed auxiliary and level values.

Level and auxiliary variables are subscripted K for the present value and J for the previous iteration value. Rates, which are assumed to flow during the iteration interval are subscripted KL for the present and JK for the previous interval.

I.D. uses the Euler integration method where rates are assumed constant during the iteration interval. This is a useful approach for industrial system modelling because:

- It is simple to understand
- It is visible; it can be written as a single equation

A typical level equation is:

$$\text{LEV.K} = \text{LEV.J} + \text{DT} * (\text{IN.JK} - \text{OUT.JK})$$

where LEV is the integrated value (say "orders-in-hand") and IN and OUT are the in-flows and out-flows (say "orders received" and "orders completed"). DT is the iteration interval during which IN and OUT are assumed constant. Provided IN and OUT are continuous functions that do not vary rapidly the integration method does not require a very short iteration interval (and therefore a lengthy computation time). If rapidly varying rates occur then the computer time used becomes excessive if the accuracy is to be retained. It appears that provided a continuous formulation is used the so called "stiff" sets of equations are not common in industrial systems; variations in the rates of change within one system are not normally different by a number of orders of magnitude. If "stiff" systems are

found another Continuous System Simulation Language (CSSL) can be used such as CSMP III (20).

To set the model into an initial state it is strictly only necessary to define the level values. The DYNAMO compiler permits initial conditions to be placed anywhere within the model. Each initial condition statement defines the initial condition of a single variable; normally but not exclusively, a level. The statements may use any variable names even though they are not included themselves as initial conditions. DYNAMO, therefore, unlike other CSSL's permits the initial condition statements to be based on the dynamic equations as well as the initial condition statements.

The I.D. (strictly DYNAMO) method is preferable for socio-economic models. It is normal to find that the models initial state represents a state of the mature real system. The system has been in existence some years and is reasonably stable. Basing the initial conditions on the dynamic equations is therefore likely to set the model into a stable or near stable state. This method usually creates simultaneous equations within the initial statements but since DYNAMO indicates these simultaneous equation chains they can usually be removed by a single additional initial condition equation.

2.3.3 Sub-models; MACRO's and Functions

Some special functions are needed for any continuous system simulation method. DYNAMO provides five categories of special functions; trigonometric, value selection (clipping and arbitrary functions), time triggered (sampling and ramp curves), curve shaping (delay functions) and random number generation. These

functions are common in CSSL's and can be treated as special operators.

A more important concept is the provision for creating sub-structures that can be imbedded in a larger model. Some computer languages permit subroutines which may be written as a separate block. The block may be entered by referring to it in the main program. An alternative method is the MACRO where the user statements are repeated in the program when the MACRO is referenced.

DYNAMO, like most current CSSL's, allows the user to define and use his own MACRO's. These user defined routines are a collection of rates, levels and auxiliary equations. The diagram notation cannot represent the substructure with a single symbol. Forrester (1) uses a special level-like, symbol for the built-in function (actually constructed in DYNAMO II from a built-in MACRO) DELAY 3. A BOXCAR function, only available in earlier versions of DYNAMO similarly uses a special symbol.

The rate-level-auxiliary notation is simple, consistent and represents adequately most aspects of the variables perceived in industrial systems. It permits the simulation of any order of feedback system because the integral variables occur once (at least) in every feedback loop and allow the simulation method to break into each causal chain. The MACRO concept destroys the essential simplicity of this approach.

2.4 Summary of Industrial Dynamics Case Studies

Forrester initiated the Industrial Dynamics approach at the Sloan School of Management, M.I.T. in 1956. The first application, to the Sprague Electric Company (10, 11, 21)

included some of the development of the methodology and is one of the two case studies in Industrial Dynamics (1). The first paper on Industrial Dynamics (22) appeared in 1958. From then until Forrester's book appeared in 1961 was a period of consolidation, concentrating on the development of the simulation package, DYNAMO (23), simulations of "steady-state", mature firms and the preparation of teaching material (24).

From 1960 the work at M.I.T. turned towards the simulation of industrial growth. In the earlier work, the models simulated orders, production and manpower. The growth models are characterised by the acquisition of a resource, often capital investment. Most of the reported growth models (25, 26, 27, 28) are concerned with timescales of a few years and do not include the same production detail as the earlier models.

During this period of developing the simulations of company growth there were a number of industry wide simulations produced. Katz's work (29, 30) on research and development lead to the more generalised models of Roberts (4). Yance (31) has simulated the shoe, leather and hide industry and compared the model with actual performance. Ballmer (32) and Schlager (33) have simulated the copper and aluminium industries while Weymar (34) has similarly simulated the dynamics of the world cocoa market.

In the late 1960's the emphasis at M.I.T. turned from industrial projects towards simulations of social behaviour and the environment. In 1969 Forrester published Urban Dynamics (3) on urban renewal and in 1971, World Dynamics (5) on world population, pollution and industrialisation. Much of the effort in the last few years at M.I.T. has been involved in the

development and presentation of these socio-economic models. The M.I.T. group has generated most of the work on dynamic models of the firm, industry and the socio-economic environment.

The I.D. approach, the flow diagram notation and the simulation language DYNAMO have found a much wider application outside the M.I.T. group. In the area of natural resource management there have been a number of studies of fishing policies (37), farm management (38) and agricultural systems (39).

It is common to discover that the notation of I.D. has been used for a continuous system simulation study (40) followed by the use of DYNAMO and a later transfer to another Continuous System Simulation Language (CSSL) such as CSMP (20). The flow diagram notation appears to be generally acceptable (41) but, for the more detailed models, the need for special outputs and control statements implies the use of FORTRAN based CSSL's.

For this study the I.D. simulations of the firm and of resource acquisition have been the most relevant. The Production Dynamics Model (Chapter 5) was influenced by the Sprague Electric Company model, Roberts (19) food distribution company model and the basic simplicity of Wrights (17) trucking company model. The financial models attempted during this study utilised some of the concepts presented by Smith and Waltz (42) regarding the dynamics of financing Inland Steel and Forresters Corporate Growth model papers (12, 13, 28).

The Market Dynamics Model (Chapter 4) developed from attempts to combine the "simulations of the firm" type of model, based on process flows and the "resource-acquisition" type of model based on capital investment and market growth. Initially the M.D.

model used simple "economic multipliers" to simulate the market growth in a manner similar to that of Tustin (43). The M.D. model is not closely related to any other I.D. study and represents a simple but specifically B.S.C. based structure.

2.5 Validation

In the evaluation of a model two distinct activities are worth consideration:

- Determination of the contribution of the model to the business
- Verification of the accuracy of the model to represent some essential aspects of the business

2.5.1 Contribution to the Business

One of the claims frequently made for I.D. is that it creates a better understanding of the causes of dynamic behaviour, the factors creating production and market oscillations, the causes of variations in productivity and the factors determining growth. It appears from this study that to gain such a benefit it is essential that:

- Senior management indicate the problems and outline the causal relationships that are believed to create the dynamics, otherwise it will be impossible to transfer the knowledge captured in the model.
- The problems are of significant importance. The dynamics of growth and market oscillations for example are more likely to show a large return than production flow variations.

Secondly, I.D. can contribute by demonstrating that the mechanisms suggested create a different behaviour than that

observed. There were a number of examples of this during the study. Speeding the response of the sales office to delivery delays for example worsened rather than reduced the variation in orders shown by the M.D. model. An assumption that most Strip Mills Division customers base their forecasted consumption on a seasonal cycle prediction and a trend prediction seems erroneous; they appear to be overwhelming influenced by the current demand. Ingot stocking in the P.D. model was shown not to be caused by soaking pit inadequacies but by differences in the steel making and slabbing procedures.

The expected contribution from I.D. is, however, that it will help indicate how some behaviour can be modified to bring a financial gain. In these studies as with most I.D. simulations of the firm, the behaviour observed has been oscillatory. The successful studies have been characterised by the implementation of procedures to reduce these oscillations without creating additional costs. In the Scannell Trucking study (17) oscillations in the freight carried was reduced by shipping empty trucks. In the Sprague Electric Company study (21) production and labour oscillations were reduced by giving priority to customer orders, altering the stock control procedure and authorising employment on an overall productivity formulae.

In these studies a number of recommendations have been made but none of the proposals have been implemented. The Division may, in the future, hold stocks but this is unlikely to be a direct consequence of the study. It is possible, however, to obtain some measures of the potential improvement and to indicate

those recommendations which can be assigned to the I.D. approach.

In the M.D. study seasonal cycles in production were recognised as having two components

- A cycle in orders received which varied more than the consumption of steel by manufacturers
- A cycle in production which followed the orders received. (There are some orders-in-hand but no buffer stock)

The production cycle can be reduced by holding a buffer stock.

What was not apparent until the I.D. study commenced was that the orders-received cycles could be reduced by reducing the lead time.

A number of methods of reducing the lead time that did not require the holding of a large buffer stock of finished steel were proposed;

1. Holding part finished stocks; slabs or hot rolled coil.
2. Offering a limited range of off-the-shelf products mainly for bulk order customers and stockholders.
3. Producing steel to a regular schedule, calling off against the schedule later in the production sequence.

The potential reduction in the order variation can be calculated by assuming that if the lead time were reduced to zero, customers need only order to replace the steel consumed. This would result in the amplification of orders (orders vary more than consumption of steel) being reduced to zero. From the data presented in Chapter 4 this would result in the orders received by Strip Mills Division in the first quarter being

reduced by 3.8% and a similar increase in orders in the third quarter. This corresponds to a shift of approximately 56,800 tonnes.

It is difficult to state this as a specific saving. One estimate of the benefit of transferring this production from a low demand to a high demand period assumed that the steel transferred would save reheating and multiple handling costs, these were very roughly estimated at £5 per tonne i.e. £284,000.

It is likely that the Division may hold some finished stock. If this proves viable, then an estimate of the savings can be made on the assumption that by reducing the seasonal cycle in orders a smaller buffer stock can be held. If the 56,800 tonne transfer of stock from the first to the third quarter can be achieved, this implies that a saving can be achieved by not holding 56,800 tonnes at approximately £70 for six months. At a cost of capital of 15% this amounts to £298,200.

2.5.2 Accuracy of the Simulation

I.D. studies are concerned with identifying and correcting dynamic behaviour. It is unlikely that simple models based on a few causal relationships will ever be able to make predictions about the magnitude of a variable some time in the future because of random or unknown mechanisms.

I.D. models, if they are to be useful, must, however, be able to predict the type of behaviour that the model was intended to show. The model can be tested by checking;

- The structure of the model; whether there is general agreement that the decisions and feedback variables relate to the managers experience.

- The behaviour of the model; whether the magnitude and the timing of the behaviour relates to the observed behaviour.

It should be stated that checking the timing of the behaviour can be a difficult problem. It appears from this study that careful consideration should be given to such exogenous variables as national holidays and Christmas shutdowns. These external stimuli tend to align the causal dynamics often forcing different modes of behaviour.

It became apparent in this study that the simulations of resource acquisition, which assume relatively little data knowledge and the simulations of the firm (process type models) which assume a high level of plant and control knowledge are very different in their validation requirements. In Chapter 3 it is shown that the Policy (Resource Acquisition) models require about 25 times less computing time than the Process models. This reflects the difference in the behaviour that can be recognised in the output results.

From a theoretical viewpoint only level and auxiliary variables can be compared with the data. Rates of flow are instantaneous rates and would not be visible in the real system. In practical terms this makes comparisons difficult. Production rates, rates of receiving orders and rates of delivering steel must be summed over periods of a month, quarter or year for comparison with the data.

A special routine was written which accurately accumulated the rate but which was not sensitive to the time at which it was sampled (DYNAMO sampling times are not regularly spaced!). This

problem has not been reported elsewhere and suggests that previous validation exercises may not have been particularly precise.

Finally it is my opinion that the M.D. model demonstrates an adequate representation of the mechanisms causing the amplification of orders and that the amplification is shown in a similar form in the data. The results presented, however, are not based on the model itself but on estimates of the potential benefits derived from the data. This appears to be a generally useful means of using an I.D. model; to demonstrate and investigate the behaviour and its cause and to pinpoint aspects of the behaviour that were not previously seen. Recommendations should be based on the data rather than the model, thereby overcoming any reluctance to accept the mechanisms modelled.

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3. Development of the Research

This chapter deals with the development of the research including a brief description of each of the models. Problems of formulating the models and the effort involved are discussed and the models are compared with those built elsewhere. The computer programs are related to the models developed and specific problems with the research are discussed.

3.1 Research Sequence

Figure 3 shows in outline how the research progressed. Initially it had been hoped that a single area of study would be possible following the presentation of the two test models; a model of a section of the steel production flow and a model of decision making affecting capital investment, export sales and delivery performance.

The I.D. approach was viewed within Management Services as a means of identifying the cause of dynamic behaviour and the means to modify this behaviour. This thinking led to the models being developed with little contact with the relevant managers and consequent difficulties in isolating; the problem dynamics, the causal network creating the behaviour and the alternative policies and procedures.

Five main models were built; Works Model, Operations Planning (allocating orders between the works), Financial Model (Capital investment and production capacity), Market Dynamics (Chapter 4, amplification of orders by customer stockholding) and the Production Dynamics Model (Chapter 5, generalised flow process model of a Strip Mill). Only two of these have been considered successful; the Production and Market Dynamics models.

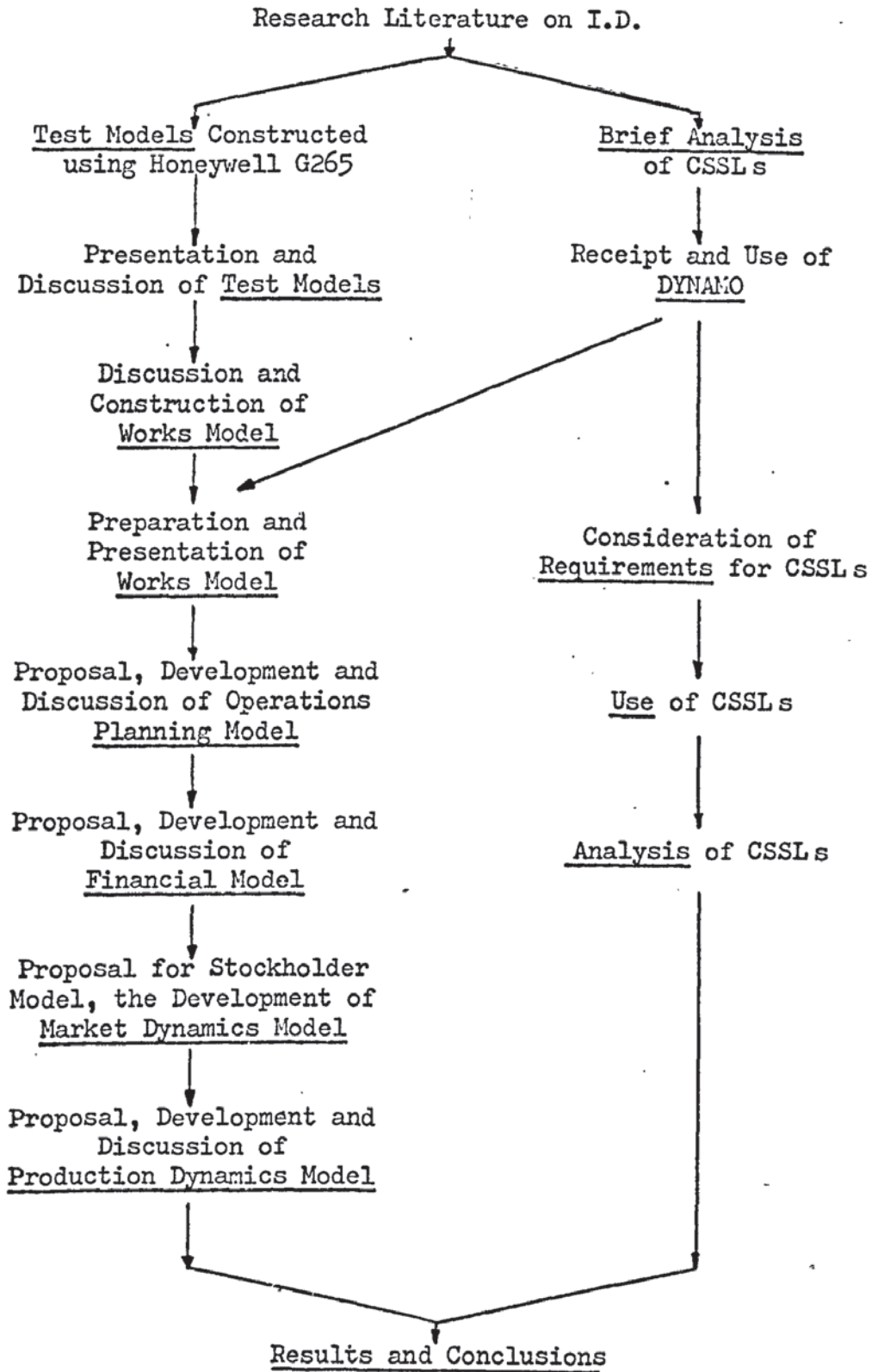


Figure 3 Research Sequence

These were the models which could be checked and discussed because of easier communications with production and sales staff.

3.2 Development of the Models

The models, developed during the research, fall into six main categories:-

- Test Models A "process" and a "policy" model to initiate the research, gauge reactions, test the computer programs and indicate the problems associated with process and policy type, continuous system, simulations.
- Works Model The initial attempt at a continuous system simulation of a steel works.
- Operations Planning Models Investigation of the dynamics created by allocating orders to five main steel works.
- Production Dynamics Models A steel works process flow model concentrating on steel throughput. Discussed in Chapter 5.
- Financial Models Examination of the dynamics created by major capital investment programs.
- Market Dynamics Model Examination of market reactions to production and sales policies, Chapter 4.

Figure 4 shows the actual models developed and where they are discussed in this section.

3.2.1 The Test Models

Early in the research it was realised that to obtain sponsorship and general interest in the models it would be necessary to present a preliminary model, even if unrealistic, as a starting point for discussion. It was further recognised that the computer program, DYNAMO, needed to compile the models, might be

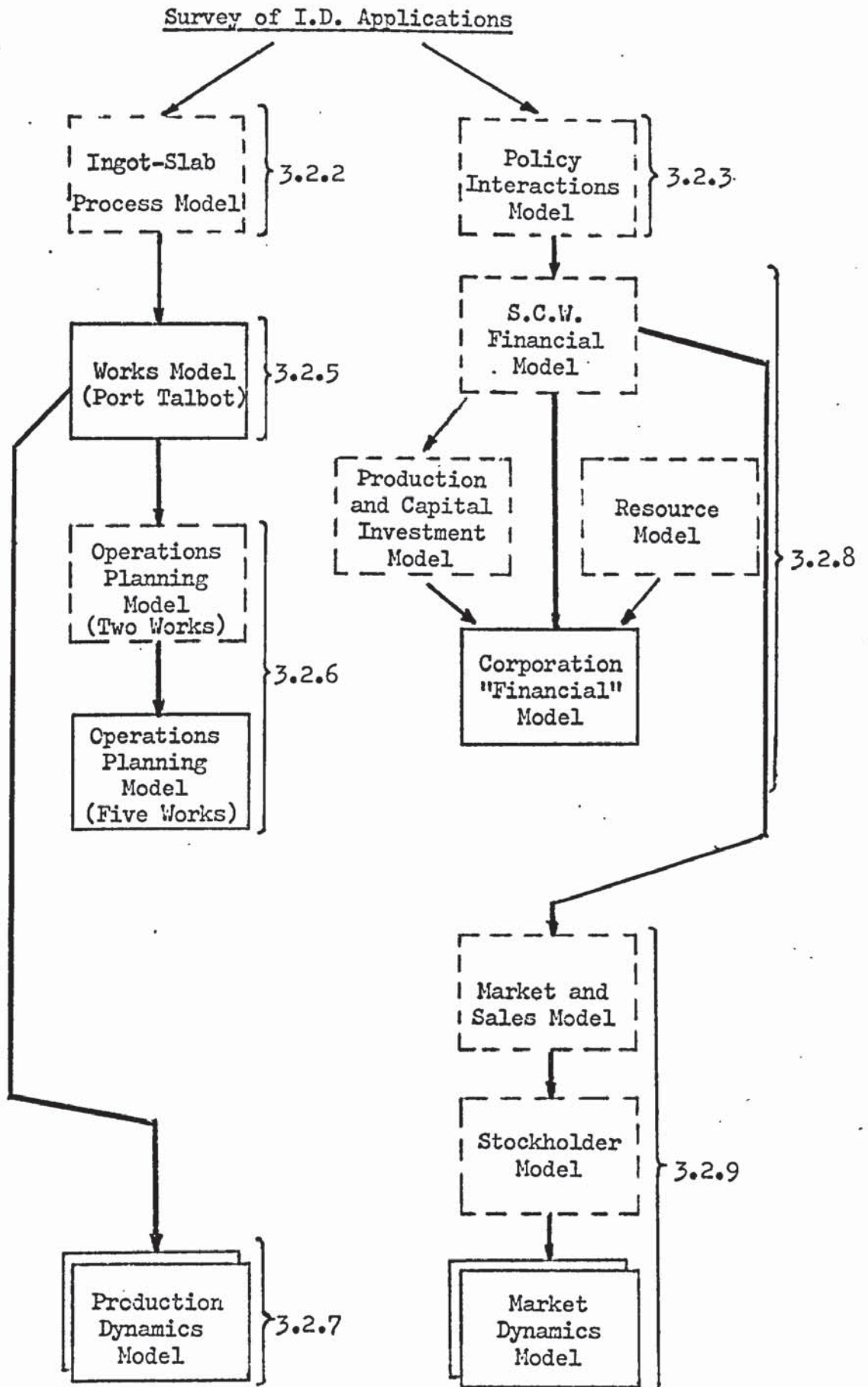


Figure 4 Development of the Models

expensive or be unable to compile on the Port Talbot, IBM 360/40 computers. Alternative compilers would have to be tested independently of the need to evaluate CSSL software.

It was decided to construct two preliminary test models:

- . To test the Industrial Dynamics approach.
- . To gain a better insight into possible application areas.
- . To test various CSSLs.

To develop these models efficiently it was decided to:

- . use the M.I.T. work as a basis and develop one or more of their generalised Industrial Dynamics models,
- . keep the models deliberately simple,
- . keep the number of equations and special functions to a minimum,
- . examine a process flow type model, concentrating on physical processes and known procedures,
- . examine the socio-economic type model, concentrating on Forrester's "management pressure" systems and policy decisions.

3.2.2 Ingot-Slab Process Model

The model was based on the type of mechanism occurring in Forrester's "Industrial Dynamics", main example of a Production-Distribution system. This model uses similar principles, concentrating on stock control procedures and does not attempt to simulate the effects of management actions. The model was deliberately reduced to a minimum of equations and uses only a single function; a sinusoidal input to disturb the model.

The model is shown diagrammatically in Figure 5 and assumes very coarse control procedures. Ingots and slabs are

treated as a single stock and steel making is determined only by the scheduled level of steel making. This short term (scheduled) loading is assumed to be based on a longer term loading but modified by the need to adjust the ingot-slab level.

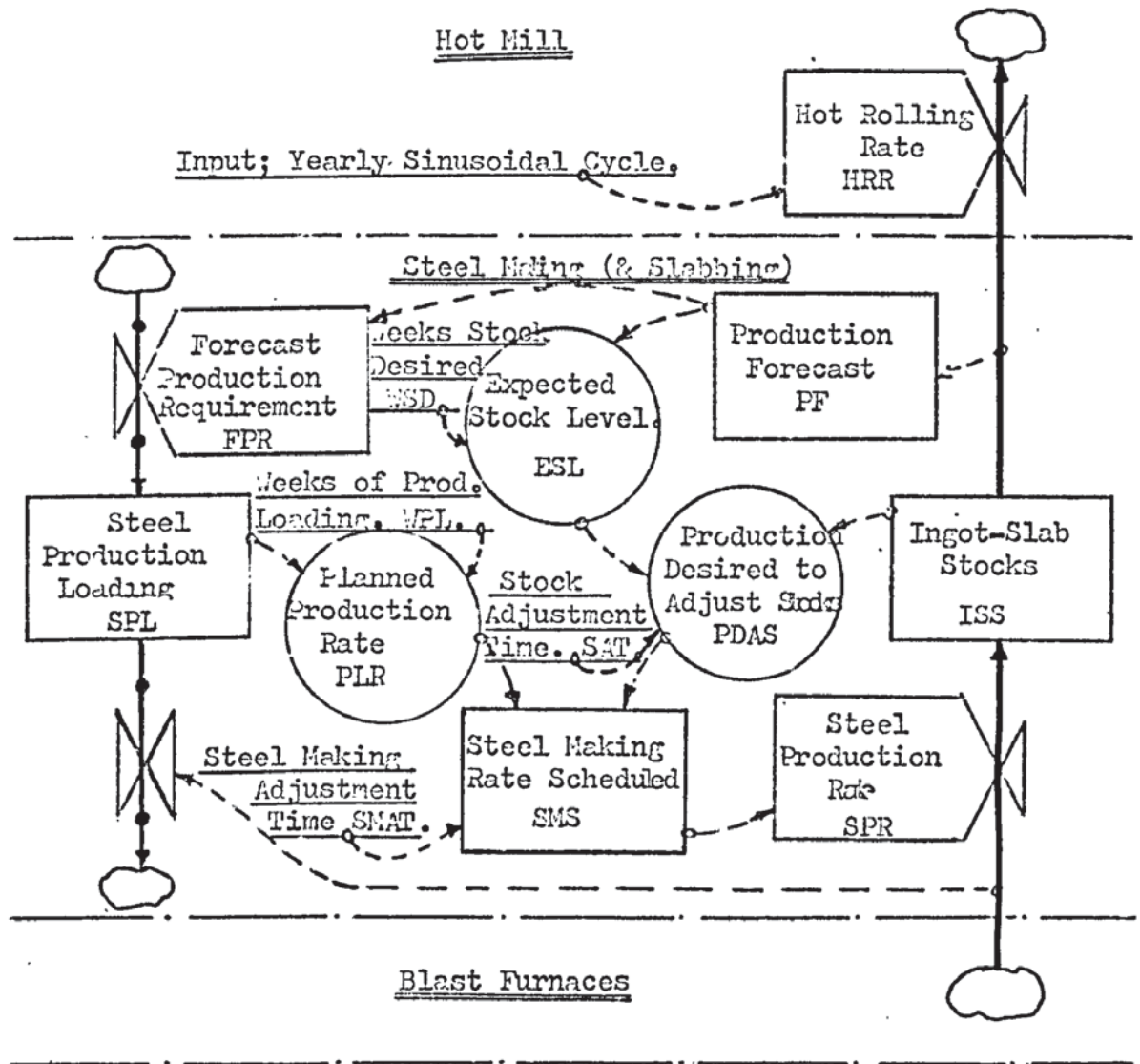


Figure 5 Ingot-Slab Process Model - Test Model.

The steel production loading is normally a month's steel production and is determined by the accumulated difference between the actual and forecast production rates. The production forecast is assumed to be dominated by the current consumption of steel for hot rolling. An exponentially smoothed average of the hot rolling rate is used in the model for this forecast.

The Ingot-Slab Model reacts to the hot rolling rate (input to the model). The hot rolling rate would be determined by the available orders if this simple model were embedded in a larger model. The loading and expected stock level are both determined from the hot rolling rate. However, there are two control structures within the model which do not include the hot rolling rate, Figure 6. The stock control loop attempts to hold the stock at a given level by varying the production rate. The loading-production loop attempts to hold the production rate proportional to the current total month's production loading.

The model incorporates two feedback loops and four integrations. Since each loop contains two integrations it is potentially capable of oscillatory behaviour. There are no limits placed on any variable and under certain conditions it is capable of creating impossible situations. For example, steel can flow back from the ingot-slab stock to the blast furnaces because negative steel making rates are possible. Normally, limiting conditions are placed on the variables, but have been deliberately omitted in this test model to aid comparisons between the CSSLs.

The model has been run using CSMP, SPEED, DYNAMO and two packages developed for the research CSS and QSS.

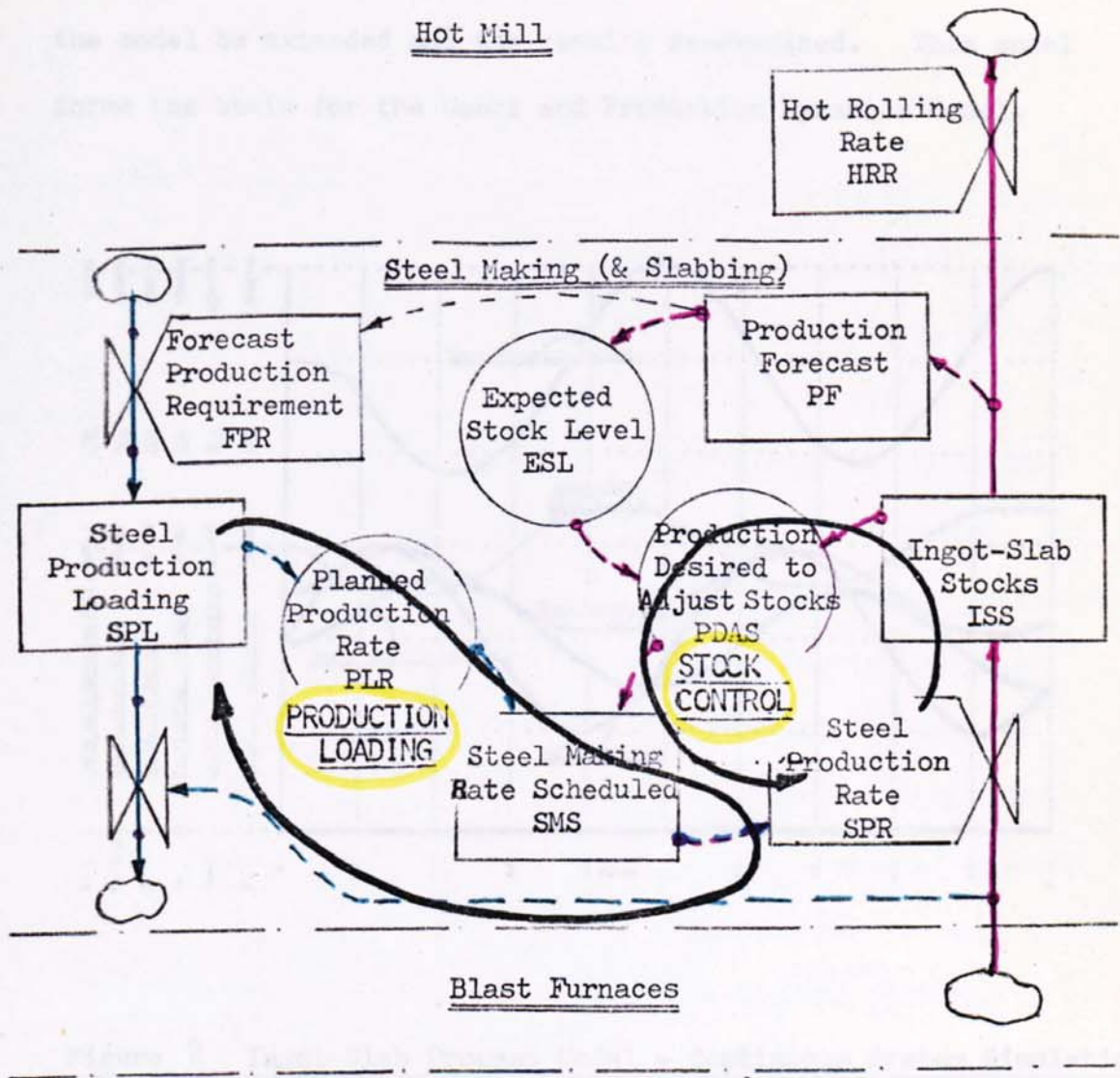


Figure 6 Ingot-Slab Process Model - Stock Control & Production Loading

Figure 7 shows the effect of the sinusoidal input on the model. The model is stable with production variations oscillating with a smaller amplitude than the hot rolling rate. However, when this stock control area is added to the hot rolling, cold rolling and finishing process the delay in the process can create a more dynamic situation.

The model itself was not thought to be useful since more complex models of ingot stocking had been built by the Port Talbot Operational Research Department. It was suggested, however, that

the model be extended and the results re-examined. This model forms the basis for the Works and Production Dynamics Model.

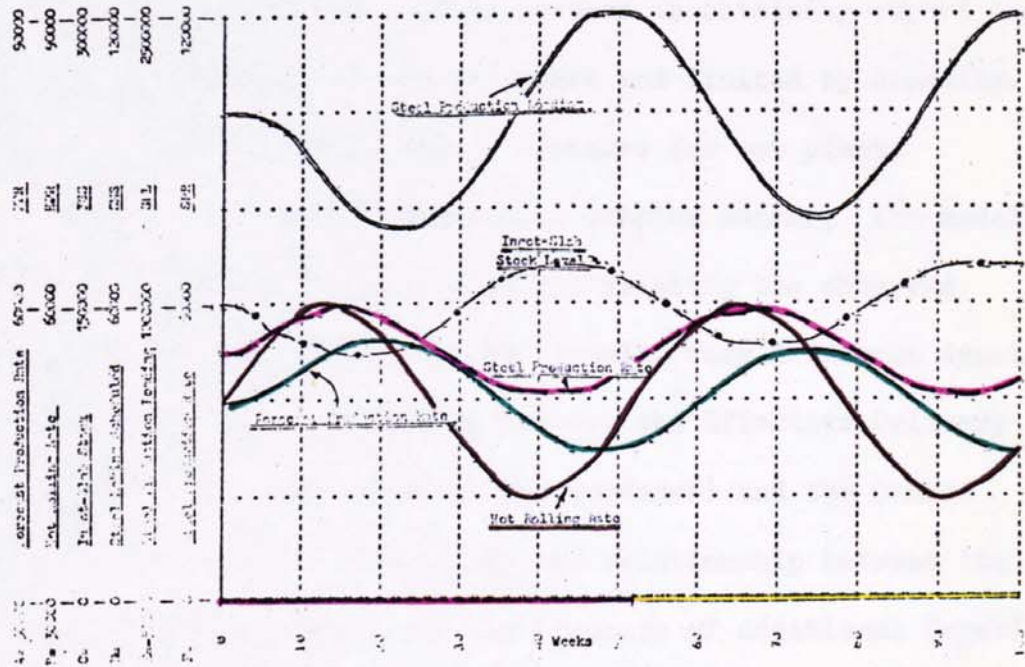


Figure 7 Ingot-Slab Process Model - Continuous System Simulation.

3.2.3 The "Policy Interactions" Model

The model was devised to demonstrate the broad consequences of major policies and strategies. The model was based on Forrester's "Market Growth" model although it uses feedback loops relating a little more closely to the steel industry and was based on the Steel Company of Wales operations.

The model incorporates a few "management pressure" loops that determine the rate of acquiring new production facilities, the quantity of export sales and the production rate.

Figure 8 shows the model diagram and the four basic pressure systems

1. Delivery Performance - market response to the lead time.
2. Sales Pressure - effectiveness in obtaining export orders.
3. Production - based on orders and limited by capacity.
4. Capacity Acquisition - Pressure for new plant.

These four loops interact in a complex manner; the model being sensitive to the relationships relating the observed variables to the "action". For example, very different dynamics can result if the relationship between the Effective Delivery Period (the lead time known to the customer) and the Orders Received is altered. Similarly the relationship between the Accepted Delivery Period and the Pressure of Additional Capability determines the rate of acquiring new plant and the production limits, which in turn determine the order backlog, delivery performance and sales pressure.

The model was used to test CSMP, DYNAMO and CSS/QSS. The model is typical of the "Policy" or "Resource-Acquisition" type of model. The variables are highly simplified (aggregated) and the decisions are also simple and based on one or two variables.

The model construction and dynamics were discussed with Management Services personnel and it was generally agreed that to be useful it had to be used at the Corporation level and be firmly based on acceptable aggregations of the decision rules and information channels (variables). In retrospect it appears that this model, suitably developed, was of the appropriate complexity for a one man study. The model could only have been built, however, in direct contact with a Corporation planning department.

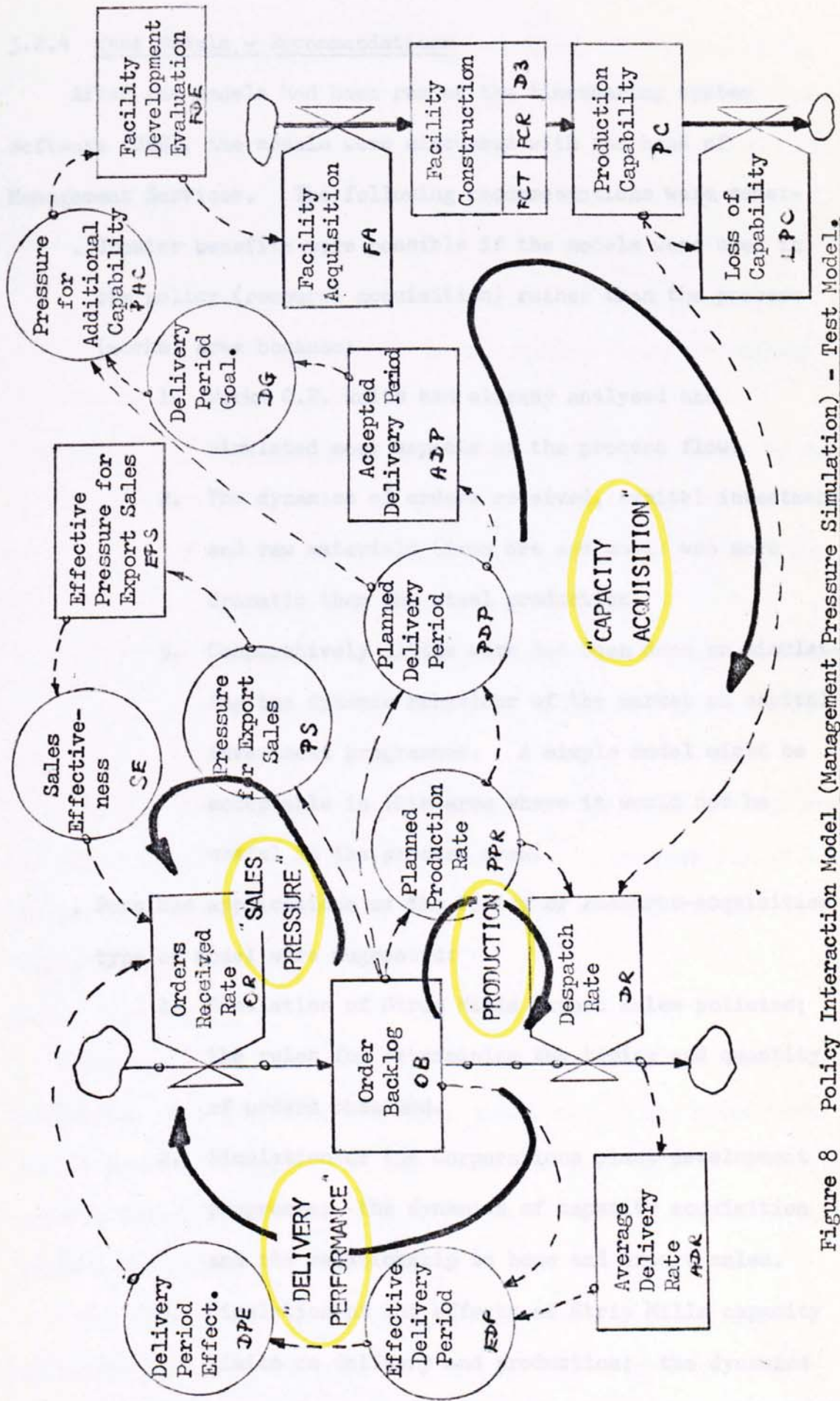


Figure 8 Policy Interaction Model (Management Pressure Simulation) - Test Model.

3.2.4 Test Models - Recommendations

After the models had been run on the timesharing system software (CSS), the models were discussed with the head of Management Services. The following recommendations were made:-

- . Greater benefits were possible if the models were used in the policy (resource acquisition) rather than the process (works) area because:
 1. Works O.R. units had already analysed and simulated most aspects of the process flow.
 2. The dynamics of orders received, capital investment and raw materials (iron ore and coal) was more dramatic than the steel production.
 3. Comparatively little work had been done on simulating the dynamic behaviour of the market on capital investment programmes. A simple model might be acceptable in this area where it would not be useful in the process area.
- . Possible applications of the Policy or resource-acquisition type of model were suggested:
 1. Simulation of Strip Mills export sales policies; the rules for determining the timing and quantity of orders obtained.
 2. Simulation of the Corporations plant development programme; the dynamics of capacity acquisition and its relationship to home and export sales.
 3. Simulation of the effects of Strip Mills capacity limits on delivery and production; the dynamics of orders received created by production limitations.

4. Simulation of the market factors affecting Strip Mills Division; the dynamics created by stockholding, delivery performance, sales price and quality.
- . Possible applications of the Process flow or works type of model were suggested:
1. Simulation of orders, production and manning dynamics similar to the Sprague Electric Company Study(11).
 2. Simulation of flow process dynamics; recovery from breakdowns, raw material shortages and strikes.
 3. Simulation of maintenance policy effects on plant dynamics and plant operating costs.
 4. Simulation of interprocess stock holding procedures; resilience to variations in quantity and type of orders.

It was decided that a simulation of the Port Talbot works should be constructed. It was an area of potentially smaller return but it was felt that previous O.R. experience in process simulation could be beneficial.

3.2.5 Works Model

The model was based on the Port Talbot Works. Labour levels, production rates, work in progress, cash flow and the order book were simulated as aggregated variables. Orders were for a single product (sheet steel) and production was shown as a single variable (tonnes per week).

The G265, Honeywell timesharing computer system was used initially and later the model was transferred to the IBM 360/40 using the DYNAMO compiler.

The model demonstrated short term labour variations, cash flow cycles and production oscillations. The model showed both a seasonal and long term tendency to cycle. It was suggested that it could form the basis for an operations planning model simulating the dynamics of order allocation within the, then, newly created Strip Mills Division.

3.2.6 Operations Planning Models

The model was devised to examine the dynamic effects of alternative allocation procedures. The model was broadly based on the works model but excluded labour and cash flow. The cost terms were expanded and the equations representing the production facility duplicated to create a dual works model. Various allocation algorithms were tried; a least cost allocation with fixed costs, least cost allocation with variable costs and maximised steel throughput.

The model was extended to five works, creating 260 variables in the model. The dynamics created depended on the allocation algorithm used. The maximised steel throughput runs suggested works could get into a situation of low productivity and remain there for long periods. A deliberate policy of allocating a special mix of orders to assist productivity recovery was suggested. Allocating "fast rollers" (orders that could be rolled at higher rates) and very slow rollers were considered.

When the models were being used, the production capacity was adequate within the Division. It was decided to investigate the effect of assuming a reasonably constant level of orders and to consider the reduction of the production capacity. Figure 9 shows the result of reducing the total capacity to determine

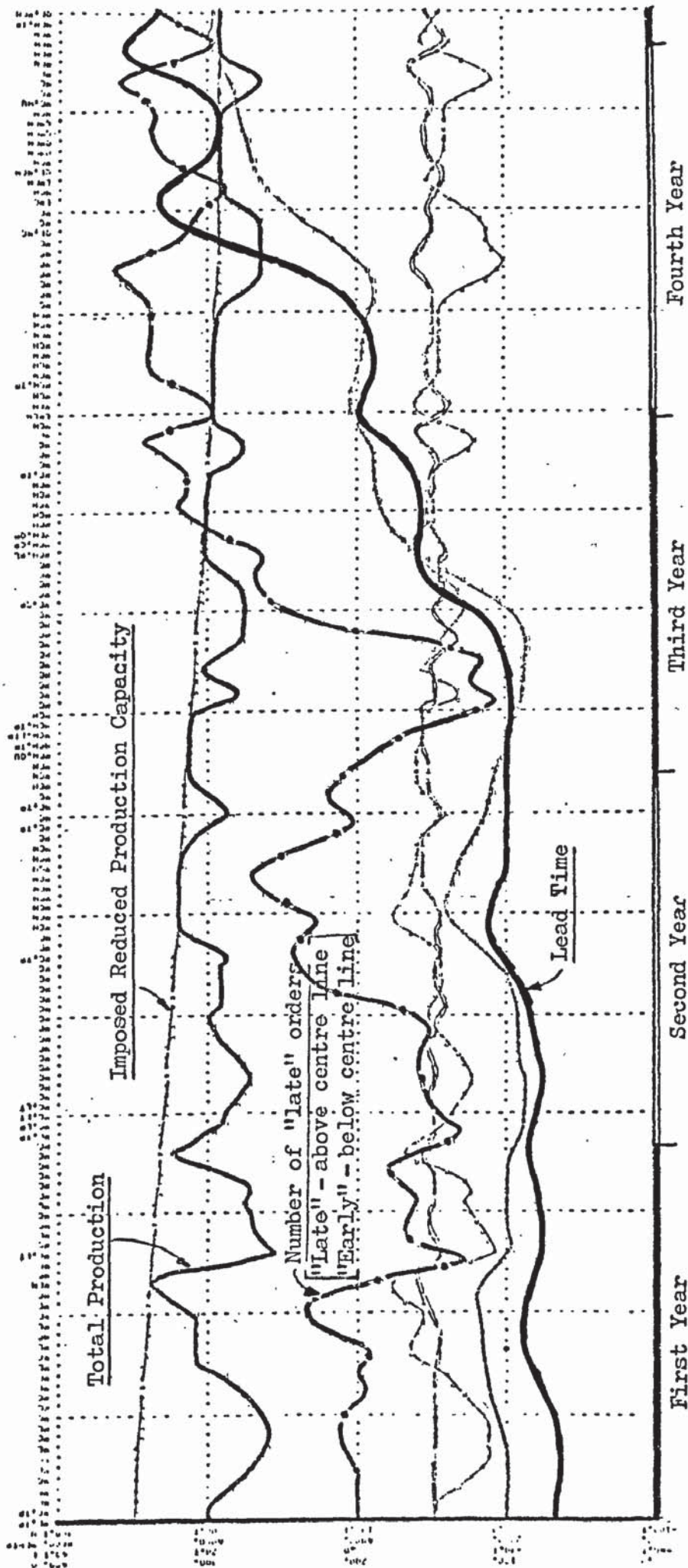


Figure 9 Order Allocation Model - Examination of Selective Closure (Reduced Capacity) - Minimal Cost

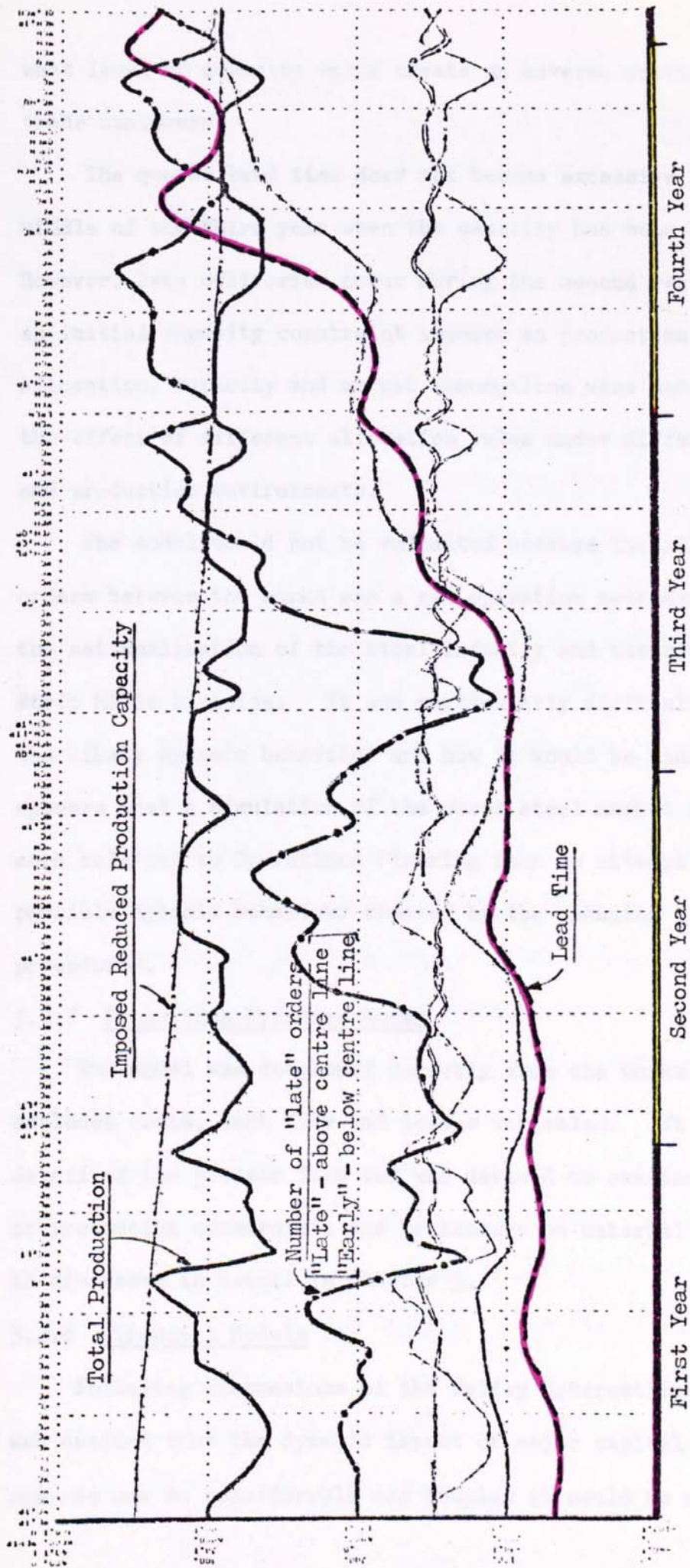


Figure 9 Order Allocation Model - Examination of Selective Closure (Reduced Capacity) - Minimal Cost

what level of capacity would create an adverse service to home trade customers.

The quoted lead time does not become excessive until the middle of the third year when the capacity has been reduced by 15%. However, late deliveries occur during the second year when there is an initial capacity constraint imposed on production. Alternative allocation, capacity and market assumptions were made to determine the effect of different allocation rules under different market and production environments.

The model could not be validated because the allocation of orders between the works was a new operation necessary because of the nationalisation of the steel industry and the creation of Strip Mills Division. It was particularly difficult to determine the likely dynamic behaviour and how it would be caused. It appears that a simulation of the sheet steel market dynamics is more relevant to Operations Planning than an attempt to predict possible dynamic behaviour created by the changing allocation procedures.

3.2.7 Production Dynamics Model

The model was developed directly from the works model but excludes costs, cash flow and labour variables. It includes the detail of the process flow and was devised to examine the effects of production constraints and breakdowns on material flows. It is discussed in detail in Chapter 5.

3.2.8 Financial Models

Following discussions of the Policy Interactions Model it was decided that the dynamic impact of major capital investment schemes was so considerable and complex it would be a suitable area

for a dynamic simulation exercise. Smith and Waltz (42) have created a dynamic model for Inland Steel considering "... the investment decision, the financial decision and the dividend decision. The criteria for making these decisions independently under static conditions, are fairly well defined. As these decisions are dynamically inter-related, however, the purpose of the model is to consider their joint long run impact." Their model was unlikely to relate closely to the B.S.C. situation so a pilot study was initiated into ten years of operation of the Steel Company of Wales prior to nationalisation.

The Steel Company of Wales was chosen because data was readily available over a sufficient period to observe dynamic relationships and behaviour. The model had to be rewritten for the B.S.C. but the S.C.W. data provided a basis for discussion and experiment. The S.C.W. model incorporated depreciation, production capacity, revenue, operating expenditure, profit and capital expenditure relationships. When a realistic market was provided for the model, allowing for the development of the R.T.B. works at Llanwern, the model was able to reproduce the dynamics of Return-on-Investment, capital employed, capital investment and steel produced.

Two important factors emerged from an analysis of the data. Work-in-progress appeared to accumulate during capital investment programs and the cost of raw materials was having a major effect on altering cost and profit figures. Two simple models were developed to examine these factors; one simulating the capital investment and production relationship, the other the growth in the consumption of raw materials.

It was found that these models could not be easily constructed as submodels. They could not be used in isolation and then simply added to the main model. It was necessary to modify and expand each submodel before inclusion in the main model. The difficulty arises with the submodels because the level of detail is different. Variables used in the main model tend to be less aggregated than those in the simpler models. This is a consequence of the I.D. approach where "simpler" tends to imply "more aggregated" and suggests that a hierarchical approach to I.D. model building is inappropriate. These models proved particularly useful, however, in developing the relationships and demonstrating the broad consequences of material usage and capital investment programs.

The Corporation model was developed to allow for the different financial situation of the nationalised industry. Data was available for all the U.K. steel producers in the Iron and Steel Bureau Statistics (44) which have been continued for the B.S.C. To a limited extent data was available over a period longer than the existence of the B.S.C. The Corporation model was used only as a means of checking the dynamics and to provide a specific example of investment effects. It is hoped that this model may be used in the consideration of cash flow during future capital investment programs.

3.2.9 Market Dynamics Models

These models were developed directly from the financial models. It had been suggested that the market reacted significantly to deliveries and lead times, and should be modelled separately. The initial model is shown in Figure 10. Three

main feedback loops were included; the creation of a basic demand, imports/exports and the effect of the lead time on orders received. The model created a five year cycle but no shorter term dynamics.

It was suggested that stockholders would also affect the dynamics. A separate model was created which excluded the demand loop and imports/exports so that the dynamics were determined only by the stockholding procedures. Stockholding appeared to amplify the changes in demand but did not, of itself, appear to create the cycles.

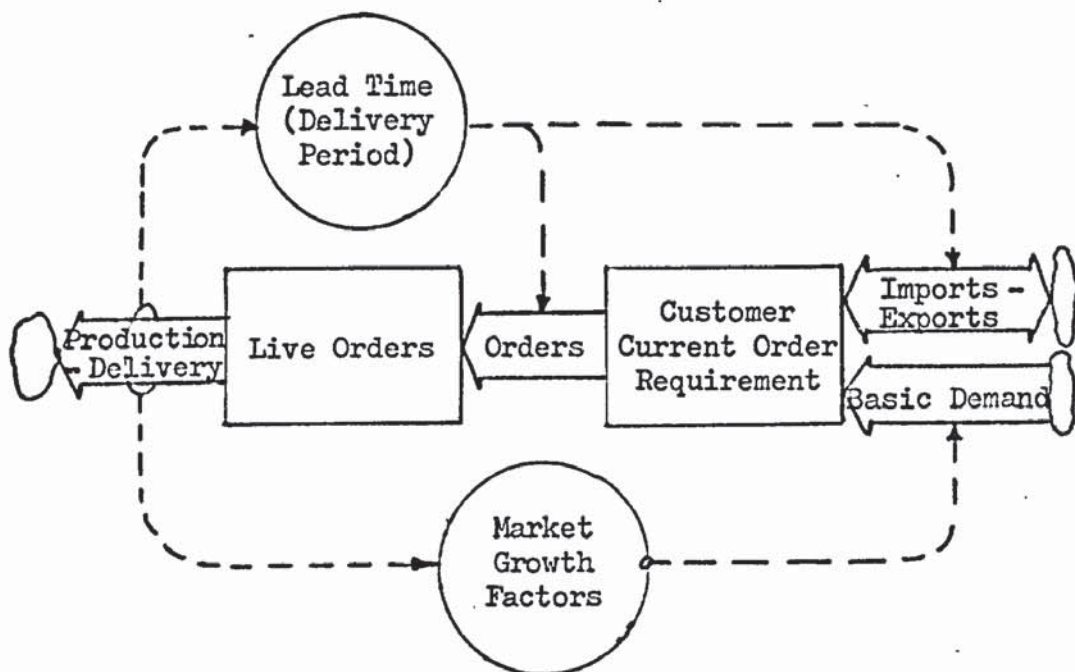


Figure 10 Outline of Initial Market - Sales Model

These two models formed the basis for the main study and the creation of the Market Dynamics Model discussed in Chapter 4.

3.3 Problems in Developing the Models

The research has been made considerably more difficult due to the variety of problems that had to be considered. These problems

could have been reduced if the models had been conducted for an individual or department. I.D. models simulate the dynamic behaviour that management feel are important. Different managers have different views and consider alternative causal relationships. While there is general agreement concerning many relationships, the initial structures suggested are often modified considerably as their effects are noted. Consequently, considerable effort is needed to develop some firm idea of the basic structure being modelled.

The research has been conducted for Management Services and not directly for a single user department. It was difficult to maintain a consistent interest in these models. The reasons for this may, in part, be independent of the I.D. approach and relate to factors in B.S.C. during the research period:

- Organisational changes within the Corporation, particularly from a Group to a Divisional structure, absorbed the efforts of senior managers. This was noticeable during the first, crucial, eighteen months of the research.
- Operational problems dominated the activities of Strip Mills Divisional managers during the first year, particularly the setting up of Divisional facilities, procedures and lines of communication.
- The models were simple when initially constructed. The elementary assumptions made to initiate the studies did not relate well to managers experience and did not generate confidence. The developed models were better received.
- No solution is offered by the simulation method. It only presents the results of the interaction of the causal relationships.

- Problems are presented by the method. The approach tends to demonstrate problems created by the dynamics. The problems need solutions which can be tested by altering the model.
- Not an operational procedure. The model cannot be used repeatedly like a Linear Programme. It loses much of its usefulness as soon as it demonstrates the dynamic behaviour. It requires further effort to consider alternative policies; restructuring of the model and discussion of the new structure simulated.

These barriers reduced during the research, particularly as the market, financial and production models developed to a stage where they presented complex and realistic dynamic behaviour. The problems in communication and involvement, however, created the following specific difficulties:-

- Obtaining data was difficult. Little can be done without some expression of the causal relationships to be modelled. In practical terms these relationships must in outline be stated by the person who will use and act upon the results of the simulation because of the need to use aggregated decision rules and variables.
- The results were challenged on the basis of the dominating feedback structures. When there had been inadequate discussion of the relationships used confusion arose as to the cause of the behaviour.
- Target problem changed probably due to the lack of communication in some cases.

3.4 Comparison of the Models

The test models were useful in checking the software and illustrating the structure and type of behaviour that can be simulated. They indicated that the simple, three or four loop models, were not acceptable at the process level because the procedures are so well known that the models are unlikely to make any contribution. However, at the policy level the feedback structures are not so well understood partly because of the problems of identifying the variables and decisions involved. Simple I.D. models appear to offer a contribution only at the policy level and require considerable effort in isolating suitable aggregate variables and decisions.

The financial models were an attempt to include in greater detail the decisions relating to capital investment programmes. The models have not gained acceptance because they have not been presented to the financial accountants. It seems likely that the Corporation model might be useful in determining the relationship between long term investments and the "economic" cycles in the market.

The Operations Planning models indicated a fundamental problem with I.D. simulations. To gain confidence in the model it is necessary to check that it includes the mechanisms believed to create the behaviour. During this study, the allocation of orders between works was a fairly recent procedure and little was known about the dynamic behaviour created by the allocation. It is necessary to previously understand (or at least hypothesize) a feedback mechanism creating a known behaviour before a model can be created. In this study it was impossible to agree upon a

feedback structure that would cause an oscillation in orders placed with a works that would be caused by the allocation procedure. Inadequate data was available to identify any such oscillations.

The Market and Production Dynamics models have indicated specific dynamic behaviour, confirmed some ideas on how this behaviour is caused and cast doubt on others. Experiments were conducted to investigate how alternative policies and procedures could improve the behaviour and recommendations made.

The major study has been in applying the Market Dynamics model to a proposed Divisional stockholding operation. The study suggests that stockholding by the Division will be particularly successful in reducing order variations as well as smoothing production.

During the study a careful check was made on the details of each simulation run. Figure 11 lists three values computed for a few of the models built in this study and compares them with some of the reported I.D. studies. The models have been listed in three categories:

1. Simulation of the Firm. (Process models; production and orders. Some include labour and interactions between the firm and the market. Works, Operations Planning, Production and Market Dynamics models are included.)
2. Resource-Acquisition. (Market growth, financial and raw materials.)
3. Socio-Economic. (Social and economic environment studies.)

It would be expected that simulations of the firm can be based more firmly on known procedures and processes than the resource

Model	Comment	Type	Iterations	Equations Thousands	Equations Computed Thousands	
Production-Distribution Model	Same model of Retailer-Wholesaler-Manufacturer	Simulations of the Firm	1600	78	125	
Forrester (1)			2000	78	156	
RPSS	Buffa (45)		Advertising section added to Production-Distribution	3460	91	315
Advertising-Production Model	Forrester (1)	Socio-Economic Models	1360	111	151	
Electric Component Industry	Forrester (1)		Sprague Electric Co. - Results reported by Fey (11)	200	27	5.4
Market Growth Model	Forrester (23)		Salesmen, Delivery and Production Capacity interactions	200	30	6
Gas Reserve Model	Swanson (27)	Resource Acquisition	200	27	5.4	
Dominion Typesetters	Jernain (ed) (24)		Orders, Employment and Production interactions	200	27	5.4
Urban Dynamics	Forrester (3)		Housing, Employment and Industry interactions	250	153	38
World Dynamics	Forrester (5)	Socio-Economic Models	400	140	56	
Research and Development	Roberts (4)		Resources, project evaluation and project progress interactions	300	215	64
<u>Research Models</u>						
Works Model	P.T. Works Model	"Simulation of the Firm"	300	121	36	
Operations Planning Model	Dual Works Example		1200	112	134	
Production Dynamics Model	Chapter 5		10000	67	670	
Market-Sales Model	Market growth and delivery		1000	17	17	
Market Dynamics Model	Chapter 4		1600	72	115	
Financial Model (S.C.W.)	Initial Model	Resource Acquisition	200	29	5.8	
Financial Model (Corporation)	Developed Model		500	45	22.5	
Ingot-Slab Process Model	Test Models based on M.I.T. Work		200	14	2.8	
Policy Interactions Model		200	33	6.6		

Figure 11. Comparison of I.D. Models.

acquisition or socio-economic models. It appears that the range of time constants simulated in the production based models is wider than for the illustrative resource-acquisition and socio-economic models. The number of iterations of the models appears to breakdown into two groups:

- Resource-Acquisition and }... 0 to 500 iterations
Socio-Economic Models
- Simulation of the Firm ... 1000 to 10000 iterations

This is not simply related to the complexity of the models. From Figure 11 the models appear to breakdown, very approximately into three categories when ranked by the number of equations.

- Resource Acquisition 10 to 50 equations
- Simulation of the Firm 50 to 120 equations
- Socio Economic 120 to 200 equations

The resource acquisition models are illustrative and use highly aggregated variables. The problems of coding the models is likely to be small but the effort is redirected towards determining how the variables are to be aggregated. The socio-economic models attempt to cover a much wider range of feedback mechanisms, tend to be richer in the types of behaviour they display but assume relatively simple relationships.

The number of algebraic equations computed per simulation run varies considerably. The number of variables in each equation and how the simulation time and iteration interval are set make this figure highly variable. However, it is usual to reduce the iteration interval until the errors of computation just become noticeable. Secondly, the simulation is normally run for the periods for which there is data.

The number of equations computed is likely, in broad terms, to indicate the error that can be recognised. Simulations of well understood systems are likely to require many computations, those only partly understood requiring few equations to be computed.

	<u>Number of Equations Computed</u>
Resource Acquisition	5,000 to 20,000
Socio-Economic	20,000 to 60,000
Simulations of the Firm	60,000 to 300,000

The simulations of the firm need approximately 25 times as many equations to be computed than the resource acquisition models. (The very large number of equations computed in the P.D. model is due to a single time constant included in the ingot soaking pit simulation. The mechanism can be removed without affecting the dynamics reported here and permits the model to be simulated in 134,000 equations computed.)

The resource-acquisition models appear to offer the greatest potential as illustrative models. It is suggested that I.D. models are more appropriate at the Corporate Planning level than the process simulation level. Considerably greater effort is needed in the setting up and validation of the process models but greater management involvement is needed for the policy (resource-acquisition) models.

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4. The Market Dynamics Model

There have been many simulation studies of processes and plants in the major steel works. Simulation of the interactions between the works and their customers have been rare by comparison. It was suggested that pricing, delivery performance and production times, for example, may create or exaggerate the growth in orders, possibly worsening seasonal and long term order variations.

It was proposed that an I.D. model be constructed and experiments conducted to determine those factors which might be used to reduce seasonal and longer term ordering cycles. The model was to be used to investigate the consequences of alternative policies and procedures and to indicate the dynamic behaviour created.

The following objectives were stated for the initial development of the Market Dynamics Model;

"To apply the Industrial Dynamics method to the simulation of Strip Mills market and the dynamics of orders received, created by; stockholding, work-in-progress, pricing and delivery dates."

Figure 12 shows the development of the model and where these stages are described in this chapter.

4.1 Steel Market

To construct a dynamic model of the market it is necessary to obtain an idea of the type of dynamic behaviour, the problems caused and how the behaviour is created. This section describes some of the data considered and the deductions from this data. Some possible causes of the

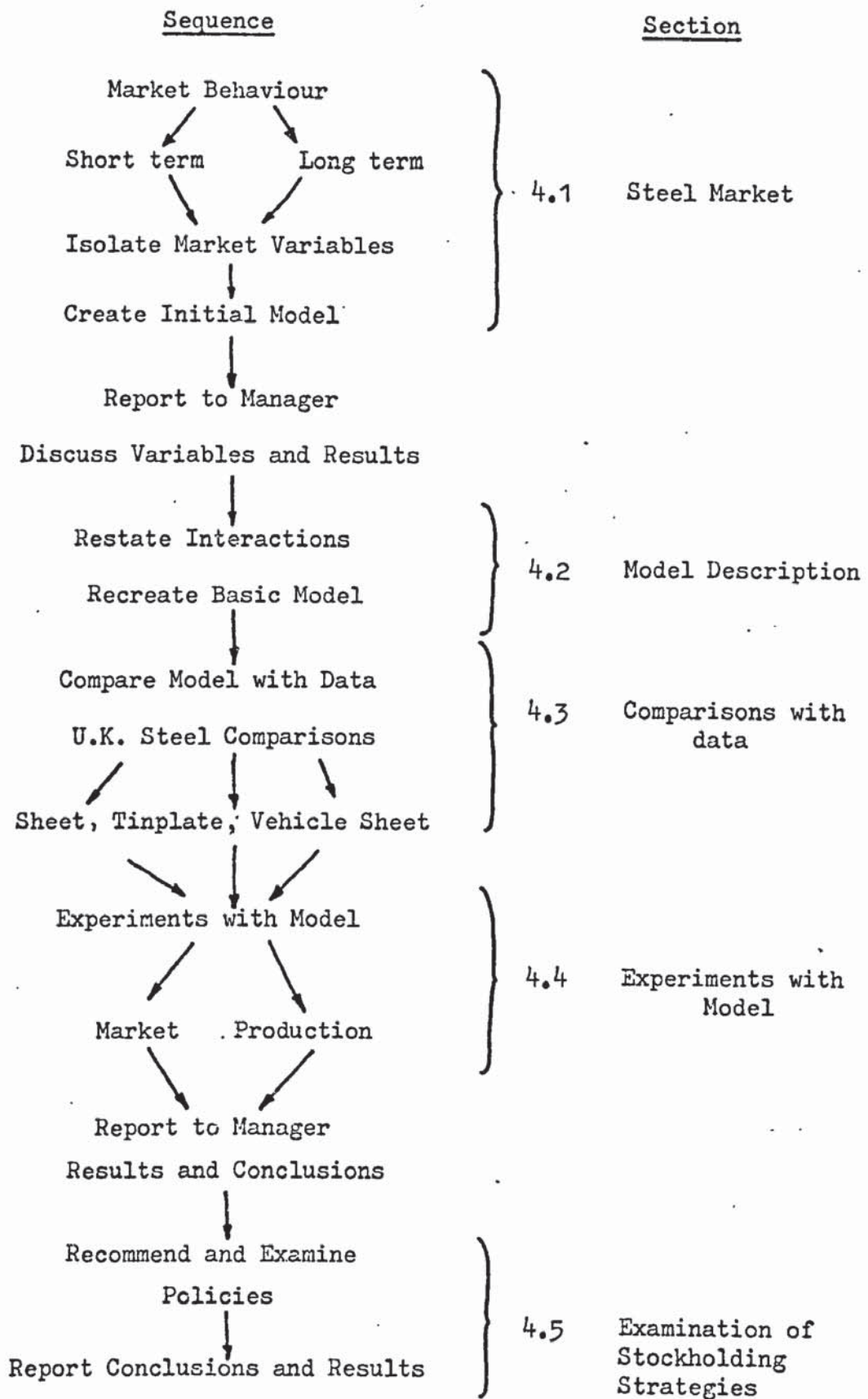


Figure 12. "Market Dynamics" Research Procedure and Chapter Sequence

dynamic behaviour are discussed and two major marketing factors, customer forecasting and stock control are considered in detail.

4.1.1 Market Behaviour

In 1967 the steel industry was renationalised. Comparisons before and after this date are difficult because the sales and production were reorganised across the old company boundaries. Only the total U.K. steel sales, orders and production can be compared. Because timescales of a few years must be considered it was necessary to look at data during the 1960's, mainly prior to nationalisation.

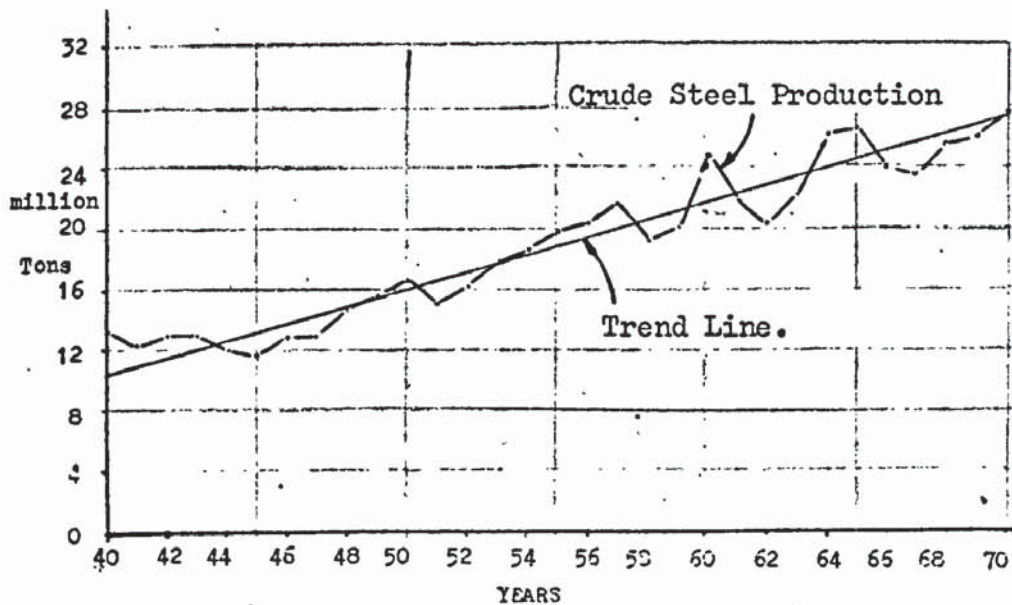


Figure 13. U.K. Crude Steel Production.

Crude steel production for the U.K. is shown in figure 13, for the 30 year period 1940-1970. Since 1945, it shows a growth of about 640 thousand tons per year, modified by an apparently cyclic fluctuation. It is likely that the consumption and production of steel reflects the economic situation; increased consumer spending creating a demand for steel.

The problem that arises, is whether the steel industry reinforces the variation in orders and production of steel. Some of the factors which may create feedback between the U.K. market and the steel producer are considered in section 4.1.2.

The "economic" or five year cycles apparent in figure 13 are only part of the dynamics. Figure 14 shows the monthly steel deliveries and new orders over a six year period. These are the only years for which data was available; more recent data would have been preferable. Included in figure 14 is a comparison of the monthly averages for the six year period, showing clearly the fall in orders in July/August and December and the peaks in February/March and October/November. The steel industry may reinforce the seasonal cycles even though they will align with the holiday periods.

The two types of behaviour considered were;

- . The seasonal variation in orders.
- . The long term "economic" cycle in orders.

The research investigated the dynamics of orders for the Strip Mills Division which makes flat rolled products.

Initially, the steel production of the major steel works at Port Talbot, Llanwern, Ravenscraig, Shotton and Ebbw Vale were analysed to determine the total behaviour of Strip Mills Division. The data used was primarily for a period prior to nationalisation and it became apparent that the competition for orders between the separate steel companies had distorted the orders, deliveries and production figures.

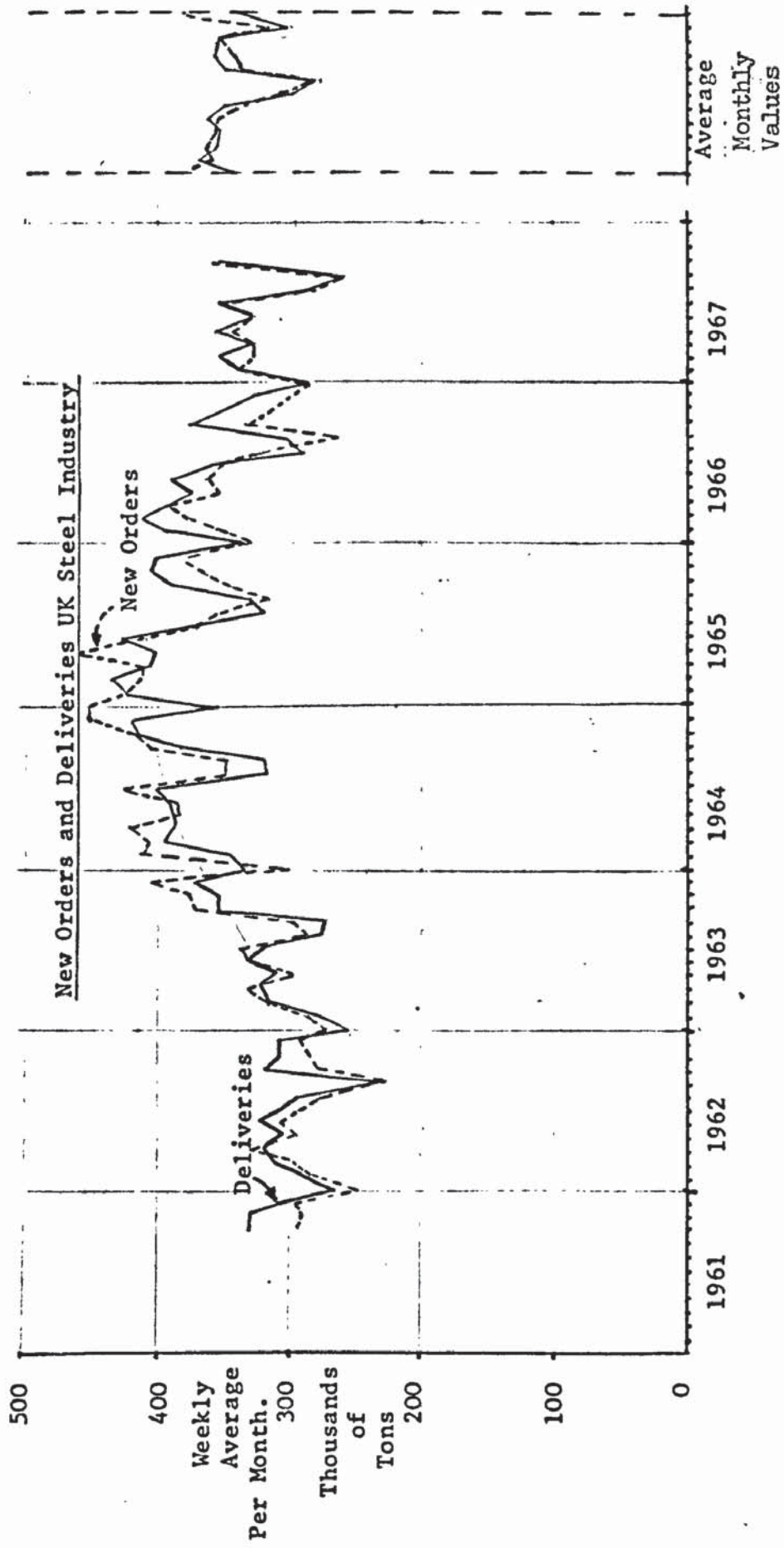


Figure 14. Total Monthly U.K. New Orders and Deliveries.

The data initially used to check the models was the total U.K. steel production, consumption, stockholding and new orders. Data for the total U.K. steel output is more readily available and over a longer period allowing the comparison of the dynamics over repeated cycles. Collecting data for the Strip Mills Division was more difficult. It was not until 1973, for example, that the orders for all the main Strip Mills works were handled by the same order entry system.

Strip Mills Division has a few easily identified markets which were simulated in separate models allowing for the differences in customer ordering, stockholding and forecasting procedures. To observe the longer term market dynamics, where the ordering and delivery of steel appears to cycle with a period of five years, it was necessary to have data spanning ten or more years.

Consistent data over an adequate period is not available for the Strip Mills Division. However, the B.I.S.F. Statistics (44) includes some data on Sheet Steel. The term "Sheet Steel" refers to sheet steel in coil form or cut up, whether sold as hot rolled or cold reduced. It excludes narrow strip (less than 24 inches wide), often produced by works outside the division. It also excludes tinplate (and blackplate) which has a distinct market of its own.

By considering U.K. Steel, U.K. Sheet Steel, Tinplate and Sheet for Vehicle Manufacturers it was possible to examine the dynamics for:

1. An industry wide market.
2. Strip Mills main markets; sheet and tinplate.

3. A growth market with major economic cycles - sheet for vehicle manufacturers.

4. A seasonably dependent market - tinplate.

4.1.2 Market and Production Interactions

The model described in this chapter is the successor to a number of models dealing with market, investment and production dynamics. The original Market Dynamics Model was completed towards the end of 1969, prior to the current divisional structure of B.S.C. The models were developed for the South Wales Group which consisted primarily of the Port Talbot, Llanwern and Ebbw Vale steel works.

The early models assumed the continuation of some pre-nationalisation policies and were based on the structure of the South Wales Group. Since both the structure of the organisation and its policies have changed with the introduction of the Strip Mills Division so the model became increasingly unrealistic and had to be rewritten.

The early models followed Forrester's recommendations and used the "Industrial Dynamics" technique of treating an organisation as an enclosed system. An enclosed loop structure implies that each variable is linked directly to at least two others; all the variables are linked indirectly with one another. There is only one independent variable; time. In the model, time is incremented in small steps causing the remaining variables to interact and create the dynamics.

The early models were not driven by an external stimuli. The market "demand", for example, was generated by the model itself. The term "demand" has been used in a general sense to

indicate some basic need of the customer for steel. The "demand", however, is an elusive concept. To be useful it has to be defined more rigorously. Definitions such as "orders placed in a week" or "customers estimated consumption of steel for the following month" are more useful. In addition it is necessary to specify the measures of the "demand"; tonnes of steel per week or ingot tonnes equivalent (tonnes of steel needed at the ingot stage to produce the final finished product as ordered) per month.

Multi-dimensional measures of the orders including, say, sales value, finished tonnage, width and gauge are even more difficult to specify. Only the delivered finished product weight is used in this model.

Two important and controversial loop structures were incorporated in the early models to create an environment for the works group; "capital investment" and "demand". These feedback networks were difficult to model. Each discussion with interested departments emphasised different causal relationships. Figure 15 shows a highly simplified diagram of one method of simulating these loops.

In the "Investment" structure it was assumed that a more profitable steelworks was able to obtain greater capital investments, increase its production capacity and gain increased profits from a higher production throughput. The profit, however measured, would depend on prices, costs, labour availability and orders.

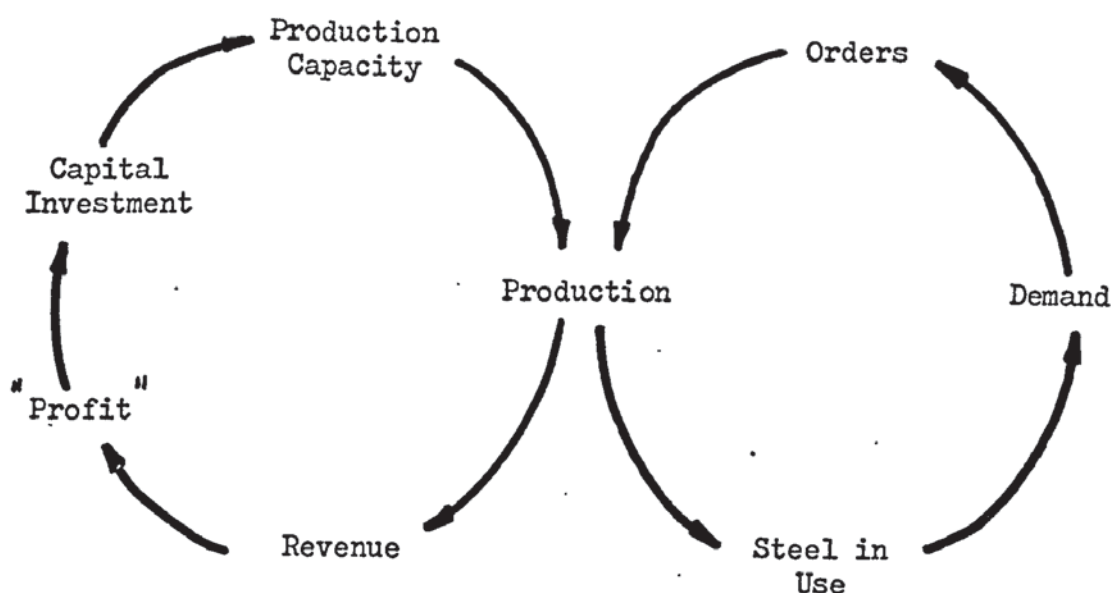


Figure 15 Possible "Capital Investment" and "Demand" Feedback Reactions.

In the "Demand" structure, it was assumed that the massive investments in a steelworks helped to create a market for the steelworks. In 1968 1.38 million tons of steel was consumed by the Iron and Steel Industry itself from a total U.K. consumption of 16.57 million tons. The increased flow of money was further assumed to create, particularly in the locality of the steelworks, an increase in consumer expenditure and increase steel orders.

It must be recognised that such expenditure may still be small compared with the effects of government policy or "economic cycles". It appears likely, however, that the capital expenditure in the B.S.C. would align with "economic cycles" and reinforce them. In the early models the link between "capital investment"

and generated demand was deliberately overstated since it was felt that the steel industry generated cycles would adequately simulate the feedback loops in other industries.

When the model was initially devised, it was expected that the production policies, interprocess stocks and orders-in-hand would create the dynamics. The "demand" and "investment" loops were expected to provide a fairly static long term growth in "demand" and production capacity.

As a check on the model it was re-run for a longer simulated period. Figure 16 shows the first re-run of the model for a simulated twenty year period. It shows a periodic cycle for the South Wales Group even though no external demand pattern was incorporated.

Although this model was extensively modified it received extensive criticism from Operational Research and the Sales Office. It was felt that the structures were too simple and did not reflect the complexity of such decisions. For example, capital investment it was said would be planned by the Corporation with regard to long term development of the industry and its market. It would not be substantially influenced by short term market changes.

Interactions between the steel producers and the market may be short or long term. The steel is delivered, in the main, to consumers who produce the finished product. The short term dynamics appear to be primarily, created by interactions between the steel producers and purchasing departments of the consumers. The longer term dynamics appear to be influenced, if at all, by the development of a market.

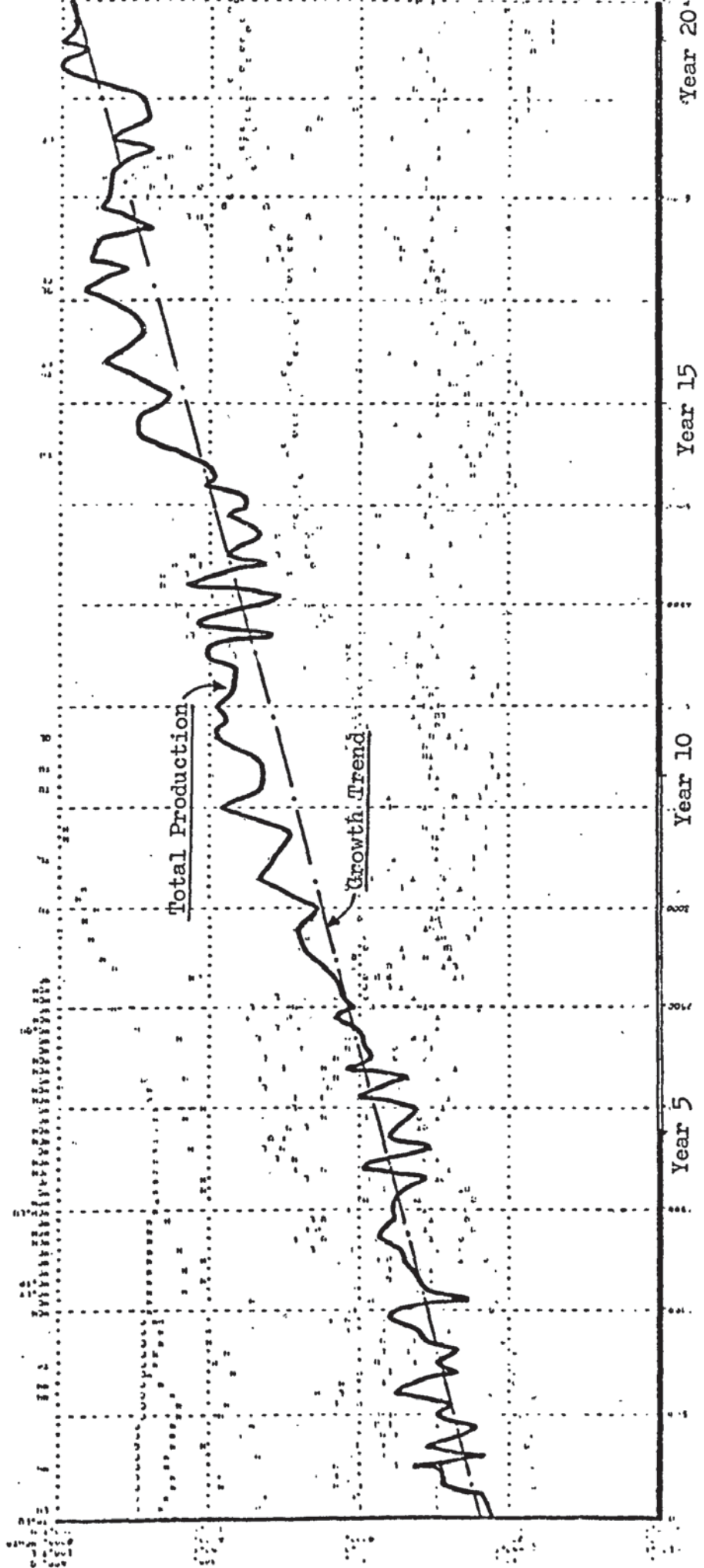


Figure 16. Output from the Initial Market/Production Model - 20 Year Period.

The availability of wider sheet, special coatings, research into new uses of steel, image improvement through advertising and prompt delivery will all encourage a preference for steel and long term market growth. Figure 17 shows some of these market factors diagrammatically. Delivery and price can create a fairly immediate (months) response affecting the orders placed by the customer. The product range, applications and advertising, however, affect the marketing of the end products and take much longer (years) to alter the order placement.

Pricing and delivery also influence the longer term dynamics by determining customer allegiance and reducing the need for second and third suppliers.

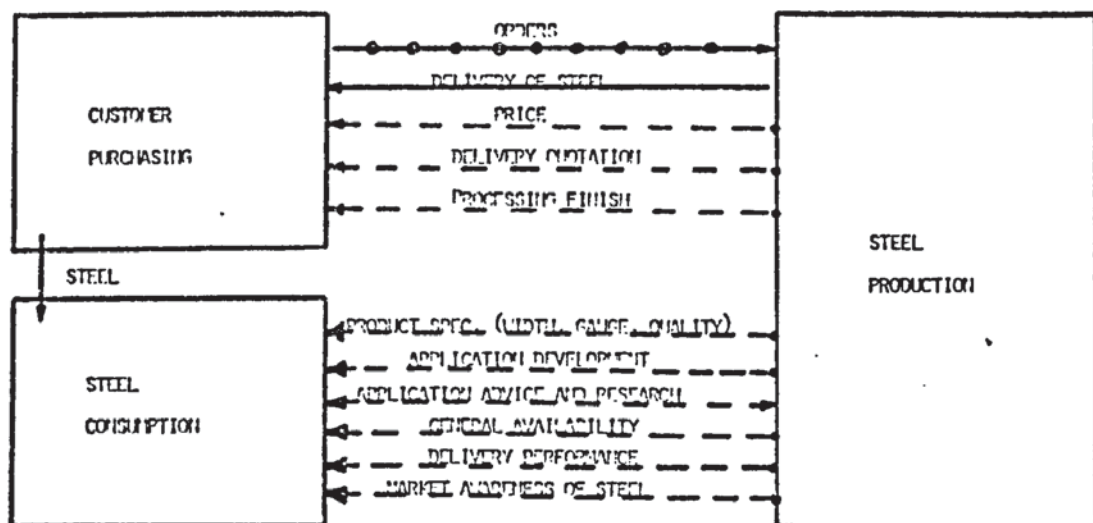


Figure 17. Market - Production Interactions.

Strip Mills Division gives priority to home trade orders, accepting export orders when there is a recognised gap between home trade orders and production capacity. The home market also imports sheet steel if it is unable to purchase it from the Division or if world steel prices fall. Some initial attempts

at modelling imports and exports showed that it was difficult because of the complexity of the interactions. Further, without adequately simulating the home market it was impossible to simulate the export sales.

Home trade sales are considered of prime importance by the Division. The basic model described in this Chapter includes only home trade orders. Imports and exports have been ignored in the basic model.

Pricing is one of the major links between a company and its market and is usually viewed as a prime determinant of demand. Home sales steel prices have been effectively controlled since the war, being maintained at a fairly constant level. Product specifications have not changed significantly so that the total revenue per ton of steel produced gives a fair indication of the "price" of steel on the home market. Figure 18 shows the revenue per ingot ton for the Steel Company of Wales over the period 1956-1966.

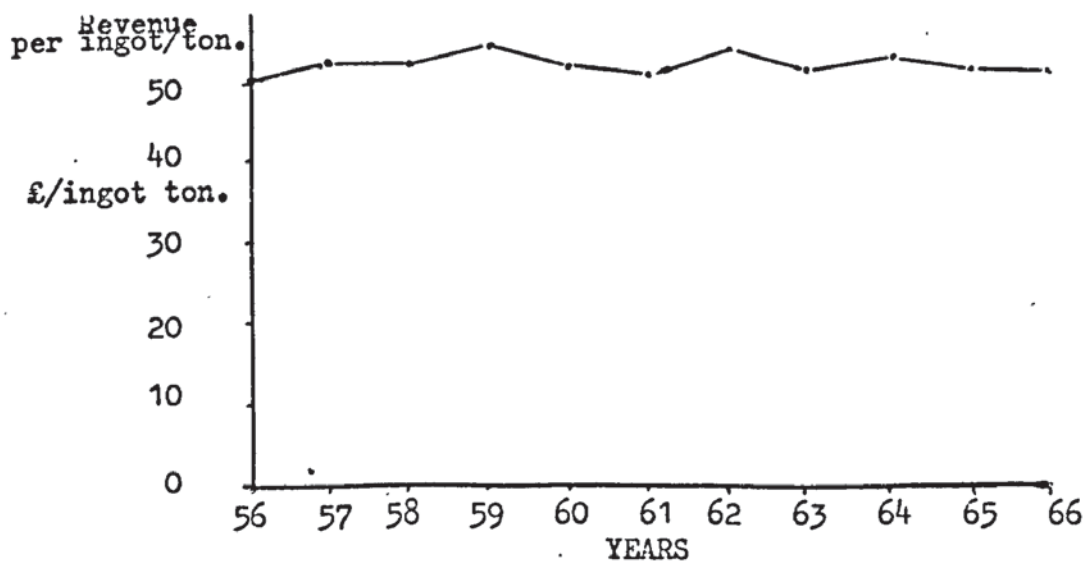


Figure 18 Revenue per Ingot Ton - S.C.W.

Since nationalisation the price of steel was fixed more rigidly but, following the general trend in increasing costs, the price of steel has been increased in steps every six months or so since mid 1969 (figure 19). Even though the price of steel has risen in recent years, the price has not reflected the demand. The government controlled steel prices have

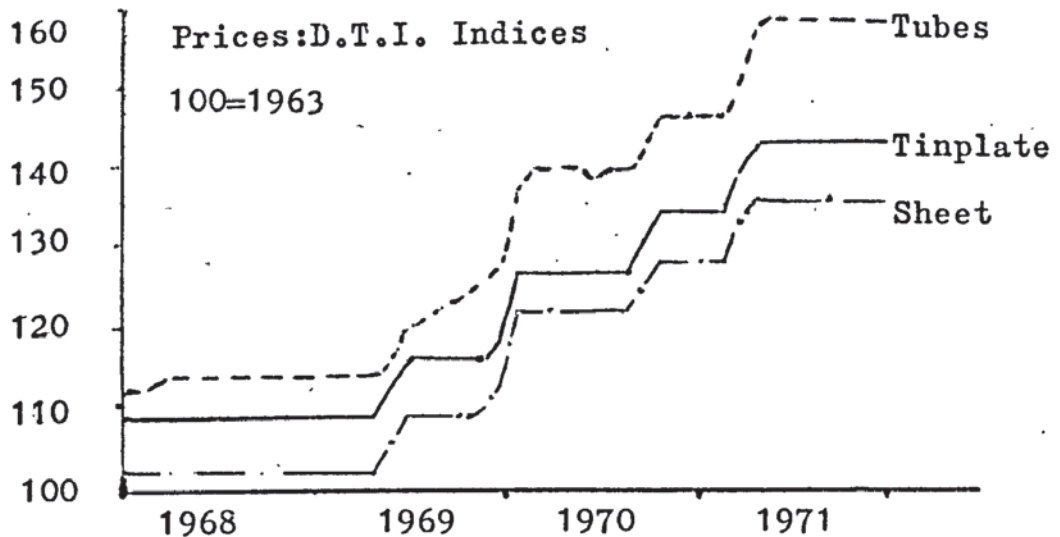


Figure 19. D.T.I. Price Index.

excluded a demand/price mechanism from operating. It appears unlikely, therefore, that pricing contributes directly to any "feedback" generated dynamic behaviour in the home market, simply because the price is unresponsive to demand fluctuations.

Following the development of the early enclosed models it became generally agreed that pricing would not create feedback oscillations and the main interactions that would be considered were; the delivery period recognised by the market, the deliveries of steel and the orders placed. The model would include stockholding and forecasting procedures adopted by the

market and be driven by the steel consumed by manufacturers. The production side of the model would include order handling, the production delay and the delivery quotation procedures.

4.1.3 Stockholding

The control of stocks by the Division's customers is believed to contribute to variations in orders received. Figure 20 shows the sheet steel consumed by manufacturers (excluding tinplate) and the consumer/merchant stocks. The merchant stocks have increased during the ten year period while the consumer stocks, after a fall in the early sixties have remained at a similar level.

In the short term both the merchant and consumer stocks have tended to follow the steel consumption variations. An increase in consumption has been accompanied by an increase in consumer and merchant stocks. This accumulation and liquidation of stocks is a result of the stock control policies and procedures adopted by the customers. It can be seen to operate for the total U.K. steel stocks, for individual product categories such as tinplate and for customer groups such as vehicle manufacturers.

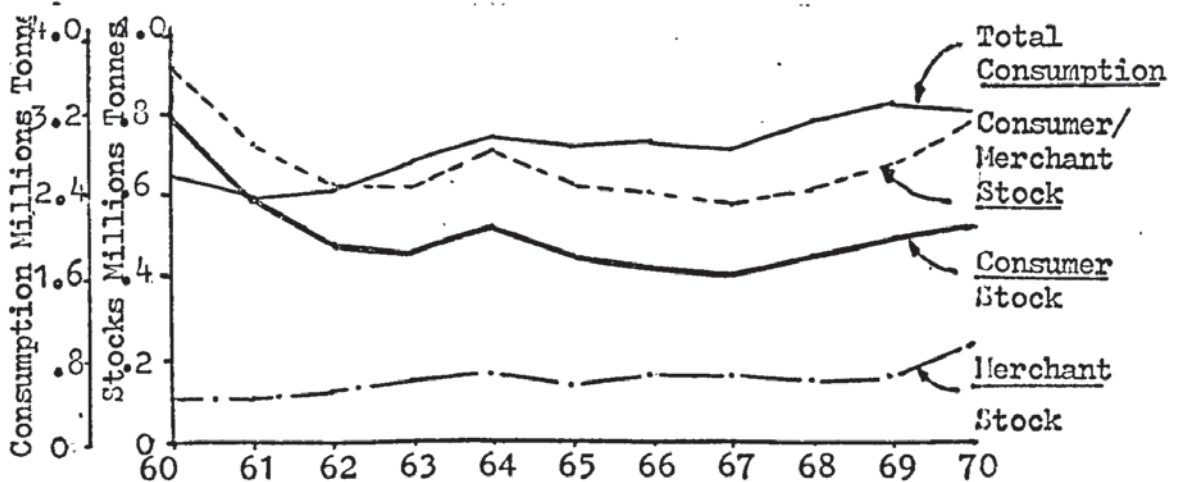


Figure 20 Sheet Steel Consumption and Stockholding.

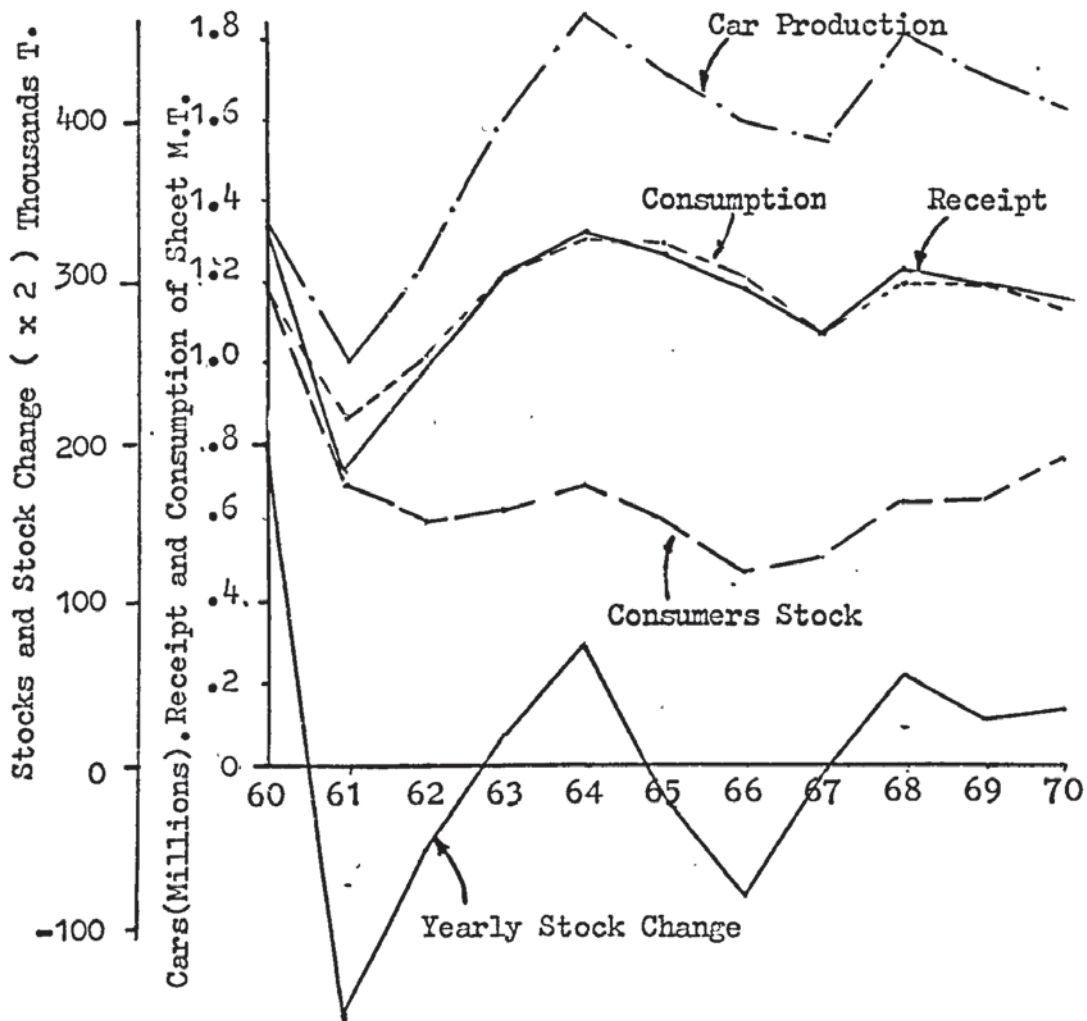


Figure 21 Sheet Steel for Motor Manufacturers.

Figure 21 shows how the control of stocks by the motor manufacturers has exaggerated the variation of sheet steel sales. The variations in car production have caused similar variations in the sheet steel consumed in producing car bodies. The peak consumption in the early sixties, however, was lessened by the reduction of the steel used per car.

The stocks can be seen to have increased during the peak years and fallen during the consumption downturns. The stock increases in 1964 and 1968 coincide with the peaks in car production. The increased stock level had to be created by the deliveries of steel exceeding the consumption. Steel deliveries (receipt by the manufacturer) therefore tend to vary more widely

than the consumption.

Part of the purpose of this model was to formalise and understand the procedures adopted by the market causing this amplification of demand. Stock control procedures were considered and parameters estimated to determine whether they would create the expected gain.

In discussing these procedures it is necessary to distinguish between the stock that the customer desires (desired stock) and the actual stock (stock). The procedures determine the desired stock level. The actual stock is dependent on the ordering and delivery of the steel, the production lead time and variations in consumption during the lead time.

Four types of stock have been identified corresponding to different requirements. These stocks have been termed: Work-in-Progress, Active, Buffer and Strategic stocks.

Some of the customer stocks incorporate steel as work-in-progress. These stocks are assumed proportional to the consumption rate and the desired stock has therefore been made proportional to the forecast consumption rate:

$$\underline{\text{Work-in-Progress Stock Desired}} = a \times \text{Forecast Consumption}$$

The active stocks are those which are required to allow for the normal consumption during the period between deliveries of steel. Two types of active stocks were recognised; those determined by "Economic Order Quantity" rules and those dependant on the lead time.

If the price, cost of handling, storage costs and consumption rate are considered, calculation of an economic ordering quantity

normally indicates that the stock should be made proportional to the square root of the forecast consumption:

$$\text{Active (E.O.Q.) Stock Desired} = b \times \sqrt{\text{Forecast Consumption}}$$

Without considering in detail the products, customers and stocks it is difficult to determine the response of an aggregate market. If the market were divided equally among n customers so that each consumed the same proportion of the total consumption (S), then the total desired, E.O.Q., active stock (D) would be:

$$D = k_1 \cdot \sqrt{S/n} + k_2 \cdot \sqrt{S/n} + \dots + k_n \cdot \sqrt{S/n}$$

where k is the constant proportionality factor.

If the costs are similar, $k_1 = k_2 = \dots = k_n (=k)$.

$$D = k \cdot \sqrt{n} \cdot \sqrt{S}$$

This analysis is crude but indicates that the total E.O.Q. active stock desired is likely to remain approximately proportional to the square root of the forecast consumption. Even if the costs are known, however, the proportionality factor cannot be easily determined because of its dependence on the fragmentation of the market.

If a customer is consuming small quantities of a particular width and gauge of sheet steel the orders will be widely spaced to minimise handling and delivery costs on small orders. The Corporation's pricing policies also discourage very small orders.

Large customers, ordering large quantities of the same steel are able to place orders over a long period (a year) and

call off against this allocated tonnage at regular short intervals. The smaller customers are unable to do this and need to wait the full delivery period.

It appears that the small customers tend to reorder on the basis of this lead time. The "small order" active stock has been assumed to be proportional to the stock required during the lead time to cover the expected consumption.

$$\frac{\text{Active Stock Desired}}{\text{(Small Orders)}} = c \times \text{lead time} \times \text{Forecast Consumption}$$

The buffer stock allows for variations in the consumption of steel during the lead time and for variations in the lead time. Analysis of these variations indicates (46) that the desired buffer stock can normally be computed from:

$$\text{Buffer Stock} = d \times \sqrt{E_c^2 \cdot V_l + E_l \cdot V_c}$$

where E_c and E_l are the expected consumption and lead times, V_l and V_c their variances.

These stock control procedures were combined in the model to give a total desired stock level for the market:

$$\begin{aligned} \underline{\text{Desired Stock}} = & a \times \text{Forecast Consumption} \\ & b \times \sqrt{\text{Forecast Consumption}} \\ & c \times \text{Lead Time} \times \text{Forecast Consumption} \\ & d \times \sqrt{(\text{Forecast Consumption})^2 \times e + \text{Lead Time} \times f} \end{aligned}$$

(a to f are constants, determined for each market)

4.1.4 Customer Forecasting

Customers have to forecast their requirement some time in advance of receiving the steel because of the production time and length of the order book. The orders placed with the Division are based upon some estimate of the rate at which steel will be consumed. The forecast is therefore a prediction of the likely consumption of steel at the time of the next delivery.

Forecasts are "based very largely on an assumption of persistence. This may include a belief in the persistence of present values of variables, and a belief in the persistence of a recent trend, and a belief in the persistence of past cyclical fluctuations" (1). In this model four forecasting methods are included:

- (1) Exponential Smoothing assuming the continuation of the current average consumption.
- (2) Trend Prediction assuming a continued increase or decrease in consumption.
- (3) Cyclical Prediction assuming a seasonal cycle in consumption.
- (4) Trend plus Cyclic Prediction assuming a seasonal cycle overlaid by a longer term trend.

In some markets, where changes in consumption appear random, the best prediction is one which takes a recent average value and assumes its continuation. For reasons of computational simplicity a common method of forecasting used in stock control systems is an exponentially weighted average; creating a new forecast (F_k) by adding a fraction (α) of the difference between the actual demand (x) and the previous forecast (F_j).

Exponentially Smoothed Forecast :- $F_k = F_j + \alpha(x - F_j)$

Exponential smoothing creates a gradually changing estimate of the current consumption. If it is used when the consumption has a significant trend the value given lags the actual consumption by $1/\alpha$.

Forrester (1) discusses a means of projecting a trend by using two exponentially smoothed average values of the consumption. An estimate of the trend gradient is computed from the two exponentially smoothed averages.

$$\text{Trend Prediction} = \text{Current Consumption} + P \times \text{Trend Gradient}$$

where P is the forecasting period.

For flat rolled products produced by Strip Mills Division, the lead time is normally six to ten weeks. For many manufacturers it is the lead time which determines the forecasting period. In this model the forecasting period is variable and depends on the lead time. This is in contrast to the formulae devised by Forrester which uses a constant forecast period.

$$\text{Forecast Period (P)} = a + b \times \text{Lead Time}$$

Forrester discusses a method for simulating cyclic forecasts (1). The method consists of producing a smoothed, exponential average for a period, placing the resultant value in the first of a chain of "boxes" which are shifted along at the end of a period. The value held in each box represents the average for the month. The list of values is substituted in a table which is used to provide a forecast for any time in the future.

Unfortunately the software used to compile the models, DYNAMO II available on the 360/370 computers does not permit this train (BOXCAR) nor the use of variables in a table of values.

The seasonal cycle forecasting method used in this model includes four accumulators (Levels) which are uniformly emptied one into the next in a cyclic chain. The first level is an exponential smoothing function, averaging the output from the fourth level and the consumption. Each level represents a quarter. A fifth level is used to represent the current quarter but a year earlier.

By using the appropriate levels a seasonal forecast can be obtained or a trend weighted seasonal forecast. The method is not general and cannot be easily used in other I.D. forecast simulations. The MACRO approximating the DYNAMO I function BOXCAR (BOX) and the seasonal forecasting equations are included in appendix 1.

The dynamics created by the forecasting methods will depend on the dynamics of the consumption and the parameters of the forecasting technique. To some extent the linear trend prediction also depends on the steel producers declared lead time.

Both the magnitude and the timing of the forecast is important. If the forecast overstates any variations in the consumption, then the ordering procedures will have to compensate for the exaggerated stock levels. If the forecast does not swing widely but incorrectly anticipates changes in the market, then again orders will have to be adjusted to compensate for the incorrect stock level.

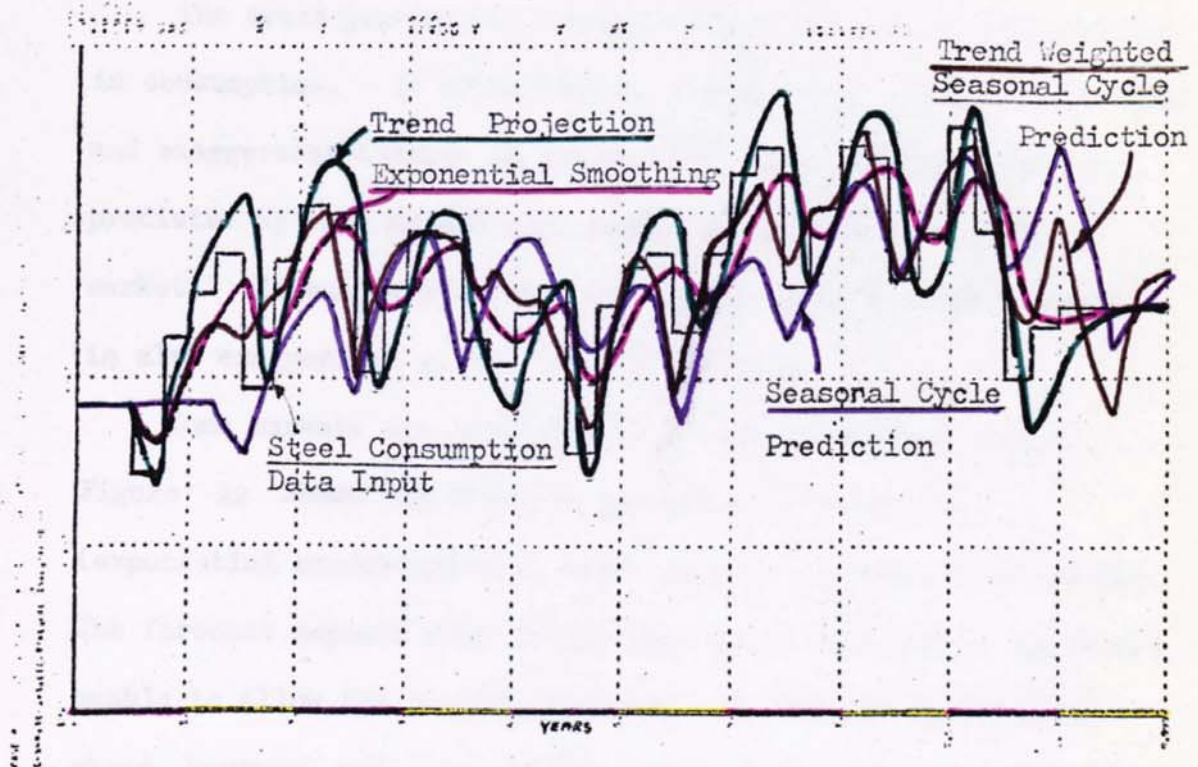


Figure 22 Steel Consumption and Simulated Forecasts.

Figure 22 shows ten years quarterly U.K. steel consumption and the forecasts generated by the four methods incorporated in the model. These forecasts are only illustrations of dynamic behaviour of the four methods using reasonable values for the parameters.

The exponentially smoothed forecast understates the dynamics, which is generally desirable, since it allows the customer stocks to absorb the highest peaks in consumption. However, the forecast does not anticipate the peak demands which is necessary because of the long lead time. In consequence, the forecast generated, tends to predict a peak demand during a slump in consumption.

The trend prediction assumes a continued growth or reduction in consumption. It overshoots when there is a seasonal downturn and exaggerates changes in the market. The peak forecast predicted by this method also occurs during a downturn in the market. It can be seen that the longer term "economic" cycle is also exaggerated by the trend prediction.

Some markets are dominated by a regular seasonal cycle. Figure 22 shows the forecast generated by averaging (exponential smoothing) five years quarterly consumption figures. The forecast depends only on previous years data and is therefore unable to allow for current demands. It is able to forecast ahead, however, and allow for the lead time. Because the steel consumption in the U.K. has a major seasonal cycle it is to be expected that it would create a less dynamic response from the orders placed than the exponential and trend predictions.

A further refinement is to add a trend prediction to the seasonal cycle. This is shown in Figure 22 and indicates that for the U.K. steel consumption data any trend weighting will tend to worsen the predictive ability of the cyclical forecasting method.

4.2 Model Description

This section describes the basic structure of the market dynamics models. The main interactions are described and the model split into two sectors; Production and Market. The flow paths and equations are detailed, together with brief explanations of each variable.

4.2.1 Model Structure

The two sectors of the model are related by the material flow path. The basic elements of the production and market sectors are discussed and some of the feedback loops in the model described.

4.2.1.1 The Prime Interactions

The basic model is in two parts; the steel producers and customers. The dynamics which the model is intended to simulate, cover a period of a few months to a few years and the variables included in the model reflect this simulation period. The model concentrates on the delivery, delivery date quotation and order placement interactions between the market and steel producers, Figure 23.

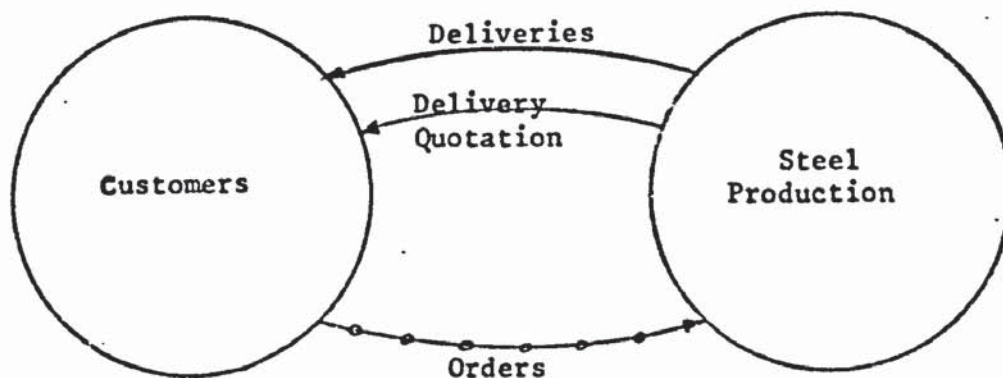


Figure 23. The Interactions Assumed in the Model.

The main material flowpath linking these sectors is the production, delivery and consumption of steel, Figure 24. The steel producers work-in-progress and consumer stocks form the main reservoirs in this conservative flowpath.

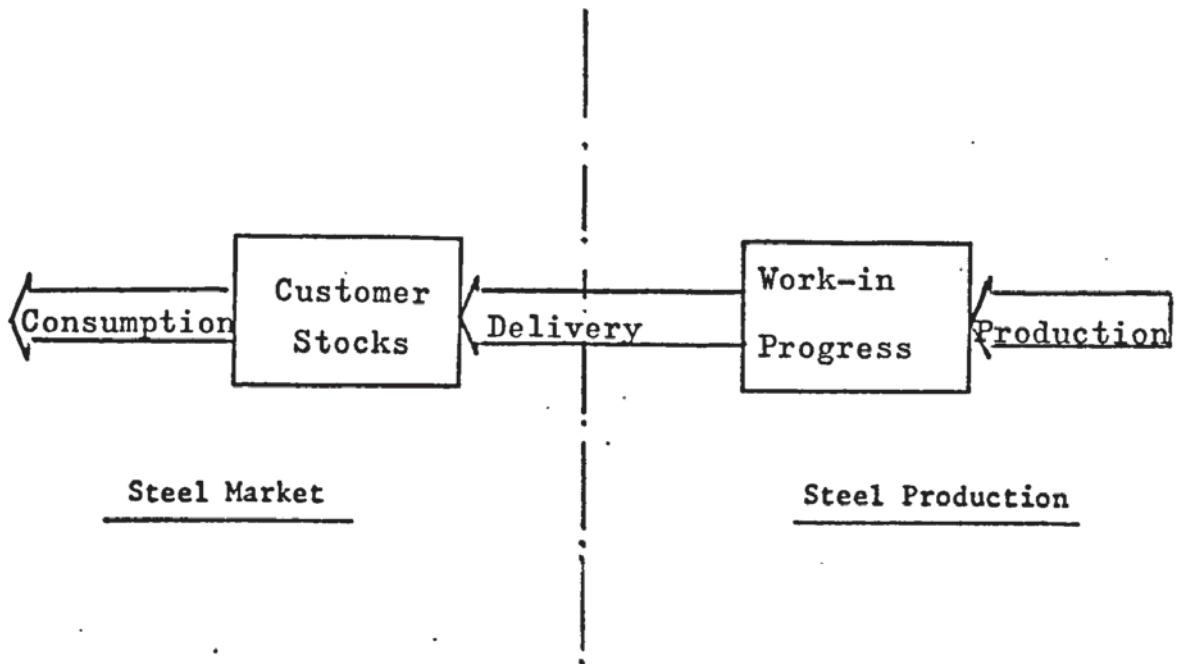


Figure 24. The Material Flow.

4.2.1.2 The Production Sector

In outline, the production sector consists of receiving orders, and producing the steel at a rate determined by the order backlog and delivery date promised, Figure 25. Orders are received from the market and form a pool of orders which is depleted by the completion of the order. The pool of orders determines the desired level of production and the quoted delivery date.

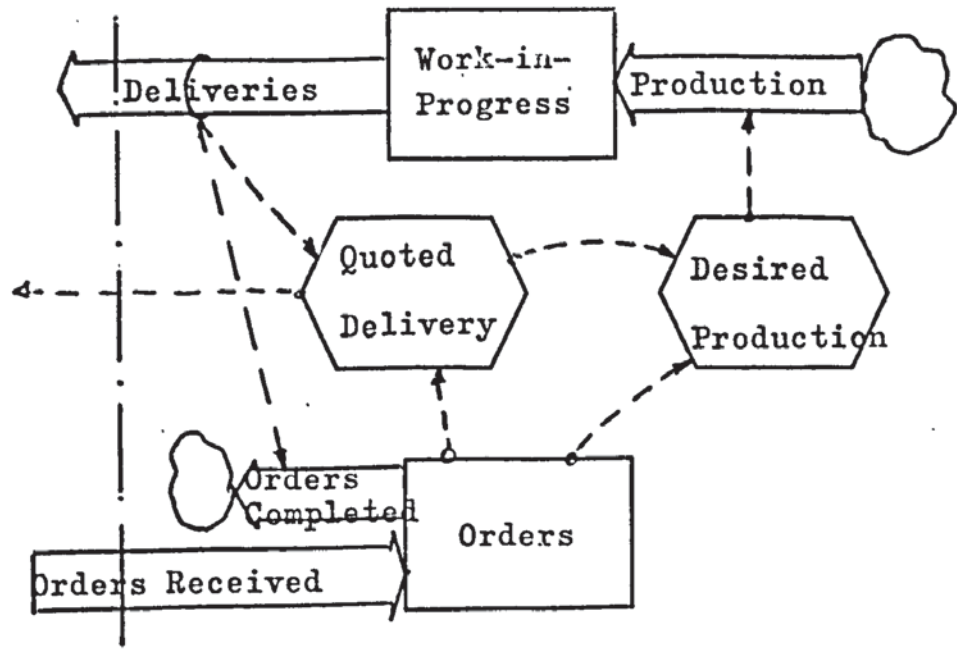


Figure 25. The Production Sector

4.2.1.3 The Market Sector

In outline, the market sector consists of consuming and maintaining adequate stocks of steel. The orders placed with the steel producers depend on ordering procedures that include stock control, consumption forecasting and allowances for the quoted delivery date, Figure 26.

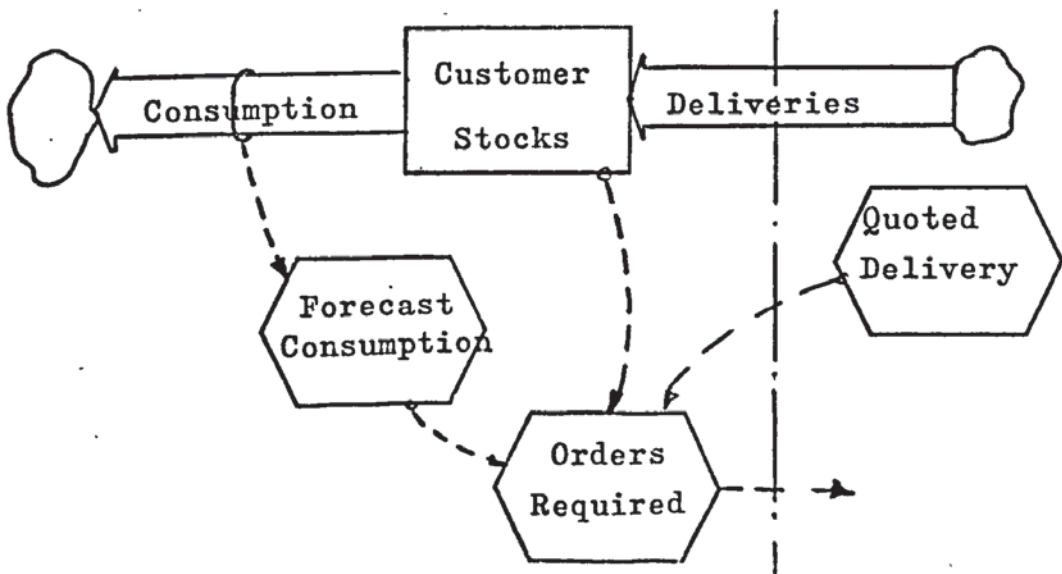


Figure 26. The Market Sector.

4.2.1.4 Feedback Loops in the Model

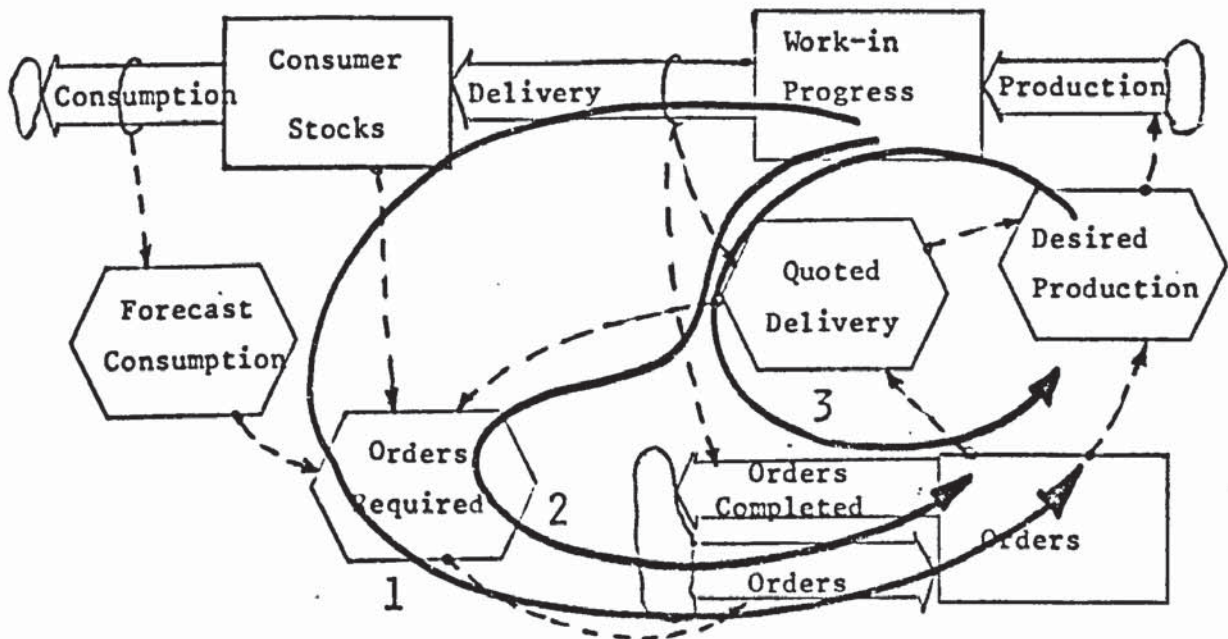


Figure 27. Three Typical Feedback Interaction in the Model.

Figure 27. shows the basic model and three typical feedback loops, that were expected to create dynamic responses in orders received and steel production.

1. Orders - Production - Delivery - Customer Stocks - Orders

This loop was expected to reinforce the ordering fluctuations especially if the customers stocks and production order backlog were out of phase.

2. Orders - Production - Delivery Promise - Orders

The rise and fall in the delivery promise was expected to create variations in the orders placed to cover the delivery period.

3. Production - Delivery - Delivery Promise - Production

Long delivery periods were expected to create considerable pressure for increased output. The response time of the

production facility and the work-in-progress was expected to reinforce the ordering variations.

4.2.2 Production Sector

The production sector of the model includes a production rate, work-in-progress and a delivery rate. The effective stages of the production process are assumed to be hot rolling, cold rolling, finishing and delivery. Each of these stages is assumed to take a few days with the output from each stage being dependent on the interprocess stock.

These rates and stocks are shown in Figure 28.

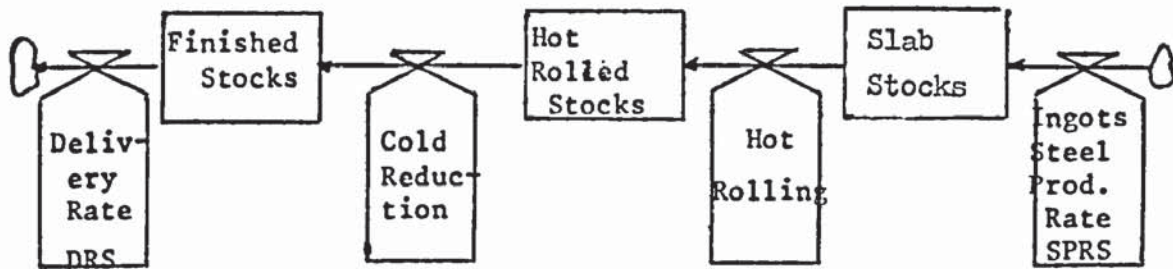


Figure 28. Production Rates and Interprocess Stocks.

This is a simplification since hot and cold rolled steel is also delivered directly to customers. However, since the simulation period of prime interest is from a few months to a few years, the minor differences in the flow path, with periods of a few days would not be detectable.

If each rate is made proportional to the stock available and the delay in each stock level is approximately similar for each stage, then the DYNAMO MACRO, DELAY3 can be used as in Figure 29.

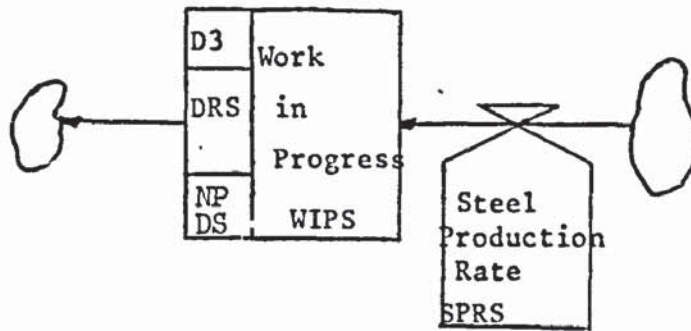


Figure 29. Delivery, Production and Work in Progress.

The Delivery Rate (DRS) will, therefore, be dependant on the cascaded rates and levels shown in Figure 28. The first rate, the Steel Production Rate (SPRS) supplies the input to the production chain. The total work-in-progress (WIPS) is the sum of the slabs, hot rolled and cold rolled coils measured in ingot tonnes equivalent.

$$R \quad DRS.KL = DELAY 3 (SPRS.JK, NPDS)$$

$$L \quad WIPS.K = WIPS.J + DT * (SPRS.JK - DRS.JK)$$

$$N \quad WIPS = CRS * NPDS$$

$$C \quad NPDS = 0.115 \text{ (6 weeks)}$$

DRS Delivery Rate

DELAY 3 DYNAMO function representing three cascaded stocks

SPRS Steel Production Rate

NPDS Normal Production Delay

WIPS Work-In-Progress

CRS Consumption Rate

The Steel Production Rate (SPRS) is determined in the model by the orders which have been received but which have not been released for production.

The orders which have not been released - Unscheduled Orders (USOS) - are loaded on the basis of the normal Number of Weeks Orders expected to be held in the order file (NWOS). This release period (NWOS) is determined by the delivery quoted. The relationship between the quoted delivery and release to production is specified in a table and is discussed in section 4.4.1.2.

R $SPRS.KL = USOS.K / (NWOS.K - NPDS)$
 A $USOS.K = UOS.K - WIPS.K$
 A $NWOS.K = TABHL (TNWOS, QDDS.K * 52, 2, 14, 2) / 52$
 T $TNWOS = 7, 7, 10, 14$
 N $NWOS = 0.192$ (10 weeks)

SPRS Steel Production Rate
 USOS Unscheduled Orders
 NWOS Number of Weeks Orders
 NPDS Normal Production Delay
 UOS Unfinished Orders
 WIPS Work-In-Progress
 TNWOS Table relating quoted delivery and No. Weeks Orders
 QDDS Quoted Delivery Delay
 TABHL Dynamo Table Function

Order handling by the works is simulated in the model by a receipt rate, an unfinished order file and deletions from the file as orders are completed, Figure 30.

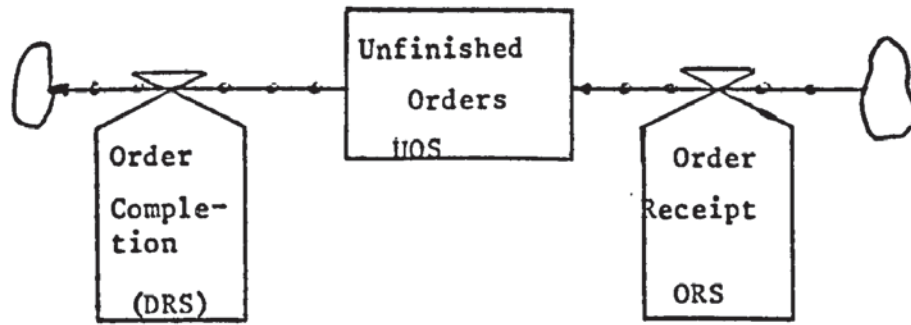


Figure 30. The Order Handling Flowpath.

L $UOS.K = UOS.J + DT * (ORS.JK - DRS.JK)$
 N $UOS = DCRS * NWOS$
 R $ORS.KL = DORS.K + SAMPLE (NORMRN/0, ORSDS), 0.02, 0)$
 C $ORSDS = 0$

UOS Unfinished Orders
 ORS Orders Received
 DRS Delivery Rate
 NWOS Number of Weeks Orders
 NPDS Normal Production Delay
 DORS Desired Orders Received (Placed with the Division)
 SAMPLE DYNAMO function sampling a distribution
 NORMRN DYNAMO function creating a normal random distribution
 ORSDS Order Rate Standard Deviation

The Orders Received (ORS) would vary from week to week, even if the overall requirement (DORS) were constant, due to the

variations in individual orders. The Orders Received rate (ORS) can be made to vary by selecting a suitable value for the Orders Received rate Standard Deviation (ORSDS). The normal distribution is sampled to give a suitable frequency distribution. Experiments were conducted to determine the sensitivity of the model to these random variations but results presented in the thesis assume no random element in the Order Rate. The Order Rate is, therefore, deterministic; all variations are created by the model equations.

Customers become aware of the delivery delay (the lead time plus the production cycle time). The delivery delay is the period during which the orders are visible to the production sector. This delivery delay, as expressed to the customer, is termed the quoted delivery in the model, since it is via the original delivery quoted and the experience of the customer purchase department that the delivery delay is estimated.

In the model an Average Delivery Delay (ADDS) is calculated from the Unfinished Orders (UOS) and the Average Delivery Rate (ADRS). The Expected Delivery Delay (EDDS) represents the delivery delay that would be expected by the sales office. The expected delivery delay is a smoothed, delayed value of the average delivery delay. This exponential smoothing represents the unwillingness to accept a rapidly increased delivery delay if there is a sudden jump in orders or a production breakdown. It includes the time to receive and accept orders.

The quoted delivery (QDDS) is based on the expected delivery delay except that the minimum delivery period quoted is that determined by the production cycle time (NPDS), Figure 31.

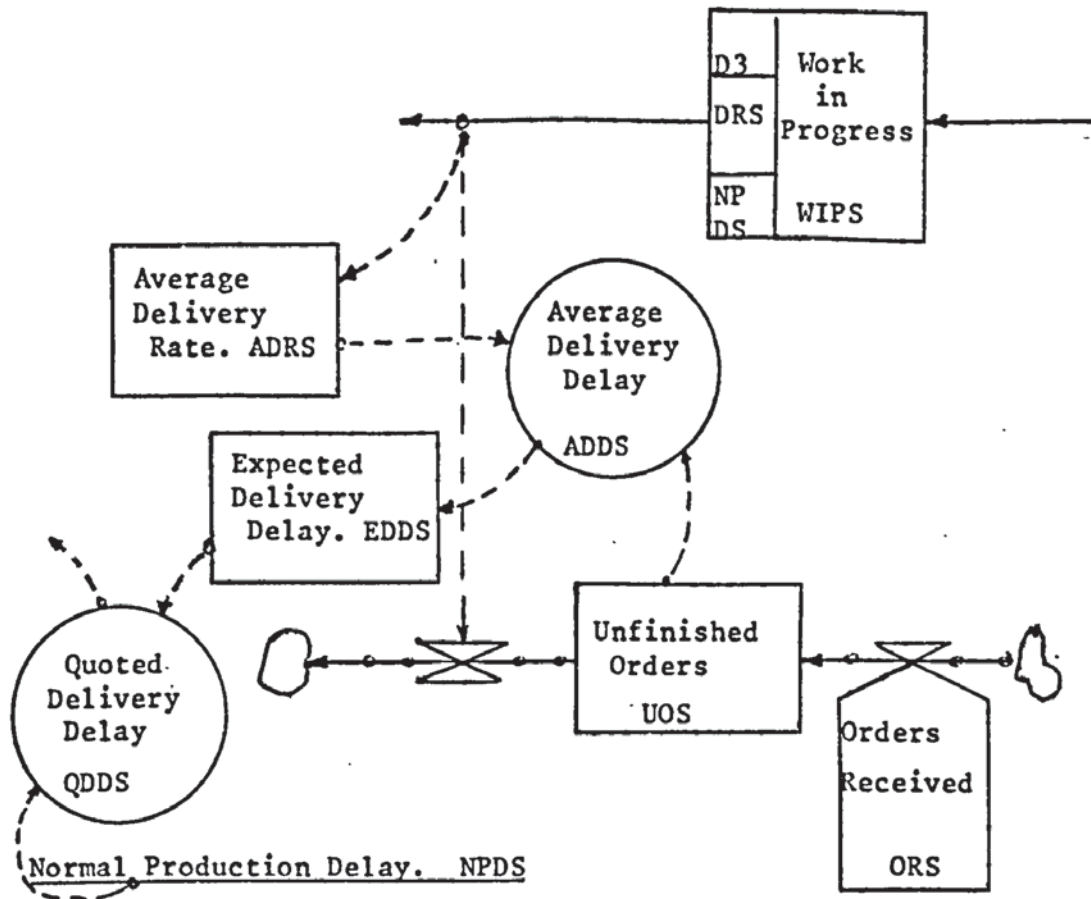


Figure 31. Simulation of the Delivery Quotation Procedure.

A $ADRS.K = ADRS.J + DT \times (DRS.JK - ADRS.J) / TADRS$

N $ADRS = DCRS$

C $TADRS = 0.25$ (13 weeks)

A $ADDS.K = UOS.K / ADRS.K$

A $EDDS.K = SMOOTH (ADDS.K, TADDS)$

C $TADDS = 0.25$ (13 weeks)

A $QDDS.K = MAX (EDDS.K, NPDS)$

ADRS Average Delivery Rate

DCRS Desired Consumption Rate

DRS Delivery Rate

TADRS Time to Average Delivery Rate

ADDS Average Delivery Delay

UOS Unfinished Orders
 EDDS Expected Delivery Delay
 TADDS Time Average Delivery Delay
 QDDS Quoted Delivery Delay
 MAX DYNAMO function selecting the maximum value
 NPDS Normal Production Delay

4.2.3 Market Sector

The market sector includes the delivery and consumption of steel by consumers, the stocks held, forecasting methods and orders placed. The material flow is shown in Figure 32. The steel is consumed from the consumer/merchant stocks. These stocks being built by the delivery of steel.

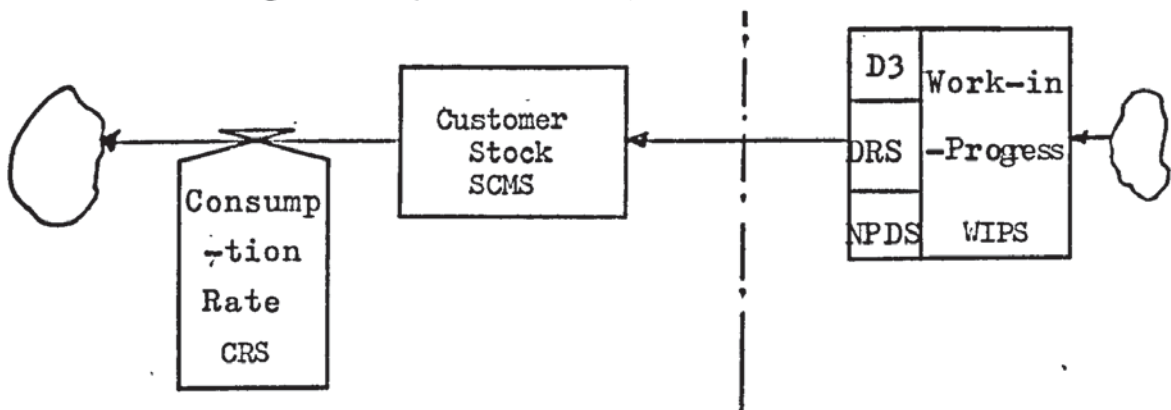


Figure 32. Consumer Stockholding.

L $SCMS.K = SCMS.J + DT * (DRS.JK - CRS.JK)$
 N $SCMS = NSCMS$
 C $NSCMS = 900E3$
 R $CRS.KL = MIN (SCMS.K/DT, DCRS.K)$

SCMS Stocks at Consumers and Merchants
 DRS Delivery Rate
 CRS Consumption Rate

NSCMS Initial Value of the Consumers and Merchant Stocks
DT Iteration Interval
MIN DYNAMO function selecting the minimum value

The Consumption Rate (CRS) is varied differently in the experiments with the model. Seasonal cycles, random variations and tabulated values have been used.

When a customer places an order it has been assumed that he will have to consider:

- the forecasted consumption at the time the steel is delivered.
- the building or reduction of stocks in alignment with the expected consumption at the time the steel is delivered.
- the orders placed with the works but not yet received.

The forecasting methods used in the model are:

- (i) Exponential Smoothing.
- (ii) Linear "trend" prediction.
- (iii) Seasonal cycle prediction.
- (iv) Trend weighted seasonal cycle prediction.

The exponential smoothing method uses the Average Consumption Rate (ACRS) smoothed over a thirteen week period. The trend prediction projects the trend indicated by the difference between two exponentially smoothed rates.

A $ACRS.K = ACRS.J + DT * (CRS.JK - ACRS.J)/TACRS$
 N $ACRS = CRS$
 A $PACRS.K = PACRS.J + DT * (ACRS.JK - PACRS.J)/TPACRS$
 N $PACRS = CRS$
 C $TACRS = 0.25$
 C $TPACRS = 1$
 A $LTFS.K = ACRS.J + AFPS.K * (ACRS.K - PACRS.K)/TACRS$
 A $AFPS.K = FLFS * QDDS.K + FFPS$
 C $FFPS = 0.06$
 C $FLFS = 0.6$

ACRS Average Consumption Rate
 CRS Consumption Rate
 TACRS Time to Average Consumption Rate
 PACRS Previous Average Consumption Rate
 TPACRS Time to Average Previous Average Consumption
 LTFS Linear Trend Forecast
 AFPS Average Forecasting Period
 FFPS Fixed Forecasting Period
 FLFS Fraction of Lead Time in Forecast Period

The seasonal cycle forecasts depend on an approximate method devised for these models, which is far from being generally applicable. In particular the method assumes that the forecasting period is of the order of six to ten weeks. A special function called BOX has been written, which accurately accumulates a running total for a given period;

MACRO BOX (IN.JK, L.K.)
 N L = IN * TA
 L L.K = L.J + DT * (IN.JK - BOX.JK)
 R BOX.KL = SAMPLE (L.K/TA, TA, L.K/TA)

MEND

L Level representing the value accumulated during
 period TB

IN Input rate being "averaged"

TA Period of "Averaging" rate

BOX Rate at which the level is uniformly depleted

SAMPLE DYNAMO function which ensures that the level is
 depleted uniformly during the period TP

These BOX's are concatenated to give four quarterly averages
 for the previous year plus a current quarterly value. The
 seasonal forecast (SCFS) is the value of the fourth BOX divided
 by the period (a quarter). The trend weighted seasonal forecast
 is given by multiplying the seasonal forecast by the ratio of this
 years and last years relevant quarter.

R RA.KL = RE.JK + (CRS.JK - RE.JK)/(NYWS * TA)

R RB.KL = BOX (RA.JK, LA.K)

R RC.KL = BOX (RB.JK, LB.K)

R RD.KL = BOX (RC.JK, LC.K)

R RE.KL = BOX (RD.JK, LD.K)

R RF.KL = BOX (RE.JK, LE.K)

C TA = 0.25
 C NYWS = 5
 A SCFS.K = LD.K/TA
 A SATFS.K = (LD.K/TA) * (LA.K/LE.K)
 N RA = DCRS

RA to RF Rates into each box

LA to LE Level of each box (quarterly consumption)

TA Time to Average the consumption

NYWS Number of years for which values smoothed

SCFS Seasonal cycle forecast

SATFS Seasonally Adjusted Trend Forecast

DCRS Desired Consumption Rate

The forecasting method is selected, in the model, by four switch functions, operated by the variable SFMS. SFMS is set to 1, 2, 3 or 4 to correspond to the exponential, trend, seasonal or weighted seasonal forecasts.

A FCDTS.K = SWITCH (ACRS.K, 0, SFMS - 1)
 + SWITCH (LTFS.K, 0, SFMS - 2)
 + SWITCH (SCFS.K, 0, SFMS - 3)
 + SWITCH (SATFS.K, 0, SFMS - 4)
 C SFMS = 1
 N FCDTS = DCRS

FCDTS Forecast Consumption at Delivery Time

SFMS Switch for Forecasting Method

The Desired Stock Level (DSLS) has been discussed in Section 4.1.3. It allows for active, buffer and work-in-progress stocks.

$$\begin{aligned} A \quad DSLS.K &= WPCFS \times FCDTS.K + SLFS \times \text{SQRT}(FCDTS.K) \\ &+ FMCLTS \times QDDS.K \times FCDTS.K \\ &+ BSFS \times \text{SQRT}(FCDTS.K \times FCDTS.K \times VLS \\ &+ QDDS.K \times VCS) \end{aligned}$$

$$C \quad WPCFS = 0.04$$

$$C \quad SLFS = 30$$

$$C \quad FMCLTS = 0.2$$

$$C \quad BSFS = 1.5$$

$$C \quad VLS = 0.016$$

$$C \quad VCS = 2E11$$

DSLS Desired Stock Level
WPCFS Work-in-Progress at Consumers, Factor
FCDTS Forecast Consumption at Delivery Time
SLFS Stock Level Factor, economic order
SQRT Square Root function (DYNAMO)
FMCLTS Fraction Market Concerned with Lead Time
QDDS Quoted Delivery Delay
BSFS Buffer Stock Factor
VLS Variance in Lead Time
VCS Variance in Consumption During Lead Time

The Orders placed to Build the customer's Stocks (OBSS) is the difference between the actual and desired stock divided by the time to build the stock. The customer expects to be able to adjust his stock to a desired level when the next delivery arrives. In the model it has been assumed that the expected time to adjust the stock level is similar to the quoted delivery delay.

The allowance for orders already placed but not received is based in the model on the difference between actual Unfinished Orders (UOS) and the Expected Unfinished Orders (EUOS). The Expected Unfinished Orders (EUOS) is based on the orders to cover the forecast consumption and the orders to build the stocks (OBSS). The Orders to cover the Manufacturing Delay (OMDS) is this difference between the expected and actual unfinished orders divided by the adjustment time.

The adjustment time may be fixed if the customers regularly review the order position. Since they know both when they expected the order and whether it has arrived, they are able to allow for the backlog of undelivered orders not only for orders of the same type but for other orders also. The Time to Adjust the Orders awaiting delivery (TAOMDS) has been set either equal to the delivery quoted (QDDS) or a constant (TAOMDS).

A DORS.K = OBSS.K + FCDTS.K + OMDS.K
A OBSS.K = (DSL.S.K - SCMS.K) / QDDS.K
A EUOS.K = (FCDTS.K + OBSS.K) * QDDS.K
A OMDS.K = (EUOS.K - UOS.K) / TAOMDS.K
A TAOMDS.K = SWITCH (CTAOMDS, QDDS.K, SAROS)
C CTAOMDS = 0.25
C SAROS = 1

OBSS	Orders to Build Stocks
SCMS	Stocks at Consumers and Merchants
DORS	Desired Order Rate
EUOS	Expected Unfinished Orders
FCDS	Forecasted Consumption at Delivery Time
QDDS	Quoted Delivery Delay
OMDS	Orders to cover Manufacturing Delay
UOS	Unfinished Orders
TAOMDS	Time to Adjust Orders in Manufacture
CTAOMDS	Constant Time to Adjust Orders in Manufacture
SAROS	Switch Constant Adjusting Order Rate
SWITCH	Switch function;
	SAROS = 0 constant adjusting time
	SAROS \neq 0 variable adjusting time

4.2.4 Input and Output Specifications

The model includes three basic input functions; a yearly and five yearly cycle and an arbitrary function. The arbitrary function is generated by the DYNAMO function TABHL and the sampling function SAMPLE. These two functions permit a quarterly histogram to be input to the model of steel consumed.

A special routine has been devised to output quarterly values. This has been implemented using DYNAMO II (4.1) by creating a MACRO which accurately accumulates during a period (unlike an exponential smoothing function).

Print, plot and control parameters are listed for a typical run in Appendix 1.

4.3. Comparisons with Data

The model was constructed and tested by checking the assumptions, structure, equations and the magnitude of variables with people in the Division. This section deals with the comparisons made between the model and data.

The model is not enclosed. It is driven by a basic demand; the steel consumed by manufacturers. The orders received, steel produced and steel delivered are all internal variables, created by the model and can be compared with the data. Initially a synthetic demand pattern was used including:

- . A seasonal cycle (sine wave, period one year)
- . An economic cycle (sine wave, period five years)
- . A random demand (sampled random numbers)

This demand pattern was used to initialise the model and for sensitivity tests.

To be able to validate the model, the data and output from the model, need to be in a comparable form. The data is available as monthly or quarterly totals; consumption, deliveries and production for a quarter. DYNAMO (I.D. simulation program) normally permits only the output of instantaneous rates of flow. A special routine was devised that output accurate totals for a period but was not sensitive to the output timing. (Sampled values can give inaccurate results because the DYNAMO output generating routine does not evenly space the output data.)

To further ease testing, the automatic plot scaling feature of DYNAMO was set so that the lower limit of each scale was fixed at zero. The upper limits for similar variables (orders, production and delivery) were set at the same value but

automatically by DYNAMO. The relative values of the variables can be compared, without reference to a scale, reducing the possibility of errors during checking of the model results and encouraging an examination of the dynamics rather than the magnitude of variables.

The model was set up for different markets. By changing the appropriate values it was possible, using the same model, to alter:

- The number and duration of the finishing processes
- The loading rules
- The forecasting method dominating the market
- The balance and type of stock control methods used in the market
- The normal level of stock held by the market
- The range of delivery periods quoted by the sales office
- The speed of response of the quoted delivery

The model results were compared with:

- Total U.K. Steel Market (excluding imports, exports and stockholding)
- Total Sheet Steel Market (excluding imports, exports stockholding and tinplate)
- Tinplate Market
- Sheet Steel for Motor Manufacturers

For these comparisons the data was divided into two parts:

- Calibration data for developing the model and setting parameters
- Comparative data for determining the models validity

Pre-nationalisation data was not easily available and it was necessary to develop the model using the 1968-1972 data.

Comparisons were made later using the pre 1968 data.

4.3.1 U.K. Steel Production Comparisons

The model used as input, the steel consumed by manufacturers and excluded imports, exports and stockholders. Figure 33 shows some typical comparisons.

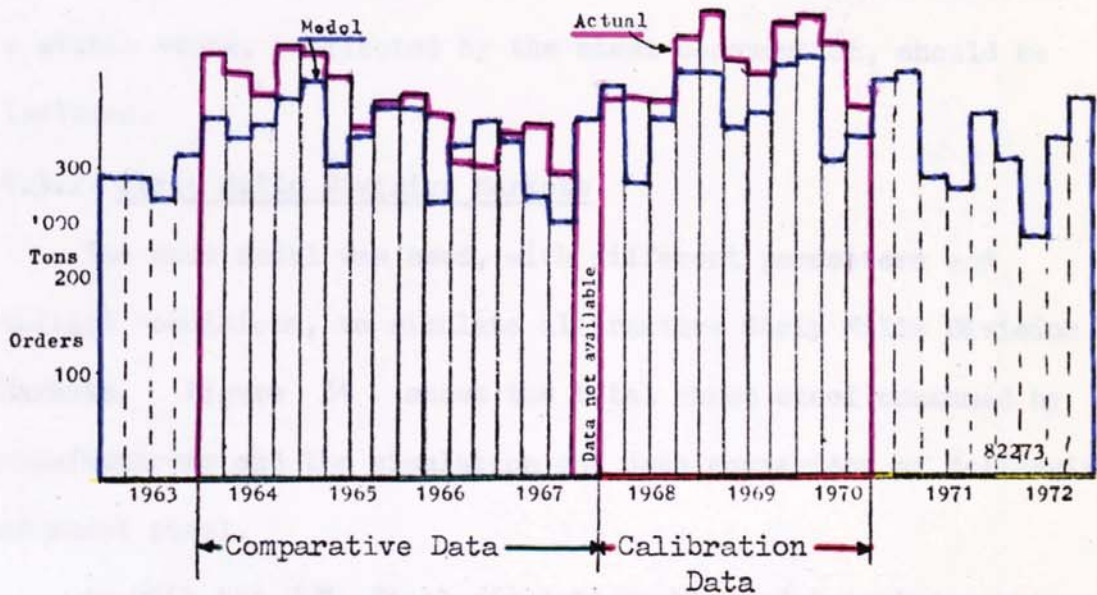
The model generates the orders for, and the deliveries to, manufacturers based on their consumption of steel. Because the data shows the total orders and deliveries, the model results are somewhat less than the data. The purpose of these tests, however, were to determine whether the model would create similar dynamic behaviour to that exhibited by the total market.

The model demonstrates a fall in deliveries each third quarter which is created by a fall in orders in the second or third quarter. This appears to agree reasonably well with the data although the orders appear to fall later in the data (generally in the third quarter).

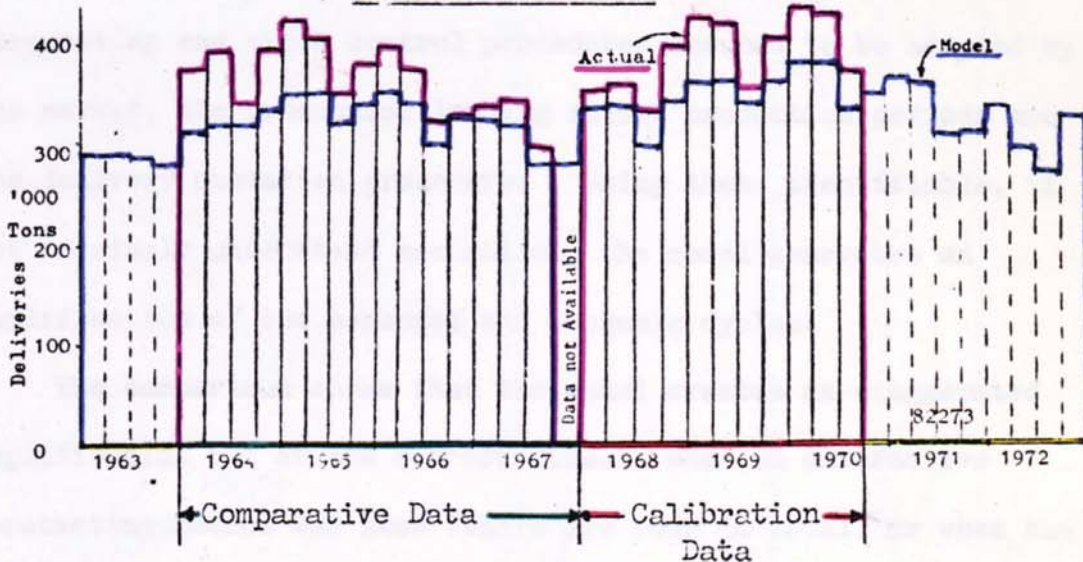
The number of weeks of normal consumption held as stocks shows a peak each third quarter in both the data and the model. The longer term cycle in the stocks also occurs in the model but they do not coincide. Initialising the model in a non-static state can cause this cycle to be realigned.

The results were encouraging but were thought to show an inadequate fit for useful conclusions to be drawn. It is apparent that dynamic models of aggregate markets require careful checking before they can be used to substantiate a particular dynamic behaviour. Further work has suggested that an effectively shorter

Orders Received



U.K. Steel Deliveries



Number of Weeks Use Held as Stocks

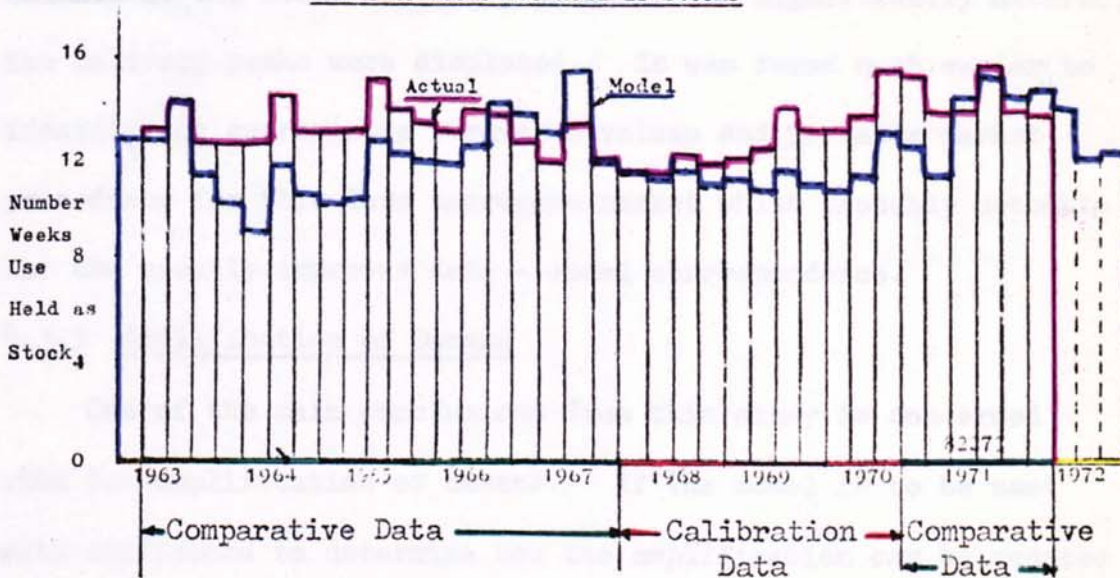


Figure 33. U.K. Steel - Data and Simulation Comparison.

production time should be used, that a greater emphasis be placed on ordering on the basis of current consumption and that a static stock, unaffected by the steel consumption, should be included.

4.3.2 Strip Mills Division Markets

The same model was used, with different parameters and initial conditions, to simulate alternative Strip Mills Division Markets. Figure 34 shows the total sheet steel consumed by manufacturers and the simulation and data comparison of deliveries of sheet steel.

As with the U.K. Steel simulations the model includes the forecasting and stock control procedures assumed to be adopted by the market, the production loading rules, production periods and the delivery quotation procedure. Using these identifiable, if not precisely understood mechanisms, the model generates an amplification of the seasonal and economic cycles.

The comparison shows that the model creates an exaggerated amplification but at the correct time. When an alternative forecasting method was used (there are four in total) or when the balance of the stock control procedures was significantly altered, the delivery peaks were displaced. It was found much easier to identify the approximate parameter values and probable market procedures for this less aggregate market which probably accounts for the greatly improved data - model correspondence.

4.3.3 Amplification of Demand

One of the main conclusions from this study is concerned with the amplification of demand. If the model is to be used with confidence to determine how the amplification can be reduced

Total U.K. Sheet Steel Receipts and Consumption by Manufacturers.

DATA - SIMULATION COMPARISON.

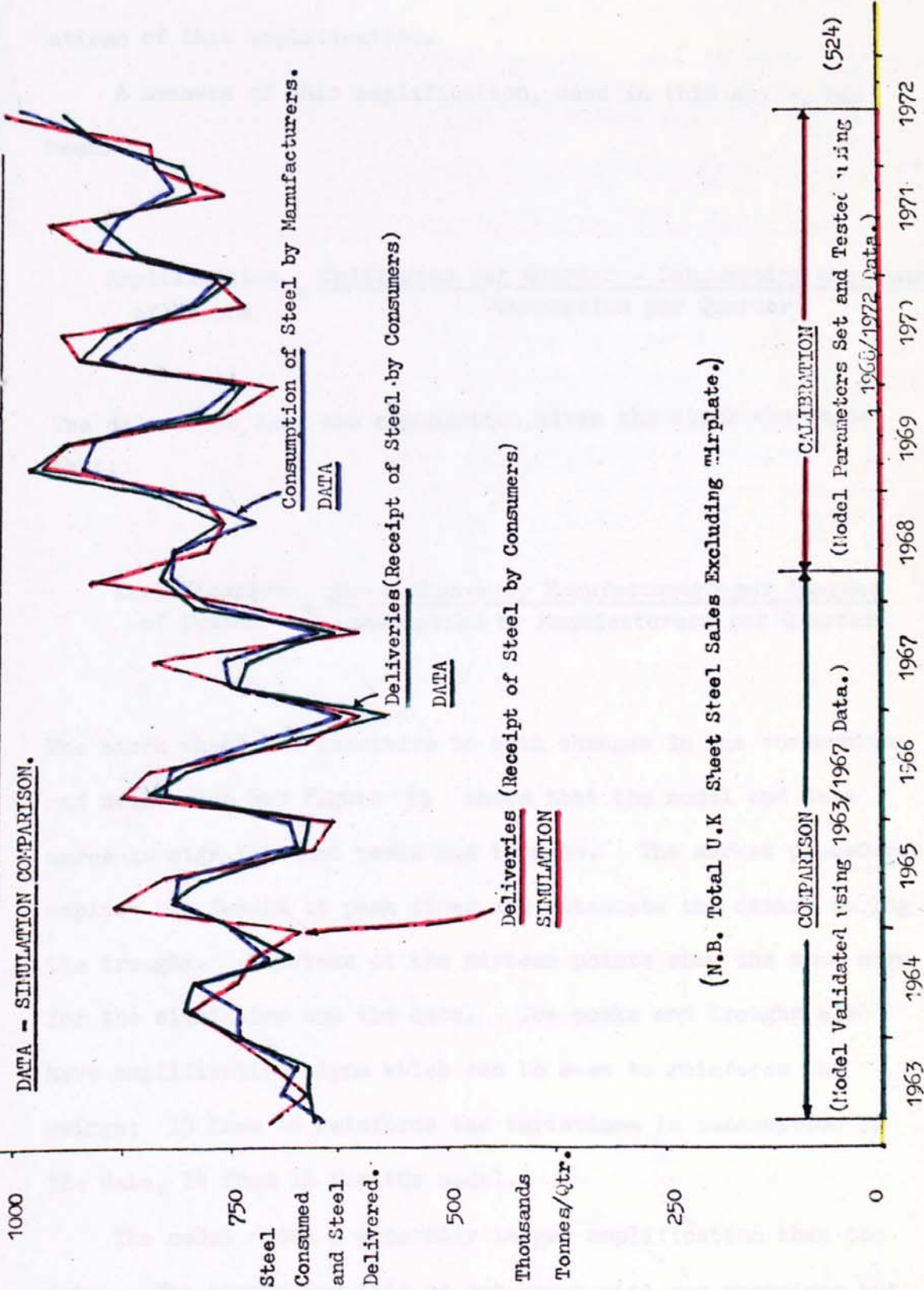


Figure 34. U.K. Sheet Steel Receipts and Consumption by Manufacturers; Validation.

(or even converted to attenuation), then it is necessary to demonstrate the relationship between the model and data representations of this amplification.

A measure of this amplification, used in this study, has been:

$$\text{Amplification of Demand} = \frac{\text{Deliveries per Quarter} - \text{Consumption per Quarter}}{\text{Consumption per Quarter}}$$

The deliveries, less the consumption, gives the stock change, so that:

$$\text{Amplification of Demand} = \frac{\text{Stock Change by Manufacturers per Quarter}}{\text{Consumption by Manufacturers per Quarter}}$$

The stock change is sensitive to both changes in the consumption and deliveries but Figure 35 shows that the model and data agree in sign for most peaks and troughs. The market procedures amplify the demand at peak times and attenuate the demand during the troughs. Thirteen of the sixteen points show the same sign for the simulation and the data. The peaks and troughs also have amplification signs which can be seen to reinforce the swings; 13 from 16 reinforce the variations in consumption in the data, 14 from 16 for the model.

The model shows a generally larger amplification than the data. The reason for this is not known with any certainty but it appears likely that there is a substantial stock held by the market that is not dependant on the consumption rate. With a

large fixed stock the amplification is reduced. No fixed stock level was included because it could not be estimated.

The model demonstrates that the demand amplification can be generated by assuming stock control, forecasting, loading and production procedures. This model, simulating sheet steel sales, has been used in later sections to show how this amplification can be reduced.

Dates Qtr-Year	Delivery Peak or Trough	Amplification = Stock Change/Consumption		
		Data %	Simulation %	Agreement
1 - 64	P	+8.7	+ 9.25	✓
3 - 64	T	-1.4	+ 5.9	X
1 - 65	P	+0.8	+ 9.0	✓
4 - 65	T	-6.2	- 9.4	✓
1 - 66	P	+2.5	+ 6.8	✓
4 - 66	T	-9.7	- 5.4	✓
2 - 67	P	-3.6	+10.4	X
3 - 67	T	-2.3	- 7.4	✓
1 - 68	P	+1.5	+11.3	✓
3 - 68	T	+1.7	+ 0.6	✓
1 - 69	P	+6.5	+ 6.1	✓
4 - 69	T	-2.0	- 7.1	✓
1 - 70	P	+2.7	+ 2.3	✓
4 - 70	T	-2.2	- 0.5	✓
2 - 71	P	-2.5	+ 8.9	X
3 - 71	T	-2.9	- 7.6	✓

Figure 35. Amplification of Orders - Data and Simulation Results.

4.4 Experiments with the Model

The experiments can be divided into two parts; those concerned with production policies or rules and those related to customer responses. Some conclusions regarding these experiments are discussed briefly in Section 4.4.3.

4.4.1 Production Policies

Three experiments concerned with alternative production procedures are discussed. The first assumes a reduction in the production time by assigning steel to specific orders at a later production stage. The second examines loading rules to stabilise production or to stabilise the lead time. Finally, production limitations are related to the orders received.

4.4.1.1 Production Cycle Time

The market appears to react to long delivery delays by increasing the orders placed with the Division to cover the delivery delay and the increased stock-out risk. Strip Mills Division may be able to minimise this response by maintaining a shorter delivery period.

The delivery period could be reduced if steel were assigned to orders at a later stage in production. Alternatively a proportion of the orders could be delivered directly from stock.

The model was run to determine the sensitivity of the market to realistic reductions in the production time. The production time was reduced from 6 to 3 weeks. The reduced delivery period produces a significant reduction in the fluctuation of orders received, Figure 36. The orders vary by 12% less, reducing the ordering peaks by 5 to 6%.

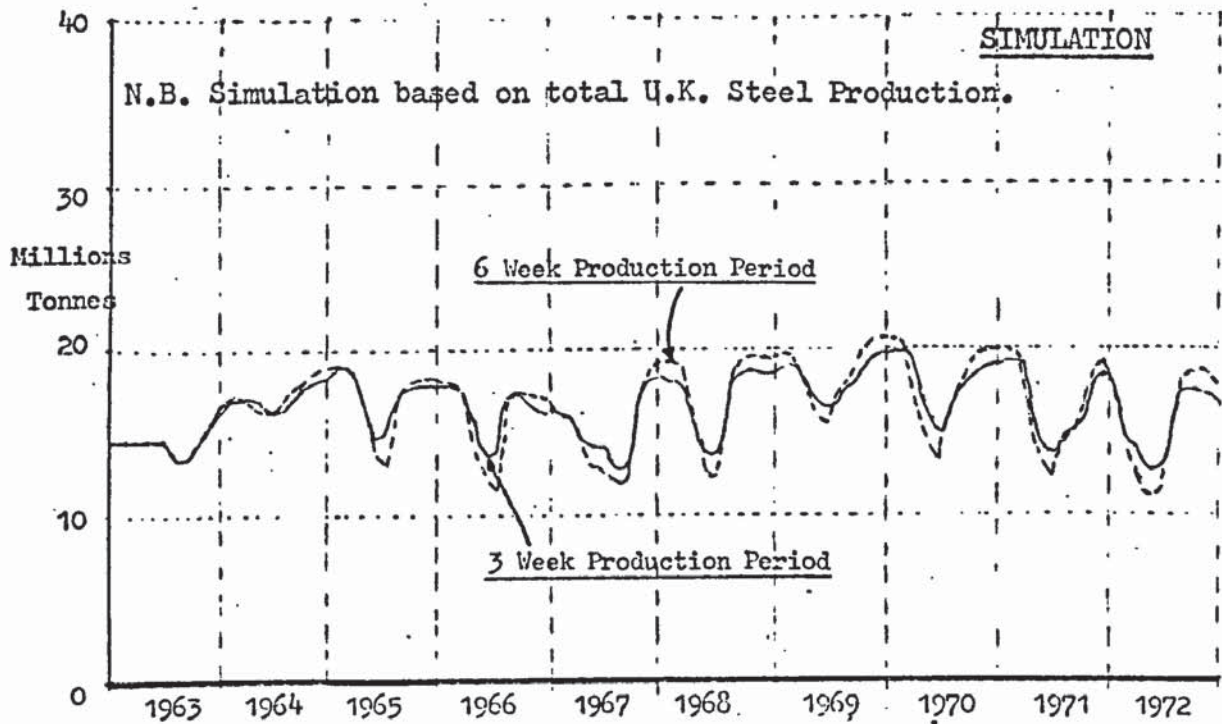


Figure 36. Orders Received with Differing Production Times.

These figures, as with others in this section, must be treated with caution because the simulated amplification shown in 4.3 was exaggerated. However, it does appear that some reduction in the variation in orders received is possible if the production time were reduced.

4.4.1.2 Production Loading Rules

When an order is accepted a hot rolling week number is assigned to the order. The orders are released to production a few weeks prior to the hot rolling week. If orders are released at the rate at which they are received, the works would have to vary production quite significantly. Alternatively the orders may be released according to the current order backlog less the scheduling and production time.

The model assumes a relationship between the delivery quoted and the time of release of the orders to production. (This relationship is easily varied in the model and may be quite complex; it is determined by an arbitrary function generator.) Various relationships have been considered. Two examples will suffice, however, to illustrate the consequences of adopting different loading rules.

Rule 1 Stabilised Lead Time

Orders are released to production after a fixed period passing on the full impact of a changing order rate.

Rule 2 Variable Lead Time

Orders are released to production after a period equal to the quoted delivery less the production and scheduling time.

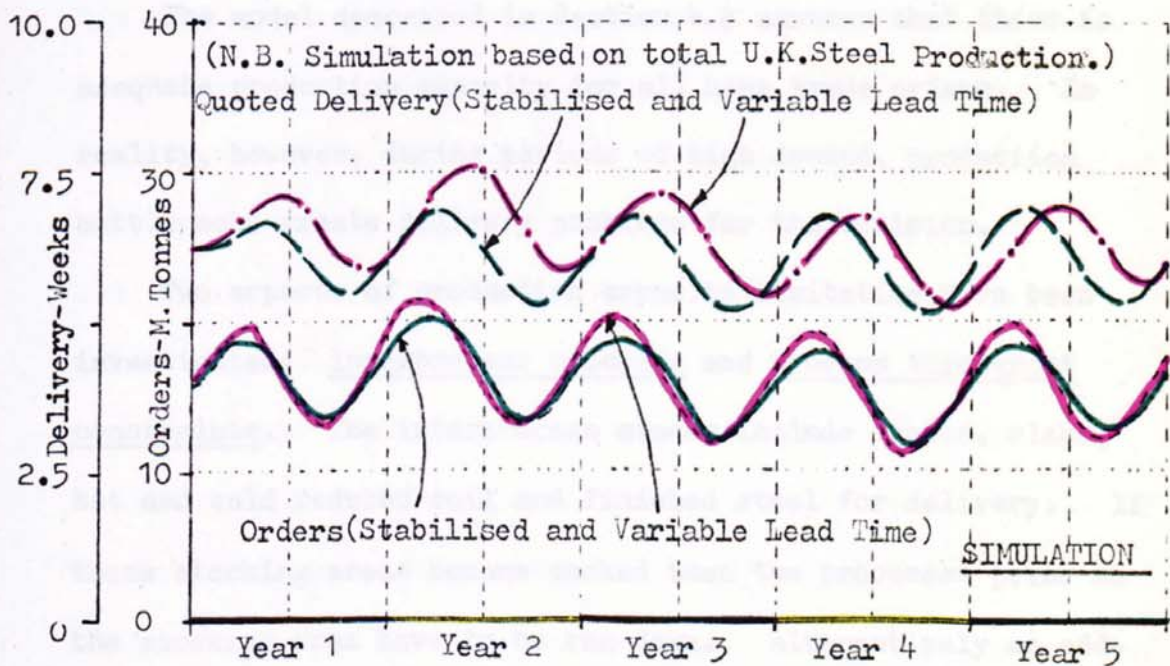


Figure 37 Production Loading Rules.

Figure 37 shows the quoted delivery and the orders received for the two rules. The model is driven by an assumed steel consumption rate over a simulated five year period. The steel consumed by manufacturers was simulated as a five year cycle modified by a seasonal cycle. This test data was devised to determine the sensitivity of the model to "economic" and seasonal demand cycles.

The stabilised lead time creates a more stable ordering pattern and helps maintain a shorter delivery period particularly during the peak of the "economic" cycle (year 2). The peak orders received reduced by 7% for the stabilised lead time case.

Loading rules which allow the works to respond promptly to a change in the orders placed seem preferable. They reduce the possibility of customers responding to changing delivery quotes and creating a large order backlog.

4.4.1.3 Production Constraints

The model described in Section 4.2 assumes that there is adequate production capacity for all home trade orders. In reality, however, during periods of high demand, production bottlenecks create delivery problems for the division.

Two aspects of production capacity limitation have been investigated; interprocess stocking and process throughput constraints. The interprocess stocks include ingots, slabs, hot and cold reduced coil and finished steel for delivery. If these stocking areas become choked then the processes prior to the stocking area have to be run down. Alternatively an additional stocking area has to be found to act as an overflow from the first. Usually the second stocking area is more expensive,

requiring additional handling of the steel and is used reluctantly.

An example of an interprocess stock is the hot rolled coil bay at the Port Talbot Works. Hot rolled coil enters the bay and is stacked. The coils are recorded and scheduled, either for despatch or for pickling. If the bay becomes heavily congested hot rolling is reduced or coils are transported by lorry to an outside stocking area.

The reduction in hot rolling is simulated in the model by reducing the hot rolling rate when the stocking area becomes full. In addition the model allows the stocking areas to be increased as the average delivery rate increases.

Process throughput limits can also be included for each production stage. In this modification to the model the constraint has been placed on the finishing processes.

The model has been used to simulate the total response of the Division. Only the broad outline of the stocking problem has been simulated. For example, only three stocks have been identified rather than perhaps ten. The same interprocess stock capacity has been used for each stock and adjustment times have been assumed similar. This level of detail appears consistent with the remainder of the model, although further detail could be included.

Customers import steel to overcome long ordering delays. The model has been extended to allow for this "release valve" of steel importing. It has been assumed that because of a lower price on the home market, steel consumers will stop importing when the delivery period is short.

It is difficult to ascertain the effect of a long quoted delivery period on imports, but it is likely that for a period of greater than ten weeks the imports will rise rapidly with each additional weeks delay. Figure 38 shows the relationship assumed in the model.

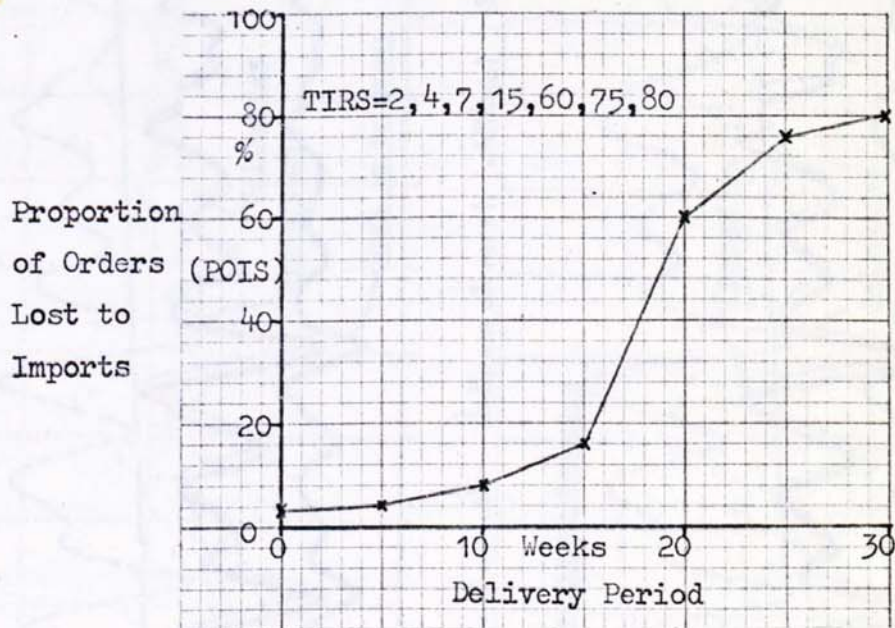
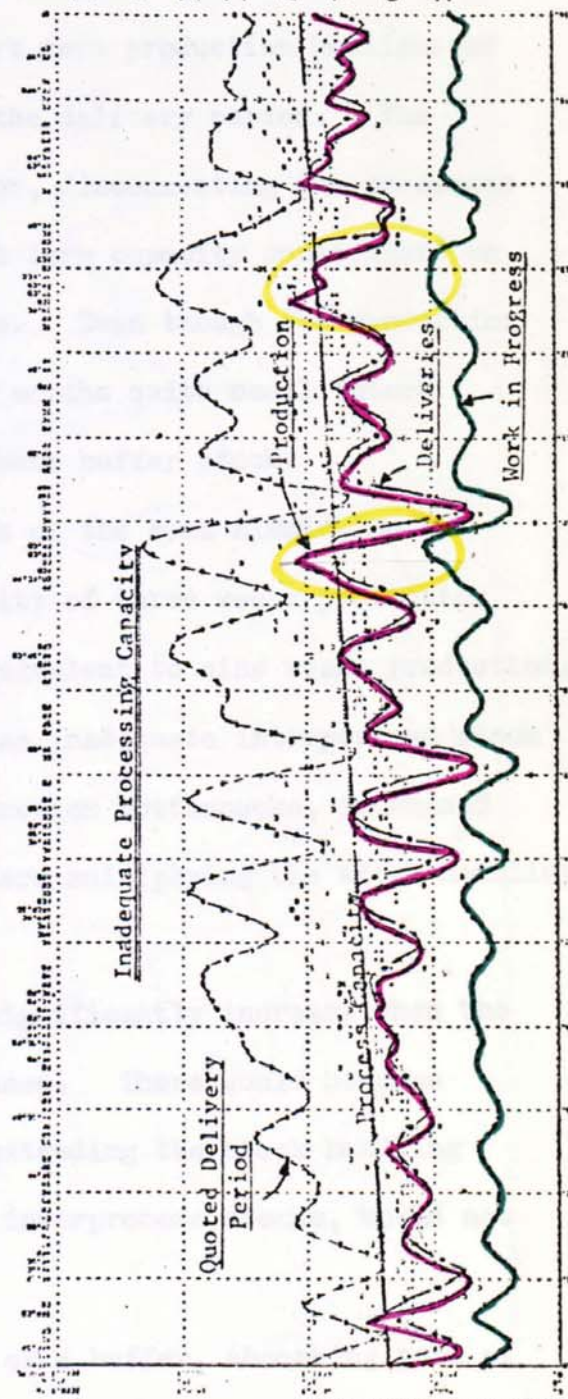
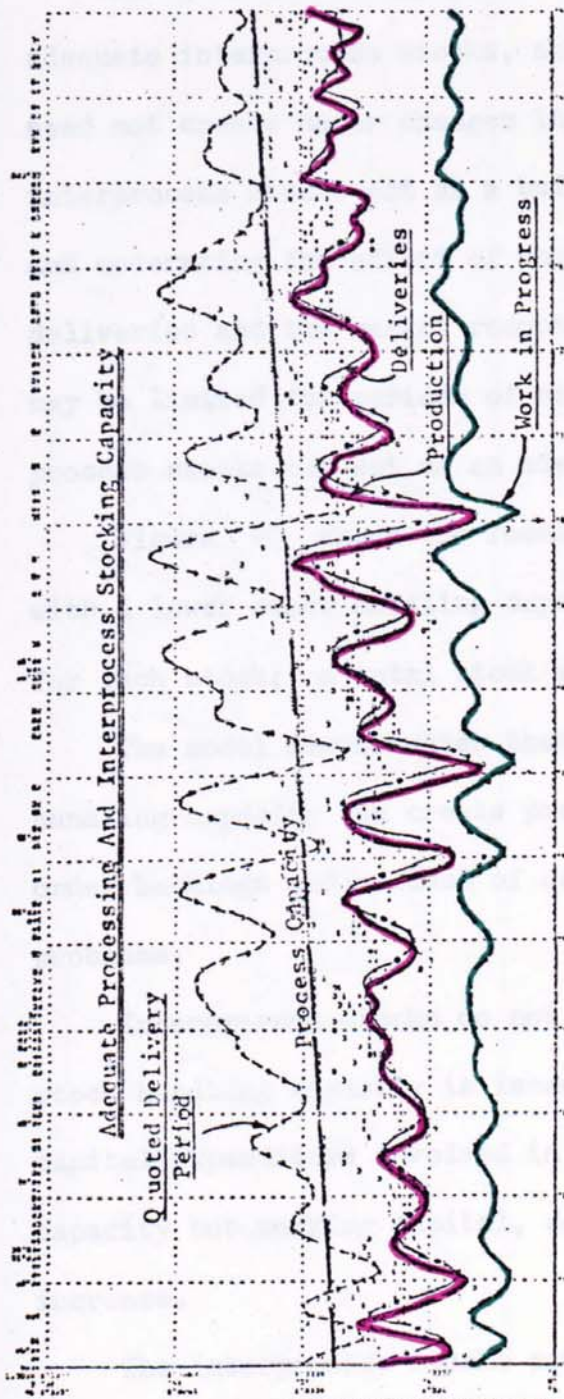


Figure 38 Relationship Assumed between Imports and the Delivery Period Quoted.

The model was set up to simulate the market and production of U.K. Sheet Steel orders. The simulation used as input the quarterly sheet steel consumed by manufacturers in the U.K. for the period 1960-1973. The 1973 data was repeated for 1974 and 1975. Adequate interprocess stocking capacity was provided but the finishing process rate was limited.

Figure 39 shows the results of simulations with adequate and inadequate processing capacities. In the second case the delivery rate is restricted to the current process capacity. The production of steel, however, is able to exceed the process rate because of the interprocess stocks. As can be seen in



Inadequate capacity for peak production. Interprocess stocks are able to absorb short duration peaks in orders.

Figure 39. Simulated Sheet Steel Production with Processing Constraints.

year ten the production of steel exceeds the maximum finishing rate for some months while the work in progress increases.

The quoted delivery period is similar in both cases. With adequate interprocess stocks, short term production bottlenecks need not create major changes in the delivery period. The interprocess stocks act as a buffer, disconnecting the processes and moderating the effect of short term capacity constraints on deliveries and the market response. Even though the production may be limited for periods of six months quite small interprocess stocks can act as an adequate buffer stock.

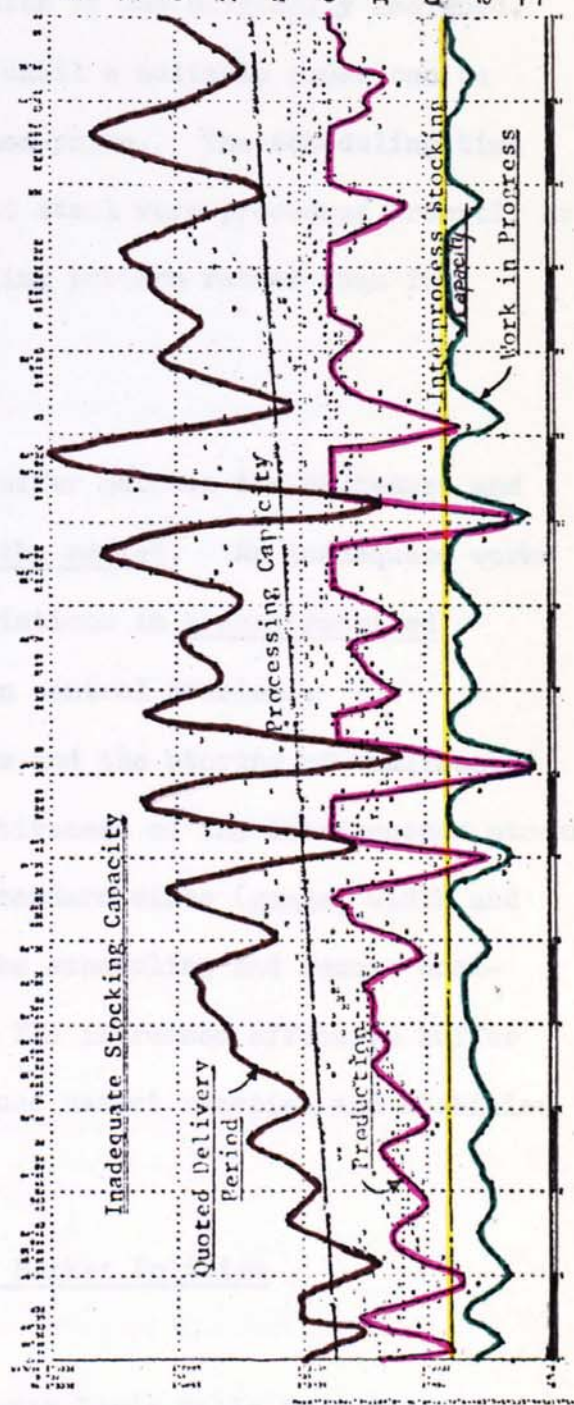
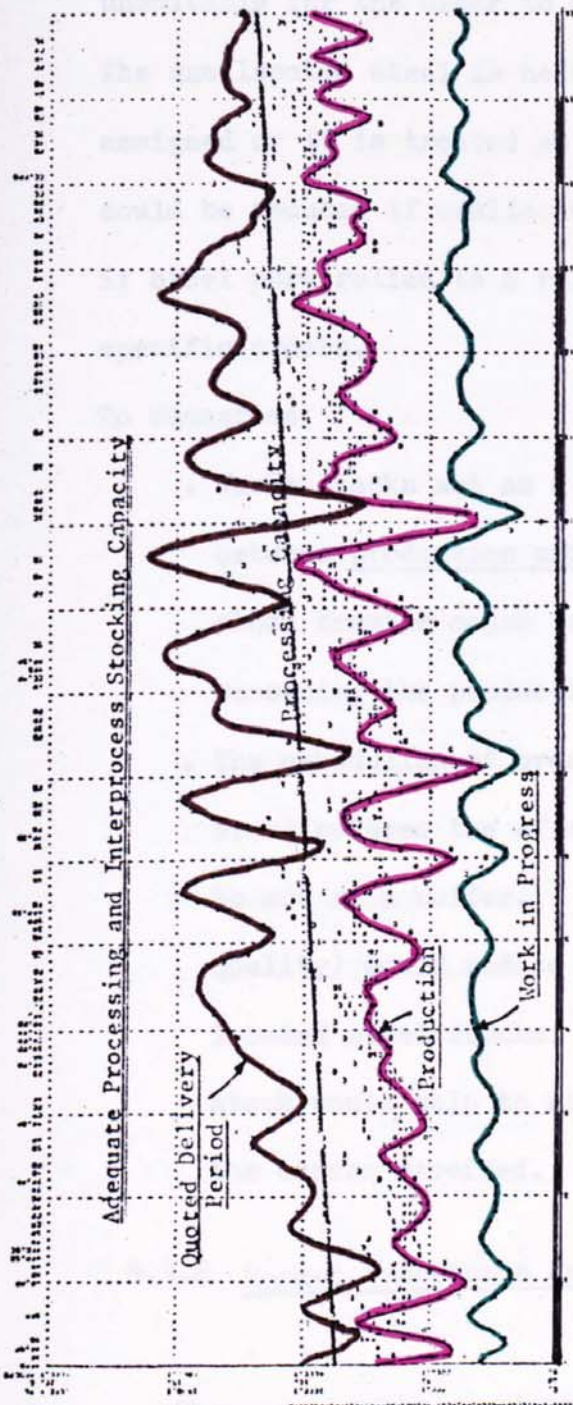
Figure 40 shows the results of the same simulation but with a lower stock handling capacity of three weeks production for each stock; a total stock equivalent to nine weeks production.

The model demonstrates that an inadequate interprocess stock handling capacity can create production bottlenecks, increased order backlogs and a flood of orders multiplying the stock handling problems.

Interprocess stocks do not significantly increase when the stock handling capacity is increased. There would be some capital expenditure involved in extending the stock handling capacity but working capital, as interprocess stocks, would not increase.

The interprocess stocks act as a buffer, absorbing part of the difference between the orders received and steel delivered. The ability to handle short term peak stocks ensures a long term, higher level of output.

The interprocess stocks allow for variations in production and rescheduling for the next process. Rescheduling is required



Adequate processing capacity but interprocess stock limit creates major reductions in deliveries and an increased lead time.

Figure 40. Simulated Sheet Steel Production With Interprocess Stocking Constraints.

because the sequence of orders may differ from one process to the next. Further, because of quality or damage, the steel may be unsuitable for the order to which it was originally assigned. The unallocated steel is held until a suitable order can be assigned or it is treated as non-prime. The scheduling time could be reduced if unallocated steel were processed promptly or if steel were rolled to a rolling pattern rather than for specific orders.

To summarise:

- . Works stocks act as a buffer between the processes and between production and the market. An inadequate works stock creates major variations in orders received worsening the production control problems.
- . The scheduling of orders and the storing of unallocated steel reduces the effectiveness of the interprocess stocks to act as a buffer. Standard sizes (gauge, width and quality) would reduce the scheduling and remove unallocated steel stocks. The increased effective buffer stock would help to reduce market reaction and stabilise the orders received.

4.4.2 Market Procedures and Market Policies

The market places orders with Strip Mills Division at a varying rate. The rate of orders placed varies more than the actual consumption of steel because of variations in customer stocks. These variations in customer stocks are believed to be created by customer

forecasting methods, stock control procedures and reactions to the delivery period quoted by the sales office. These three factors are discussed in the following sections.

4.4.2.1 Customer Forecasting Methods

The rate at which orders are placed will be determined, primarily, by the forecast of future consumption. The forecast will also determine the orders needed to cover any variation in the delivery period and the orders required to cover the stockout risk.

The forecasting methods are likely to be different for each aggregate market. The effect of the forecasting method will also depend on the stock control procedures and response to the delivery period. Three forecasting methods were examined using the U.K. quarterly steel consumption data, 1963 to 1972:

1. Exponential smoothing of consumption; assumes the persistence of the current consumption.
2. Linear extrapolation of the consumption trend; assumes the persistence of a linear trend.
3. Seasonal cycle prediction of the consumption; assumes the persistence of a seasonal cycle.

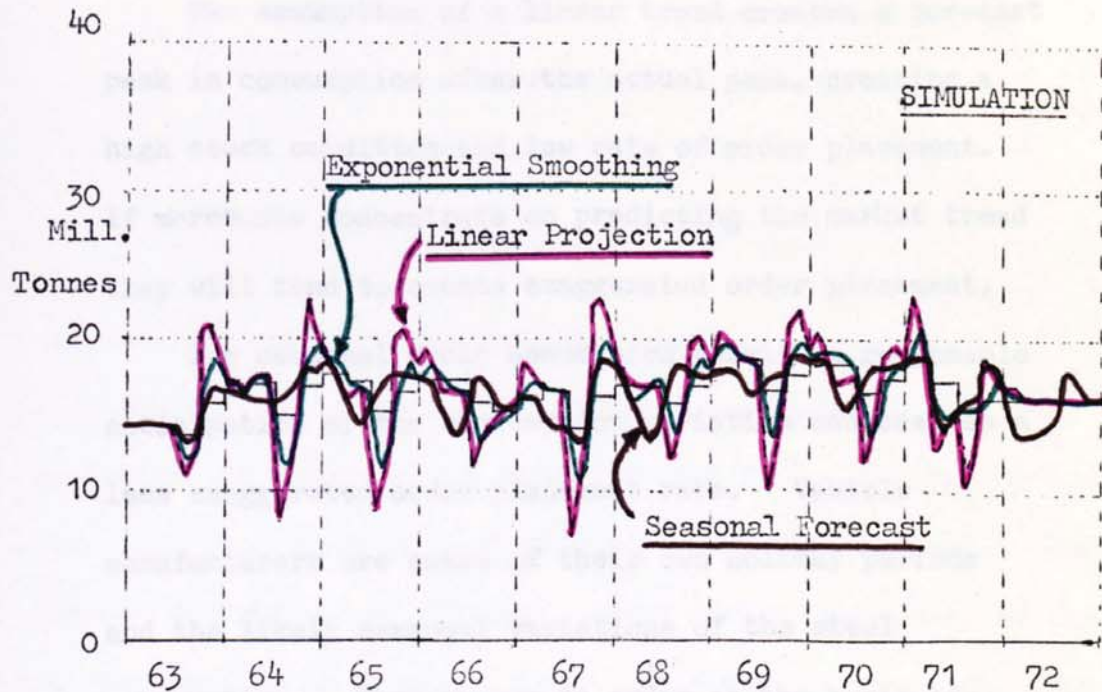


Figure 41 Orders; Customer Forecasting Experiment.

The simulated orders received by the Corporation assuming the market to be dominated by these three methods is shown in Figure 41. The exponentially smoothed forecast represents a forecast dominated by the current awareness of the consumption rate. Tinplate production is likely to be dominated by the "current awareness" because the demand is not easily predicted. The timing of picking of fruit and vegetables for canning varies unpredictably. Although the exponential smoothing creates a gradually changing but reasonable fit to the actual consumption the rise and fall in the forecast follows (rather than precedes) the actual consumption. An exaggerated order placement is created.

The assumption of a linear trend creates a forecast peak in consumption after the actual peak, creating a high stock condition and low rate of order placement. If merchants concentrate on predicting the market trend they will tend to create exaggerated order placement.

The seasonal cycle assumption permits a reasonable anticipation of the consumption variation and creates a less exaggerated order placement rate. Vehicle manufacturers are aware of their own holiday periods and the likely seasonal variations of the steel consumption. They appear to order on the basis of this seasonal cycle.

It appears from these experiments that customers whose forecasts of expected consumption are dominated by trend or exponential smoothing procedures are likely to create an exaggerated ordering rate.

To summarise:

1. Orders based on an "average" value of consumption or on a trend prediction tend to exaggerate any seasonality in demand.
2. Seasonal cycle predictions allow for the most likely short term variations but leave the stock control procedures to compensate for the longer term variations.
3. Merchant stockholding may be dominated by a trend prediction. If this is so the

dynamics created by an increasing merchant presence is likely to further exaggerate the variations in orders received by the Division.

4.4.2.2 Customer Stockholding Procedures

The control of stocks by customers may itself worsen the variations in orders placed with the Division. In Section 4.1.3. four main procedures adopted by customers were discussed. These include the control of stocks to cover work in progress, to allow an "Economic Order Quantity" to be purchased, to cover the lead time consumption and to allow for variations in the lead time and order size (buffer stock).

The relationship between the desired stock level, the forecast consumption and lead time was shown to be:

Desired Stock = a x (forecast)	"W.I.P."
+ b x $\sqrt{\text{forecast}}$	"E.O.Q."
+ c x (lead time) x (forecast)	"lead time"
+ d x $\sqrt{(\text{forecast})^2 \times e + (\text{lead time}) \times f}$	(variability (of lead time (and order (size

where a to f are constants.

The problem is whether these different stock control methods reinforce the order variations or help to remove them. If suitable values were chosen, the stocks held by the consumers could amplify or attenuate the consumption variations.

The model was supplied with a sinusoidal input to simulate the seasonal cycle in orders. The stock level and the consumption rate were based on the total U.K. steel production.

Three stock control procedures were considered:

1. Orders placed with the Corporation on the basis of an economic order quantity.
2. Orders placed with the Corporation on the basis of maintaining thirteen weeks consumption as stock.
3. Orders placed with the Corporation on the basis of four weeks consumption held as stock plus some stocks controlled on the basis of E.O.Q.

Figure 42. shows these three results, demonstrating that the more aggressive policy of maintaining stocks proportional to the consumption increases the amplification of the seasonal demand cycle.

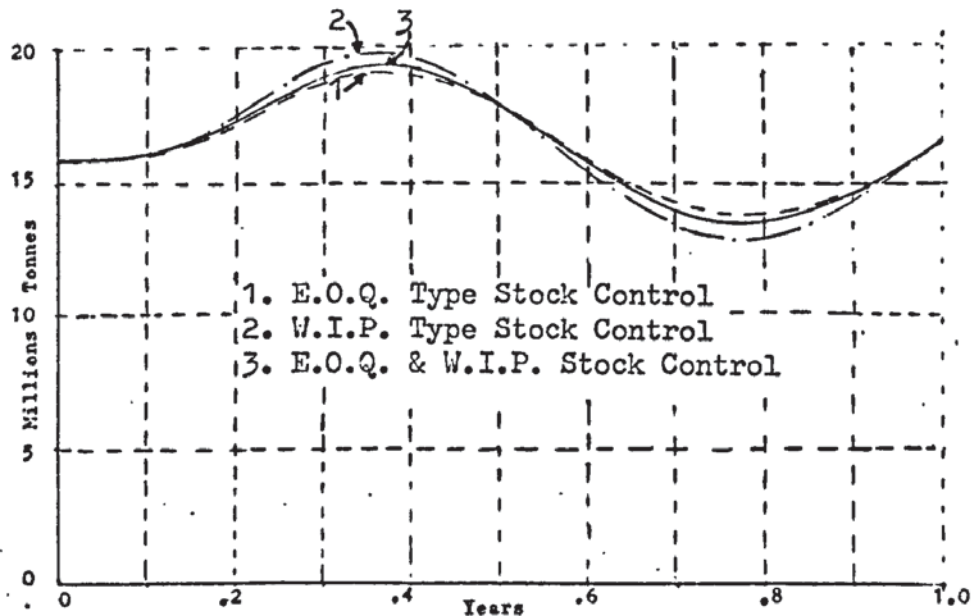


Figure 42. Comparison of the Dynamics of Customer Stock Control Procedures.

The "lead time" active stock and the buffer stock (allowing for lead time and order size variations) create a more complex amplification of consumption because of the interaction between the delivery promise and orders placed due to the stock control procedure.

If the Corporation expands its stockholding activity consideration needs to be given to the dynamics of the stock control procedures adopted. Procedures which have a high "gain" will considerably worsen the variation in orders placed increasing the first quarters production and reducing the third quarters production even further.

To summarise:

1. Consideration needs to be given to the dynamics of customer and stockholder order procedures to reduce the amplification of consumption.
2. If the division or Corporation undertake further stockholding, consideration needs to be given to the dynamics of the procedures.

4.4.2.3 Delivery Date Quotation

The market is believed to react to an increasing delivery period by increasing orders to cover the increased stock-out risk. Figure 43 shows the result of a simulation run in which the

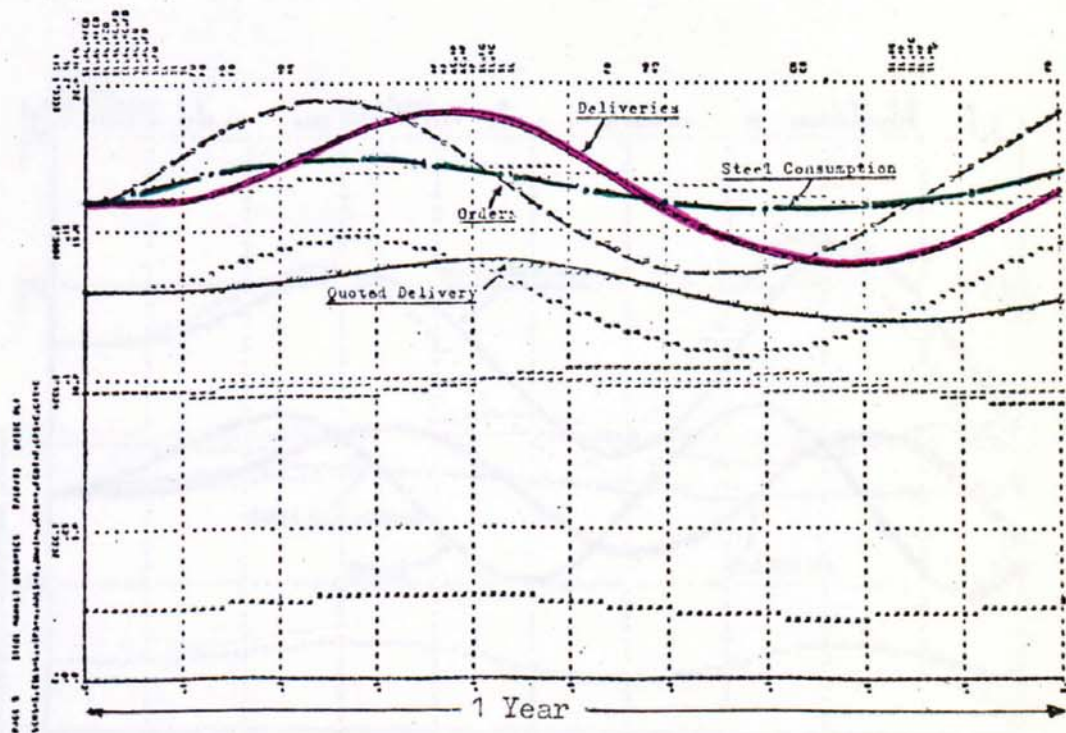


Figure 43 Amplification of Demand (Slow Sales Office Response).

consumption of steel oscillated by 10% with a yearly periodicity. It can be seen that the orders fluctuate by about 40% of the normal delivery. The quoted delivery remains fairly constant at about six weeks. Further runs with the model suggested that even if the quoted delivery time were fixed the market-production system has a natural frequency of approximately one year.

One method suggested to reduce these swings in orders was for the sales office to respond more quickly to changes in the orders received. If the orders increased a longer delivery period would be quoted. In the models discussed in this thesis, the sales office are assumed to take approximately 13 weeks to pass on to the market, as a whole, the full change in the delivery period. Figure 44 shows the result of informing the market of the full change in the delivery time within two weeks. The system appears unstable creating increasing order oscillations.

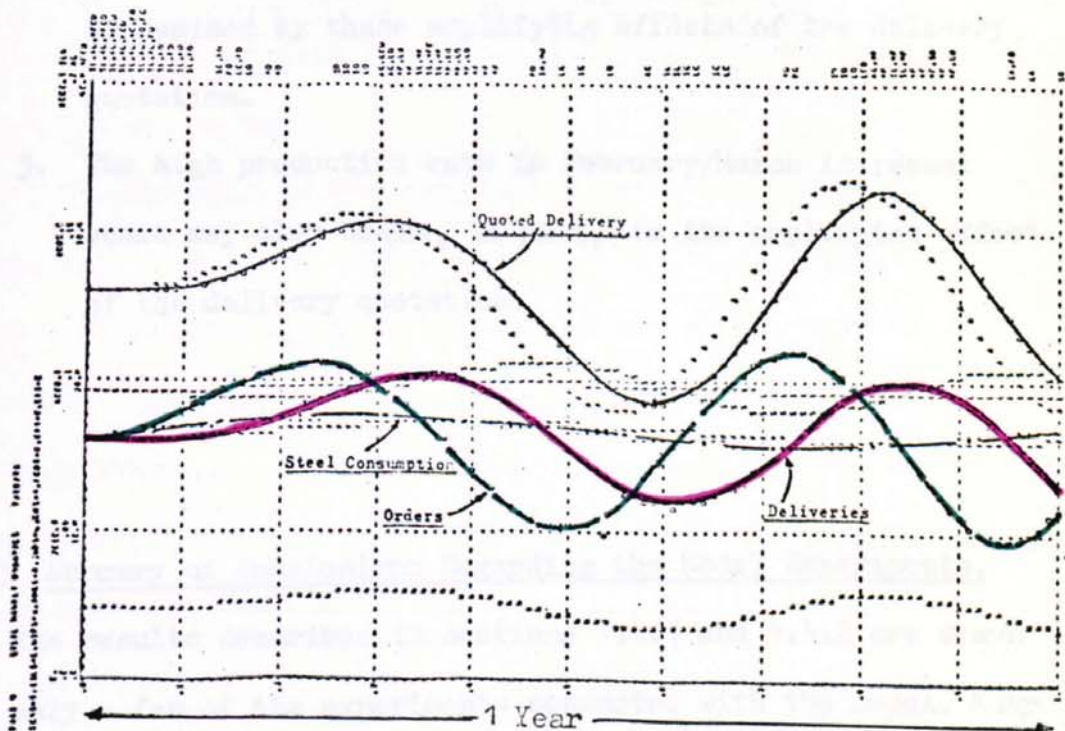


Figure 44 Unstable "Demand" Created by Quickened Sales Office Response.

While the two week response time is an extreme case it indicates that the market is sensitive to the delivery period. Stabilising the delivery quoted may reduce seasonal cycles in orders placed (and steel delivered).

To summarise:

1. The delivery period quoted to customers plays a major role in creating wide variations in orders placed with the division.
2. Speeding the response (quickenig) of the delivery quotation worsens the dynamics of the orders placed.
3. Whether the quoted delivery period is effective or not the orders tend to cycle with a periodicity of one year.
4. The down turn in orders during the third quarter may be emphasised by these amplifying effects of the delivery quotation.
5. The high production rate in February/March in recent years may also be due, in part, to the amplifying effect of the delivery quotation.

4.4.3 Summary of Conclusions Regarding the Model Experiments.

The results described in sections 4.4.1 and 4.4.2 are drawn from only a few of the experiments conducted with the model. Many

of the experiments, while reducing the orders received or production oscillations were based upon situations that were found to be impracticable. The experiments described depend primarily on the reaction of the market to the delivery period quoted. It appears that there are procedures that can reduce this period.

There is general agreement that the market does attempt to increase stocks during peak periods and that forecasting procedures, particularly trend predictions, overstate the orders to be placed. Both these factors are further exaggerated if the delivery period increases.

These results indicate that there are a number of ways of stabilising the delivery period; loading procedures, inter-process stocking, assigning steel to orders at a later stage and holding finished stocks. The model indicates that the peak rate of receiving orders may be reduced by up to 7% provided that this reduced rate (93% of the original peak) is less than the production capacity. These reductions in the variation of orders are not accumulative since they each treat the same feedback response by different means.

Stockholding by the Corporation or Division has been suggested. A stockholding operation is usually evaluated on the basis of its ability to hold adequate stocks to overcome peak demands. These experiments suggest that a suitably controlled stockholding operation would reduce the amplification created by the market. A small stock would reduce the delivery quotation response and variation in orders.

Stockholding policies are discussed in Section 4.5.

4.5 Examination of Stockholding

The model described in the previous sections combines the stockholders and consumers into a single market. By combining these areas the merchant stocks are ignored together with the associated stock control procedures.

This section is concerned with experiments to determine the significance of stockholding. Three modifications were made to the model;

- Inclusion of a merchant sector, purchasing steel and selling it to manufacturers of finished products.
- Inclusion of a Corporation stockholding operation but excluding a merchant sector from the model.
- Inclusion of Corporation and Private stockholding with the model set up to simulate sheet steel sales.

4.5.1 Stockholders Effect on the Market

The stocks held by stockholders have been viewed as a useful means of holding a buffer stock without the Corporation investing in large finished stocks and not becoming involved in the complexities of small volume orders. The Corporation has been viewed as a bulk supplier of the basic steel. Consequently there has been an increase in stockholders and the total stocks held. Some consumers have extended their stockholding activities to operate as stockholders.

It was suggested that the model be used to examine the effect of this increase in stockholding and whether the buffer stock is effective in reducing the swings in orders placed with the Corporation.

The model described in section 4.2 needs to be extended to incorporate the interactions between production, stockholders and consumers. Figure 45 shows the prime interactions assumed in this model. Deliveries, quotations and orders occur between production and the consumers and stockholders. The stockholders similarly receive orders and supply the consumers, although a fixed short delivery delay is assumed, rather than a lengthy, varying, delivery promise.

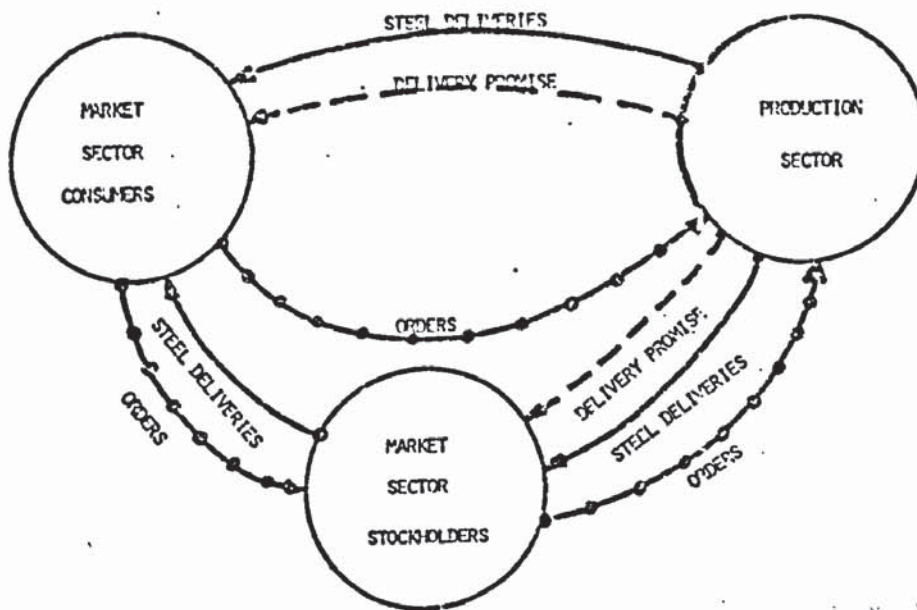


Figure 45. M.D. Model with Stockholders; Prime Interactions.

Figure 46 shows the detailed model diagram compared with the model described in section 4.2. The stock control procedures adopted by the stockholders are assumed similar to those of the consumer. Two order files and production rates are used in the production sector to permit the identification of consumer and stockholder orders.

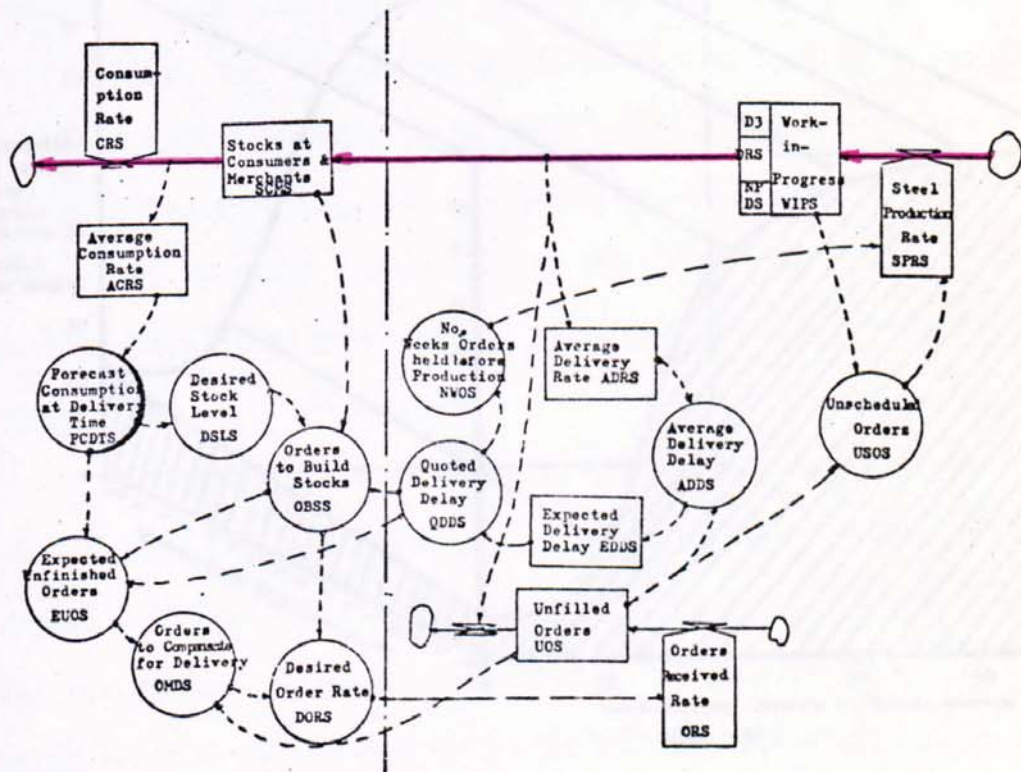
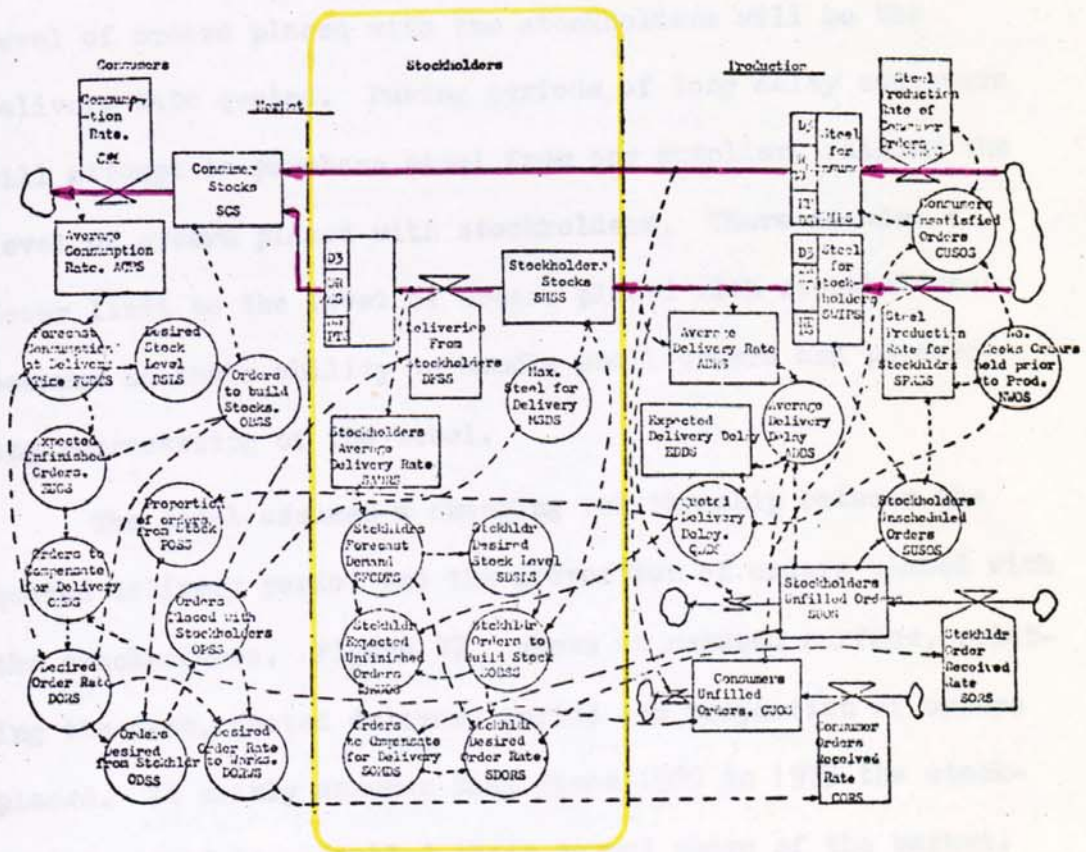


Figure 46. Comparison of the Market Dynamics Model with and without the Stockholder segment.

It has been assumed that a prime determinant of the level of orders placed with the stockholders will be the delivery date quoted. During periods of long delay customers will attempt to purchase steel from any supplier, raising the level of orders placed with stockholders. There is also a lower limit to the level of orders placed with stockholders because of their ability to handle small orders and performing reprocessing of the steel.

The model assumes a changing relationship between the quoted delivery period and the proportion of orders placed with the stockholders. Figure 47 shows an assumed surface, relating the date, quoted delivery period and proportion of orders placed. It mainly assumes that since 1960 to 1975 the stockholders would have doubled their normal share of the market.

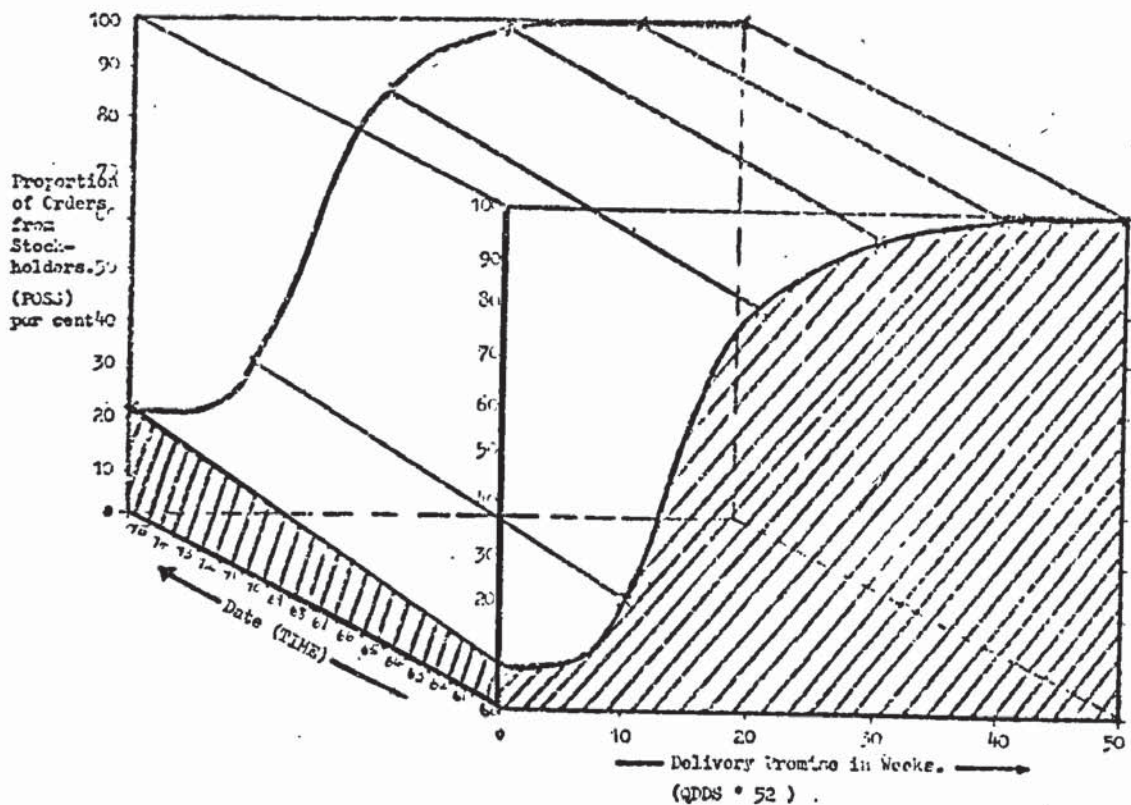


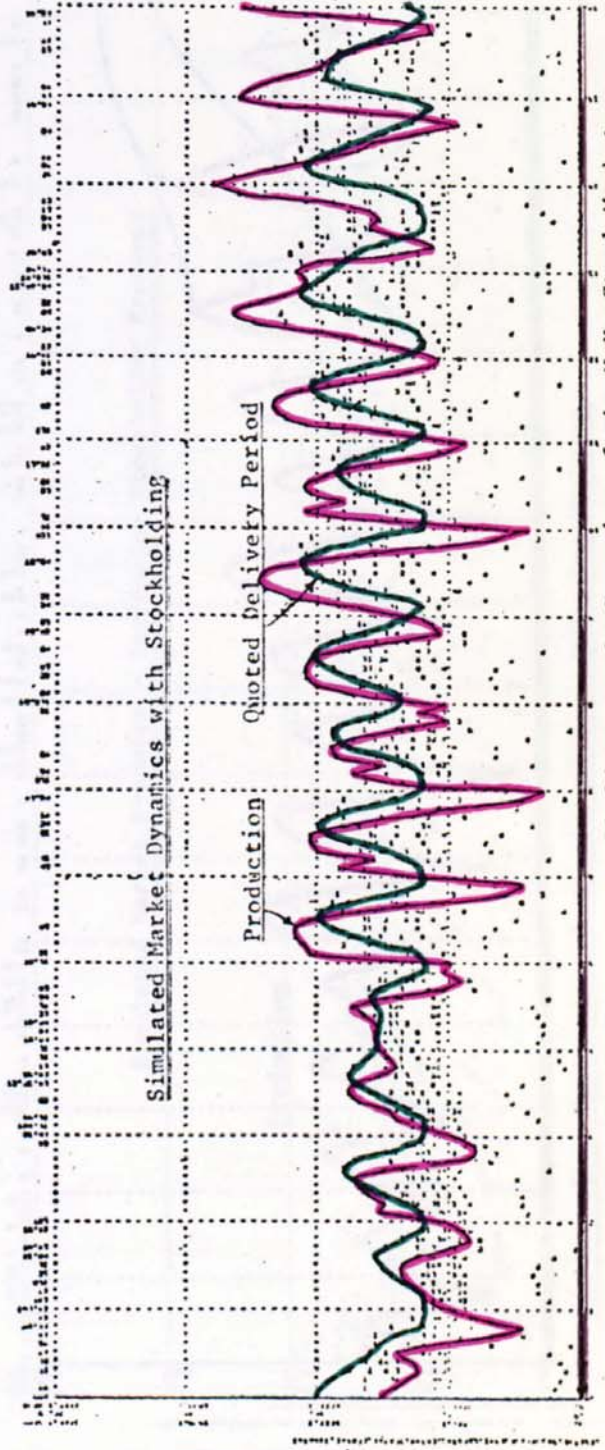
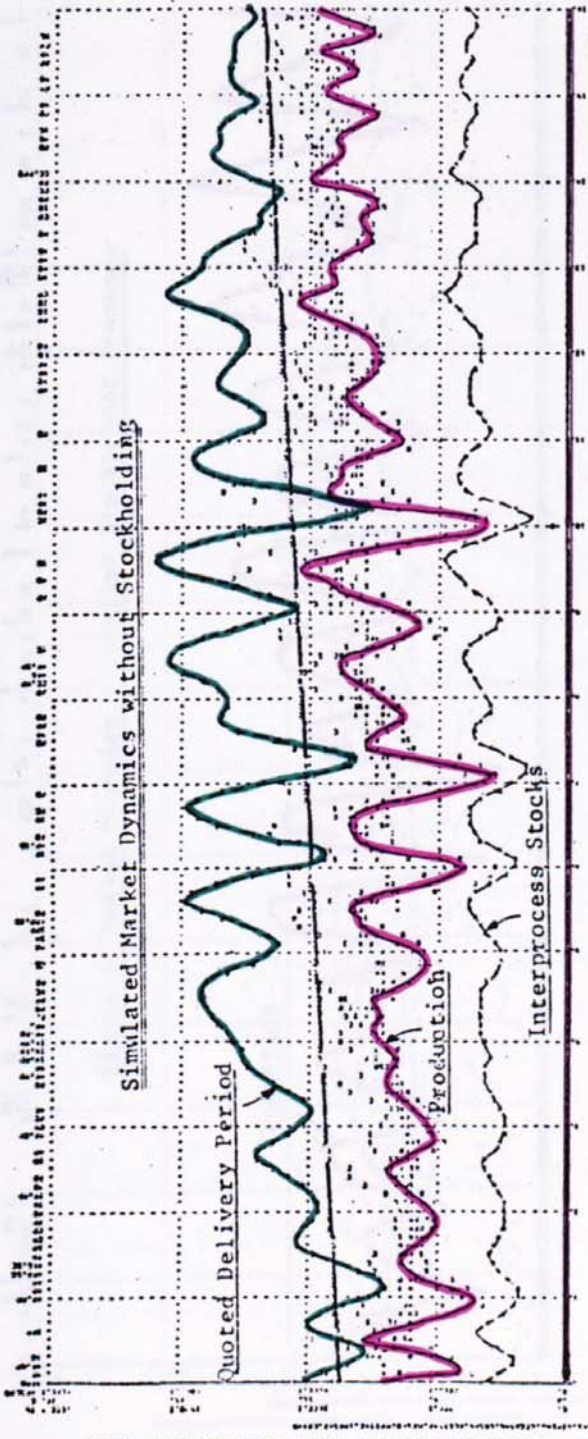
Figure 47. The Increasing Deliveries from Stockholders.

The model was executed using the U.K. Steel Production data for 1960 to 1973; the 1974/75 years of the simulation used the 1973 data. The results of two runs are shown in Figure 48. The first run is without stockholding. The second run assumes a constant stockholder market using the "1960" relationship between quoted delivery and the proportion of the market captured by stockholders. Both runs assume adequate process and interprocess stocking capacity.

The quoted delivery period tends to be shorter with the stockholders included in the model. This is because the stocks act as a buffer maintaining a source of short term delivery during peak consumption periods. However, the stockholders amplify the orders, tending to over order during these peak demand periods. The result is the increased ordering swings and wide fluctuations in production shown in Figure 48.

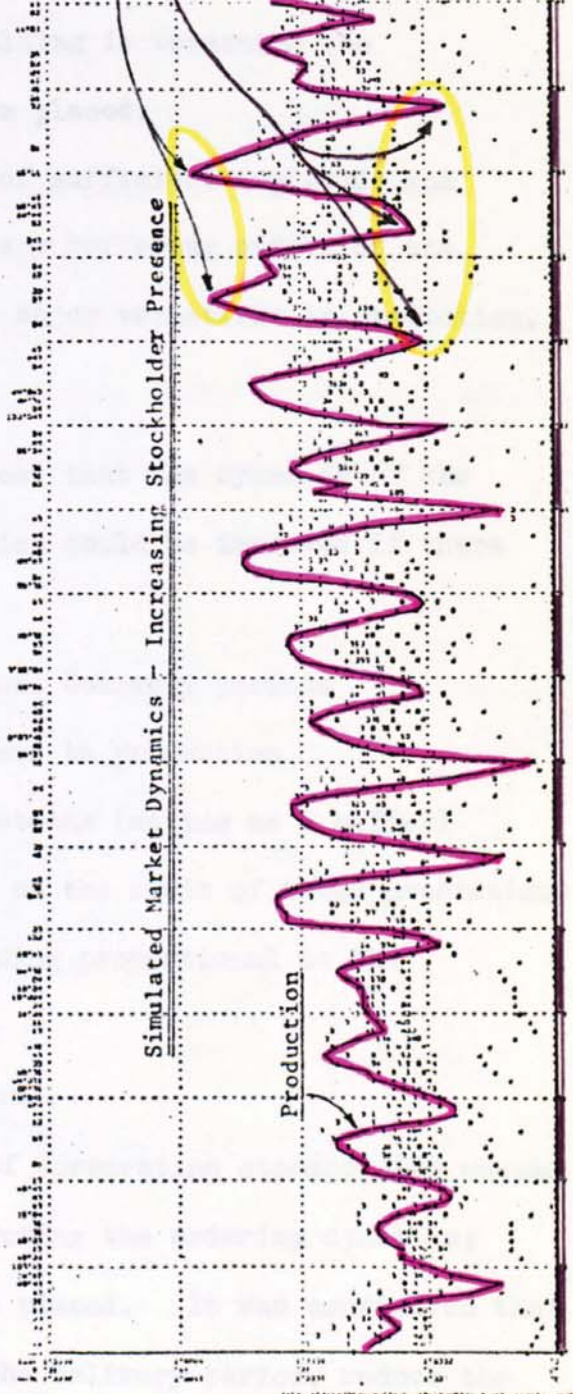
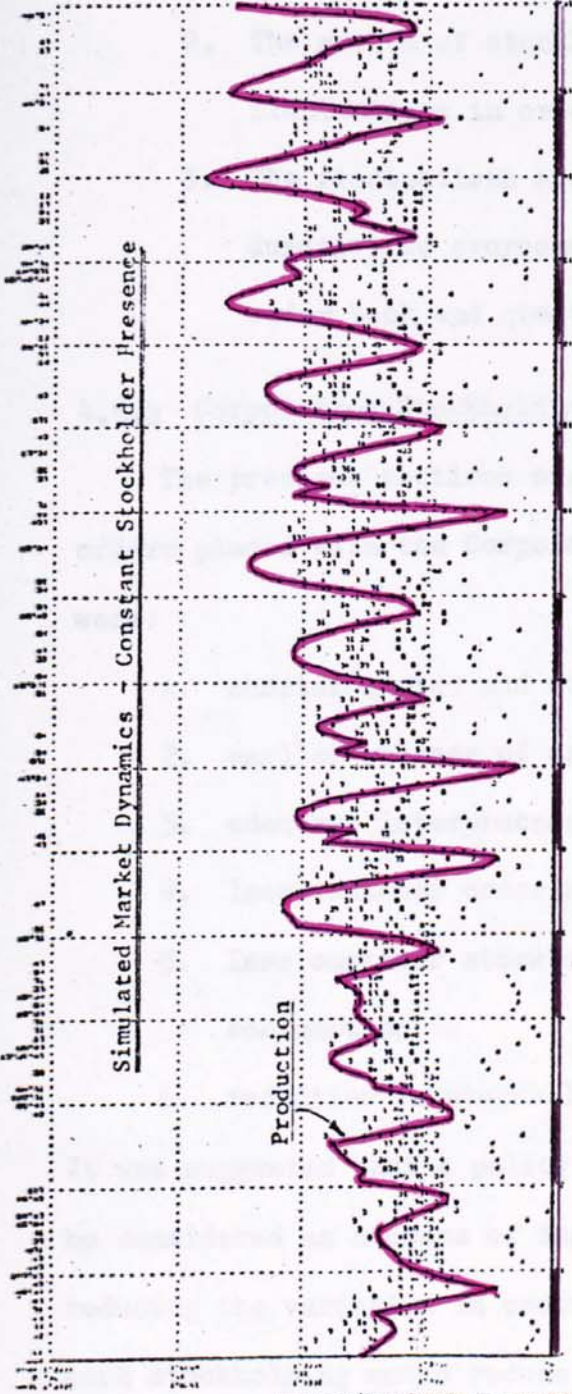
Figure 49 shows the effect of the increasing stockholder market. The production varies more in the latter years as the stockholding increases and creates a marginally different behaviour. Further runs have indicated that the increasing stockholders cause the cycle to lengthen creating two year rather than one year cycles.

The result of these runs is that two factors dominate, amplification due to stocking and amplification due to the quoted delivery. These factors tend to work in opposition but the amplification of the ordering fluctuations due to stock control procedures outweighs the benefit of the buffer stock.



N.B. Provided there is adequate production capacity the stockholders help reduce the delivery period at the expense of wider order and production variations.

Figure 4. The Effects of Stockholders on the Dynamics of the U.K. Steel Market.



N.B. Increased peaks and lower troughs created by the increase in Stockholders.
 (For a data comparison see figure 55, page 149)

Figure 49 Comparison of Static and Increasing Stockholding.

To summarise:

- 1, Stockholders increase the amplification of ordering variations by their forecasting and stock control procedures.
2. The growth of stockholding is worsening the fluctuations in orders placed.
3. The fluctuations are of sufficient amplitude and duration to overcome any buffering effect of the order book and create major variations in production.

4.5.2 Corporation Stockholding

The previous sections suggest that the dynamics of the orders placed with the Corporation could be improved if there were:

1. shorter quoted and actual delivery periods
2. earlier release of orders to production
3. adequate interprocess stocks (acting as a buffer)
4. less customer ordering on the basis of trend predictions
5. less customer stockholding proportional to the consumption
6. reduction in stockholding.

It was suggested that a policy of Corporation stockholding should be considered as a means of improving the ordering dynamics; reducing the variation in orders placed. It was considered that such stockholding would reduce the delivery period, reduce the need for customers to hold stocks to cover the lead time, and allow a greater proportion of the customer stocks to be based on an economic order size. The stockholding by the Corporation, however, might create the wide order variations similar to those created by the stockholders, Section 4.5.1.

Delivery from stock would be possible if standard sizes and quality ranges were introduced, particularly for the bulk orders. It would allow the works to concentrate on long runs, reducing tracking, handling and scheduling problems as well as changes to the mills.

Works would be removed from the need to handle customer orders, concentrating on bulk production of each size and quality. Sales offices would be able to place total tonnages on the works with a minimum effort since only the loading, not actual orders, need be altered. Works would be able to maximise throughput by such means as rolling wide and slitting which becomes more effective for bulk orders.

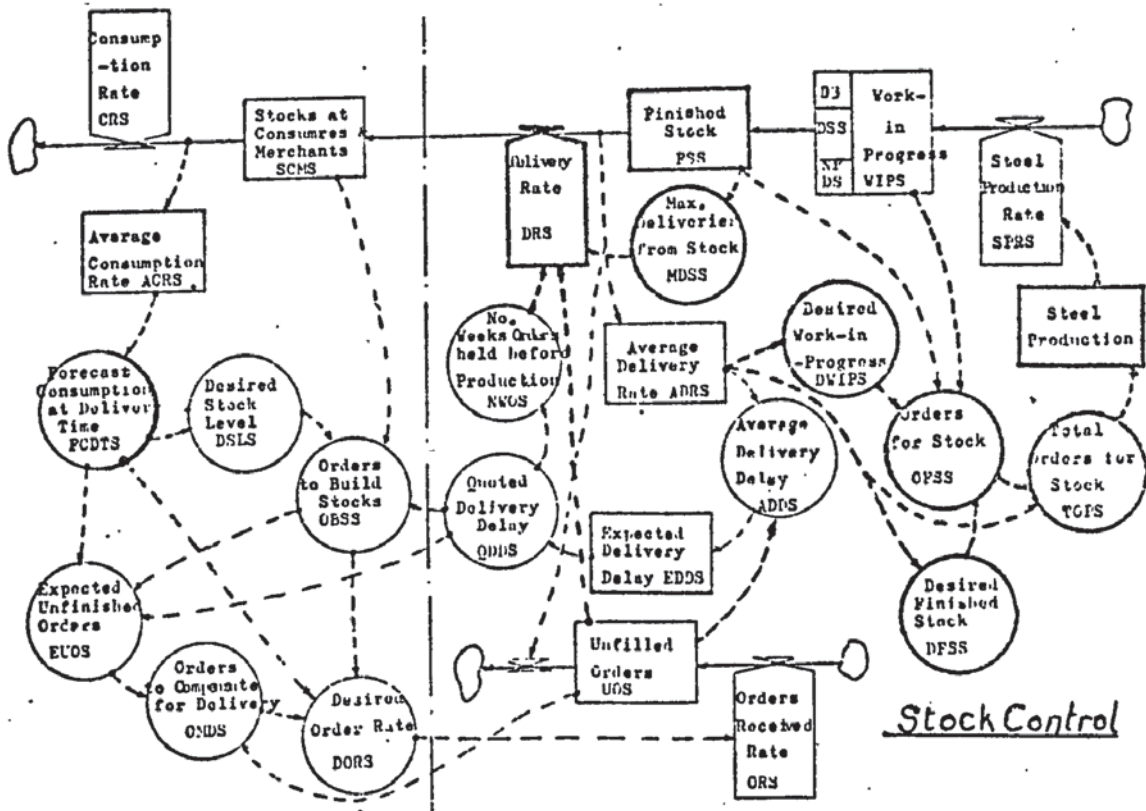


Figure 50 The "Sell-from-Stock Model Diagram."

Figure 50 shows the "Sell-from-Stock" model diagram. The "Sell-from-Stock" model incorporates a finished stock and stock control procedures.

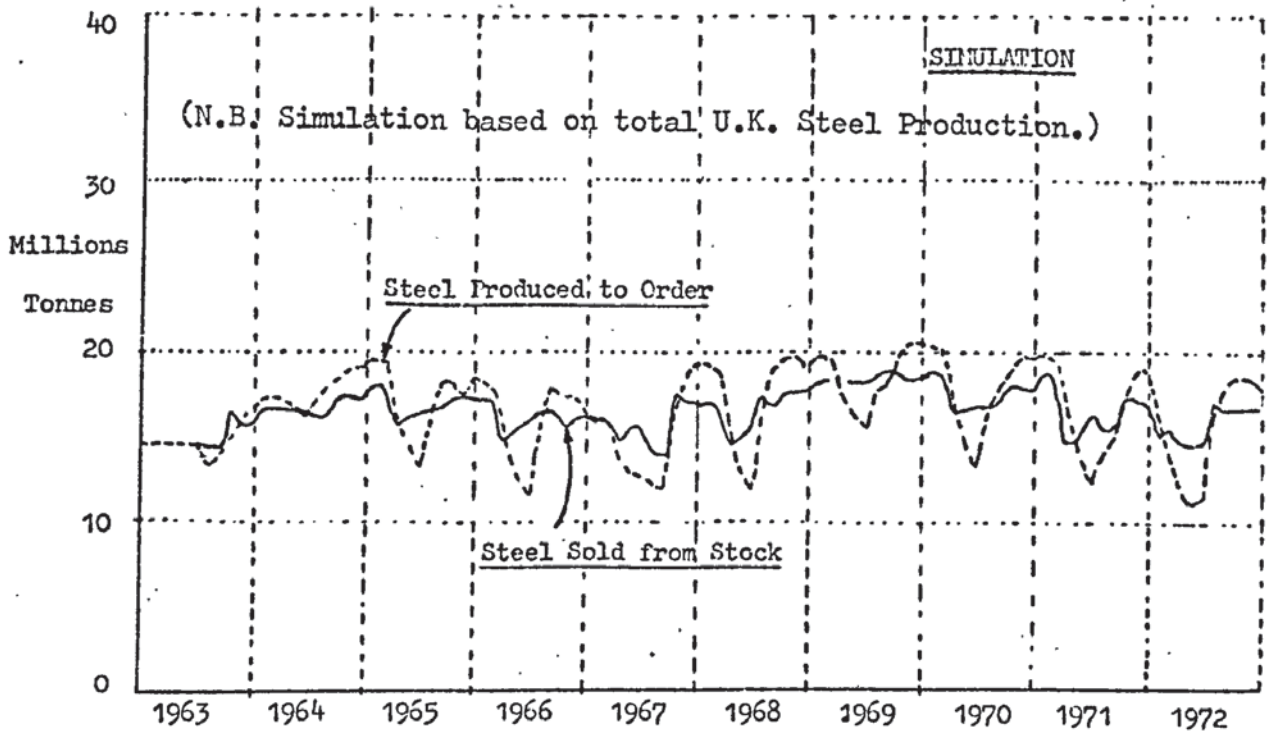


Figure 51 Orders Received; Production to Order and Production for Stock.

The simulation results are compared in Figure 51. The orders received varies less when the steel is sold from stock because the lead time is shorter and more stable.

To summarise:

1. If stockholders are ignored, consumer ordering variations can be reduced by delivering steel from stock.
2. The introduction of a stockholding operation between the consumer and producer need not create an increase in ordering variations provided the stockholding operation does not attempt to increase its own stocks with the short term, seasonal, increases in the orders received rate.
3. Private Stockholders and a Corporation Stockholding operation behave in different ways. The private sector amplifies the dynamics, the Corporation stockholding could attenuate the dynamics.

4.5.3 Analysis of the Dynamics of Strip Mills Stockholding

The results of the investigation of stockholding by stockholders and by the Corporation was presented to Divisional and Corporation managers. It was suggested that the model should be developed to compare Strip Mills performance with and without its own stockholding. The model was to be set up with the following elements:

1. Sheet Steel Consumption data as input to the model
2. Include the stockholders
3. Include the growth of stockholders
4. Compare the "make-to-order" and "sell-from-stock" situations over the last few years and up to 1976

The model developed for this comparison combines the Stockholder Model and the Corporation Stockholding Model.

Figure 52 shows a diagram of the model structure. The orders are placed with the Divisional stockholding outlet and the production of steel is to the standard product specifications.

Figure 53 shows the detailed model diagram.

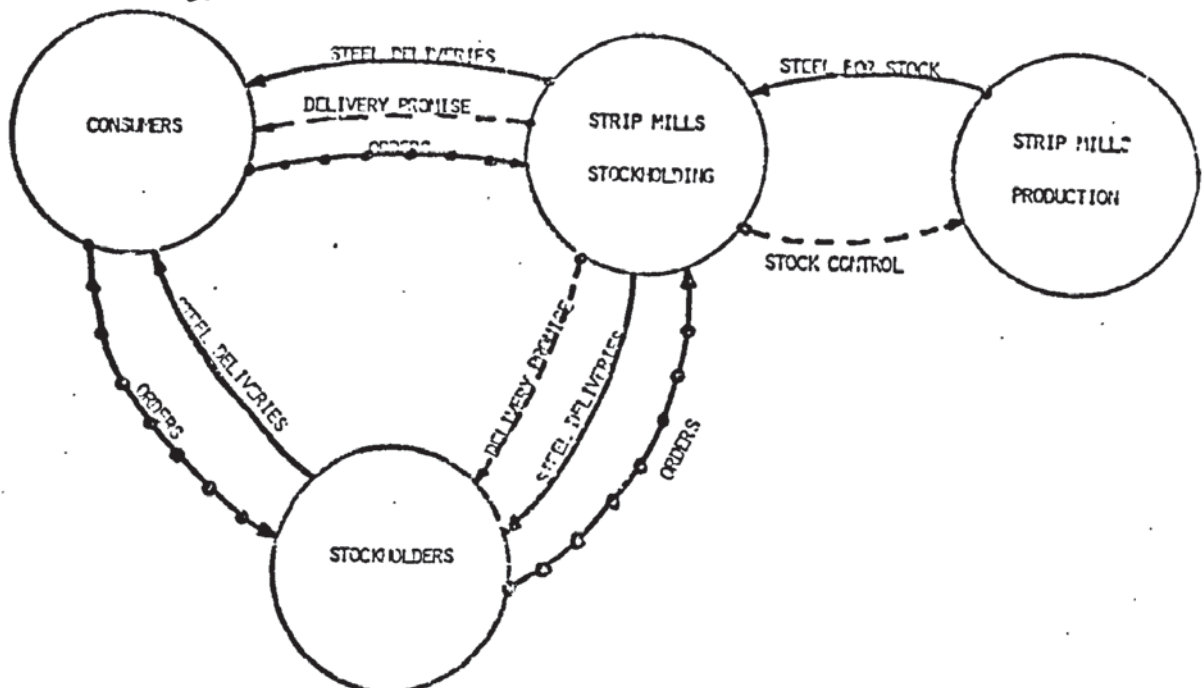


Figure 52 Structure of the Strip Mills Stockholding Model.

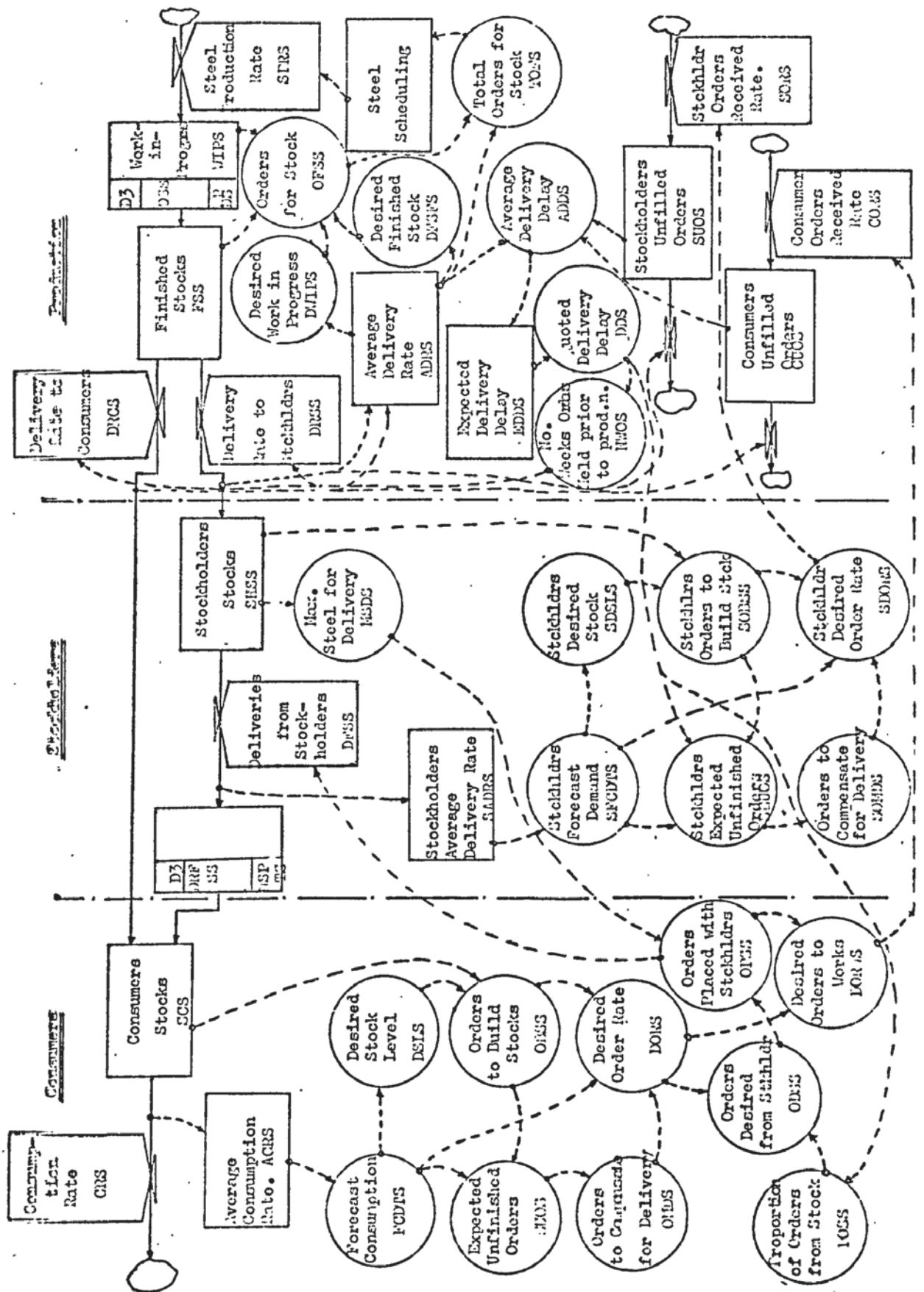


Figure 53 Strip Mills Stockholder Model.

The production rate and the delivery period are compared in figure 54. with and without a Divisional sheet steel finished stock. An increasing stockholder presence has been included in both runs so that a reasonable comparison can be made. However, it would be expected that the reduced delivery time created by Divisional stockholding would have moderated the growth in the Private sector stockholding. The effect of the Divisional/Merchant competition has not been included in the model.

It is apparent that the provision of a Divisional stockholding facility does not worsen the dynamics. The reduced lead time outweighs any increases in production cycles created by the Divisional stock control procedures. The variation in production is reduced because;

- The reduced delivery period permits a shorter forecasting horizon and reduces the forecasting error.
- Customer buffer stocks are reduced because of the shorter lead time. The reduced buffer stock variation reduces the amplification of demand.
- The reduced lead time allows the customer stock level to be adjusted quickly. The responsive delivery reduces the amplification of demand.
- The finished stocks held by the Division act as a buffer smoothing short term variations in production. However, if only a few weeks production is held (six weeks in the model) the buffering effect is reduced. (The small buffer stock held in the model actually amplifies the seasonal variation because no seasonal

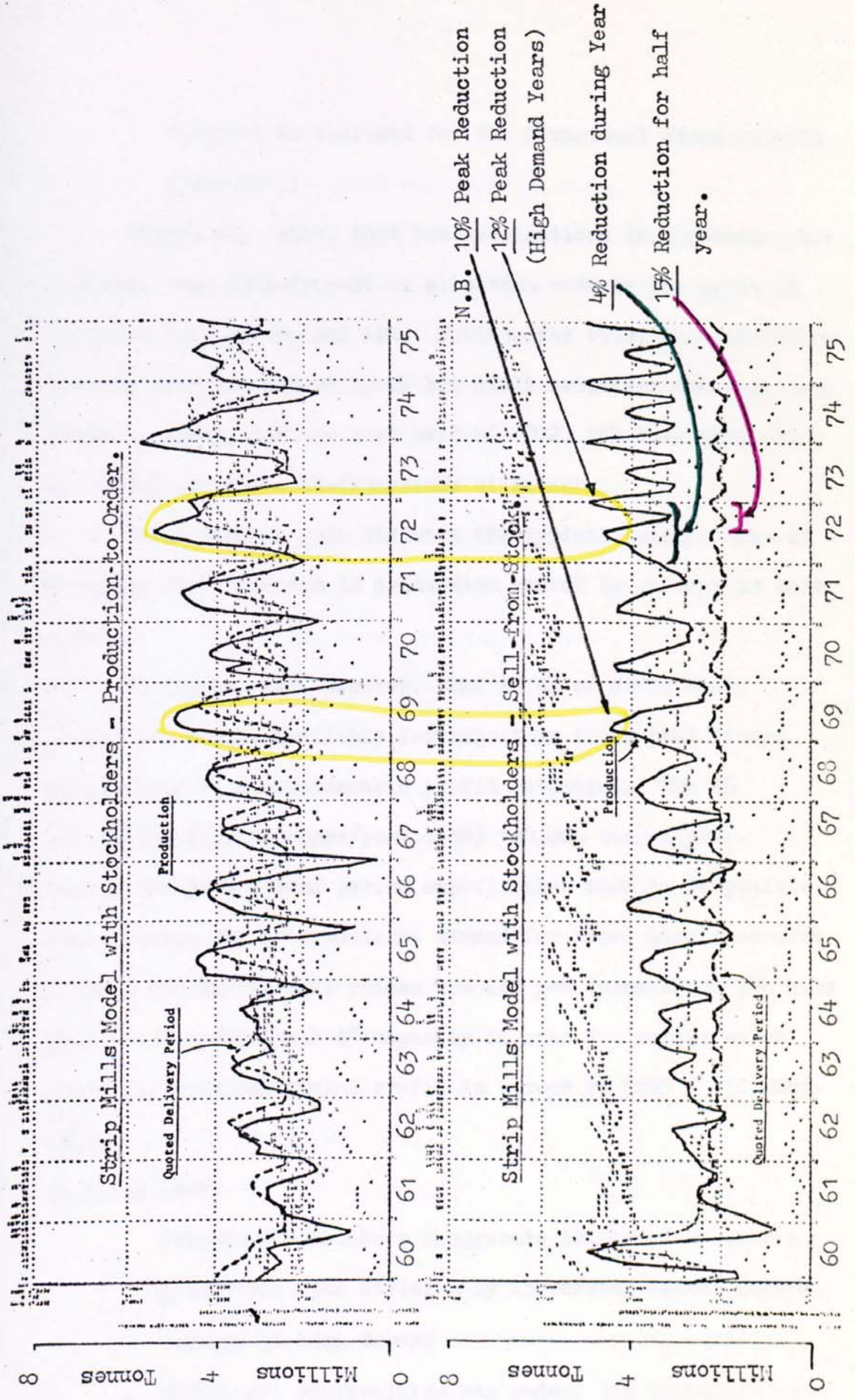


Figure 54. Strip Mills-Stockholder Model Comparisons.

forecast is included for the Divisional stock control procedure.)

Figure 54. shows that the oscillations in production are reduced. The Sell-from-Stock situation reduces the peaks in 1969 and 1972 by 10% and 12%. Further for 1972, the production for the year is reduced by 4% but still satisfied the long term demand. Again, for the last half of 1972, 15% less production is needed for the sell-from-stock situation.

These figures only indicate the typical consequences of reducing the variation in production caused by changes in home orders.

It can be seen, however, that if 4% of Strip Mills production became available for export in these peak demand years there is a considerable profit potential. The 4% represents (3.5 m tonnes/year x 4%) 140,000 tonnes/year. During the peak demand period export sales tend to be profitable because the international demand for steel also increases. Current Hot Rolled Coil prices are £40 per tonne above the home price. The additional 4% capacity if used for export sales would imply an additional profit in excess of (£40 x 140,000) £5.6m.

To summarise:

- Private Stockholders exaggerate the level of orders placed with the Division by increasing stocks during periods of high demand
- Divisional stockholding can reduce the variation of orders received while giving an improved customer delivery

- Divisional stockholding can reduce production variations by holding a buffer stock

4.6 Conclusions from the Market Dynamics Models

The models were developed to investigate the dynamic behaviour of orders placed with Strip Mills Division. The seasonal and longer term cycles in order placement appear to be amplified by consumers and stockholders. Strip Mills Division appears to exaggerate these fluctuations creating production capacity and delivery problems. If the volume of orders placed varied less or if Strip Mills could moderate the effect of variations in orders placed, then the available capacity could be used more effectively.

The previous sections suggest that variations in the volume of orders placed could be reduced if;

- the delivery period were reduced
- orders were released earlier by the sales office for production
- there was an adequate interprocess stocking capacity for peak demand periods
- customers were discouraged from ordering on the basis of trend predictions
- customers were discouraged from holding stocks proportional to consumption ("economic re-order quantity" method of stock control being preferable)
- there were a reduction of stocking by the private sector

The models cannot be used to determine an optimum policy. They can be used, however, to demonstrate the result of a particular policy. In this study two policies were recommended for consideration which advantageously affect the factors mentioned above.

These policies were:

- "Sell-from-Stock" rather than "Make-to-Order"
- Introduction of "Standard Products"

These policies are closely linked. To be able to sell from stock it is necessary to be able to identify a reasonably small number of products. A continuous spectrum of qualities, widths and gauges creates an infinite range of final products. In practice the qualities, widths and gauges quoted in the price schedule limits the normal variation in products. Gauges are quoted in 0.025 mm steps and standard widths are encouraged. In the past standard gauges, such as Birmingham Wire Gauge have caused designers to select these gauges. Similarly a very large proportion of the current orders are for 36 inch and 48 inch wide sheet.

Standardisation of widths and gauges is familiar to customers and seems acceptable, particularly if this means the steel can be ordered "off the shelf" and delivered promptly. The probable number of products that would need to be stocked to cover a given proportion of the orders placed is a difficult problem and requires further work. If standard products were introduced with delivery offered immediately it is likely that many consumers would alter future designs to fully utilise the standard product gauge/width combinations.

"Selling-from-stock" is likely to improve Strip Mills performance for the following reasons:

- A shorter delivery period, reducing the amplification of orders and making the works competitive on delivery with stockholders
- Reduced stock held by Stockholders, orders coming directly from consumers reducing amplification effect of stockholding
- Finished steel buffer stock reducing the amplification effect of a varying delivery quote and smoothing production variations
- Shorter customer forecasting horizon and reduced need for trend prediction due to short delivery period
- Reduced stock held by customers proportional to the consumption reducing order swings

The introduction of standard products would be necessary for a sell from stock system but would itself assist in improving Strip Mills performance by;

- Minimising interprocess stocks and stock handling without reducing the effective buffer stocks, because non-prime steel can be quickly rerolled to an optimum standard product

Stockholding by the Division would help to reduce the amplification of demand variations. The potential reduction can be summarised as follows;

Orders. Variations in orders received can be reduced by shortening the delivery period. Stockholding reduces the delivery period to a minimum by selling "off-the-shelf". With a very short delivery period, customers need only order to replace the steel consumed. The amplification of orders can, potentially, be reduced to zero; orders fluctuate similarly to the consumption rate.

Production. The stock held by the Division would act as a buffer between the orders received and production. With a sufficiently large stock, the seasonal cycle in production could be completely removed. The buffer stock permits an attenuation of the ordering variations.

The stockholding operation should be more effective than normally estimated on the basis of a buffer stock. Because of the reduced ordering fluctuations a smaller buffer stock would be needed for a similar smoothing of production.

Figure 55. summarises the amplification shown by the sheet steel data. The change in sheet steel stocks held by consumers, merchants and the total market are shown as a proportion of the quarterly consumption. It can be seen that;

- . Stock changes create an amplification of demand; increasing the peaks (64, 66, 67, 69, 70, 72) and reducing the troughs (64, 66, 69, 71)
- . Merchant stockholding variations appear to be aligning with consumer stock changes as the merchant stockholding increases (69, 70, 71)

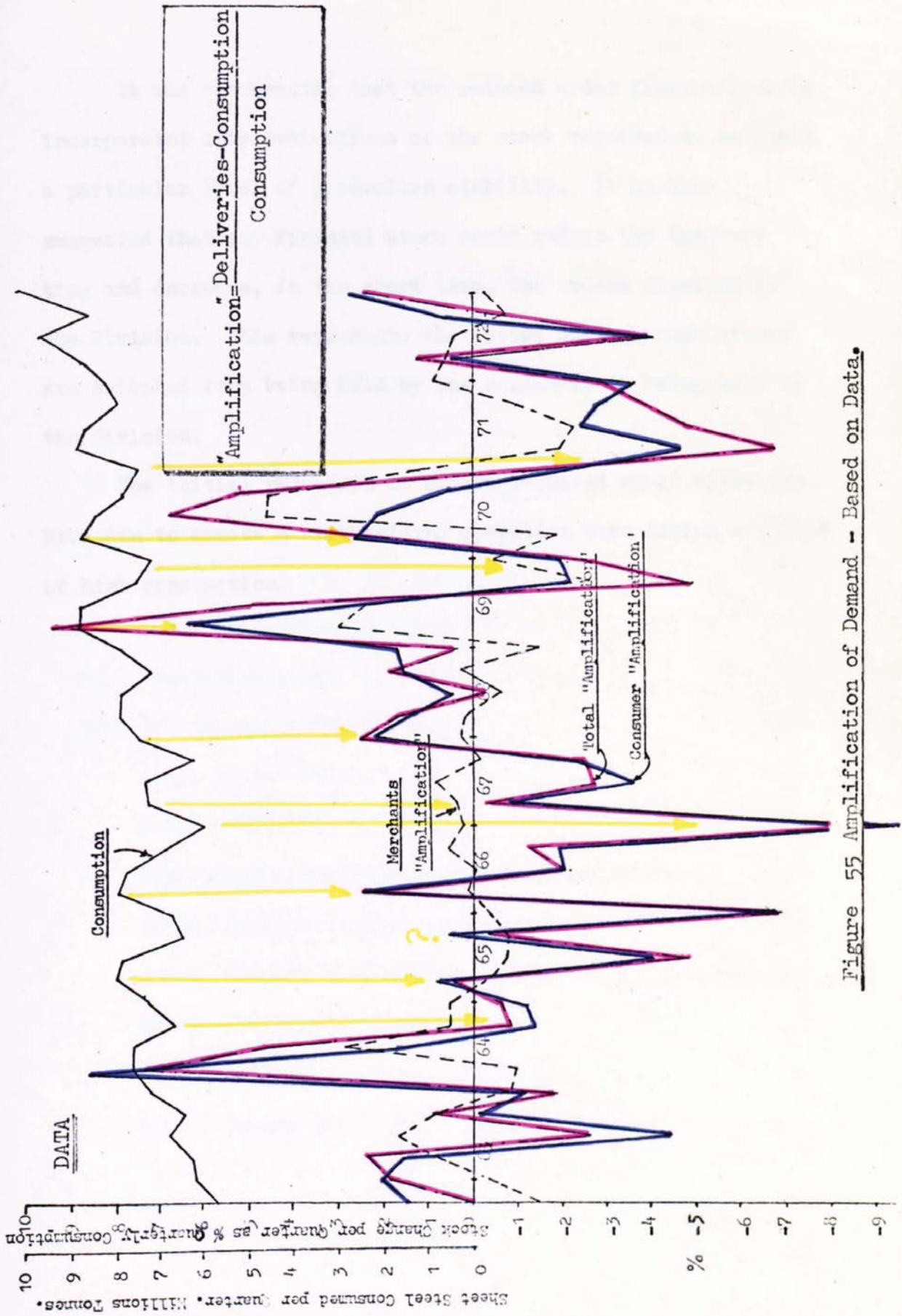


Figure 55 Amplification of Demand - Based on Data.

It was recommended that the reduced order fluctuations be incorporated into evaluations of the stock required to maintain a particular level of production stability. It is also suggested that any finished stock would reduce the delivery time and decrease, in the short term, the orders received by the Division. This represents the period during which stocks are switched from being held by the consumers to being held by the Division.

The initial reduction in orders received would allow the Division to create a stockholding operation even during a period of high consumption.

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5. Production Dynamics Model

Initially, a model was constructed of the control of ingot and slab stocks (Ingot - Slab Process Model). The model was created to illustrate the typical dynamics of material flows in a Strip Mill. The model was extended into a continuous flow process model of the Port Talbot Works.

The works model was discussed with the System Dynamics Group at the Sloan School of Management, Massachusetts Institute of Technology. The model was loaded onto the IBM 360/67 at M.I.T. and demonstrated to C. V. Swanson (author of papers on the dynamics of resource management (27)), A. L. Pugh (author of current DYNAMO versions), E. B. Roberts (author of "The Dynamics of Research and Development" (4)) and J. W. Forrester. Briefly their comments can be summarised as;

- The greatest potential benefits were where major oscillations or growth patterns were apparent. The problems created and the outline of the causes of these dynamics should be discussed with senior managers.
- Variations in production were likely to be closely monitored and controlled. The greatest potential would probably be outside the production area; material purchasing, orders received and capital investment.
- In the production area, interprocess stocking and order handling control procedures were likely to be the causes of production cycles.

Discussions were held at some length with representatives of Hoogovens and Inland Steel who were also at M.I.T. In both cases they felt that the immediate applications of I.D. would be in financial modelling.

It was decided that the works model should be restructured to remove some doubtful mechanisms created during the expansion of the model. The opportunity was also taken to generalise the model so that it could be used as a flow process of any of the five main steel works in the Division.

The model was based on the material flow system and was intended to simulate the short term deterministic dynamics of the production and scheduling systems. It was originally intended that it be able to show;

- " . The response of stock levels and production rates following a breakdown or significant change in demand.
- The duration of the recovery period following a breakdown or market change.
- The effect of stock and production limits on the recovery from production disturbances."

Figure 56 shows briefly how the study developed and where the material is reported in this chapter.

Sequence

Section

Construction of two illustrative Models;

"Ingot-Slab" and "Works" Models

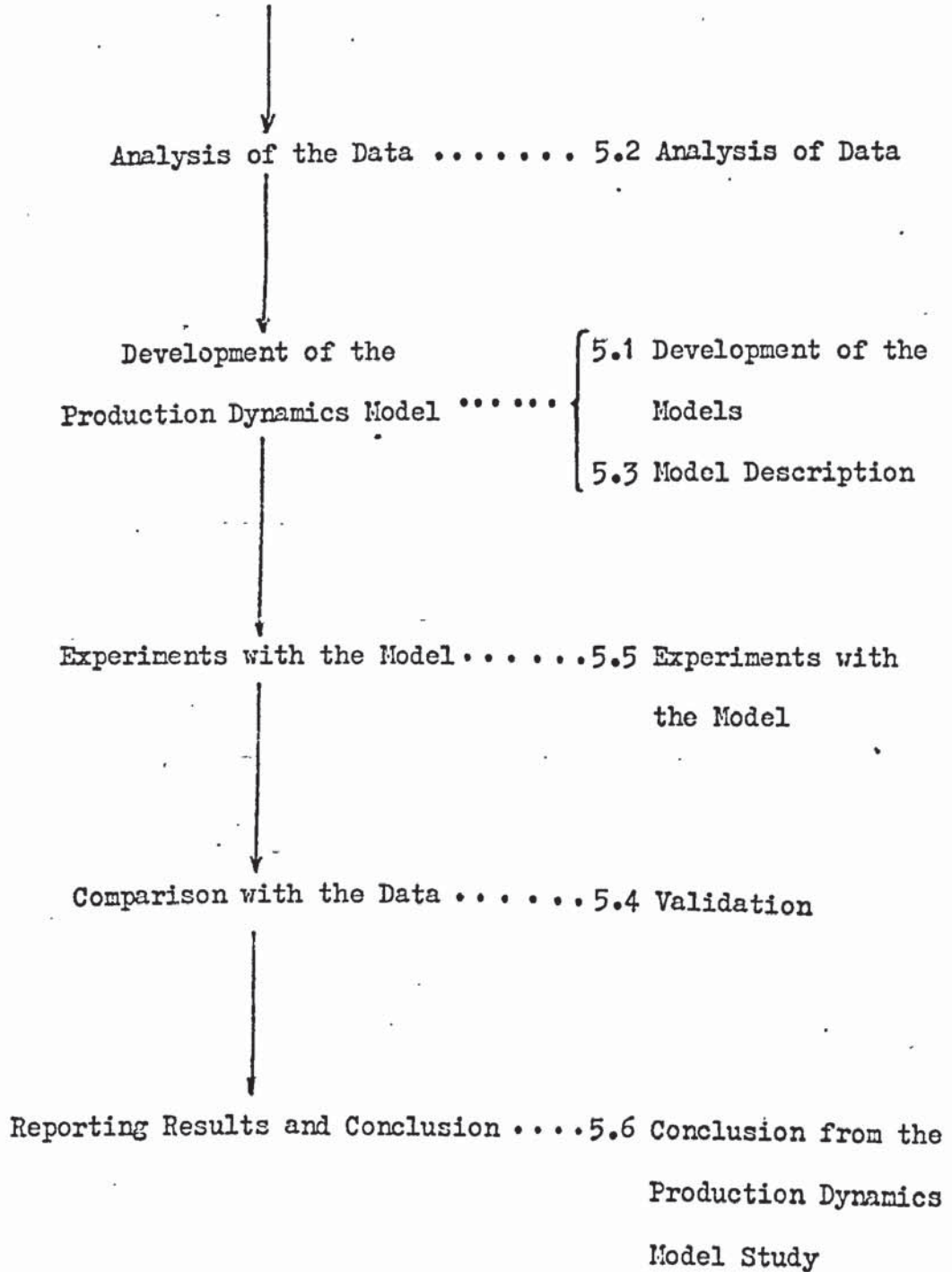


Figure 56 Development of the Production Dynamics Model.

5.1 Development of the Production Dynamics Model

Following the construction of the Ingot-Slab Process and Works models, the structure of the production flow process models were reconsidered and a generalised model prepared. Basically the Production Dynamics model simulates the steel flow through the plant as a conservative network with simple, local control procedures. The control procedures, primarily determine the level of interprocess stocks. It does not include senior management action such as the timing of cost reduction exercises or changes in manning policy.

The model was specifically designed to simulate any of the five Strip Mills Division works. Each process can be set up by specifying parameters and many of the relationships in the model are determined by tables of values permitting complex relationships to be defined.

The model was developed over a two year period. Its purpose and application changed during this period as the dynamic behaviour of the plant became better understood. It is useful to note how the model structure altered over this period and to indicate the problems encountered.

- Model 1. The model incorporated the main steel flow and control procedures for steel making and slabbing but the finishing processes were aggregated into a single process. To keep the model simple the control procedures were combined to form dimensionless measures of the pressure on management. Forrester has used this concept of "pressure" variables to permit the aggregation of a number of factors into a

- single mechanism. While this appeared to simplify the model, the pressure variables cannot be identified in the real system and created a lack of confidence in the model.
- Model 2. The model was extended to examine more fully the effects of blast furnace loading procedures. This was found difficult because of the need to reduce many discrete procedures into simple aggregate, continuously acting, rules. The model was used to demonstrate the problems created by alternative rules governing steel production and slabbing. It was shown that alternative rules created;
 1. large ingot and slab stocks
 2. slow recovery from breakdowns
 3. unnecessary reheating of ingots.
 - Model 3. It was thought that scrap handling might create the wide variations observed in scrap stocks. Scrap is generated during the steel production processes and is reused in steel making. This cycle in the scrap material flow might be the cause of scrap steel oscillations. It became apparent that the internal material flow system did not cause the variations.
 - Model 4. Following discussions with the Port Talbot Works O.R. Department, the finishing processes were included in greater detail and the ingot handling (soaking pit) simulation extended. These alterations were made primarily because they introduced variables which were familiar and which were considered important measures of plant performance. The "management pressure"

variables became unnecessary and were generally replaced by multiple variables constraining the range of the production rates.

It appears that the original model aggregated the control procedures too generally. A greater level of detail was needed before the model could be recognised as adequately representing the steel plant operations.

- Model 5. The final model, described in this chapter, includes the detailed simulation of the hot rolling, pickling and cold reduction processes. Stock handling, production restrictions, stocking capacities and scheduling rules are included for each process stage. As far as can be ascertained this model represents the most detailed flow process model reported to date, of a real industrial system using the I.D. approach. It includes 65 variables and 24 integrators. The model assumes nine process stages and requires the specification of nine tables and 44 constants.

5.2 Analysis of the Production Data

Data was collected to determine;

- the typical dynamic behaviour exhibited by the mills
- the consequences of aggregated rules; for example to determine whether interprocess stocks depend on the level of production
- parameters such as yields and production delays
- the behaviour and compare it with the model results.

Initially, the U.K. Steel production data was collected to determine the typical seasonal cycles in production and the

aggregate stock control rules. It appears that the Corporation exhibits a marked seasonal cycle reinforced by customer ordering procedures (Chapter 4). The finished and semi-finished stocks also show a seasonal cycle but part of the increase in deliveries in the first quarter originates from a stock decrease. The finished and semi-finished stocks held by the Corporation reduce the amplification of demand.

Sheet Steel data was collected for individual Strip Mills. Figure 57 shows the short term response of steel production, ingot stocks and scrap stocks for the Port Talbot Works. (The blast furnace strike in 1969 created the major reduction in blast furnace output in July and August.) Two factors were investigated initially; the cause of the ingot stocking peaks and the possible cycles in the scrap stocks.

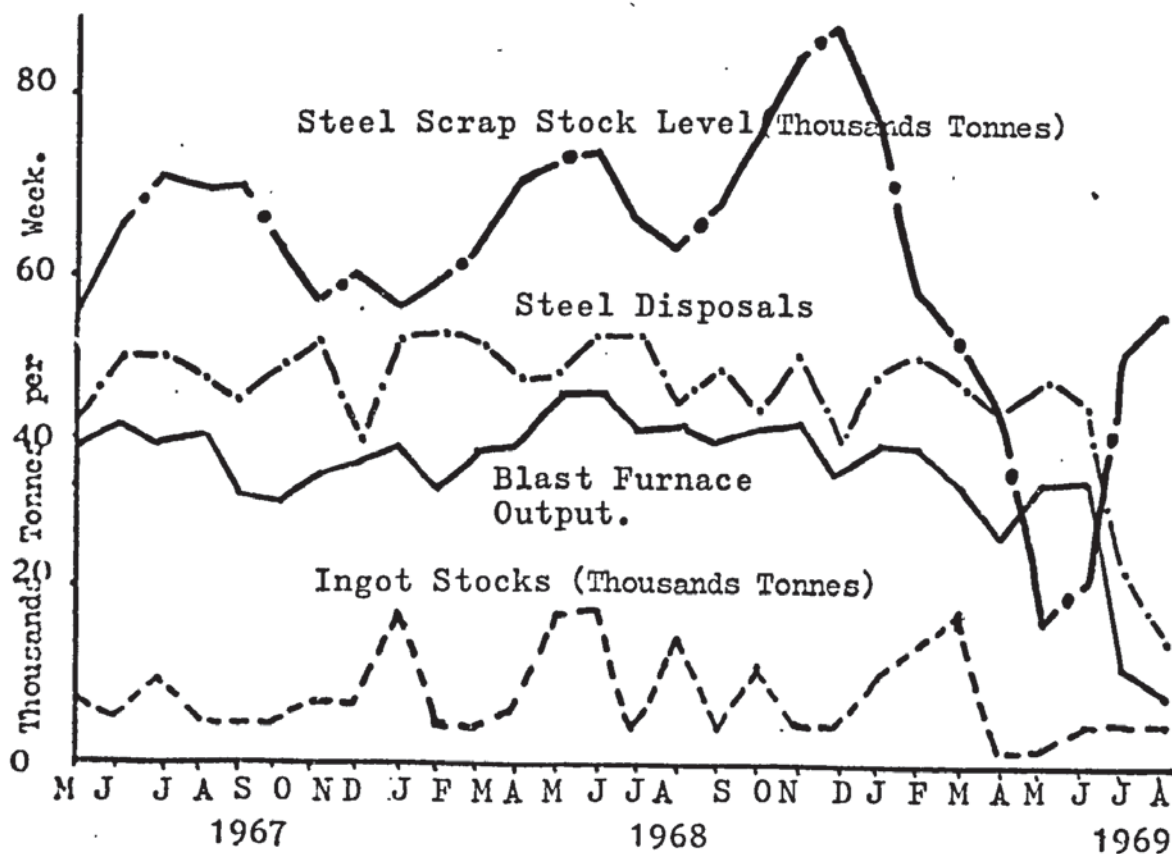


Figure 57 Stocks and Disposals for the Port Talbot Works,

It was felt, initially, that the material flow of scrap within the plant might create a long term cycle in the scrap stocks. Variations in yields might cause increased arisings which would later be corrected, thereby reducing the scrap stocks. After some extensive experiments it was realised that the yields did not vary adequately to account for the stock change. Scrap purchasing appears to be the cause of these stock changes. It was decided that scrap purchasing, scrap availability and scrap price dynamics, although a potential area of application of this technique, would be left out of the model.

Ingot and slab stocking behaviour formed a major part of this study and is discussed in section 5.5.

Data was collected for a years production at the Port Talbot Works on a weekly basis for each production stage. The data was used to determine yields, the relationships between stock levels and production rates and to verify estimated production and scheduling delays. Process rates and stock levels were compared with the model results as explained in section 5.4.

5.3 Model Description

The model is based on the simulation of the material flow processes but includes some order handling and a minimum of control and scheduling simulation.

5.3.1 Steel Production - Material Flow

The steel production process consists of consuming scrap and iron to produce steel as steel ingots. These ingots are rolled to form slabs and then into hot rolled coils of sheet steel. The steel may be sold; as hot rolled coil or be re-rolled, annealed, coated or cut-up, with various finishes and coatings.

The process is primarily a production line with interprocess stocks, where, at each stage a proportion of production is sold, figure 58.

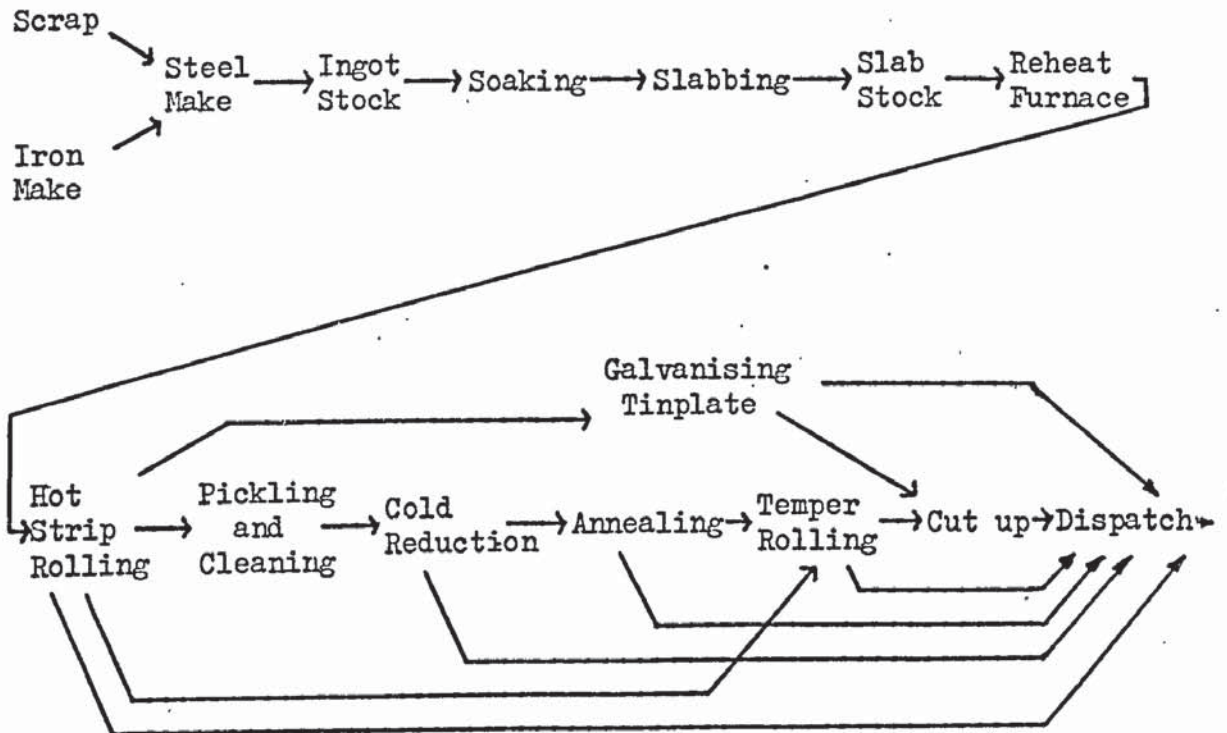


Figure 58. The Main Steel Making Processes

In the model the "flow" of materials has been simulated by assuming that the materials can be treated like a liquid flow process, it being assumed unnecessary to consider the discrete nature of the ingots, slabs or individual orders. The model is not intended to simulate variations in production which cycle with a period of less than a week and consequently can be considered to simulate the dynamics shown by "weekly totals". Many of the disturbances in the production flow, caused solely by the discrete nature of production, such as individual ingots or coils are unlikely to affect the weekly totals because they are such a

small proportion of the total; a few tons compared with 50,000 tons per week.

5.3.2 Order Handling - Order Flow

The order handling is simulated in a very simple manner in the model. Only two accumulated values are assumed, the long term orders-in-hand and those orders currently awaiting slabbing, figure 59.

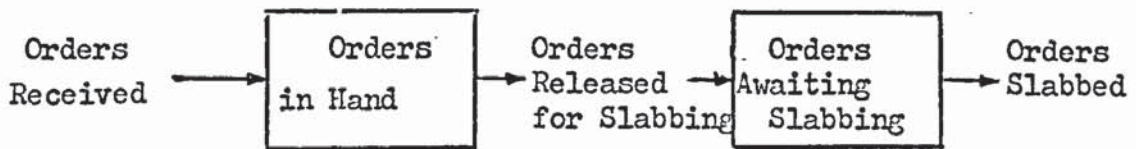


Figure 59. The Order Handling Flow.

Since the orders normally have the delivery dates agreed on arrival the orders leave the orders-in-hand at a rate similar to that at which they arrive. However, the orders awaiting rolling tend to be worked at a rate which depends on the available orders. If a large number of orders are outstanding the slabbing rate tends to be increased to reduce these outstanding orders providing there is adequate capacity.

5.3.3 Scheduling

The mechanisms controlling the rates of flow in the model are based upon the scheduling and control of the plant. These non-conservative flow paths, which link the accumulated values, such as stock levels, to the rates of production, simulate the effects of scheduling rules.

These mechanisms, which will be called "scheduling" in the model description, do not simulate the actual queueing or sequencing of orders but only the timing of the scheduling method. Most commonly, the scheduling method simulated, simply allows a normal level of production plus a change in production to build or reduce one or more inter-process stock levels.

The main scheduling or control mechanisms are shown by the broken lines in figure 60.

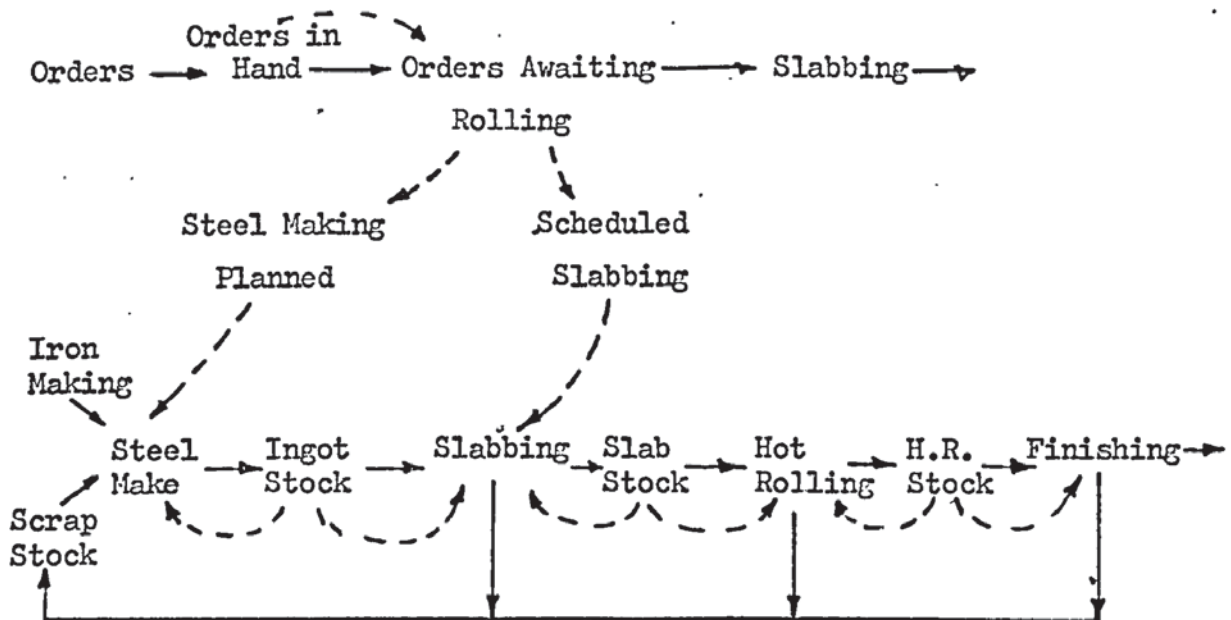


Figure 60 The Principal Scheduling Mechanisms Simulated.

The steel first becomes associated with the orders at slabbing, so that in the model, the slabbing schedule is primarily determined by the outstanding orders, provided there are adequate hot ingots to work. The steel making is in turn based upon the production planned but modified by the ingot/slab stock level.

5.3.4 Order Processing

In the model, orders are represented by the total ingot tonnage equivalent. Thus a weekly order rate of 50,000 tons represents a total ingot tonnage of 50,000 tons but an actual "through-the-door" tonnage of considerably less; of the order of 35,000 tons.

Orders are received and held in a live order file. On completion of the order it is deleted from the file. The live orders form the basis for understanding the current "demand" situation. It gives an indication of the most recent changes in demand and the required production over the next few weeks. It determines the rolling rate of ingots into slabs and production rate of the plant following slabbing, since the steel becomes associated with specific orders after slabbing.

The order processing has been modelled in many ways during the development of the model. It appears, however, that the simple structure shown in figure 61 is the most realistic. The orders are received by the sales office and are released to the works after the lead time. The slabbing rate is mainly determined by the available orders. The equations and mnemonics are given in appendix 2.

5.3.5 Scrap Handling.

The mechanisms determining the consumption, arisings and purchase of scrap have been included in the model to demonstrate how the variations in consumption and purchase occur. Scrap costs are increasing and any fluctuation in the consumption of scrap contributes to a fluctuation in the "profit" and cash flow.

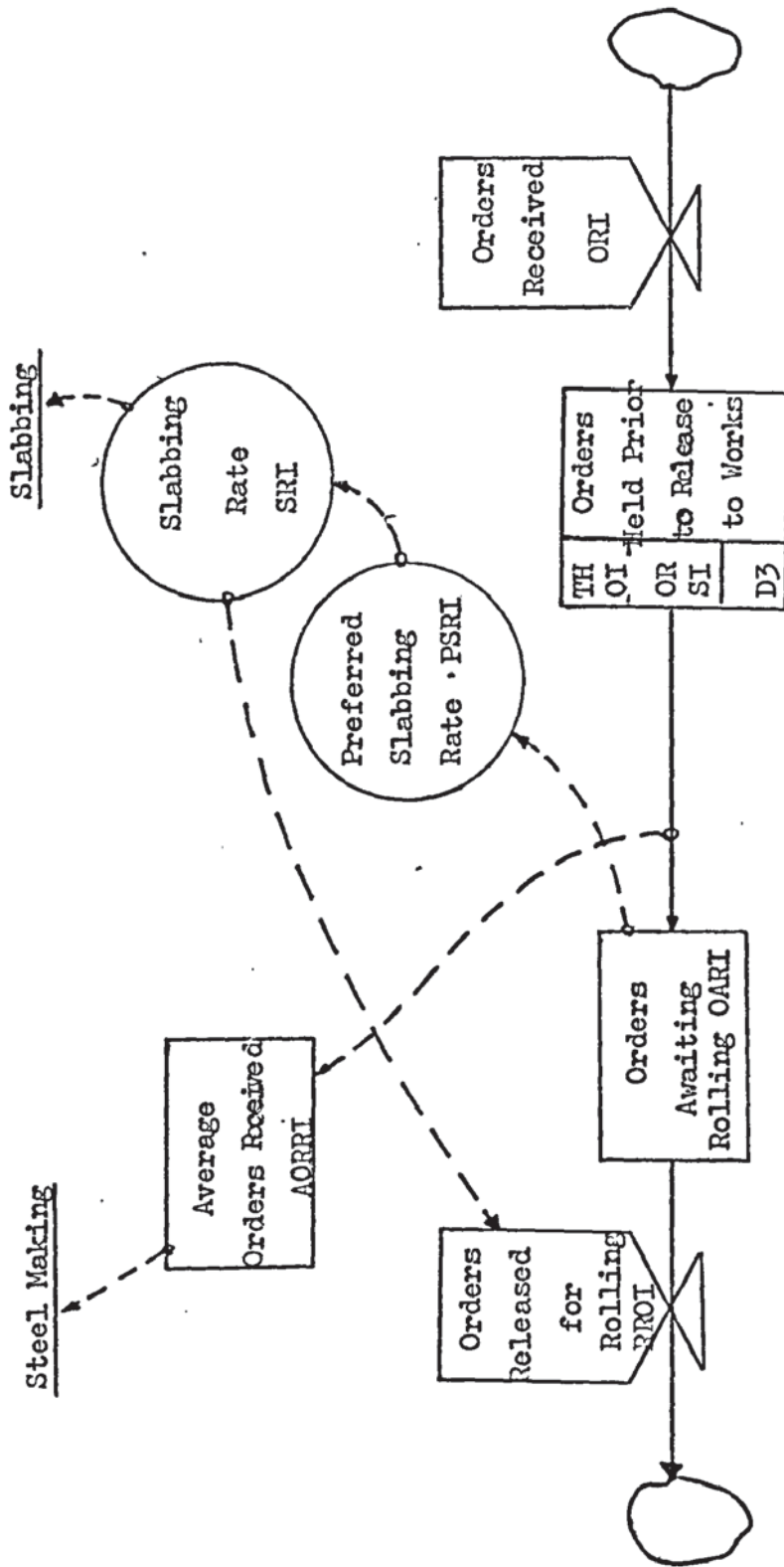


Figure 61. Order Processing.

Figure 62 shows diagrammatically how the scrap stock is depleted by the consumption of scrap and how a large proportion of the scrap is produced in steel making. Only a small proportion is purchased.

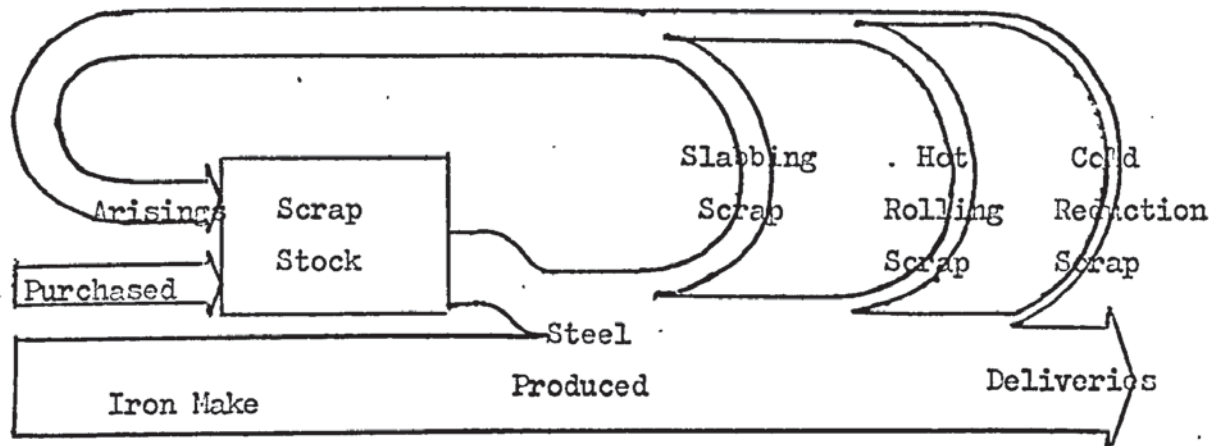


Figure 62. Scrap Recycling.

From the Port Talbot Works data it was established that scrap generated during a week is approximately 26% of ingot usings per week, by weight. Scrap is generated mainly in the slabbing and hot rolling stages. The ingot to slab yield is about 88%, so that some 12% of the ingot weight is lost during slabbing. Moreover the ingot to hot rolled coil yield is about 86%, so that 14% is lost in the ingot to slab and slab to coil processes.

Three scrap arising points have been simulated in the model; at Slabbing, Hot Rolling and Finishing. Since less than half the total scrap arisings occur during the stages following hot rolling it has been considered sufficiently accurate to aggregate all the scrap arising during cold rolling, cut up,

coating, etc., into a single scrap arisings rate at finishing, figure 63.

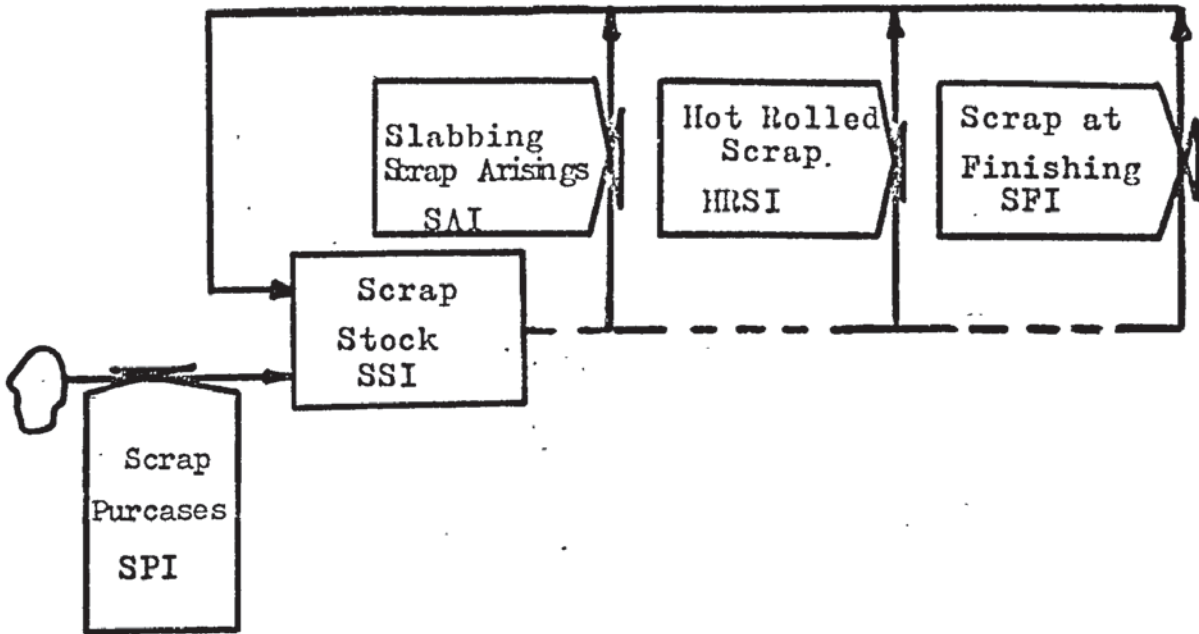


Figure 63. Scrap Material Flow Simulation.

The scrap arisings are simply simulated in the model by assuming a constant yield. A fixed proportion of the material consumed becomes scrap and the remainder is passed to later stages in the production flow.

Scrap purchasing is simulated by computing an average scrap consumption rate and an average scrap arisings rate. Scrap is purchased to maintain the scrap stock at a level proportional to the scrap consumption and to allow for changes in the average arisings or consumption. Scrap handling is shown diagrammatically in figure 64. The equations and mnemonics are listed in appendix 2.

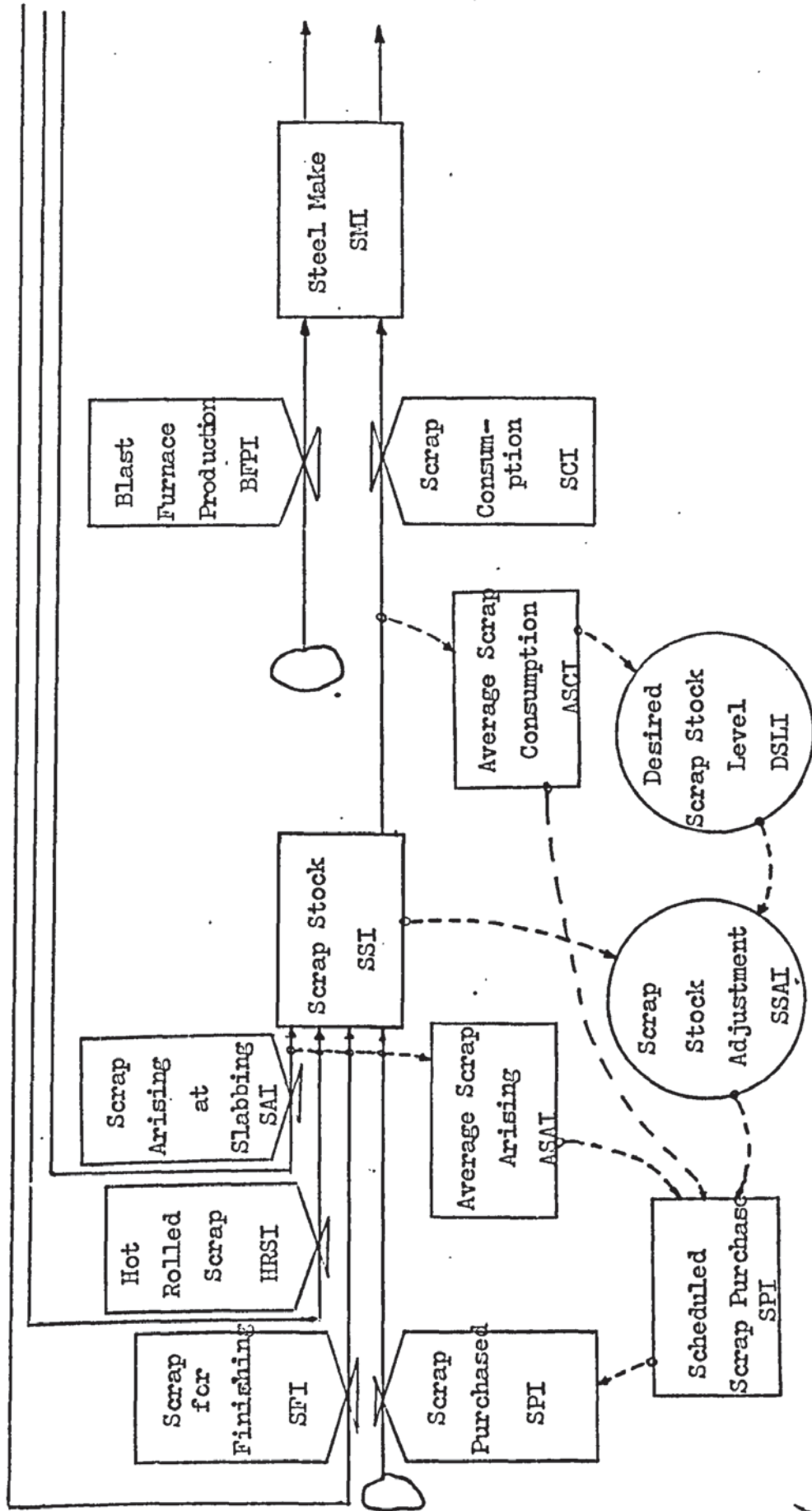


Figure 64. Scrap Handling.

5.3.6 Steel Making.

The steel making process has been simulated by making the ingot production rate dependant on the level of steel being made. The steel made is dependant on the blast furnace and scrap consumption rates. These rates are determined by the steel making scheduled, figure 65.

The scheduled steel making rate is determined by the average rate of orders received, the need to maintain adequate ingots prior to slabbing and an allowance for ingot cooling. The equations and mnemonics are given in appendix 2.

5.3.7 Ingot and Slab Handling

Ingots arrive hot from the steel making process. They may be allowed to cool or entered directly into the soaking pits. They must be heated to a uniform temperature before slabbing. Figure 66 shows four different ingot stocks; cold ingots in a stocking yard, cold ingots being reheated, hot ingots being brought to a uniform temperature and ingots ready for slabbing.

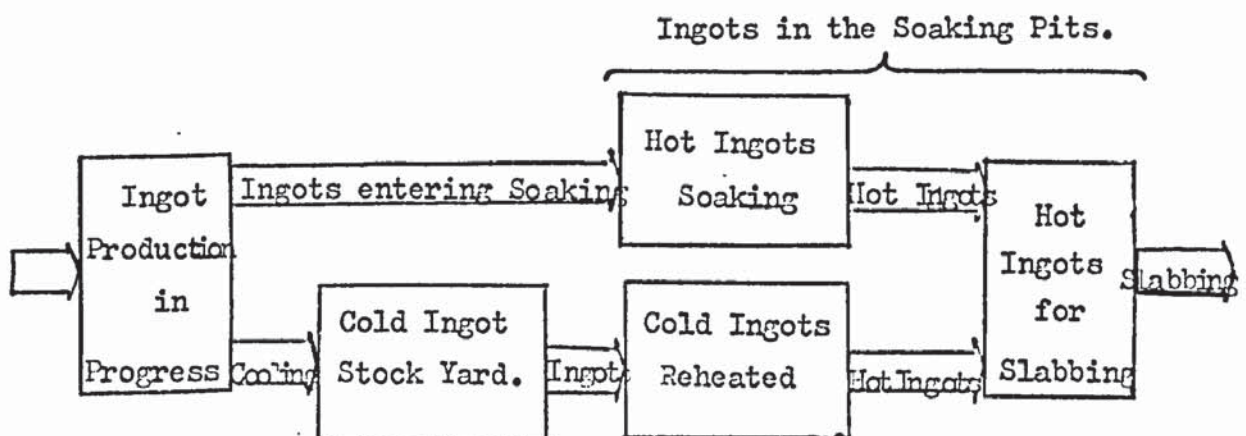


Figure 66 Material Flow - Ingots and Slabs.

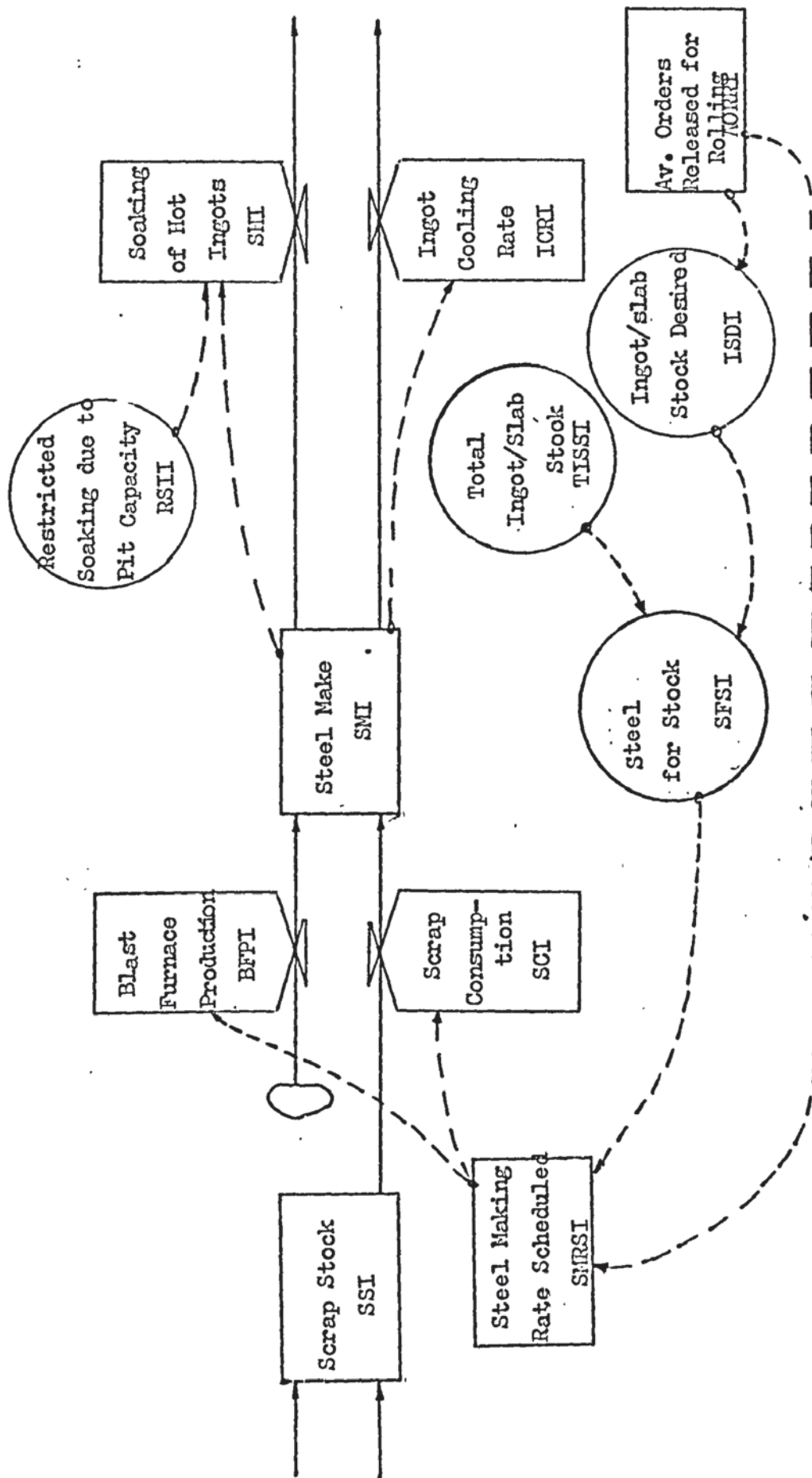


Figure 65. Steel Making.

The steel production yield is assumed constant in the model at 88% of the ingot input weight. The ingot to slab yield for the Port Talbot Works varying from 87.7% to 90% on a weekly production basis.

The slabbing rate is split into two parts in the model; the production of slabs and slab scrap arisings. The slabbing rate is based on the available ingots, the current production limit and on the scheduled orders.

The soaking of hot ingots is determined by the available steel and the soaking pit capacity. Ingots are assumed to cool when the steel make exceeds a specific limit. The reheating of ingots is determined by a procedure to keep the proportion of cold ingots being reheated at a reasonable level. Figure 67 shows these rates and levels diagrammatically. The equations and mnemonics are given in appendix 2.

5.3.8 Finishing Processes.

The finishing processes simulated include hot rolling, pickling, cold reduction and steel deliveries. Each of these production rates is separated by an interprocess stock. Scrap arisings are simulated at hot rolling and for the remainder of the finishing plant.

The model simulates scheduling algorithms, production capacities and interprocess stocks for each finishing process. The basic scheduling constraints assumed in the model can be illustrated by considering figure 68 . Production is determined by the production capability of the process, the available stocks of steel for processing and the material stocking capacity following the process.

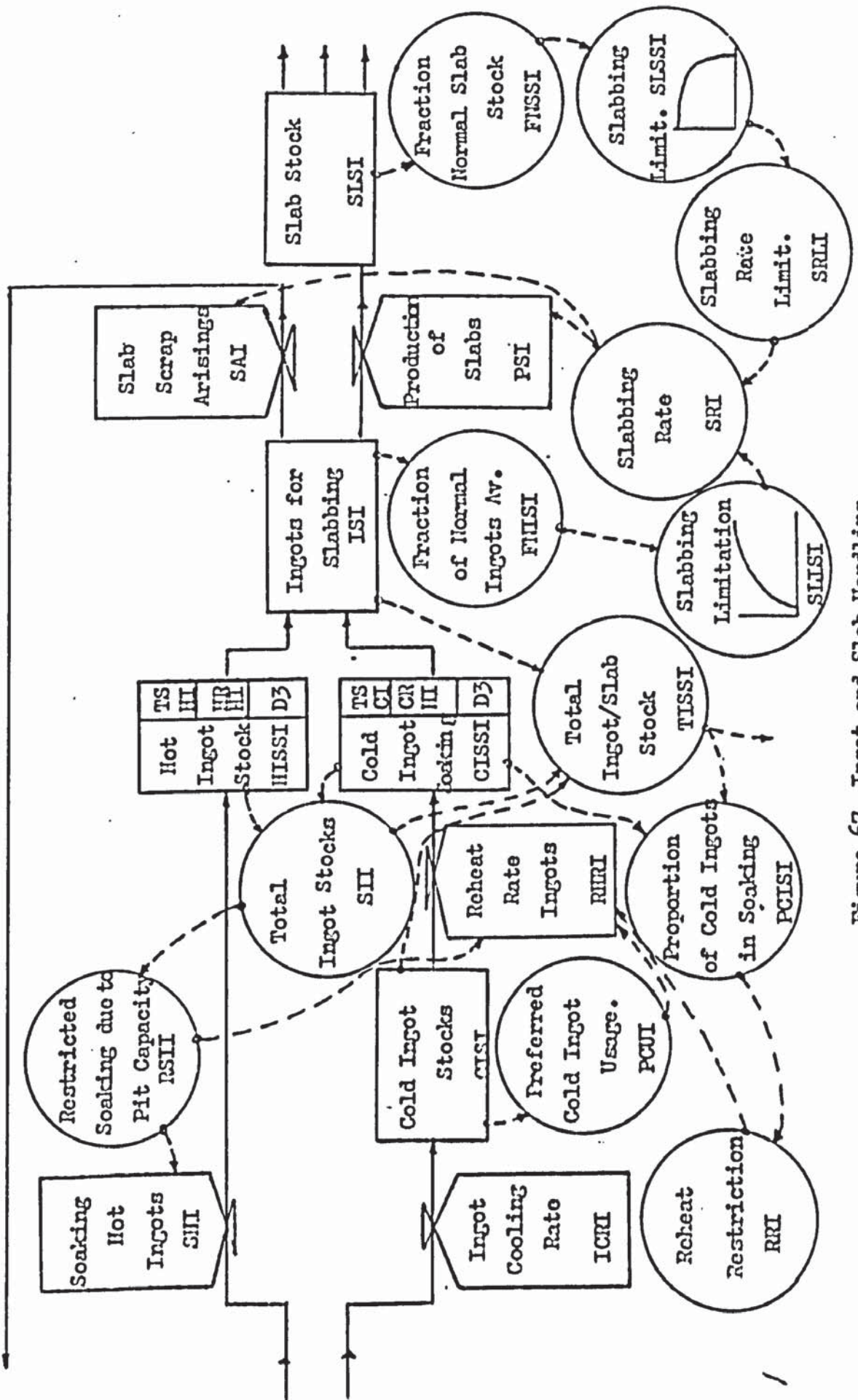


Figure 67. Ingot and Slab Handling.

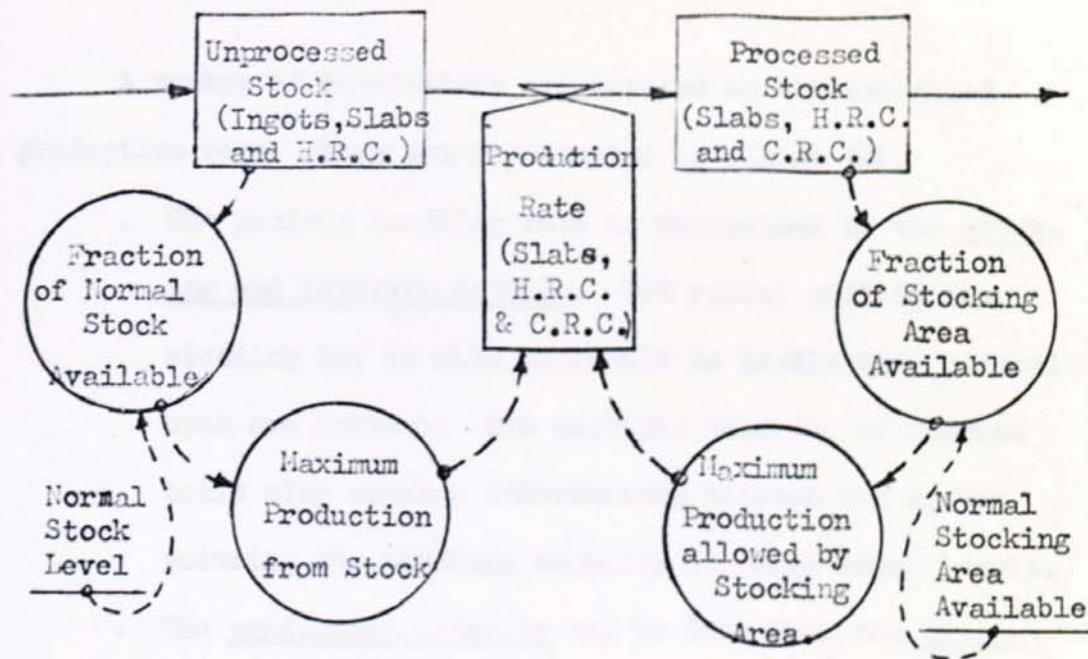


Figure 68. The Basic "Finishing Process" Simulation Module.

Figure 69. shows a typical relationship assumed in the model between the available steel for processing and the scheduled production rate. The steel is associated with specific orders so that order progressing and steel production are the same process.

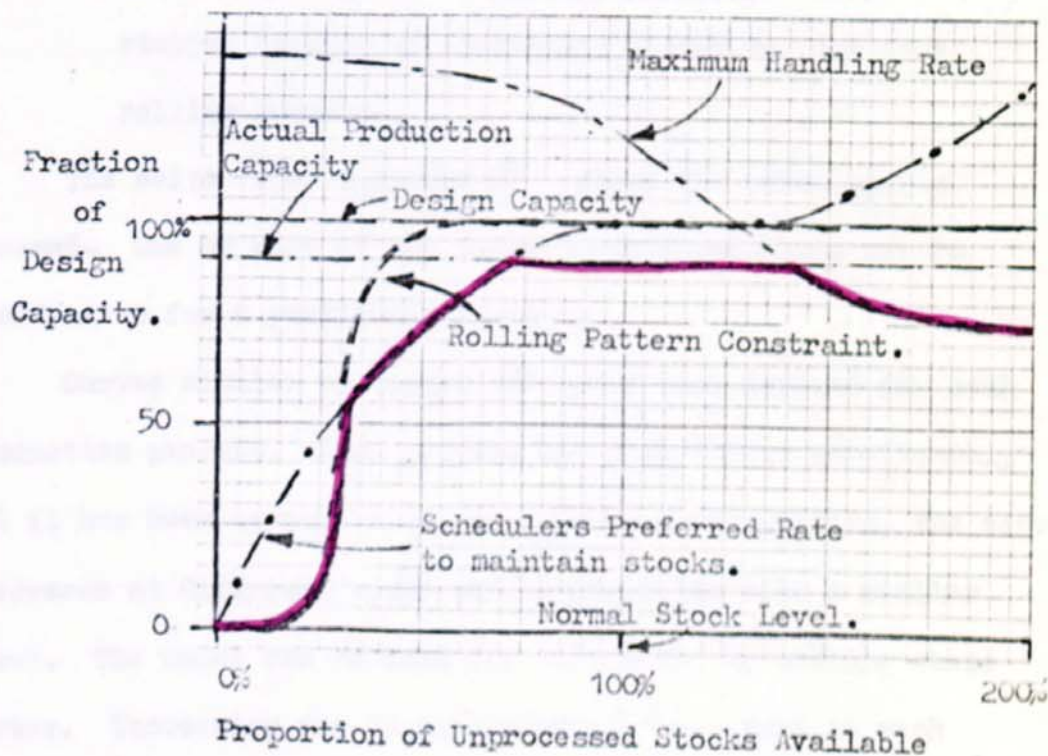


Figure 69. Production Rate Constraints Imposed by Material Availability.

A number of constraints are imposed on the scheduled production rate. Four are represented in figure 69.

- The maximum handling rate is determined by the stocking and handling methods. Hot rolled coil in the stocking bay is more difficult to handle when stacked upon one another. The multiple handling of stocked coils also creates interference between the cranes reducing the handling capacity for high stock levels.
- The production capacity may be less than the design capacity.
- A preferred stock level is maintained to allow a comfortable level of stock for scheduling purposes. The rolling rate is scheduled, in the absence of other constraints to maintain this stock level.
- Below a specific stock level it is difficult to schedule production because of rolling patterns. Production is stopped because of inadequate stocks to make up a rolling sequence.

The solid line in figure 69 shows the relationship assumed. One or more of the factors mentioned above may be ineffective for a particular process.

Curves similar to figure 69 have been devised for each production process. Each process has a different relationship but it has been assumed that, as a first approximation, the same processes at different works can be simulated with a similar curve. The model can be used for each works by scaling those curves. Increasing the "design capacity" constant in each process will multiply the actual values generated by the curve.

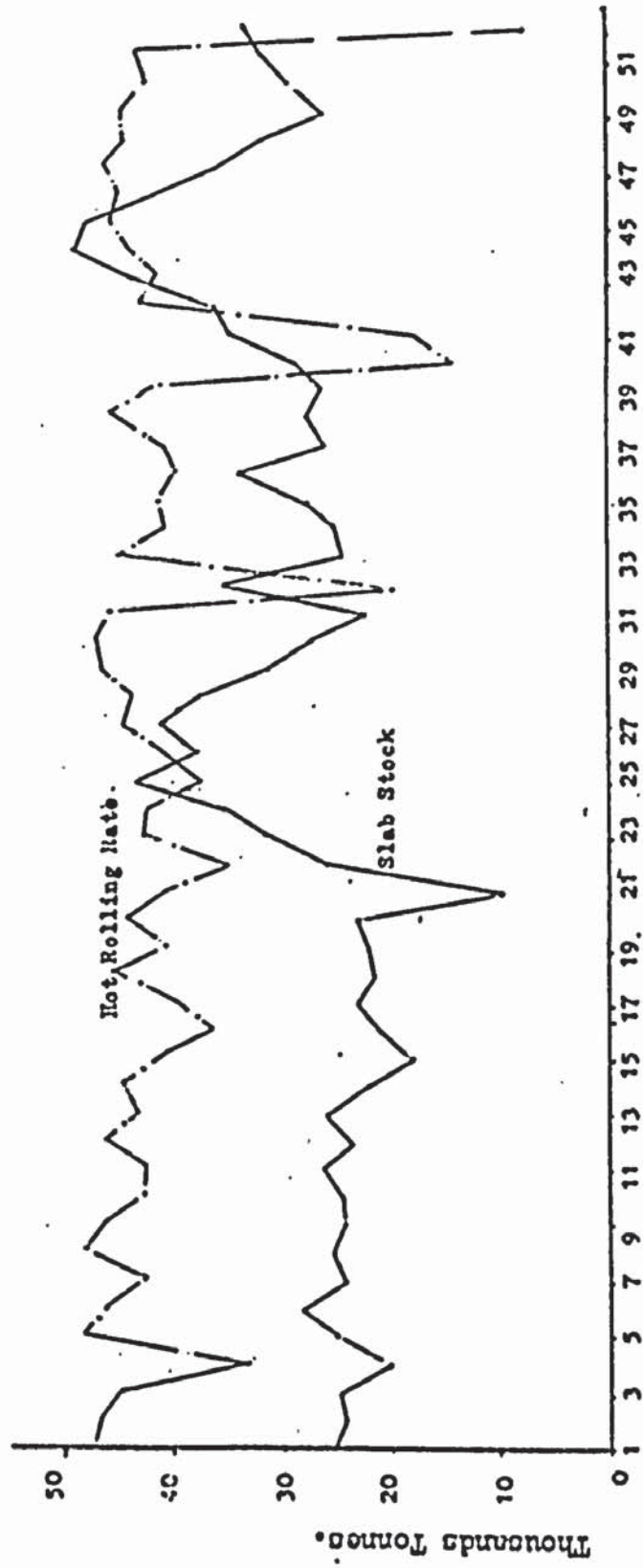


Figure 70. Slab Stock and Hot Rolling Rate - Port Talbot Works.

These relationships can themselves be altered for each works by altering a table of values. The values can be altered between runs of the model to test the sensitivity of the model to plant, scheduling or stock handling changes. The relationships have been devised from the data collected at the Port Talbot and Llanwern Works and from discussions with production managers at these works.

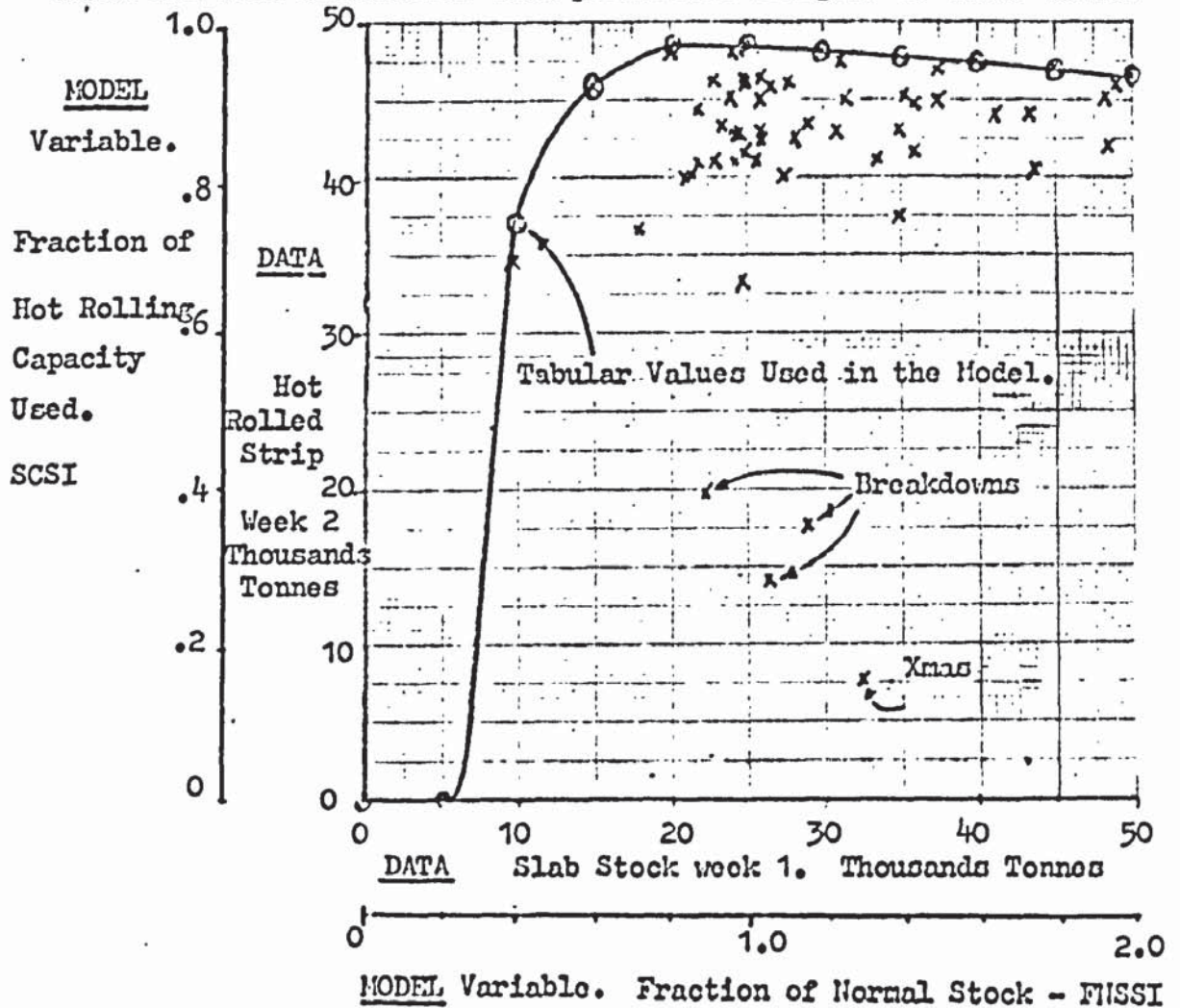


Figure 71 Hot Rolling vs the Previous Weeks Slab Stock.

Figure 70 shows the hot rolling rate and the slab stock at the Port Talbot Works. The slab stock often falls reducing the hot rolling rate in the following week. These data points have been plotted in figure 71 ; the hot rolling rate against the previous weeks slab stock. The curve shows the maximum hot rolling rate assumed in the model.

The production rate is also restricted by the available stocking capacity following the process. Figure 72 shows a typical stock capacity restraint. Production is reduced as the stocks increase.

Each variable is a fractional measure in these tables; fraction of normal stock or fraction of design capacity. Small variations in stocking or production capacity can be allowed for in the model by altering normal stocking capacities and designed capacity figures without altering the table values.

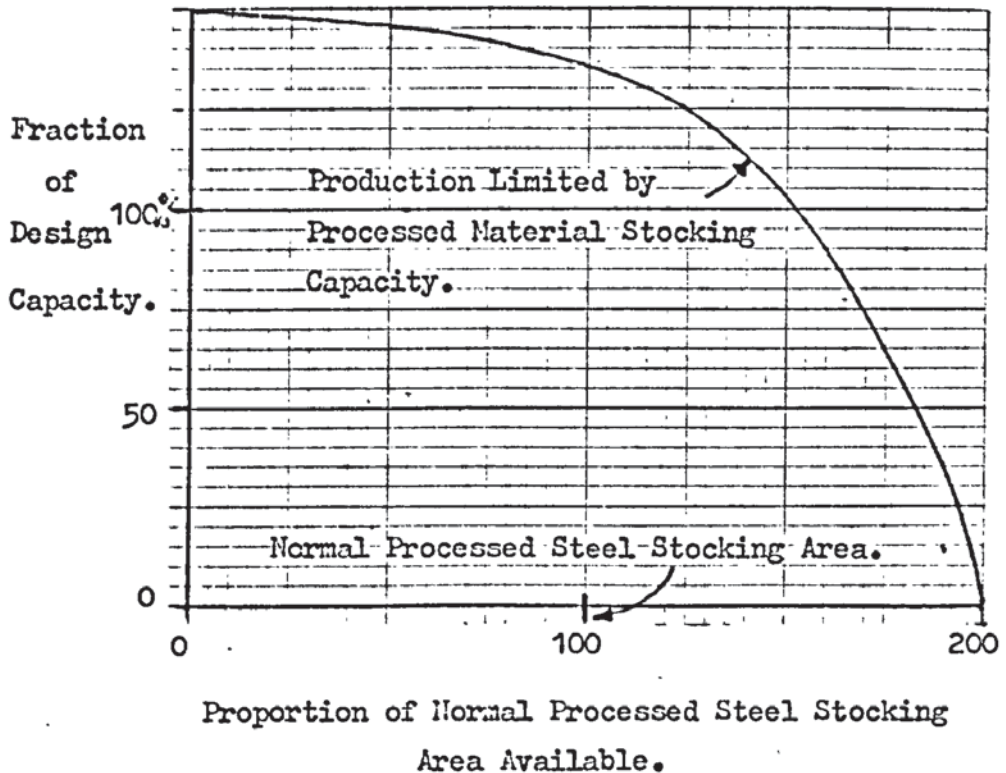


Figure 72 Production Rate Constrained by the Processed Material Stocking Capacity.

The four stages simulated are shown diagrammatically in figure 73 ; Hot Rolling, Pickling, Cold Reduction and Steel Deliveries. The equations and mnemonics are given in appendix 2.

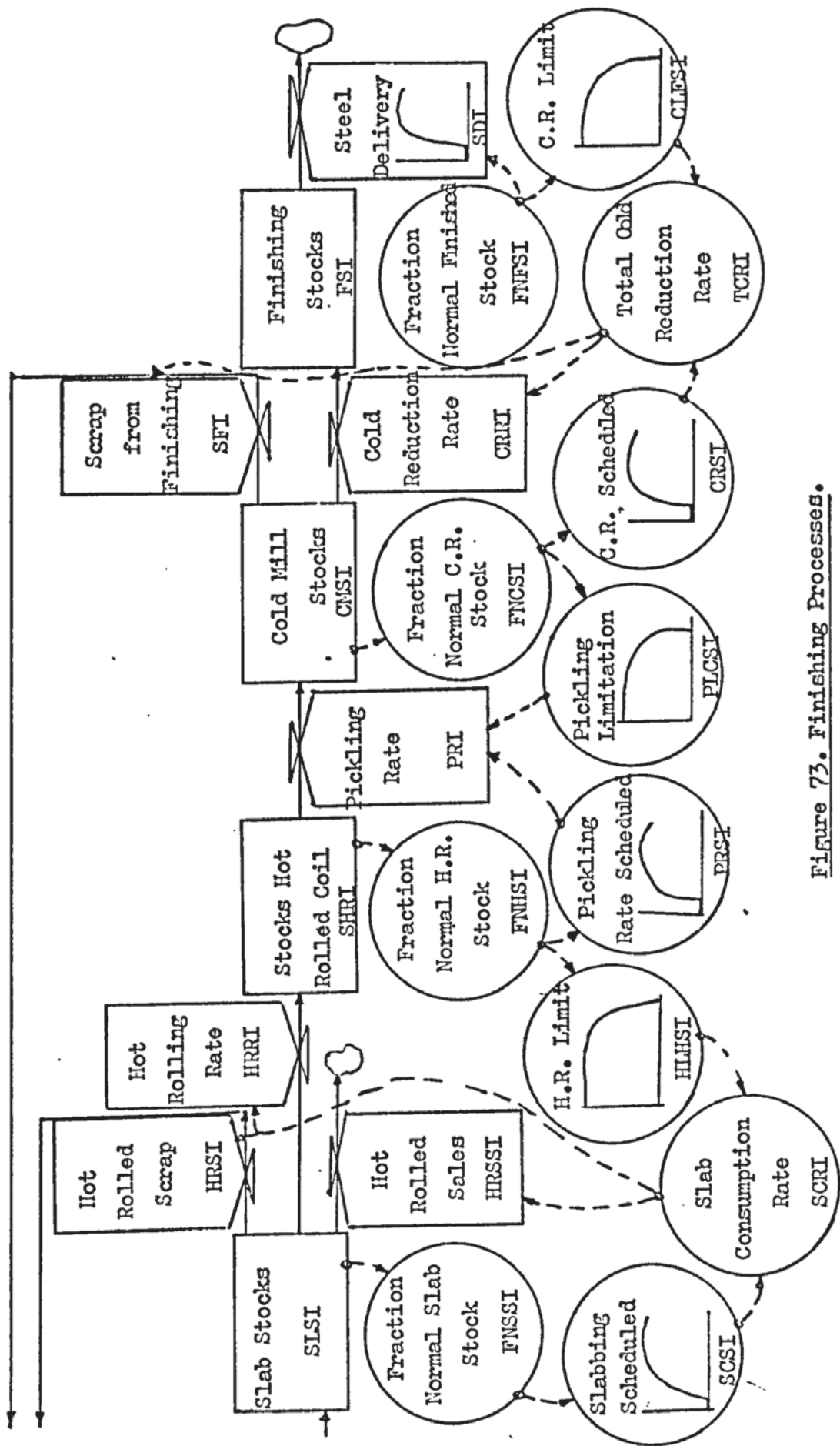


Figure 73. Finishing Processes.

5.4 Validating the Model

The model was partly checked by relying on the experience of people in Operational Research to suggest those material processes which should be included. The structure could be determined more easily than in the case of Market Dynamics Model because it depended on the identifiable material flow process.

The model was checked initially by comparing the mean levels of stocks and production rates with the Port Talbot Works data. The dynamic response of stocks and production was also broadly checked by ensuring that they responded in the correct direction and that stocks could not become negative nor ever increasing.

Finally, production and market changes were included in the model and the response of stocks and production rates compared with the data. These comparisons are difficult because it is not clear what disturbances occurred during a period.

Typical, overlapping disturbances are;

- Seasonal variations in the level and type of order`
- Large orders with unusual rolling characteristics
(Export orders, slow rolling steels, extra wide sheet)
- Short term breakdowns at slabbing, hot rolling or pickling

Figure 74 shows a typical comparison of the response of the ingots stock in the stocking yard following a 60 hour slab mill breakdown. The ingot stock is a useful comparison because it is the difference between the ingot production and soaking rate (rate of reheating the ingots). Figure 74 shows a double peak in the ingot stocks. The second peak is caused by the

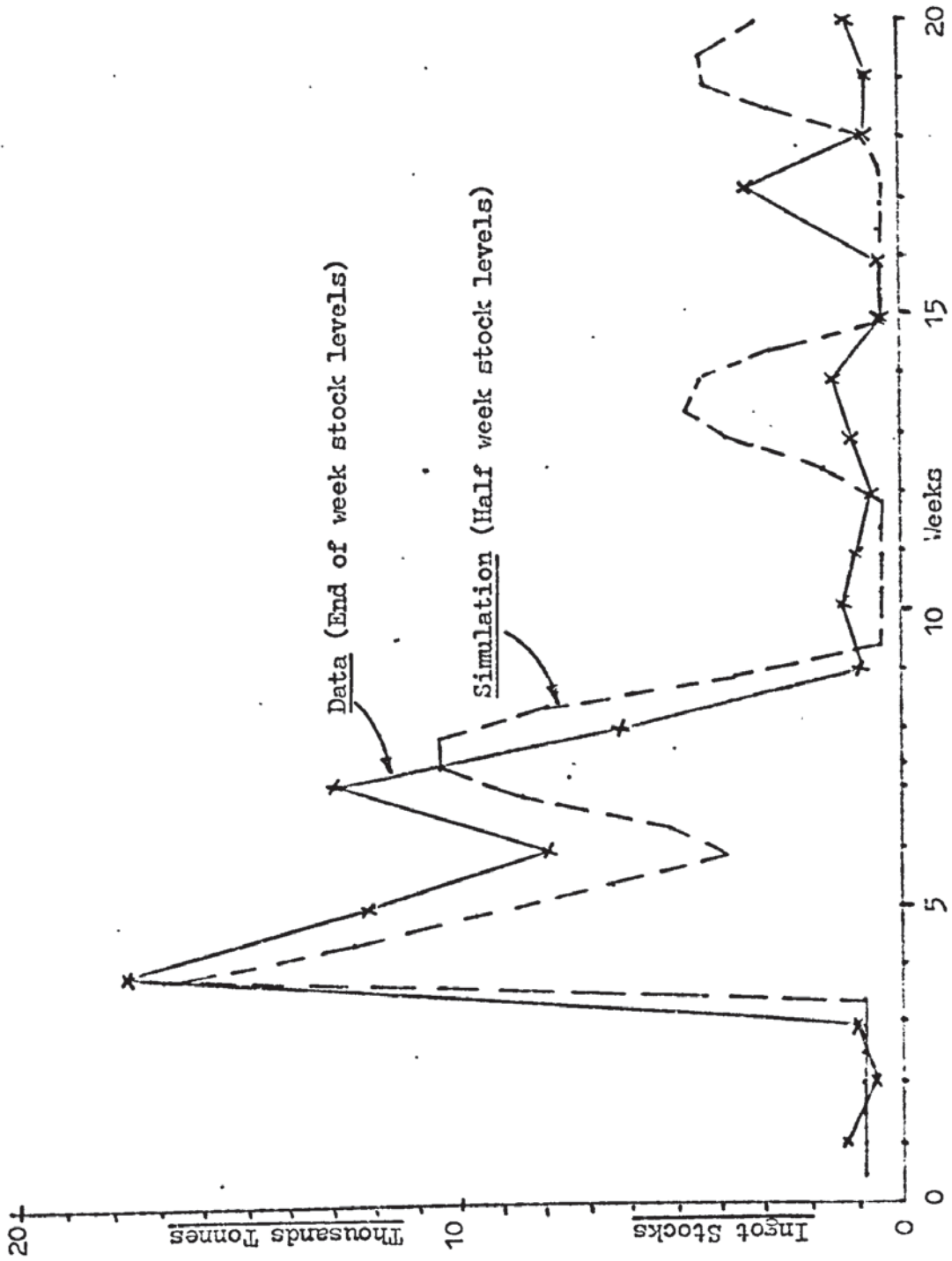


Figure 74. Ingot Stocks: Data and Model Comparisons.

blast furnace production reaching a rate which is higher than the slabbing rate. This second peak was initially assumed to be due to the soaking pit capacity. However, the model could not be made to create this behaviour by altering the soaking pit capacity or altering the soaking pit simulation. The ingots remain in the soaking pits, typically for five to twenty hours. The second peak in ingot stocks occurs some four weeks after the first suggesting that the cycle time of the soaking pits is unlikely to cause these peaks.

Similar comparisons were made with hot rolled and cold rolled coil stocks. The model was generally accepted as simulating the material flows in the strip mills and being capable of general application.

5.5 Experiments with the Model

The model was developed so that it would simulate the main steel production flow and control procedures. Each processing stage was simulated in such a way that the control procedures could be altered by redefining the relationships with a table of values. Each of the five main steel works in the Division can be simulated using this model by choosing appropriate parameters and table values. The model does not need to be altered at the equation level; it can be altered by adjusting parameters only.

Some experiments were conducted with the model to demonstrate the potential savings possible when the dynamic behaviour of the steel plant is considered.

5.5.1 Ingot Stocks

The Production Dynamics Model demonstrated a double peak in the ingot stocks following a slab mill breakdown. Examination of the data indicated that this appeared to occur and some adjustments were made to the model to determine how this second peak in the ingot stocks could be reduced.

Figure 75 shows the result of speeding the response of the slabbing rate. The increased slabbing rate shortly after the breakdown has little effect on reducing the ingot stocks but allows the blast furnace production to rise to a higher level slightly earlier creating a greater peak in the cold ingots stocked.

An alternative method is to formally recognise that blast furnace production and steel production must allow for the rate of consumption of ingots from the ingot stocking yard. In this case the steel production is allowed to increase to a level which is equivalent to the average slabbing rate less a fraction of the ingot stocks available. Steel making increases at a similar rate but does not exceed the slabbing rate and a double peak in ingot stocks does not occur.

The method is self stabilising adjusting to variations in the slabbing rate and ensuring that neither overproduction of steel nor short falls in ingots occurs due to the loading rules.

5.5.2 "Waves in Production"

The model also indicated that a breakdown early in the process chain would cause oscillations to move along the flow process. It was expected that the interprocess stocks would stop these waves of production by acting as a buffer. Figure 76

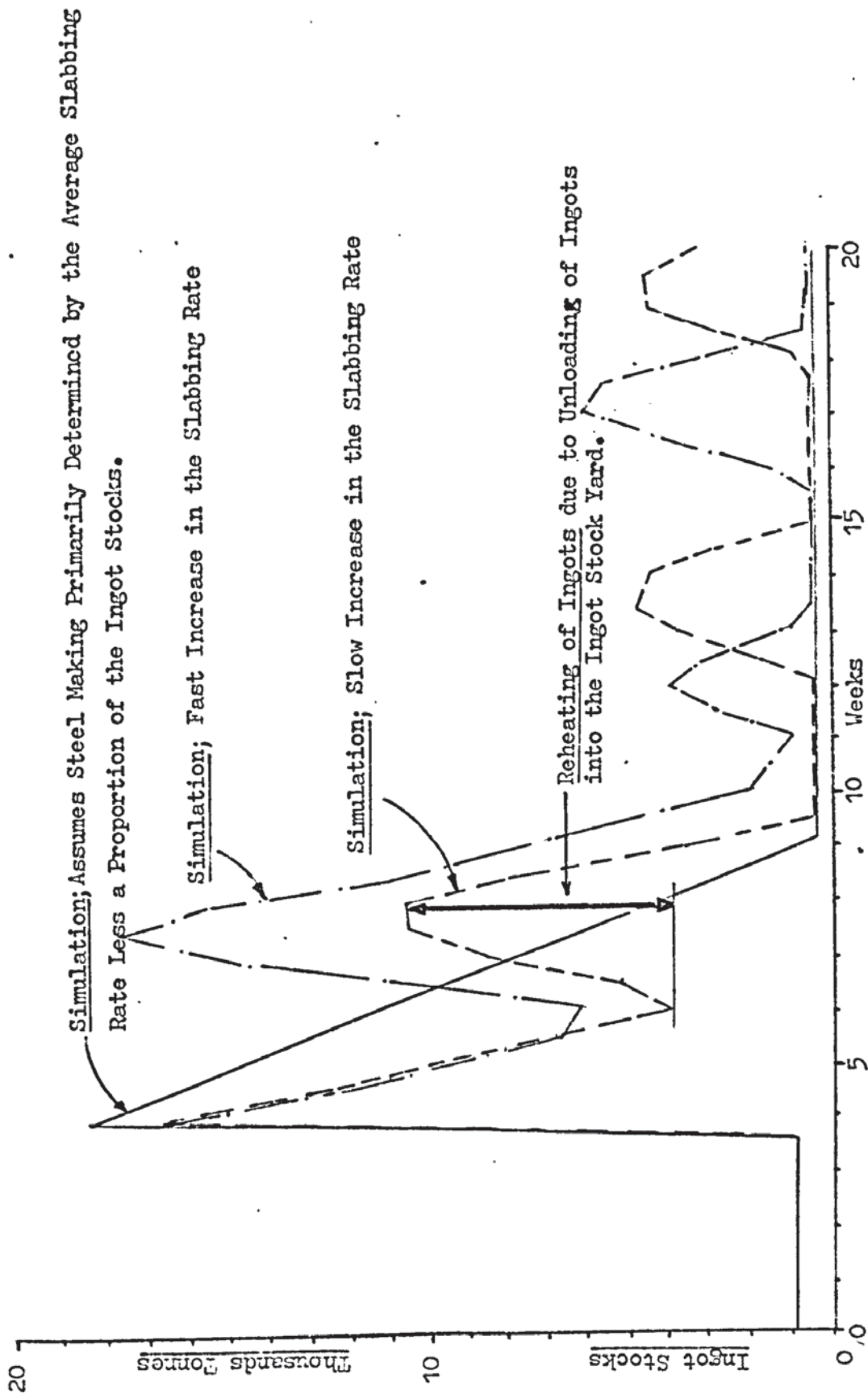


Figure 75 Simulated Ingot Stocks Following a Slab Mill Breakdown.

shows the oscillations generated by the model.

Figure 77. shows the data for the Port Talbot Works indicating that during normal periods these oscillations do in fact move through the plant. The summer months were used to make changes to the cold mill and unusual stocking and handling methods were in operation. It is not known how these rules operated nor how they affected the data.

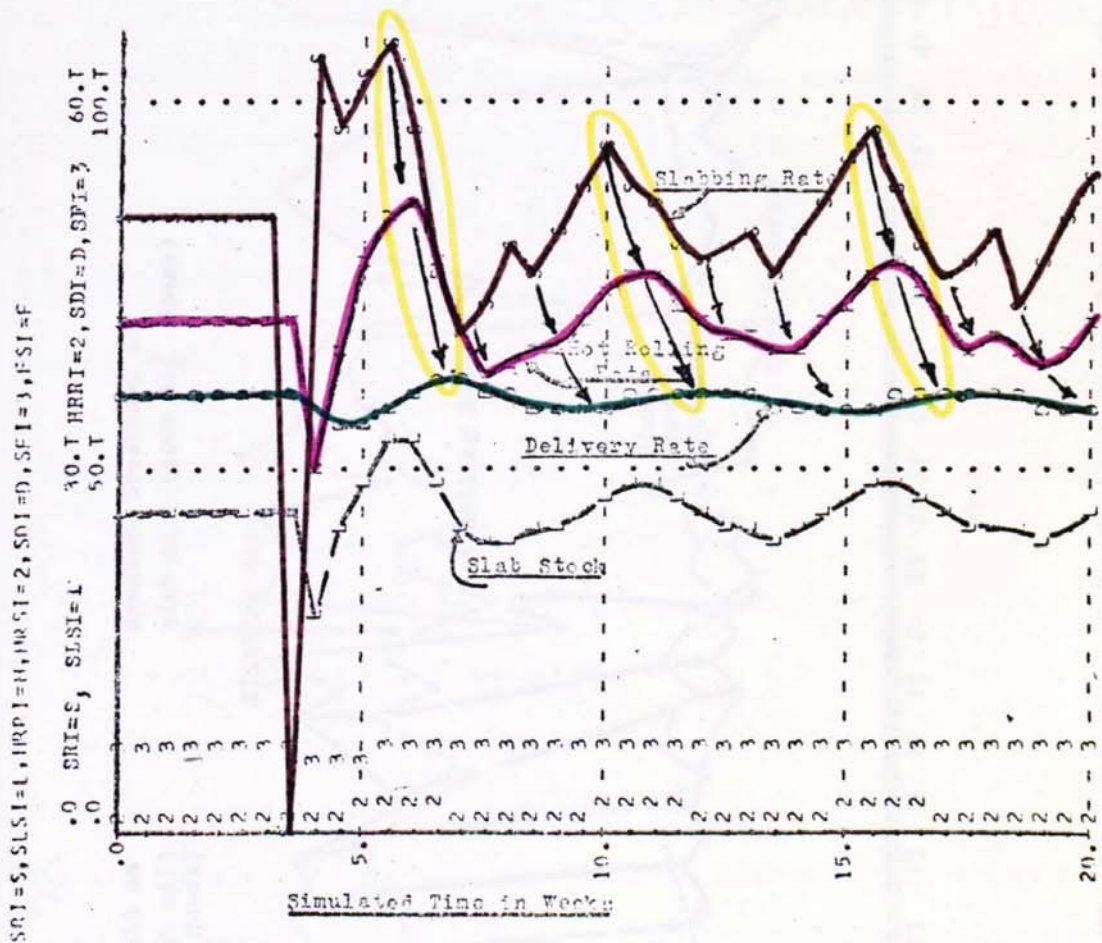


Figure 76. Simulated Production Rates.

5.6 Conclusions from the Production Dynamics Model Study

This study was conducted, in total, over a three year period. It showed that by considering the relative timing of production processes it is possible to identify large cost savings and potential increases in the effective production capacity.

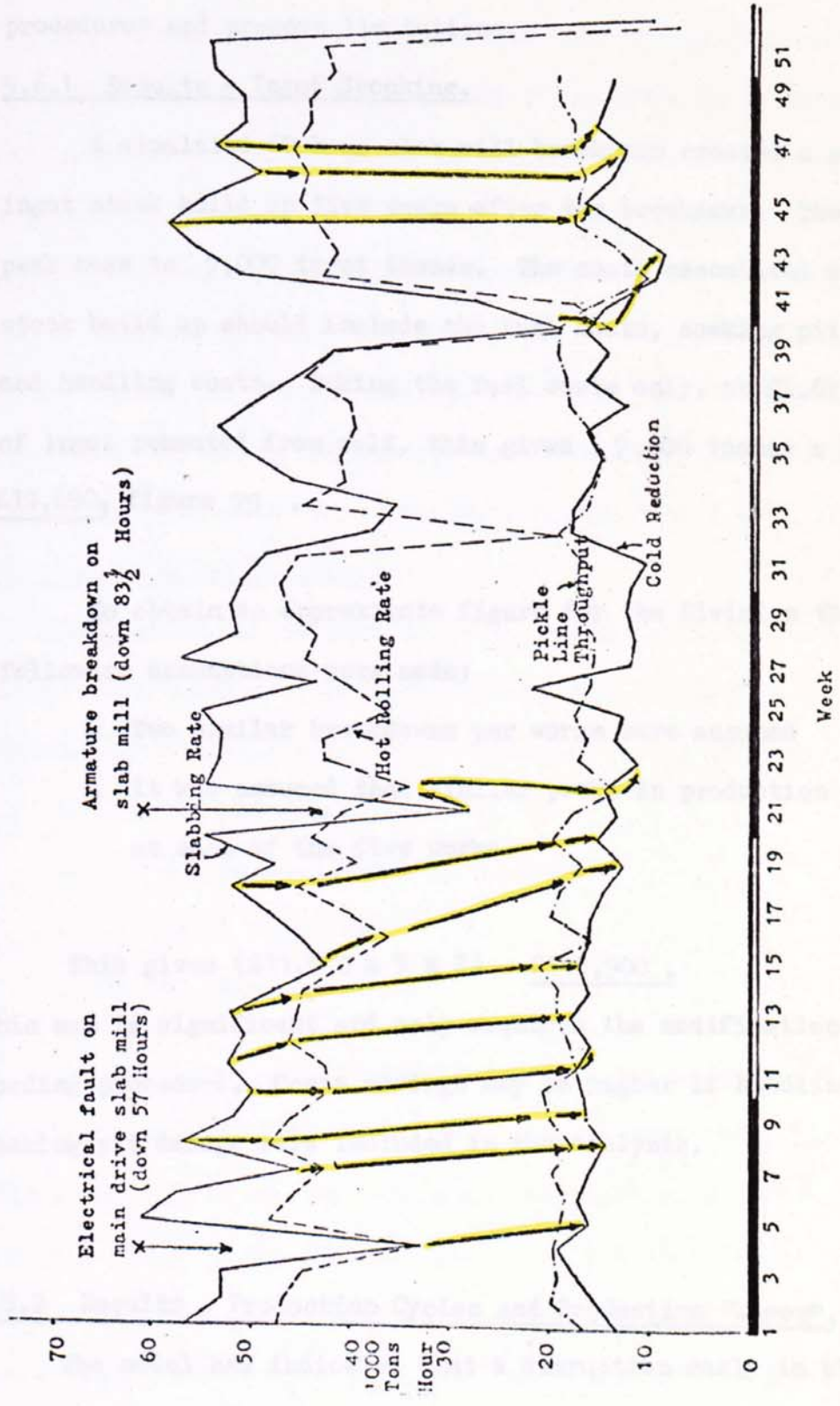


Figure 77 Transmission of Production Disturbances Through the Plant.

The study also indicated that I.D. need not always provide "one-off" models provided there is a common material flow path to be simulated. The models have been used to examine both the control procedures and process limitations.

5.6.1 Results - Ingot Stocking.

A simulated 60 hour slab mill breakdown created a second ingot stock build up five weeks after the breakdown. The second peak rose to 7,000 ingot tonnes. The costs associated with this stock build up should include the fuel costs, soaking pit damage and handling costs. Taking the fuel costs only, at £1.67 tonne of ingot reheated from cold, this gives (7,000 tonnes x 1.67) = £11,690, figure 75 .

To obtain an approximate figure for the Division the following assumptions were made;

- Two similar breakdowns per works were assumed
- It was assumed that similar peaks in production occurred at each of the five works

This gives (£11,690 x 5 x 2) = £116,900 .

This sum is significant and only requires the modification of a loading procedure. Costs savings may be higher if handling and soaking pit damage were included in the analysis.

5.6.2 Results - Production Cycles and Production "Waves".

The model has indicated that a disruption early in the production chain (slabbing) can cause a peak and trough in production which moves through the plant. It is difficult to

estimate the potential savings that may be possible but it is apparent that if these cycles can be reduced there would be an effectively higher production capability. The model indicates that the second and third peaks in the hot rolling rate are 9% above the mean hot rolling rate. If these peaks were reduced the mean level of production could be raised. There is a probabilistic component of the hot rolling rate which would ensure that this full oscillation amplitude could not be used. If, however, only half of this oscillation were available for additional production the mean level could be raised by 4.5%. The oscillations can be reduced by increasing the interprocess stocks or by reducing the scheduling dependence of the production rates (sell from stock).

5.6.3 Areas of Application

This model can be used to determine the effects, in a dynamic environment, of production and stock limitations. Specifically the following were considered during this study;

- Soaking pit capacities
- Hot rolled coil handling capacity
- Slab Mill capacity
- Pickle line capacity

The model was not devised to consider the impact of management objectives and the setting of standards upon the plant performance. However, the I.D. approach requires a similar level of detail for both the physical processes and the control system formulation. The model, therefore, simulates the decisions and procedures as much as the physical limitations of the plant. Policies were simulated where individual processes had to meet specific targets with little regard to production difficulties

before or after the process. Production throughputs could be increased by limiting some processes according to the level of the semi-finished stock following the process.

5.6.4 General Applicability to Strip Mills Division

Any simulation model is expensive in terms of human resources, both to develop and maintain. One of the problems with I.D. models is that they attempt to simulate the control structures and to identify unwanted dynamic behaviour. Once the dynamic behaviour has been recognised and recommendations made to remove or reduce the undesirable effects of this behaviour, then the model is of little value unless it can be extended or altered to consider a new area.

To overcome this objection an attempt was made to create a model that could be used for a number of studies. This was achieved by;

- Creating a model that simulated the main material flow; Steel Making to dispatch.
- Creating a generalised model that could be used for each of the works without recoding.

The application of the model to more than one works was made possible by specifying only which variables were causally related and defining these relationships by tabular data. The use of table functions was found to have a second major advantage; a number of different factors can be incorporated into the same curve.

5.6.5 Future Development of the Model

The model is probably one of the most detailed continuous flow process models developed outside the petro-chemical

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5.6.5 Future Development of the Model

The model is probably one of the most detailed continuous flow process models developed outside the petro-chemical

industry. It simulates both the management control and production processes. Although it is heavily dependent on the objectives set for each control procedure it has not yet been used to evaluate the effects of alternative objectives.

It appears that I.D. is one of the few modelling methods which could be used to demonstrate the dynamic behaviour created in a business system, including control procedures, when the objectives are altered.

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6. Analysis of Continuous System Simulation Languages (CSSL's)

Industrial Dynamics is an approach to the continuous system simulation of business systems. The computer programs were viewed from three directions; the application of a main CSSL (DYNAMO or CSMP), an analysis of CSSLs for policy models and the development of a timesharing package. Figure 78 shows how the CSSLs were analysed in practice. DYNAMO proved to be the best CSSL for the purpose and was used throughout the study. A number of CSSLs were considered to ensure that the area had been fully covered. A continuous system simulation program was devised for the timesharing network and aspects of discrete simulation, originating in the research, were investigated using a further program devised during the study, QSS, discussed in Chapter 7.

6.1 The Research Method

Forrester's book "Industrial Dynamics" (1) uses a particular notation to describe the models and assumes the use of the DYNAMO compiler. Other Continuous System Simulation Languages (CSSL) could be used to construct these policy models with similar results.

At the beginning of the research the DYNAMO compiler was not readily available and comments had been made that the compiler was prohibitively expensive to run. (This was proved false with current versions of DYNAMO.) Some consideration was given to the evaluation of alternative compilers and a simple timesharing "compiler" constructed for testing the early models. It was considered part of the research project to relate DYNAMO and Industrial Dynamics and to determine how other CSSLs could be used.

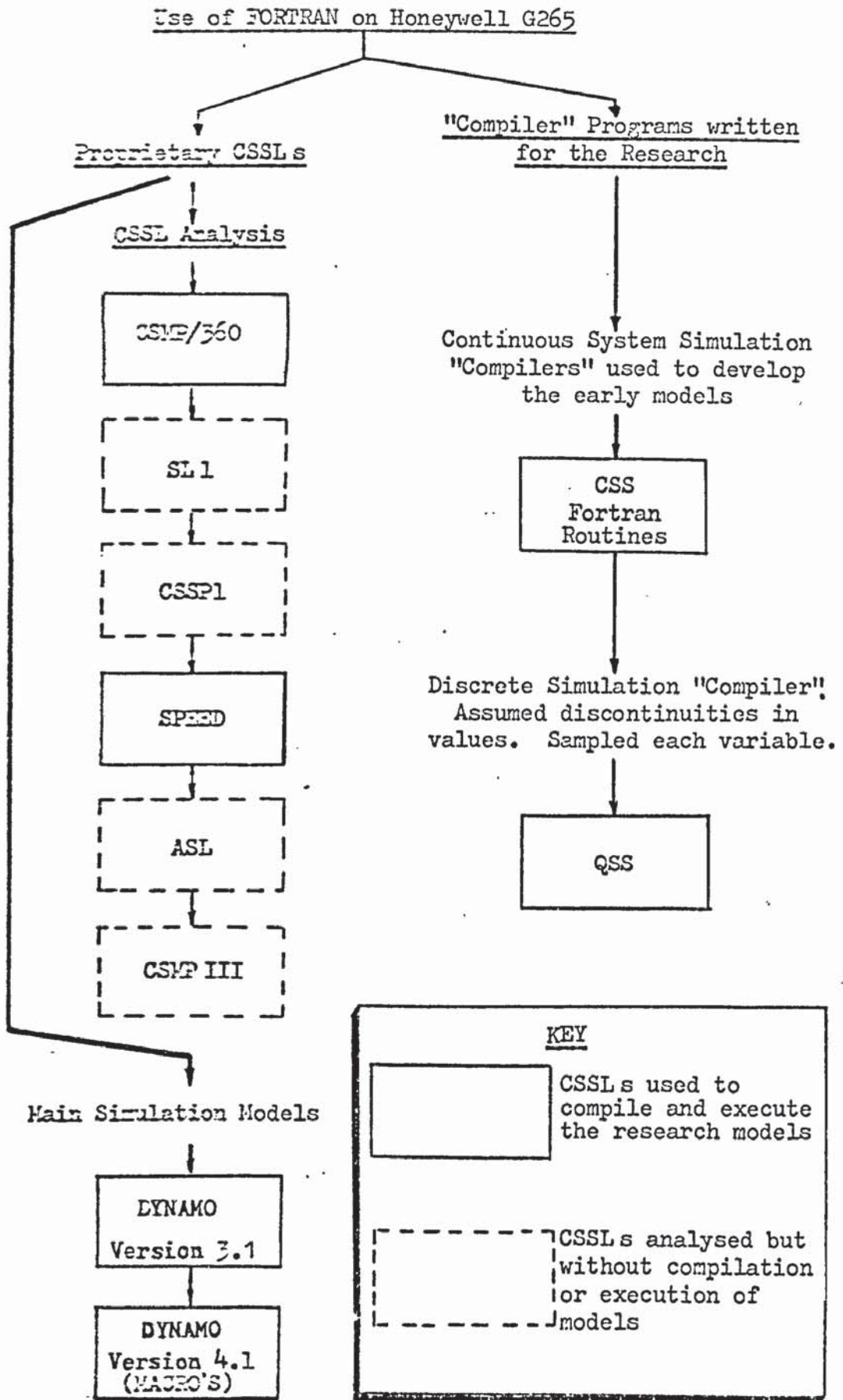


Figure 78. Use of CSSL's during the research

To evaluate the various CSSLs used in the research two "standard" models were constructed. They were devised to express two approaches to I.D. models. The first model, a process model, was called the Ingot-Slab Process Model and utilised a simple stock control algorithm. It did not include any table functions or other type of functional block except a sinusoidal input function. It included four integrations and ten simple algebraic equations in the dynamic section of the model. It was essentially a process flow model.

The second model, termed the Policy Interactions Model concentrated on management actions. It was based on Forrester's concept of "management pressure" systems and is broadly based on Forrester's "Corporate Growth" Model (28). It is an enclosed model.

Both models were devised as test models, to act as standards which could be quickly presented to a simulation system and for which the results were known.

Figure 79 shows the stages in the analysis of the computer software used in the study and where it is reported in this chapter.

6.2 Continuous System Simulation Languages

Continuous System Simulation Languages (CSSLs) are often called "digital-analog simulation languages" reflecting their ability to simulate analog computing elements on digital computers. These languages specify the syntax and semantics of statements to simulate continuous systems in a manner similar to that for an analog or hybrid computer.

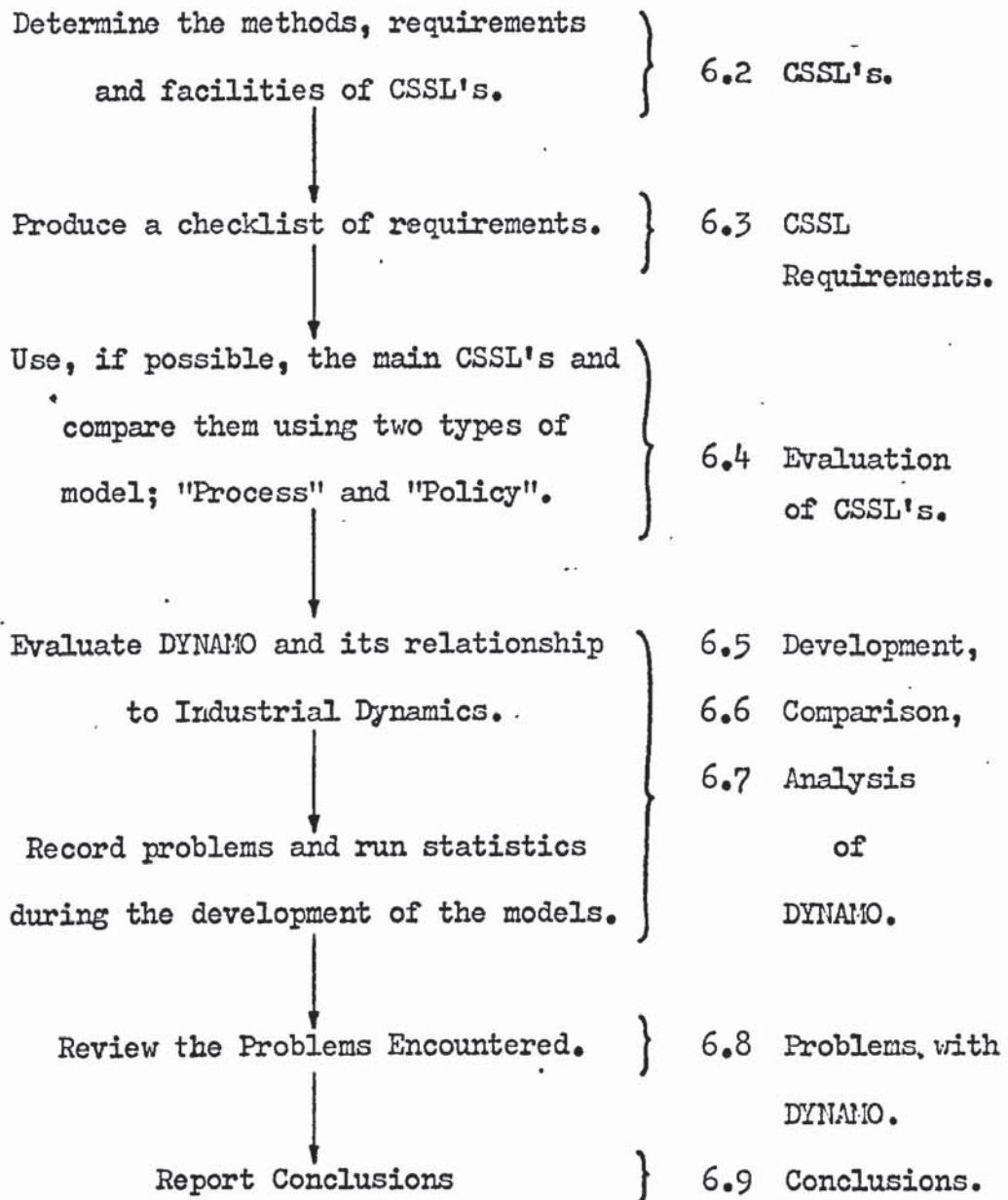


Figure 79 Steps in the Analysis of CSSL's.

Computer programs are associated with the language, which convert the users statements into a code that can be executed on a particular computer. Execution of the model is performed iteratively. An independant variable, usually assumed to be the simulated "time" variable, is updated after all the equations have been calculated once. The equations are repeatedly calculated for increasing values of "time".

All the CSSLs assume that the system being simulated can be treated as an essentially continuous process. The variables are assumed to be related by continuous functions. Some discontinuities are permitted but they tend to create computational difficulties.

6.2.1 Historical Development of CSSLs

CSSLs have been used, primarily in engineering applications because of their close connection with analog computers. Appendix 3 lists a few of the more important developments in CSSLs and has been drawn from the work of Chu (47), Brennan (48), and Sammet (49).

Morehouse et al (50) described in 1950 an interesting application of an analog simulation of an industry-consumer feedback system. The method utilised resistors, capacitors and inductors to simulate the stocks, rates of flow and causal relationships in a business-market system. The paper considers some aspects of the supply and demand system and how it was modelled using the Aeracom analog computer. The model considers a finished stock but "if inventories take the form of semi-finished goods, there would also be time lags involved in either adding to or subtracting from inventories an entire series

of inventories involving goods in various stages of production and the associated time lags could readily be introduced". The example quoted in the paper is a stock control simulation driven by a step input.

The first reference to the digital simulation of continuous systems, however, appears to be Selfridges work (51) in simulating an analog computer on a digital machine. There followed a number of developments of this technique, primarily providing a wider range of basic blocks, many of which directly represent analog elements. The ASTRAL system, in 1958 appears to be the first language implementation to translate into FORTRAN. The FORTRAN compiler subsequently produces the machine code. This method is now widely adopted because it permits the use of "free format" algebraic statements and does not require the writing of an expensive compiler. The FORTRAN compiler also provides much of the statement checking and error messages.

The first version of DYNAMO (then called SIMPLE) was written in 1958, specifically to permit "management" models for Forrester's group at M.I.T. It was a macro expanding type of translator. There were a limited number of types of equation, each equation form actually utilised a standard routine. The routines being strung together to form the model. This method limits the size of each equation but allows very fast "compilation", efficient statement coding and allows the compiler to be written quickly.

The MIDAS and MIMIC languages became widely accepted in the mid 1960s, particularly in engineering applications. These languages provided equation sorting, variable iteration intervals,

a wide range of functions and were implemented on the most popular large scale digital computers of the time, the IBM 7090 series.

In 1967 IBM introduced DSL for the IBM 7090. It was block oriented but allowed algebraic statements. It had a wide range of function blocks and integration methods. It sorted the equations as with most current CSSLs. It was written in FORTRAN IV, generated FORTRAN IV statements for subsequent compiling and permitted the mixing of DSL and FORTRAN statements. DSL was provided for the IBM 7090, 7040, 1130, 1800 and 360 computers.

IBM has extended DSL and created CSMP, a more fully supported and maintained package. In 1967 the Simulation Software Committee of the Simulation Council, Inc. proposed a standard language for continuous system simulation, CSSL (Continuous System Simulation Language). It appears to have been influenced by MIMIC, DSL/90, FORTRAN and ALGOL.

In 1968 a compiler version of DYNAMO was available permitting free format algebraic equations. The system generates and executes a machine code program without generating an intermediate high level language program.

Most of the socio-economic models that have been reported have utilised DYNAMO, CSMP or FORTRAN.

6.2.2 Operation of CSSL Compilers

To convert CSSL statements into a code that a particular computer can execute requires one or more computer programs. The suite of programs that perform this translation process will be termed the "compiler". There is some difficulties with terms, however, because most CSSLs first translate the user statements into a host language such as FORTRAN and use the FORTRAN compiler

to check and create the machine code instructions. This translation-compiling sequence is a five stage process:

- . Input the model
- . Translate into the host language (FORTRAN)
- . Compile the host language statements
- . Link the generated and referenced subroutines
- . Execute the machine code program

The main CSSLs accept functional blocks and algebraic statements. The statements and blocks may be entered in any sequence leaving the "compiler" to sort the equations. Sorting is performed so that no variable is used in an equation before it has been defined. The CSSL statements are typically grouped under three main headings: Initial, Dynamic and Terminal. Variables are initialised and constants declared in the Initial segment. The model equations are declared in the Dynamic segment. Control and output statements are stated in the Terminal segment.

The translator checks the structure and some of the syntax of the equations and then sequences the initial and dynamic equations. The execution commences by computing the constants, then the initial conditions, followed by the dynamic equations. The dynamic equations are then recomputed repetitively while the independent variable TIME is updated each cycle.

Some of the CSSLs vary the iteration interval (DT) to permit a sufficient integration accuracy. Output of values for printing, print-plotting or to a file can occur at any time interval and are determined by control parameters.

6.3 CSSL Requirements

The following points were considered of prime importance in the composition of a Continuous System Simulation Language. These points were drawn up to pinpoint the essential requirements and problems of CSSLs and in particular to clarify the simulation requirements of "policy" and socio-economic models.

- Syntactical Checks. Checking the format of variable names, statements and keywords to ensure they conform rigorously to the language definitions. Syntactical checks upon the equations after they have been translated into the host (FORTRAN) language often create difficulties in tracing the errors.
- Sorting. Sequencing of equations, blocks or sets of equations need to be performed so that a variable is not used until its value has been defined. Only integrators have their inputs defined during a previous iteration interval.
- Translation. Translation of statements into an executable machine code; directly or via a host language such as FORTRAN or ALGOL. At least three stages are common for CSSLs; Translation into FORTRAN, FORTRAN compilation and routine linkage. The more stages involved the longer the total translation process. Since most CSSL model runs require recompilation the translation process contributes significantly to the cost of the model runs.
- Initialisation. Preparation of the initial conditions. If a separate INITIAL section is used this limits variable names used in an initialisation statement to those in the INITIAL section.

- Reiteration Control. Control of the reiteration procedure, termination of runs and the restarting or rerunning of the model.
- Integration. Provision for one or more integration methods. Integrators need to be recognised during sorting, translation and initialisation.
- Input-Output. Input and output routines are needed to permit arbitrary function generation (tables), tabulation of results and a print-plotting routine to allow easy representation of the system dynamics.
- Block Structures. Permit the block structure of simulation models including the incorporation of user defined and language defined blocks.
- Equation Recognition. Permit the specification of a simulation model using algebraic expressions.
- Diagnostics. Provision of diagnostic messages clearly stating in terms of the model equations or blocks the type of error, particularly during the execution of the model.
- Availability. The compiler needs to be generally available not requiring unusual machine configurations or software.
- Efficiency. The compiler needs to be efficient during compilation and execution phases. Attempted recovery from syntactical errors can reduce recompilations particularly on batch processing systems.
- Ease of Use. A simple syntax and structure aids the development of the model. A knowledge of integration or analog devices should not be necessary and all functions performed should be easily understandable.

These requirements were tabulated in the form of specific questions and are discussed in Section 6.4.

6.4 Evaluation of CSSLs Used in the Research

CSMP, DYNAMO and SPEED were evaluated by coding, compiling and executing the two test models; Ingot-Slab Process Model and the Policy Interactions model. ASL and SPEED were written by J. Miller and the manuals for the languages are very similar although ASL has a number of extensions. Because SPEED and ASL are so similar no compilation tests were carried out on ASL. SLI and CSSPI were not used although both test models were coded according to the manuals for these languages to determine likely problems with them. Two "compilers" were written specifically for the research (called CSS and QSS) and are discussed in Chapter 7.

A check list, Figure 80 was compiled of the facilities provided by each language. Quantisation and Sampling has been included. During the research they were considered important, but not essential if user routines may be incorporated. The following general points emerged from this analysis.

. General Agreement upon CSSL Facilities

The CSSLs appear to be moving towards a common specification. User MACROs, equation sorting, array handling, variable step integration, print-plotting of output and user defined functions and routines appear common to most of these languages.

. Integration Techniques

If a suitable integration method is used and the iteration interval is altered according to the accuracy of

Facility	DYNAMO			CSMP	SPEED	ASL	SL1	CSSP1
	I	II(3.1)	II(4.1)	III				
	Ref.23		Ref.16	Ref.20	Ref.54	Ref.55	Ref.56	Ref.57
Attempted Error Recovery	Some	Yes	Yes	No	No	No	No	No
Ease of error trace	Poor	Good	Good	Poor	Poor	Poor	Poor	Poor
Equation Sorting	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Optional Sort (SORT-MOSORT)	No	No	No	Yes	No	No	No	No
Single Pass Compilation	Yes	Yes	Yes	No	No	No	No	Yes
Translation/Compilation	No	No	No	Yes	Yes	Yes	Yes	No
Host Language	None	AED			FORTRAN			
Initialisation Segment	No	No	No	Yes	Yes	Yes	Yes	Yes
Zeroise defaulted initial values	No	No	No	Yes	Yes	Yes	Yes	Yes
Iteration Interval	Fixed	Fixed	Fixed	Fixed or Automatic				
Rerun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Restart (CONTINUE or GO ON)	No	No	No	Yes	Yes	Yes	Yes	Yes
Normal or Default Integration Method	Euler			R-K	R-K	R-K	R-K-G	R-K
Alternative Integration	None			9	None	1	7	1
User Defined Integration	Yes	No	No	Yes	No	No	Yes	No
Arbitrary Functions (Dimensions)	1	1	1	2	2	2	5	1
Tabulation and Plotting	Yes	Yes	Yes	Yes	Yes	Yes	No Plot	Yes
Automatic Scaling	Yes	Yes	Yes	Yes	Yes	Yes	No	No
File Generation	No	No	No	Yes	Yes	Yes	Yes	Yes
User Defined Routines	No	No	No	Yes	Yes	Yes	Yes	Yes
User MACRO s	No	No	Yes	Yes	Yes	Yes	Yes	No
Execution Errors by Name	No	Yes	Yes	No	No	No	No	No
Array Handling	BOXCAR	No	No	Yes	Yes	Yes	Yes	Yes
Double Precision	No	No	No	Yes	No	No	No	No
Sampling	Function				User Routine Only			
Quantisation	No	No	No	Function				
Notation	Industrial Dynamics			CSSL and FORTRAN				FORTRAN & Functions
Known Machines	IBM 704 /709	IBM 7094 /360	IBM 360	IBM 360 /370	SIGMA	SIGMA	SIGMA	Money- well (G265)
Known Timesharing Services	-	-	CSS	BOC	SANACO	ATKINS	ATKINS	Time- Sharing

R-K; Runge-Kutta Integration Method. R-K-G; Runge-Kutta-Gill Integration Method.

AED; Algol for Engineering Design, Reference 58.

Figure 80. Checklist of CSSL Facilities.

integration, the computer time can be reduced. The extent of the saving in computer time depends mainly on the rapidity of the rates of change which are being integrated. If the rates vary within a small range throughout the simulation the computational accuracy remains fairly constant and it is possible to select a fixed iteration interval that will give the desired accuracy with a near minimum computation time. In this case a simpler, fixed step integration algorithm can be used.

It appears that for many Industrial Dynamics type of models, where the interactions are simulated using continuous functions, the rates vary smoothly so that the Euler integration method is adequate. Because the Euler integration method is simple and the integration error does not vary dramatically throughout the simulation, accurate fast simulations can normally be obtained with DYNAMO where SPEED for example takes longer due to the more complex integration method.

• Problems with CSSLs for formulating "Policy" models

It appears that "Policy" models are likely to have a short life. One is unable to develop the model over any length of time. Ingenuity in programming a model tends to be wasted since the data on which it is based is not sufficiently accurate to warrant high computational accuracy. It is preferable if the model can be formulated quickly, is checked thoroughly by the compiler and easily interpreted output generated. This may be at the expense of programming sophistication which is not normally required for such models.

Most of the CSSLs suffer by providing full FORTRAN facilities but inadequate diagnostics and a complex program structure.

All the CSSLs except DYNAMO require at least three sections; INITIAL, DYNAMIC and TERMINAL. This structure is inconvenient and errors occur because names used in one section may not be used, on occasions in another. Initial conditions are often made zero by default; no attempt being made to derive the initial conditions from the dynamic equations. All the compilers except DYNAMO do not attempt error recovery. DYNAMO often recovers successfully from such errors as missing brackets in equations or functions. This permits a successful run without waiting a further day for results. Even for an unsuccessful recovery where DYNAMO incorrectly assumes a particular format, the resultant run, particularly if it is one of the first runs with the model, will often indicate problems with the model formulation and save a later run.

Attempted error recovery is a powerful means of improving the efficiency of developing models of socio-economic systems particularly where batch processing computers are in use.

The FORTRAN based CSSLs seem to have an inherent disadvantage in that error checking and reporting is split between the translator and compiler. When errors occur during the execution of the model these CSSLs are unable to identify explicitly the equation at which the error occurred. It can usually be traced but is difficult. The DYNAMO II (Version 4.1) method of stating the variable name and error cause seems preferable.

Multiple dimension tables seem useful and could be provided in a language such as DYNAMO without altering the basic notation. Three or more dimensions appear unnecessary for "policy" models.

6.5 Development of DYNAMO

In 1958 a program called SIMPLE (Simulation of Industrial Management Problems with Lots of Equations) was written by R. K. Bennett for the IBM 704 computer. It contained the basis of DYNAMO including the print-plot routine. DYNAMO (DYNAMIC Models) was written by Dr. P. Fox and A. L. Pugh in 1959 to improve statement specifications and diagnostics of SIMPLE.

DYNAMO was rewritten in 1959 and was later converted for running on IBM 709. In 1962 the specification of initial values was relaxed. When M.I.T.s, CTSS (Compatible Time Sharing System) (52) became generally available DYNAMO was modified to operate in timesharing mode.

"In 1965 it was decided to rewrite DYNAMO. Although the input language gave the appearance of actual equations, DYNAMO I was basically a macro expanding program. Simple algorithms for algebraic translation were now well understood and could be utilised in DYNAMO to relax the restriction on equation formulation. Furthermore, higher level languages had advanced to the point where they could be used as a source language to simplify the chore of rewriting the compiler. Finally, the third generation of hardware was rapidly replacing the equipment for which DYNAMO was written and some sort of rewrite would be required before long. The right higher level language could also simplify the conversion from one machine to another."

(Pugh (16))

AED (Algol Extended for Design or Automated Engineering Design) had been developed at M.I.T. since 1959 under the direction of D. T. Ross (58). By 1967 it was available in batch mode and under CTSS on the IBM 7094. It was also implemented on the IBM S/360. AED is ALGOL-like but permits only single subscript arrays. However, by the use of a network of multiple pointer components a powerful data structure can be developed. The system has been used extensively for modelling at M.I.T. and to provide the basis for other translators (MAD to AED). It was used as the basis for a free format, algebraic statement, version of DYNAMO for the IBM 7094 and S/360 computers, called DYNAMO II. It does not, however, permit the use of BOXCAR trains as defined in the early versions of DYNAMO.

DYNAMO I checked the input statements thoroughly. DYNAMO II has extended this facility and attempts to recover from such errors. This is in contrast to all the other CSSLs used in the research which abandon execution if a syntactical error is discovered.

In 1970 version 4 of DYNAMO II was released which provides user defined MACROs, run time error messages related to variable names and provides error messages integrated with the model listing. It generally runs with a shorter elapse time (although the processor time is increased) and requires less I.A.S. (core store) than the earlier version (version 3.1).

DYNAMO II can be used in a timesharing mode when the output page size can be controlled. A JUMBO option is also available in timesharing mode which permits models in excess of 1000 equations.

6.6 Comparison of DYNAMO and Alternative CSSL Techniques

This comparison of DYNAMO with the other CSSLs used in the research, refers to the current version, DYNAMO II version 4.1. It has "... been designed for the person who is problem-oriented rather than computer-oriented. It makes available unsophisticated computing facilities so that the user can focus his attention on building a useful model rather than being distracted by his model's elegance" (Pugh (16)).

A model written in the DYNAMO language is specified in a single section; there is no INITIAL or TERMINAL section. Initial conditions and output statements, including those used to compute output values, are identified by a preceding letter identifier that permits the equations to be entered in any order. Time subscripts are used for each variable forcing the user to consider when and how a variable is used. The notation is redundant since the preceding letter identifier (L, N, R, A or S) specifies how the equation is to be computed. The compiler is able to utilise this redundancy to check and correct the subscripts warning the user of any incorrect subscripts.

Only the Euler integration method is permitted. The user must write the integration statement in full, so that all the computed statements are fully visible in the listed model. The visibility and simplicity of the integration procedure appears to be an important aspect of the I.D. notation since the user is constantly reminded of the operations being performed. It engenders confidence in the "programming" of the model.

DYNAMO is a "compile, load and go" system. The user does not need to be involved in the linking and loading of routines.

The FORTRAN based CSSLs carry a considerable overhead in computing time because they translate, call a FORTRAN compiler, compile, link, load and execute. The effective one-pass method of DYNAMO is efficient and provides an integrated system that allows the error messages to be closely related to the model equations. Error detection is very much better on DYNAMO than on the FORTRAN based CSSLs. The I.D. notation because of its redundancy permits extensive checks. DYNAMO is unlike the other CSSLs in that it attempts, often successfully, to recover from an error. It will introduce missing brackets, regenerate a statement if an illegal character is noted and omit doubly defined variables. The attempted automatic error recovery procedures are particularly powerful in a batch processing environment where a single error can mean a delay of 24 hours before a program can be rerun.

The FORTRAN based CSSLs, however, are more general. They permit the use of FORTRAN statements and allow routines where control can be directed other than in the strictly linear iterative manner of DYNAMO. The claim that "... there is nothing in its design that precludes its use for any continuous system" (Pugh (16)) is only acceptable if the systems considered are strictly continuous. However, if the model needs to store successive values in some manner such as a file or if an optimising procedure is needed, DYNAMO cannot normally be used. Integer values, logical variables and arrays cannot be included in DYNAMO models.

6.7 Analysis of Computing Requirements for DYNAMO Models

During the early stages of the research, the opinion was expressed, based on the use of DYNAMO I, that the reiteration of

the models would require considerable computing power. It was decided that for each of the CSSLs used, an analysis would be made of the following factors:-

- . Number of equations executed in the dynamic section of the model.
- . Number of iterations of the dynamic segment.
- . Central Processor Unit (C.P.U.) time required for each program compilation and execution.
- . Total time elapsed from job commencement to completion.
- . Immediate Access Store (core) required for each compilation and execution.
- . Printing and Plotting details; number of variables, intervals and lines printed.
- . Success of run; compilation and execution errors, actual output volume, problems and comments.

It became apparent that the AED implemented, one-pass, versions of DYNAMO (DYNAMO II versions 3.1 and 4.1) were very efficient in compiling and executing I.D. models.

Consequently, tests on other CSSLs were kept to a minimum.

Comparisons with other CSSLs were made primarily by a literature survey, coding the test models according to the appropriate manual and running the models (in the case of CSMP/360 and SPEED only).

6.7.1 DYNAMO Compile, Execute and Elapse Time

DYNAMO appears to the user to be a single pass compiler. It accepts Industrial Dynamics statements, generates the machine code and commences execution of the model; a "compile, load and go" system. The models were run on a batch processing system and reruns were possible without recompilation provided only constants

were changed. Since all the reruns were processed as a single job it was impossible to alter a rerun parameter once a job had commenced.

The "elapse time" refers to the total time that a job was active on the computer. Since up to eight other jobs also share the machine at any one time, much of this elapse time is due to other jobs. The elapse time varied considerably throughout the research period, varying from two minutes to 64 minutes. The elapse time depends on the job priority, the speed of the I.A.S. (core), the number of variables printed and plotted and the number of iterations. The most significant factor, however, is the job mix on the machine when the program is run.

6.7.2 Central Processing Unit (CPU) Time Used

The C.P.U. time is the period, during the compilation and execution of the model, that the program has captured the arithmetic unit and main data highways. Most machine accounting procedures which charge for the proportion of the computer facility used, make a significant charge for the C.P.U. time.

The two versions of DYNAMO used in the study have been identified by the M.I.T. codes, "3.1" and "4.1". Figure 81 shows a plot of the C.P.U. times related to the number of I.D. equations times the number of iterations, for DYNAMO II (3.1). Two computers were used, the IBM 360/40 and 360/50. Two types of storage were also available on the 360/50; the main "core" and the slow, Large Capacity Store (LCS). The cycle time for a 32 bit word from the main core was 2μ secs and for the D.C.S., 8μ secs. When allowance was made for peripheral transfers and "cycle stealing" the main core programs normally execute three

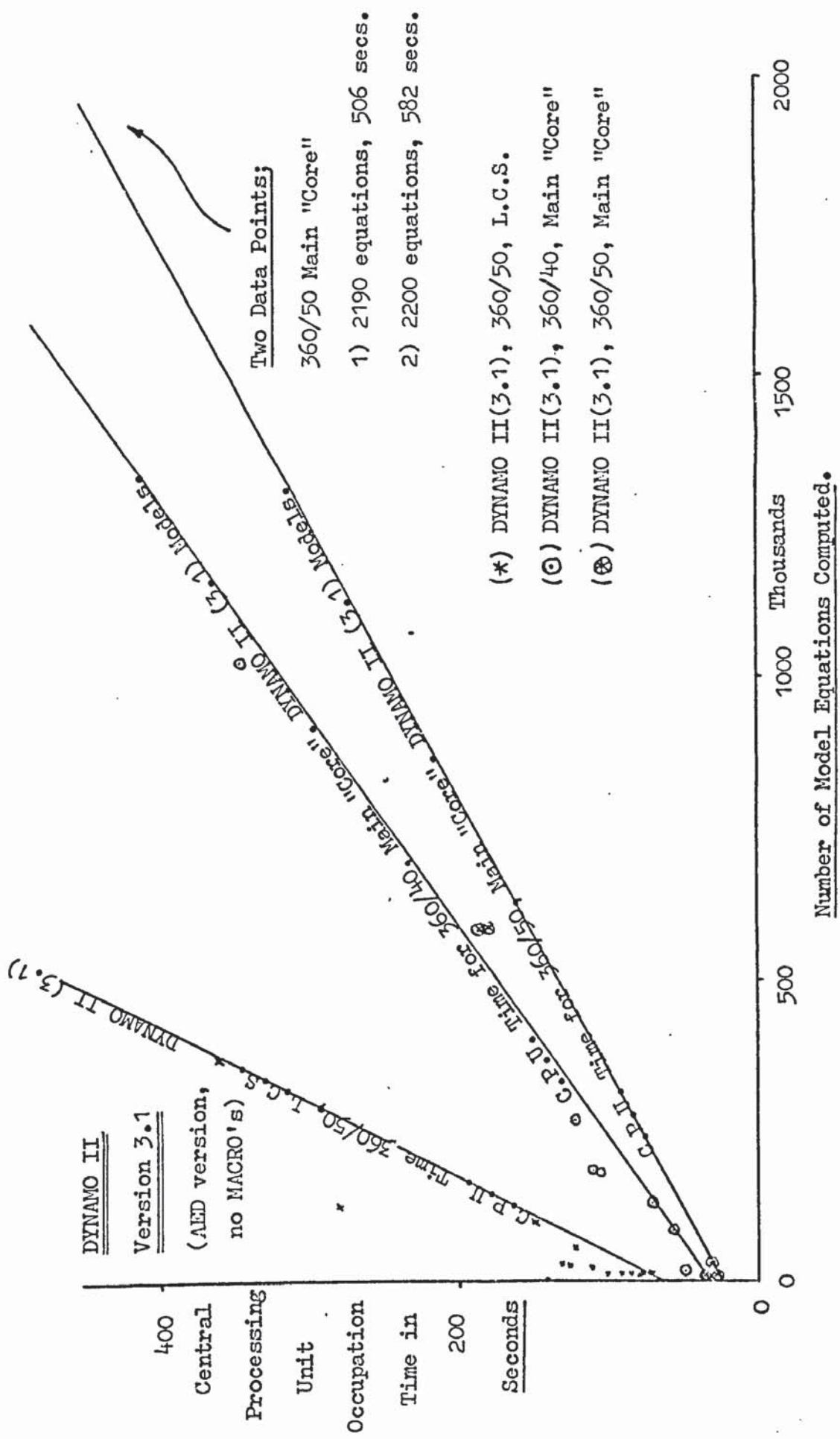


Figure 81 Compilation and Execution of DYNAMO II (3.1) Models.

times faster than L.C.S. resident programs.

In the Port Talbot installation, programs requiring more than 92000 characters (90 K bytes) of storage are normally assigned to the low priority, low speed L.C.S. It appears that an approximate C.P.U. time can be calculated from the formula:

$$\text{CPU time} = \frac{300 \times (\text{No. Equations}) \times (\text{LENGTH}) \times (\text{No. reruns}) \times (\text{LCS Factor})}{1000\ 000 \times \text{DT}}$$

where "No. Equations" refers to the dynamic equations, excluding initial and constant statements, LENGTH is the simulated "stop-time" (Use $\text{LENGTH} - \text{NTIME}$, where NTIME is the start time if a non-zero start is used).

"No. reruns" refers to the number of RUN cards incorporated in the model. If LENGTH or DT is altered the above equation should be recomputed for each rerun and summed.

"LCS Factor" is 1 for main core, 3 for LCS.

DT refers to the iteration interval.

This simple formula only takes into account the execution time and ignores the compile time. Compilation time is 20 seconds (60 seconds in LCS).

For DYNAMO 4.1, which includes MACRO facilities, uses less storage and attempts to minimise the elapse time, the C.P.U. times determined during the research are shown in Figure .

$$\text{CPU time} = \frac{500 \times (\text{No. Equations}) \times \text{LENGTH} \times \text{No. reruns} \times \text{LCS Factor}}{1000\ 000 \times \text{DT}}$$

Again a compile time of 20 seconds (60 seconds in LCS) should be added for each compilation.

As the most likely users of DYNAMO will use 360/50 s or equivalent and DYNAMO, version 4.1, it is useful to base an estimate of a typical job on them. Assuming main core, a model

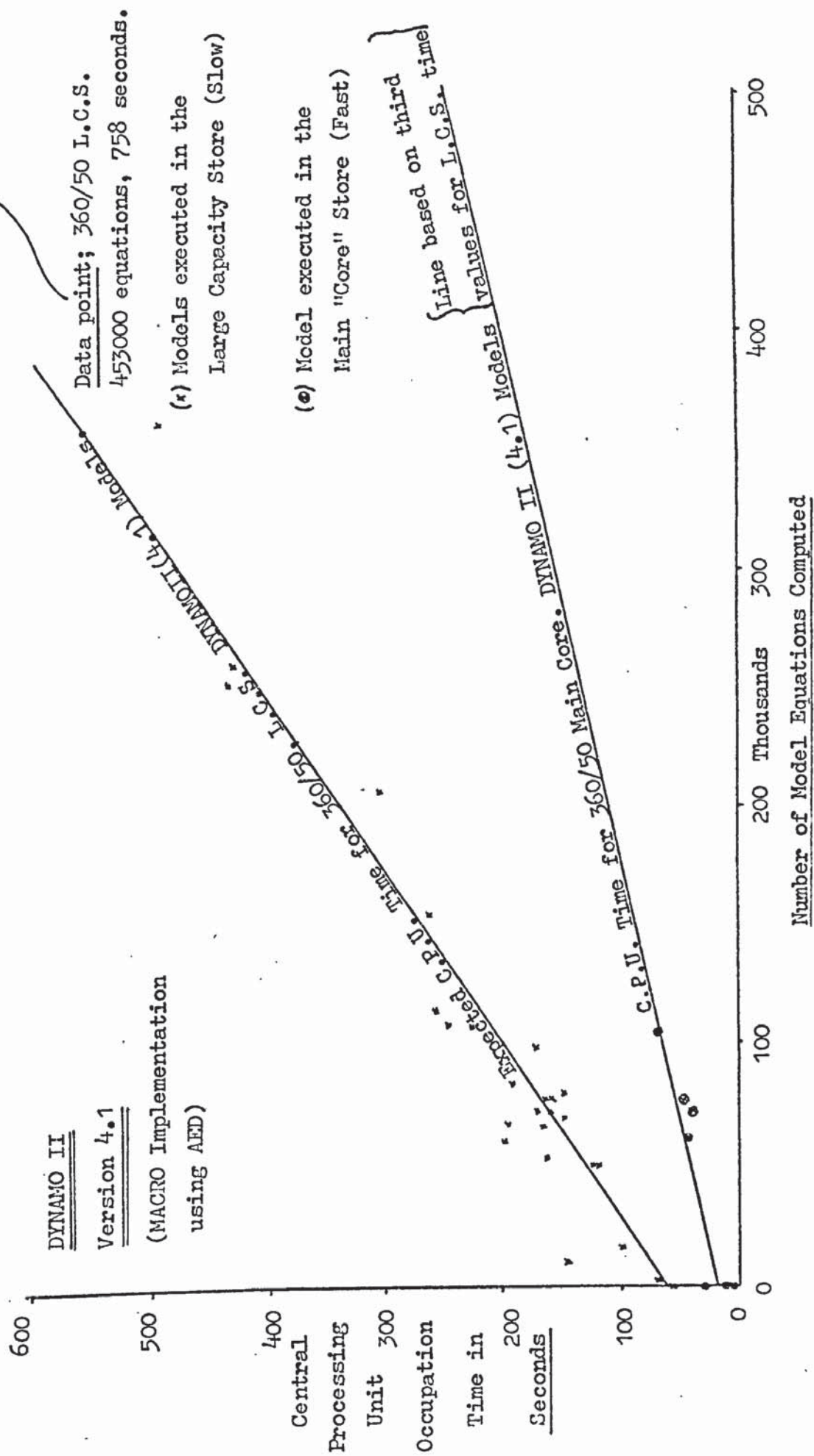


Figure 82. Compilation and Execution of DYNAMO II (4.1) Models.

executed over a simulated period of 10 years with an iteration interval of 0.01 years (twice weekly) including 200 dynamic equations would take approximately 120 seconds.

6.7.3 Machine Storage Requirements

A limiting factor for the execution of CSSLs is often the I.A.S. (core) storage available. Since the equations are executed iteratively "pageing" the main store is impracticable since most of the time the computer would be swapping pages of the model between the main core store and the disc. For version 3.1 a storage requirement of between 100 K to 180 K bytes was needed under MFT (Multiple Fixed Task Operating System). Version 4.1 requires between 70 K and 120 K bytes (MFT).

6.8 Problems with DYNAMO

This section deals with the detailed problems which seem fundamental to the design and implementation of DYNAMO. Section 6.9 summarises these problems and relates them to CSSLs in general. A number of irritating problems also arose concerned with loading the original compiler tapes, devising the operating system commands (JCL) and using the standard utilities IEBGENER and IEBPTPCH for file creating and listing. These problems relate to installation differences, are not related to the language and were solved relatively easily.

6.8.1 BOXCAR Functions

Forrester uses a function in Industrial Dynamics (1) called BOXCAR. The BOXCAR consists of a number of values which can be shifted so that the values are transferred from one element to the next. Two types of BOXCAR are permitted; a cyclic and a linear shift. The cyclic BOXCAR returns the last element value

to the first thereby cycling the values. The linear BOXCAR loses the last element value after a shift transferring a zero value to the first element. These functions create "cyclic" and "move-down" stacks. Each element in the stack is available to the rest of the model and the shifting is performed periodically according to the shift period specified. The contents of the BOXCAR could be substituted in a table function. This allows the modelling of adaptive mechanisms. The BOXCAR is commonly used to provide:

- . A precise accumulation of a value during a given interval.
- . A pipeline delay where values are delayed by the shift period.
- . Collecting and storing of data during a run.
- . Generating new functions from stored data during a run.

The more recent versions of DYNAMO, permitting free format algebraic expressions (AED implemented, versions 3.1 and 4.1) do not allow the BOXCAR function. This has caused considerable difficulties in listing values accumulated during a period (quarterly production for example) and in simulating cyclic forecasts (Chapter 4).

6.8.2 Arrays

DYNAMO does not permit arrays. For each variable name only a single stored value is allowed. Although two types of subscript are permitted for each variable name (J andK or JK and KL) only a single value is stored. The J and JK values are held up to the moment a value is recomputed. The K or KL value then replaces the previous value. This means that current versions of DYNAMO II (3.1 and 4.1) do not permit JK rates to be included on the right hand side of a rate equation because rates would then be computed

from rates during the previous cycle. Many of these rates would have been recomputed during the current iteration. Some early examples of Industrial Dynamics models do not work without the inclusion of an auxiliary equation because JK rates were included in the right hand side of an equation.

The lack of arrays in DYNAMO was partly overcome by devising the BOXCAR train. Apart from the lack of BOXCAR functions in DYNAMO II there is a more general need for array handling. For example in a simulated procedure, a decision may be based on the relationship between two variables. If arrays could be used, arbitrary functions can be generated by the model during a run and be substituted in a table and used to define a relationship. The cyclic forecast in Industrial Dynamics is an example of this type of adaptive mechanism used in a model.

6.8.3 Multiply Dimensioned Tables

DYNAMO permits the specification of an arbitrary function by assuming a constant increment of the x variable for a table of y values. A set of y values are supplied to the model and the arbitrary functions (TABLE and TABHL) generate a first order approximation assuming equal steps in the x coordinate.

If $f(x)$ has a sharp gradient or point of inflection the table can only be adequately represented for very many data points. If both x and y values could be supplied then the data points need only be dense in the region of the sharp changes of $f(x)$.

The assumption that arbitrary functions need relate only two variables is not always valid. In the Market Dynamics Model a "surface" was used which related two variables to a third;

$z = f(x,y)$. Because only single dimensioned tables are permitted in DYNAMO, a straight line extrapolation was made from two tables. This assumed that for a given x value, z was a linear function of y . This is rarely the case and a more general two dimensioned table function would be useful in DYNAMO.

In socio-economic models the data is rarely adequate to be able to define functions very precisely. It appears that functions of more than two variables are unlikely to be necessary because of the quality of the data from which they are derived.

6.8.4 Subroutines

DYNAMO II (version 4.1) permits the specification of user defined MACROs. The MACRO facility permits the user to code a section of the model and have the statements introduced into the model wherever the MACRO name is used. The compiler effectively substitutes the equations into the model; for each MACRO reference, coding is generated for the complete MACRO. An alternative method is to reference a routine which is included only once in the machine code version of the model. The coding for the routine is not repeated each time the routine is used, as is the case for the MACRO. During execution reference is made to the routine which is performed for each reference. User defined routines are not permitted in DYNAMO (except as MACROs).

In the construction of the Operations Planning Model it was decided to use a simple Linear Program to allocate the tonnage between the five works. Separate routines are not permitted in DYNAMO unlike the other CSSLs. Equations were included that simulated a single L.P. iteration. The L.P. equations were iterated only at the same rate as the complete model and the L.P.

result was sampled once a month. A near optimum allocation was possible provided there were adequate iterations during the simulated month. This method is not general and only works for simple optimising rules.

6.8.5 Computational Accuracy

It is common to hear comments that DYNAMO does not compute with adequate accuracy. These comments usually refer to the integration method which is rectangular (Euler). The most common form of the integral is the sum of the difference of two rates. It is obvious that if the rates are considered in isolation, any inaccuracy in their values will be accumulated by the integration. An error in the integration method will similarly accumulate.

In Industrial Dynamics models it is common, however, for one of the rates to be directly dependent on the integral. The negative feedback generated by this relationship improves the accuracy of the integration. Not all the integrations have such a simple negative feedback loop but many have similar but more complex negative feedback structures. This is particularly common in socio-economic systems where inherent inaccuracies in the real system require that very many "checks" or control procedures are built into the system. Problems normally occur with the integration only when positive feedback loops are present.

An exception to this, however, is the computation of the system variable, TIME. DYNAMO treats TIME as if it were an integral (Level variable). It may be given an initial value so that TIME may commence at 1960, say. This is particularly useful since the input and output tables can be related to specific dates.

The DYNAMO compiler uses the short form for handling floating-point numbers on the IBM 360 computers. All variables are treated as mixed fractions with seven significant digits and in the approximate range $\pm 10^{76}$. At a given simulated time during a run the value of time will be:

$$\underline{\text{TIME} = \text{Initial value of time} + \text{time since start of run}}$$

If comparisons are made against TIME which require the determination of the time since the start of the run, inaccuracies can occur. For example, if the initial value of time were 1960, then when TIME is 1961 it can only be known to the nearest 0.001 of a year. Because of rounding errors and because TIME is an integrated value accumulated errors can occur in the value of TIME.

Similarly the plotting and printing times can also accumulate errors. When the value of TIME and the print or plot times are compared even larger inaccuracies can occur. Moreover, the plotting feature normally only prints five significant figures on the time scale. It always counts ten lines between grid lines regardless of the value of TIME. If the grid interval cannot be accurately divided by ten it will still print ten lines but show the actual value of TIME on the scale. However, if TIME has been initialised to 1960, the five figure accuracy is reduced to four figures (the decimal point following the date uses the fifth digit position) and the inaccuracy is not shown. On one simulation run the time scale ran from 1960 to 1970. It was discovered that the actual value of TIME for the final grid scale was not 1970 as stated but 1969.7.

Where sampled values are used or periodic cycles introduced into the model the scaling and computation of time can give some

very inaccurate answers. This can be avoided if zero initial values of time are used (default condition). It would be preferable if DYNAMO computed TIME in double precision, an option which is available on IBM 360 computers and which would not require any changes to the use of DYNAMO. It would also be preferable if DYNAMO were to print TIME with a greater accuracy on the graphs and permit the user to substitute an alternative time variable for plot output purposes.

6.8.6 Output Files

When presenting the results of a model run it is useful to be able to show the actual output from the model but in a form understandable to the user. The plotted form presented by DYNAMO is readable and shows the dynamic situation clearly. However, alternative forms are often needed. If the output from DYNAMO were stored on disc in a machine readable form then suitably written programs could be used to print the data as required. PL1, FORTRAN, COBOL or ALGOL routines could be used to prepare the data for printing. A powerful facility would be the re-entry of the results of more than one run so that results could be plotted on the same graph for the same variable but from different runs.

6.8.7 Diagnostics

DYNAMO is extremely powerful in the methods used to analyse and correct errors. This is because all the equations can be treated together as a single unit not as separate segments and because the notation has some redundancy. It might be useful, however, if MACRO definitions could occur anywhere in the program as the restriction that a MACRO must be defined before it is used tends to destroy the "no sequencing" objective of DYNAMO.

If control statements are omitted DYNAMO does not attempt to execute the model. In line with the philosophy that error recovery can save both computer and user time, reasonable guesses at the control variables could easily be built into DYNAMO. For example, if LENGTH is omitted it could be assigned the value $DT \times 100$

6.9 Conclusions Regarding the Application of CSSLs to Industrial System Simulation

The study has been concerned with applying Continuous System Simulation Languages to the dynamic behaviour of works and markets of the B.S.C. During these studies it became apparent that DYNAMO was generally more suitable to simulations of aggregated management actions and was different in kind to the other CSSLs used.

Most CSSLs are now based on the CSSL standard (53) and differ from DYNAMO in three respects:

- Program Structure; the model has to be coded in three or more sections, separating the initialisation, dynamic and output statements.
- Integration; integration is performed by one or more specialised functions. The iteration interval can be controlled by the integration error.
- Translation and Compilation; the model statements are translated into FORTRAN which is then compiled. The FORTRAN language is included in the CSSL and the model may use most of the FORTRAN facilities.

There is very little difference between the CSSLs (CSMP, SPEED, ASL and SL1) and they may be grouped together for discussion.

Briefly:

- CSSLs are complex. They require considerable effort in coding structuring and debugging the models.
- DYNAMO is user oriented but provides fewer facilities. Some useful procedures cannot be coded in the DYNAMO Language.
- The best approach appears to be, to construct the early models using DYNAMO. If the models are to simulate the details of processes and require arrays, subroutines or to iterate within the model structure, then the model can be transferred to a CSSL such as CSMP. The combination of DYNAMO and CSMP III on IBM 360/370 computers permits the models to be developed efficiently (using DYNAMO) and to be extended to include further detail using CSMP III.

The following guidelines were extracted from the research and may be of use in future studies where there is a choice of CSSL or DYNAMO.

Computers DYNAMO is currently available on IBM 360 computers. CSSLs are available for most computers and timesharing services. Small models (less than 30 variables) can be adequately simulated using FORTRAN and by manually sequencing the equations.

Computational Accuracy Rapidly changing rates were found to be rare in the essentially continuous systems modelled. There appeared little need for variable iteration intervals nor more complex integration procedures.

Arrays DYNAMO cannot handle arrays. All the FORTRAN based CSSLs can.

Subprograms Substructures can only be handled in DYNAMO as MACRO s. Branching statements and input-output statements (other than PRINT or PLOT) cannot be handled by DYNAMO and a CSSL must be used.

Level of Application From this study it appears that the greatest effort is involved in devising the structure of the model not in the coding and testing of the model. The essential aspect is to ensure that the model includes the prime mechanisms rather than to model the mechanisms with a high level of accuracy. DYNAMO reduces the programming effort at the expense of programming sophistication. This appears to be a better balance than for most CSSLs where total markets, capital investment or total production flows are being simulated.

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7. Simulation Techniques Devised for the Study

It became apparent early in the research study that to develop policy models, it would be necessary to build the simpler models quickly. To delay the results would allow the thinking, discussion and motivation to evaporate. It would be necessary to use the modelling technique to record and demonstrate the system behaviour before the causal relationships had been forgotten.

If a batch processing computer system is used, with lengthy turnaround delays for programs even a simple model can take a week to build and correct. On a timesharing computer system where the user has direct access to a proportion of the machine time, the model can be built and tested immediately. On a time-sharing system, compilation and execution take only a few minutes.

It was decided to build the simplet models on a timesharing system. The larger models would require good diagnostic facilities and there would be less need for a fast turnaround on the compilation and execution of the models. A batch system was to be used for the main model using DYNAMO or CSMP.

The following requirements were listed for a timesharing CSSL:

- Main CSSL features; equation sorting, DYNAMO like features and functions, tabulation and print-plotting, user designed routines.
- General Availability; not restricted by location or time of day, reasonable response time.
- Low Cost; fast compilation, printing of results during execution low processing charge, small "core" storage requirement.

- Model Editing Facilities; storage of the model in equation form, ability to correct blocks and individual statements, ability to merge and extract groups of statements.
- Interactive Facilities; ability to alter constants and initial conditions for rerunning the model without recompiling, ability to restart from the point at which the model terminated after altering constant or restart values of variables, ability to interact with the model during execution.

This is a formidable list of requirements, some of which are in opposition. The CSSL features such as equation sorting and user routines normally increase the compilation time and increase costs. The interactive feature permitting the user to alter one or more values during execution, were, as far as can be ascertained, novel for CSSLs at the time. This feature was thought important in a policy modelling system because it could be used to demonstrate the response of the system to decisions "taken at the time" as opposed to developed policies and procedures.

No CSSL was available at the time that could satisfy these requirements. Two programs were written during the research which acted like CSSL compilers and adequately satisfied these requirements. A continuous system simulation program was devised called CSS (Continuous System Simulator). This program was later revised to permit mixed discrete and continuous systems to be simulated. This package was called QSS (Quantised System Simulator).

7.1 The Continuous System Simulator Program (CSS)

The Honeywell Mark I timesharing service (then De la Rue-Bull, later G-E Timesharing) was used. The method devised utilised the

Dartmouth FORTRAN compiler which had been specially designed for timesharing use. CSS had the following features and restrictions:

- Single Pass Compiler Modification technique used. System variables, functions and control program assembled in a main program. User model acts as a subroutine. Subscripts and the setting of system variables checked by value and subroutine declaration. Compilation of main and subroutine statements by the FORTRAN compiler.
- Poor Simulation Statement Diagnostics The statements were adequately checked by the FORTRAN compiler but language (CSSL) restrictions were not adequately checked.
- CSSL Functions STEP, RAMP, TABLE (arbitrary function generator), DELAY3, trigonometrical and limiting functions.
- Control and Print-plot Operations Iteraction control and termination methods provided. Tabulation and plotting both during and following a run.
- Initial Conditions Initial conditions and constants specified in an INITIAL section only. They have to be sequenced and depend only on values defined in the INITIAL section.
- Fifty Equation Limit Only small models can be constructed.
- Pseudo-sorting of Equations Equation sorting would require a translation phase and the use of on-line files. This would have created a lengthy translation - compilation sequence. A method was devised which overcame the sorting

requirement for small models. During the model execution each equation generates a value that is stored but which cannot be used by the other equations. After an iteration each value is made available to the other equations. All the equations therefore compute an output based on data one iteration out of date.

Each loop creates a delay which is proportional to the number of elements in the loop. If the iteration interval is reduced sufficiently the resultant computation resembles the sorted equation case. This method has been used with FORTRAN compilers on the ICL/1900 and IBM 360 computers. It can be used with any FORTRAN compiler but and IMPLICIT statement, which forces all the variables into a floating point (REAL or mixed fraction) mode seems a practical requirement.

Both the Ingot-Slab Process Model and the Policy Interactions Model were used to test the system. It was concluded that the timesharing continuous system simulator program developed was:

- . Useful for small models.
- . Able to incorporate user routines.
- . Able to use standard output packages.
- . Useful in demonstrating the response of the system to individual changes; interactions with the model during a run.
- . Impracticable for large models. Apart from the size restriction the need for thorough error checking increases with model size.

- . Not ideally structured for policy models because the INITIAL section created programming errors.

In general it was concluded that timesharing construction of policy models was a great advantage but batch processing computer systems appear adequate when large models are being constructed. The need to analyse each run in depth for the more complex models make the model "turnround" time less relevant.

7.2 Discontinuous Simulation for Policy Models

In continuous system models, variables are assumed to be related by well behaved functions. A change in one variable will not create an abrupt change in another variable. The variables are also considered to be continuously related to TIME, the independent variable. DYNAMO uses a fixed iteration interval, DT, which increments the time variable. However, DT can be reduced to the point at which the discreteness of the time variable does not affect the dynamics of the system.

It is clearly a powerful technique to assume continuous variables. Equations can be written simply and the dynamics created easily understood. Furthermore, the relative timing problems created by discontinuous simulation systems are avoided.

It is to be questioned, however, whether real systems can be adequately simulated by continuous variable models. Considering only the magnitude of variables (as distinct from their timing) it is clear that many variables are discrete. Men are employed as individuals, ingots arrive on the ingot trains and are processed as individual units, some financial reports round figures to the nearest thousand pounds. Each variable is not recorded to an infinite accuracy. In practice all rounded

variables have a reduced number set.

A similar relationship occurs with respect to time. Many variables are related to the clock. Office hours relate to a working day, at weekends the offices are unmanned. Reports are produced for each shift, for each week or for each month. Quarterly, half-yearly and annual financial reports are produced. Many of the variables change at regular intervals but not continuously.

Forrester's argument that most variables can be treated as continuous variables is reasonable for aggregate models where one feedback loop represents many in the business. However, it appears from this study that as the detail of the mechanisms are included so the discontinuities become more important.

To examine the effect of discontinuities two hypothesis were proposed and tested.

1. All variables have a discontinuous number set even though the discontinuities may be small compared with the magnitude of the variable.
2. None of the variables are continuously sampled even though the sampling period may be very small.

The digital computer, by its nature, enforces the above rules even on I.D. models. Each variable can only take up values determined by the machine accuracy (seven significant decimal digits for DYNAMO on IBM 360) and are only recomputed each iteration interval (DT).

Since it was felt that most recognisable variables would be sampled and quantised the CSS program was rewritten so that every variable was quantised and sampled automatically. This

simulation program was called the Quantised System Simulator (QSS).

The method adopted can best be illustrated by Figure 8³. Each value was computed in the model and then a check made to see whether the time had arrived for it to be assigned for use by the other equations, if not, the value was ignored. If the value was to be sampled it was quantised and made available for the rest of the model.

7.3 Variable Sampling in QSS

The simulated time at which a variable is sampled is given by $T = G + n.P$ where G is the time of any specific sample (usually the first), P is the sampling period and n is any positive or negative integer. T is computed during each iteration to ensure that accumulative errors are not generated. G and P are assumed zero by default thereby creating the continuous case. The initial and periodic times are stated for each variable. For example

REPORT (G) = 5

REPORT (P) = 7

ensures that on the fifth day the value of REPORT is assigned the value determined by the appropriate model equation. On every subsequent seventh day the value is then assigned; receives the value every Friday.

7.4 Variable Quantisation in QSS

A variable is restricted to a particular number set in QSS. The possible values are given by $V = N + n.Q$ where N is the initial value, Q the quanta steps in the value

Initialisation of Model

Setting of Quantisation and Sampling Values

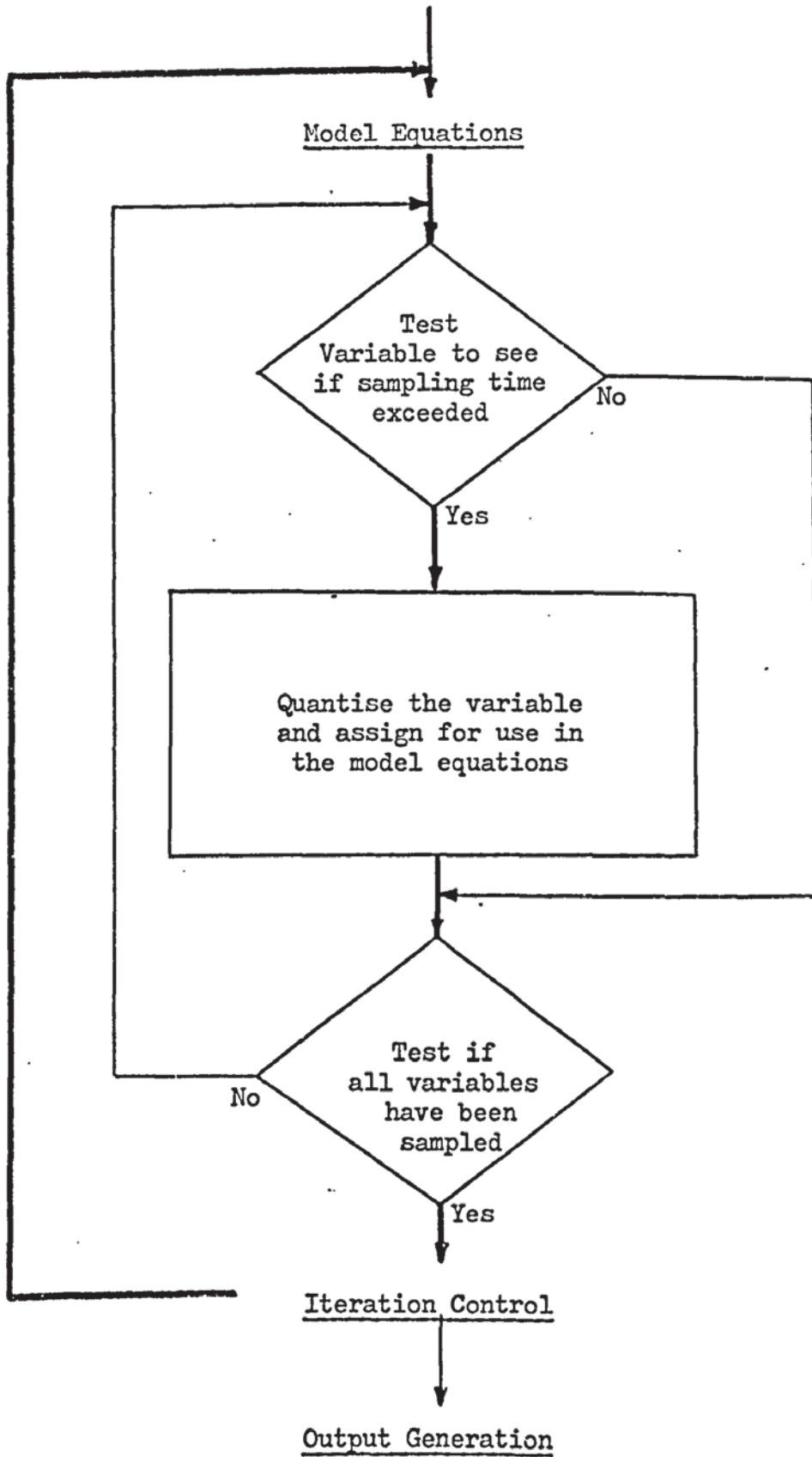


Figure 83. Outline of Quantisation and Sampling Method

and n , any positive or negative integer. The initial value is required in both the continuous and quantised cases.

As an example, if REPORT were initially 1000 tonnes and the recognisable values separated by 10 tonnes the possible values would be ;

... 970, 980, 990, 1000, 1010, 1020 ...

Any computed value is rounded to the nearest permitted value.

7.5 Results of Quantisation and Sampling

The purpose of creating the "compiler" and executing the test models was to investigate whether in a simulation of an industrial control system reasonable values of quantisation and sampling would significantly affect the dynamics.

The Ingot Slab Process Model has been described in Chapter 3. Figure 84 shows the results of simulating the system as a continuous system. The stocks also cycle but the steel production varies less dramatically. The system is stable and damps down cycles of the order of a year.

Figure 85 shows the model with the variables quantised; they may only take discrete values. The system is less stable causing the steel production rate to vary with a greater amplitude. The insensitivity or "slack" of the control system causes it to be unable to control the stock as effectively.

Figure 86 shows the effect of sampling the continuous system; none of the variables are quantised. This particular system appears to be highly unstable, the sampling causing the control system to over react to compensate for the delay in the data. The production rate tends to cycle with a twelve week periodicity. Beyond week sixty the simulation is totally

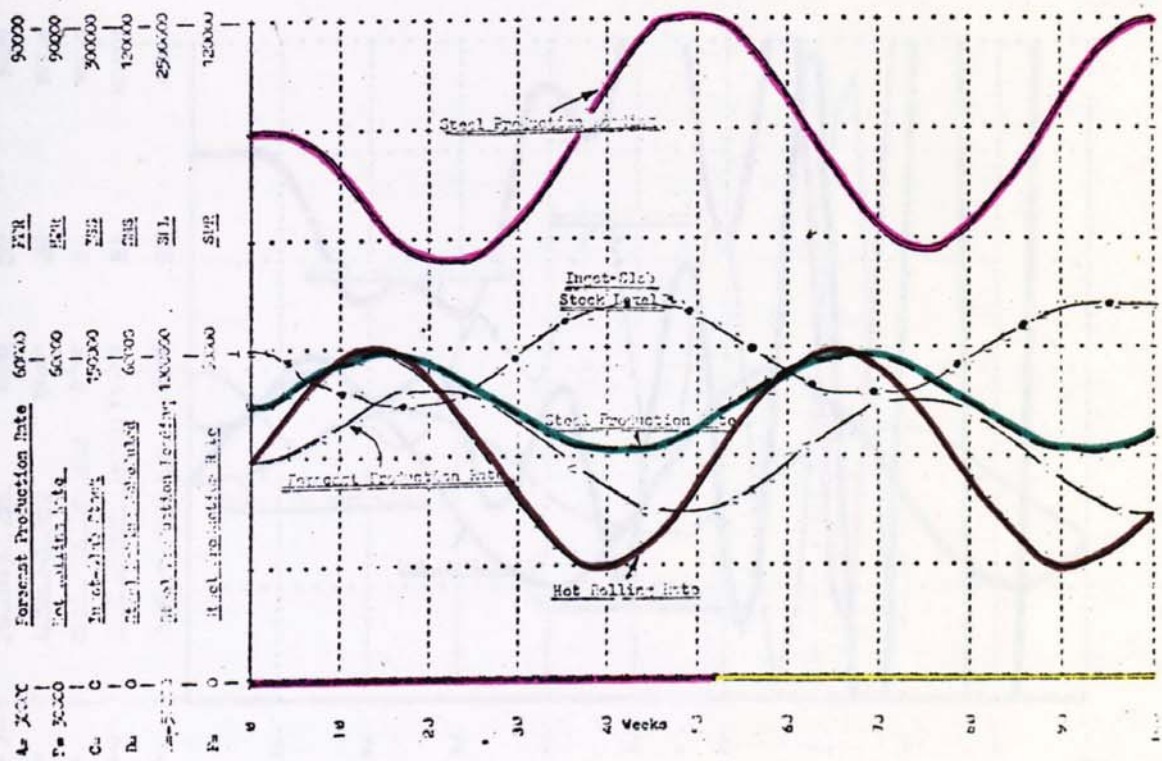


Figure 84 Ingot-Slab Process Model - Continuous System Simulation.

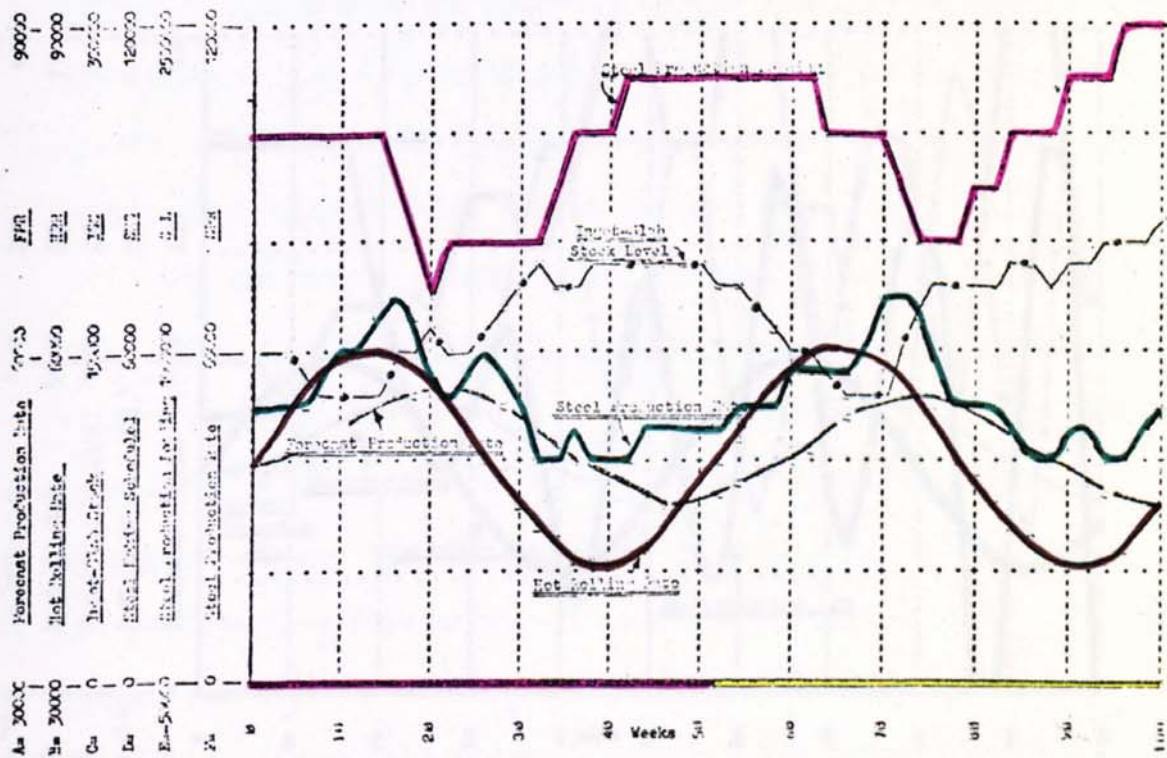


Figure 85 Ingot-Slab Process Model - Quantised Variables only.

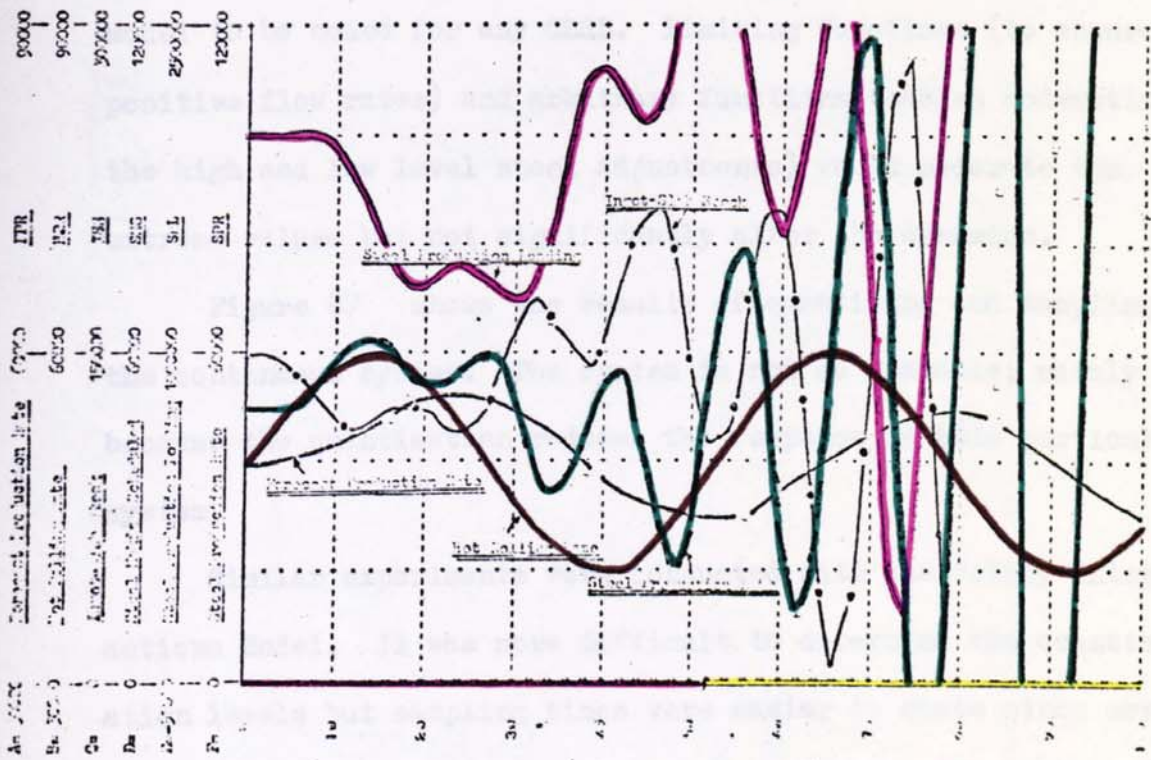


Figure 86 Ingot-Slab Process Model - Variables Sampled only.

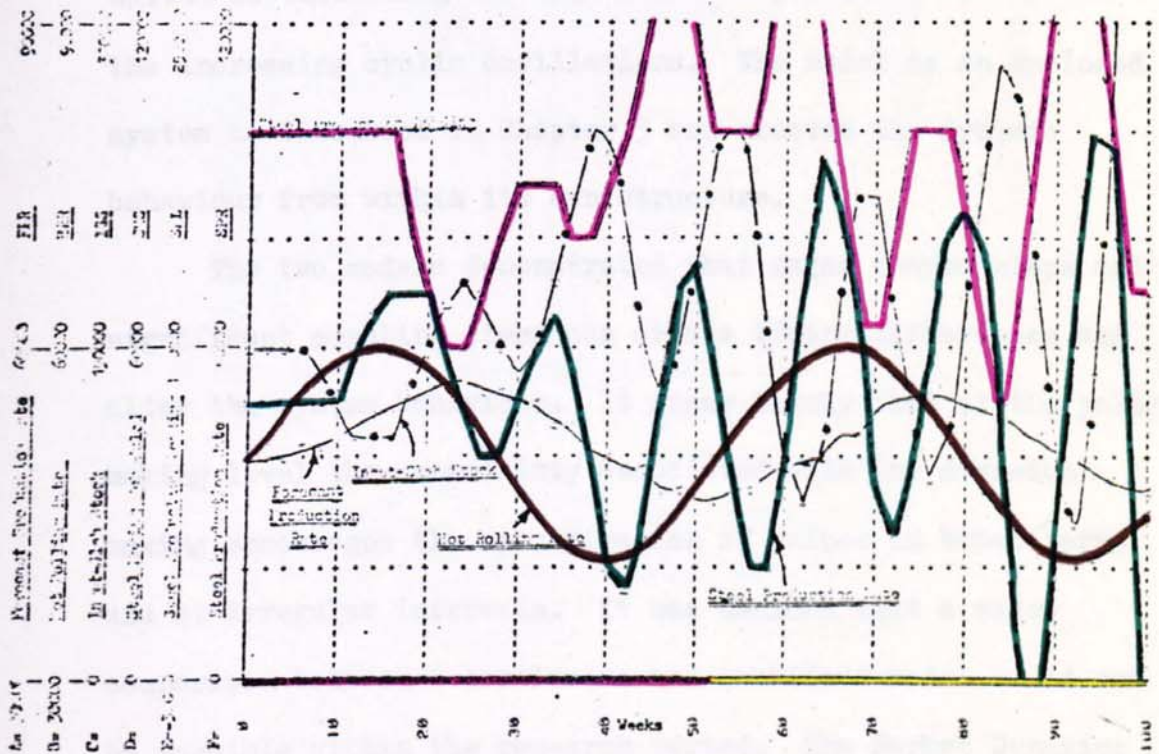


Figure 87 Ingot-Slab Process Model - Variables Sampled and Quantised.

unrealistic. This is because only simple relationships have been included, excluding special functions and permitting the model to be coded for any CSSL. Limiting functions (to ensure positive flow rates) and arbitrary functions (tables moderating the high and low level stock adjustments) would moderate the extreme values but not significantly alter the dynamics.

Figure 87 shows the results of quantising and sampling the continuous system. The system is not so unstable, mainly because the quantisation reduces the response of this particular system.

Similar experiments were conducted with the Policy Interactions Model. It was more difficult to determine the quantisation levels but sampling times were easier to state since more of the data was in the form of reports. Figure 88 shows one run of the model but with a deliberately overstated production acquisition policy. The run was performed to ascertain the affect of increasing the capacity fairly rapidly and demonstrated the increasing cyclic oscillations. The model is an enclosed system as discussed in Chapter 3 and creates the dynamic behaviour from within its own structure.

The two models demonstrated that major quanta steps and significant sampling times can create timing differences and alter the system behaviour. It seems likely that at the policy making level the uncertainty associated with the decision making encourages the specification of values in broad terms and at irregular intervals. It was decided that a major comparison between a continuous and quantised model would not be possible within the research period. The Market Dynamics

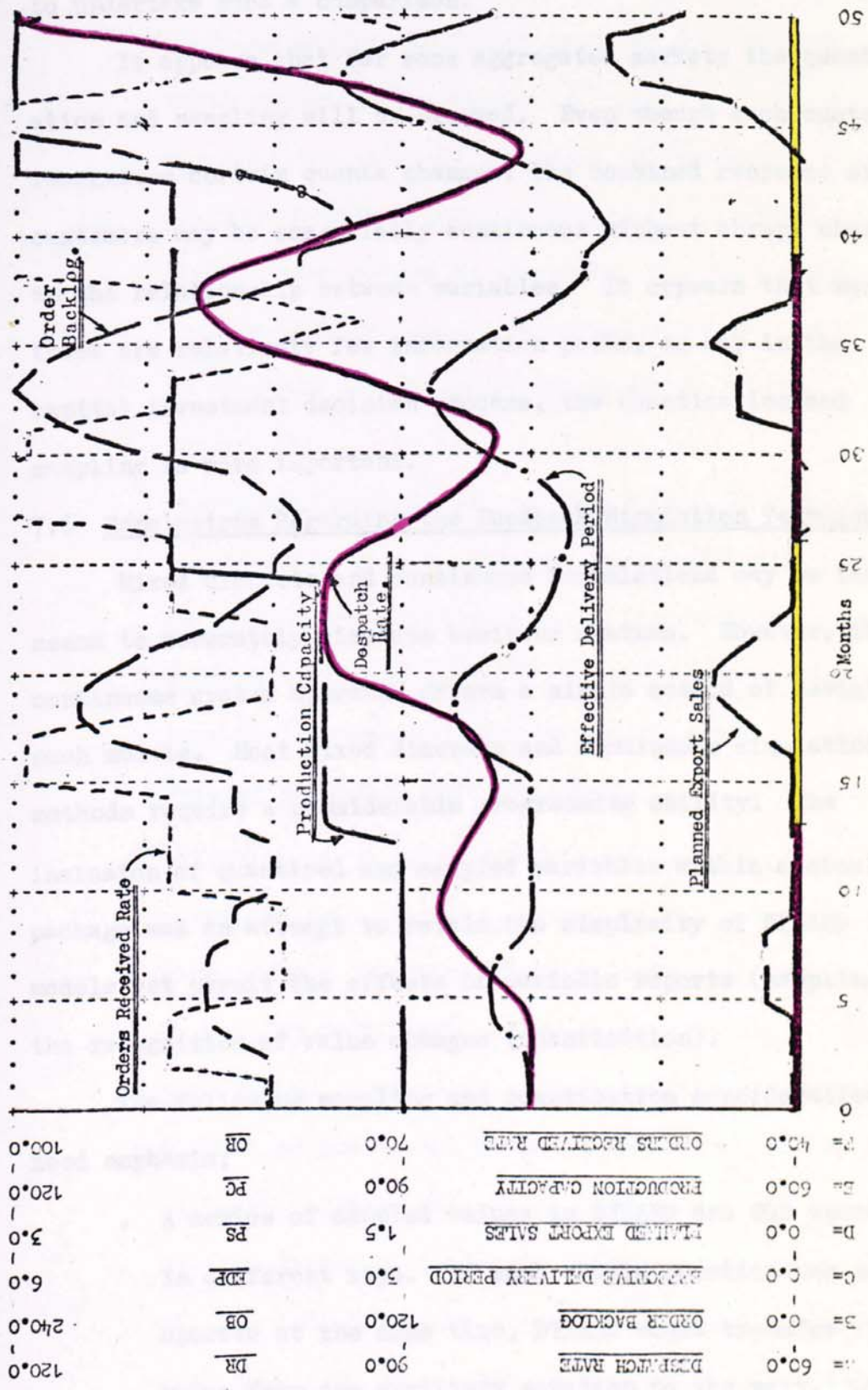


Figure 88. Policy Interactions Model (Illustrative) - Major Capacity Expansion.

Model was devised with this comparison in mind and it is hoped that a future project may utilise the software and M.D. Model to undertake such a comparison.

It appears that for some aggregated markets the quantisation and sampling will be blurred. Even though each customer recognises certain quanta changes, the combined response of many customers may be essentially continuous without abrupt changes in the relationship between variables. It appears that were there are relatively few information paths, as say in the capital investment decision process, the quantisation and sampling is more important.

7.6 Conclusions Regarding the Feedback Simulation Techniques

Mixed discrete and continuous formulations may be the only means to accurately simulate business systems. However, the continuous system approach offers a simple method of devising such models. Most mixed discrete and continuous simulation methods require a considerable programming ability. The inclusion of quantised and sampled variables within a simulation package was an attempt to retain the simplicity of DYNAMO type models yet permit the effects of periodic reports (sampling) and the recognition of value changes (quantisation).

The following sampling and quantisation considerations need emphasis;

- A series of sampled values in DYNAMO and QSS operate in different ways. If each sample function was set to operate at the same time, DYNAMO would transfer the value from one auxiliary equation to the next. QSS would transfer only once in the chain. A complete

sampling period would have to occur before the next variable would receive the value. This seems to reflect the business system more accurately; reports arriving at five on Friday will not be acted upon until the following week.

- Quantisation reflects a measure of damping in the system. People naturally "quantise" values to exclude small random values in the data. How this quantisation varies and should be modelled is not clear but is probably only a second order effect in most situations.
- The "slack" introduced into the system by sampling and quantisation permits the system to oscillate, usually at a frequency shorter than for the continuous case. This is analogous to the "hunting" of mechanical control systems. Seasonal cycles may be effected by this "slack" in the control procedure.
- DYNAMO could be modified to permit sampling and quantisation. It would default in the continuous case, retain the powerful error detection and correction facilities and operate basically in the same manner. Sampling and quantisation require only a small computational overhead and can create very different dynamic responses.
- All the feedback simulation methods require that the equations be correctly sequenced; by hand or by program. Most CSSL's automatically sequence the equations. The equation sequencing requires an additional phase in the

compilation sequence, uses more computer time and reads either I.A.S. (Core) or back store (Disk). By computing each equation independently and using a short iteration interval the compilation time and storage requirement can be reduced at the expense of execution time. This appears a useful technique where simple models (typically 30 equations) are being developed on a limited facility. For example on a PDP8 or timesharing service with small core storage limits.

- The interactive facility developed for CSS (and QSS) has proved very useful. The models can be developed with a minimum of wasted computer time because results are output during the run. The run may be stopped parameters or variables altered and the run recommenced. One or more people may role play using the terminal. All the variables are accessible and can be overwritten thereby allowing equations or tables to be ignored and the role players values substituted.
- Two areas of quantised and sampled variables have been recognised during the study. It is hoped that continuous system simulations will in future include the step nature and timing effects recognised in
 1. Capital Investment feedback simulations
 2. Process Simulations.

Quantisation of the capital to be employed is a consequence of the inability to predict future project costs and sampling (investment reappraisal) a consequence of the effort involved in the appraisal. The discreteness

of many of the physical processes causes values to be quoted in coarse terms. Ingot train tonnages and the timing of train arrivals for example create a need for quantisation and sampling of ingot arrivals.

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8. Conclusions

The purpose of this chapter is to indicate the potential benefits from applying the I.D. approach to an industrial organisation, to determine the cost, effort and facilities required and to indicate the prerequisites for a successful study. Some difficulties with the approach are considered and alternative reasons for the success of some I.D. studies are proposed.

In brief, from this study it appears that I.D.

- . Is a practical, well developed approach to recording and simulating feedback structures incorporating both physical processes and control structures.
- . Provides an integrated methodology, charting and simulation notation. There is no comparable method.
- . Provides a user oriented and reliable Continuous System Simulation Language (DYNAMO) which is efficient in user effort (coding) and machine use (compilation, run time and core storage).
- . Is directed at a potentially high return area; policy and resource acquisition decisions and their consequences.
- . Does not indicate the means of improving the dynamic behaviour; it only illustrates the behaviour and assists an understanding of the causes of the behaviour.
- . The major effort is in isolating the causal chains, devising the mechanisms to simulate the aggregate decision rules and checking the behaviour; model coding and execution is normally a small part of the total effort.
- . The approach requires the active participation of senior management by its nature.

8.1 Potential Benefits

The dynamic behaviour of the production system and the steel consuming market are not the prime areas for simulation in the steel industry. Most simulation approaches are unable to handle massed feedback structures. I.D. is able to simulate feedback systems and uses a notation that aids the formulation of a continuous system simulation language model.

In most I.D. studies of the firm, the behaviour observed has been oscillatory. It is apparent that the behaviour observed must be on-going and susceptible to advantageous change. The benefits from I.D. studies are primarily in confirming that known mechanisms can create or exaggerate the oscillations and in refining the understanding of the causes of the oscillations. I.D. is able to demonstrate the behaviour and indicate the likely consequences of altering policies and procedures.

I.D. does not provide a method of selecting an optimum policy and it is difficult to even rank those investigated because each altered procedure tends to alter the system dynamics in different ways.

Much of the M.D. study was involved in investigating the sensitivity of the system to production, scheduling and delivery times to reduce the oscillations in production and orders received. It appears worthwhile, not only to investigate the sensitivity to parameter changes but also to small changes in the system structure. These structural experiments can help indicate the areas of potential benefit.

I.D. studies appear to demonstrate areas which were thought to create dynamic behaviour but which do not. This is a more

negative result than Forrester's "Counter-Intuitive" approach in which unexpected, but recognisable, behaviour occurs.

In the P.D. model the soaking pit capacity was reported to be the cause of the ingot stocking peaks. This was found to be unlikely. By discovering such factors a better understanding of the production system is possible, although it is difficult to anticipate whether this has actually contributed to operating procedures.

In the M.D. study a 4% reduction in production to satisfy the same basic home demand, during the peak demand cycle, seems possible from this study. This is possible without excessive finished stocks and is due to the reduction of the amplifying effects created by the lead time response. A 4% additional capacity implies that exports could be handled with the same production capacity during peak periods. For Strip Mills this implies a potential export tonnage of (4% x 3.5 m tonnes) 140,000 tonnes/year. During the peak demand period, which usually lasts for a year, export sales are potentially very profitable. The excessive demand tends to be international creating a high export price. Currently Hot Rolled Coil Can be sold at £40 per tonne above the home sales price. The additional 4% capacity implies an additional profit in excess of (£40 x 140,000) £5.6 m.

In the P.D. study reduced reheating is possible if steel production loading procedures are tailored to the slabbing dynamics. Currently, reheat capacity limits some works output (Port Talbot). Reheating ingots from cold effectively reduces the soaking pit throughput. The potential saving, particularly at the current time where sales are limited by the production capability, should

be based on the marginal return from the additional finished sales. However, the study also indicate other limiting production constraints (stocking procedures) which may stop this additional production being realised. The reduced reheating should, however, save some fuel costs. These are estimated at £1.69 per tonne difference for hot and cold ingot reheating (average for non-killed steel). The suggested reduction of 7000 tonnes annually for reheating of cold ingots indicates a saving on fuel for Strip Mills Division of £116,900 per year.

These figures indicate only a small part of the potential. A reduction in the cycles of individual product categories such as electrical steels and the reduction of waves of production seem possible and may be found to be practical.

8.2 Cost and Effort

The cost and effort involved in an I.D. study depends on whether the study is an initial study or the extension of a previous exercise.

8.2.1 An Initial Study

The effort involved in an initial study can usefully be broken down into the following areas; development of expertise, of facilities, of methods of simulating the structures identified and of an awareness of the feedback generated behaviour.

8.2.2 Development of Expertise

In many of the I.D. studies some or all of the people involved are new to the approach. It is apparent that some of the effort will be in learning the approach, the notation, simulation problems and how to construct feedback models.

The greatest problem with I.D. is that it is difficult to determine what should be simulated. It is not simply a matter of simulating physical processes but in identifying structures within the plant, the market and in policy decisions that form closed loops. Much of the initial effort is in learning where these feedback loops are to be found and how to maintain a consistent level of aggregation; simulating the structures to the same level of detail.

8.2.3 Development of the Facilities

A simulation language (and compiler) and suitable computing facilities are the main requirements. FORTRAN may be used but is only suitable for small models (less than 30 equations) and tends to focus the effort onto programming elegance rather than model validity. DYNAMO on the IBM 360/50 seems to be the most effective approach for an initial study, reducing the programming effort and discouraging the use of discrete events or items and substructures in the model.

8.2.4 Development of Methods of Simulating the Structures

It is not immediately obvious how to simulate the information paths and control structures using the I.D. notation. For example, it required some months of effort to determine how to depreciate assets in the financial model; an exponential or straight line depreciation? How to simulate the actual loss of assets and how to model the corrective action involved in balancing the actual observed asset loss with the asset depreciation allowance?

A considerable effort is needed to determine these mechanisms and to state them in a simple but recognisable manner in the model. In the M.D. model some months were spent in analysing the various

forecasting and stock control methods and attempting to determine the proportion of the market dominated by each method and the parameters involved.

8.2.5 Development of an Awareness of the Feedback Structures

To be able to recommend changes and to implement them, requires that management are aware of and accept the causes of the behaviour indicated. The feedback relationships are often across departmental and functional boundaries; production, the market, personnel policy and capital investment.

It appears that senior management need to be aware of the basis for the model and to appreciate how the recommended procedures will alter the feedback relationships to create a new behaviour. They need confidence that the procedures reflect the real system and that the changes will create real dynamic improvements.

8.2.6 The Mature Study

None of the I.D. studies included in the bibliography are developments of earlier studies although some, such as the Sprague Electric Company study (11) were lengthy and were followed by a post implementation review. In the B.S.C. the size of the organisation makes it likely that there will be opportunities for applying the approach to a variety of problems provided it has adequate high level support. It appears from this study that the timing and amplification of order cycles is a phenomena wider than the Division and that similar causes are at work; customer forecasting and stockholding creating the over-ordering cycles.

8.2.7 Duration of an I.D. Study

It would be useful to indicate how a typical I.D. study progresses, how long it can be expected to take and the manpower

required. This is obviously a difficult task because it depends on the experience of the individuals involved and the environment for the study.

Forrester recommends a ten stage process (Chapter 2) to develop a model. While these stages seem sensible they do not appear to be the way most I.D. studies have developed (9,10). The procedure that most often occurs is that the initial model acts as a record of the feedback discovered, is used to extract unreasonable or unlikely mechanisms and helps in deciding what data is needed. A second model is built which is more mature. It includes some better known mechanisms, is based upon known behaviour and starts as a simple model.

The following list of stages and times is based upon this study but is confirmed to some extent by the Sprague and Scannell studies (10,17). It assumes the effort of one man but with assistance in data collection and with management involvement. It assumes a resource-acquisition type of model of about 50 dynamic equations.

	<u>Duration-Weeks</u>
. Investigation of the behaviour, its causes and feedback structures.	2 to 6
. Coding and Testing of the Model.	2 to 4
. Examination of results, validation and discussion of mechanisms modelled.	4 to 10
. Reconstruction of the model.	2 to 4
. Re-evaluation of the model, experiments (sensitivity), refinement of the mechanism.	6 to 10
. Development of new or modified procedures.	6 to 10
(. Implementation)	

It should be noted that coding, testing and rewriting the model takes about 4 to 8 weeks in a total of 22 to 44 weeks, i.e. about 20% (10% to 40%) of the time. To prepare the initial model takes 8 to 20 weeks and the restructured model 16 to 34 weeks. I.D. studies should be expected to take six months to nine months to arrive at some implementable results, to absorb considerable management effort in this period but require relatively little computing power (20 to 40 runs of the resource-acquisition type of model).

8.2.8 Type of Model

Two types of model were identified during the research which appear to require differing amounts of effort:

- . Process Flow Models; based primarily upon orders and production flows and central procedures.
- . Policy Models; simulating orders and production but incorporating the acquisition and use of a resource. Often including manpower, capital investment and market development.

The process flow models require a generally greater level of detail because they are based on known physical processes and well developed control procedures. More variables can be checked with the flow process models and validation needs to be a lengthy process if the model is to be acceptable.

The policy models are mainly concerned with the acquiring and use of a resource. The variables impinging upon each decision are not normally fully understood and it is necessary to simplify both the decision rules and the variables involved. The policy models are less precise, data is not normally as readily available and

simulations of these decisions are not common. Consequently simple models appear to offer a useful contribution in this area by illustrating the consequences of simple feedback mechanisms. The return from the policy or resource-acquisition type of model appears to be high with regard to the effort involved.

8.2.9 Computer Costs

Using DYNAMO (4.1) on an IBM 360/50 executing a typical process flow model (70 equations) over a simulated period of one year (2000 iterations) and assuming an effective charge of £100 per C.P.U. hour, a typical run would cost £2.50. DYNAMO has efficient diagnostic and recovery procedures, however, so that new models and major restructuring require only five to ten runs to debug. Most of the computer runs are concerned with sensitivity tests and trying new procedures. The Production Dynamics model required 120 runs before it could be considered to adequately simulate the Port Talbot works.

8.3 Facilities Required

The prime facilities required are concerned with the simulation; a simulation language (compiler) and computer on which to compile and execute the model.

8.3.1 Simulation Programs

There are three practical simulation methods for I.D. models; use of a high level scientific language (FORTRAN), a Continuous System Simulation Language (CSSL) or DYNAMO. For simple models FORTRAN together with suitable plotting, tabulating and special function routines is adequate. Care has to be exercised, however, in sequencing the equations and the problems of program checking increases significantly with an increase in the number of dynamic

equations. CSSPl is primarily little more than FORTRAN with output, integration and special function routines.

The CSSLs (excluding DYNAMO) are mainly FORTRAN based, sequence the dynamic equations and provide suitable routines for output and special functions. They were found to be powerful but required programming knowledge and detract from the essential purpose of I.D. in that they require the user to be involved with the methods of simulation.

DYNAMO is user oriented; all the statements are written in any sequence in the main program segment and error messages relate directly to the equations and variable names. It does not include arrays, subroutines (or procedures) nor alternative output methods. It appears less useful for process simulations where individual decisions or individual items are to be modelled.

8.3.2 Computers

DYNAMO is currently available on IBM 360 computers, requires approximately 100 k bytes of storage and takes approximately one minute per 100,000 equations executed, of Central Processing Time for a 360/50. It typically takes between five to ten times as long in waiting (elapse) time on a batch system but this is highly dependant on the job priority, machine configuration and operating system. Compilation time is about 20 seconds (C.P.U.) for small models. Compilation and execution time rises linearly with the number of equations, with the number of iterations and with the number of runs.

CSSLs are available for most computers but they require a lengthier translation and compilation phase. Generation of the machine code and its execution tends to be less efficient than

with DYNAMO because of the additional FORTRAN facilities. For large models, however, it appears that the CSSLs tend towards a similar efficiency to DYNAMO because they use a variable iteration interval. Large models tend to exhibit more complex behaviour and offer greater scope for variable iteration procedures.

8.4 Prerequisites for a Successful Study

From this study two essential requirements for a successful I.D. study were identified; senior management involvement and the recognition of the behaviour and its cause before a model is constructed. It also appears that a slavish adherence to specifying relationships as simple equations is unrealistic and likely to create an inaccurate model. It was found that because the variables used are often aggregations of a number of variables the decision rules should be represented by superimposed decisions; tabular data relationships (arbitrary function generators) permit the specification of superimposed curves.

8.4.1 Management Involvement

It appears from this study and others that were concerned with specific applications, that I.D. requires the involvement of senior management, perhaps more than most simulation approaches. Fey (10, 11) in his discussion of the Sprague Electric Company study makes repeated reference to the involvement of top management and the orientation of the study around the company's prime objectives, "No progress was made, however, until it became evident that (a) the system study should develop a feeling for the company's objectives and the major dynamic problems and their causes, ... (b) the system should be visualised as a whole, and (c) recognition should be given to the relationship between the aggregate decisions ...". Similar comments are made by Roberts (19) in his

study of a food manufacturing and distribution company. He suggests that senior management need to be familiar with the concepts and tools of I.D. not simply the results of a study.

Schlager (9) in his discussion of three companies in which I.D. was applied also indicates the problems of implementation.

"Human problems of program implementation, however, were alleviated in the three companies by two factors:

1. Continuing top-management support.
2. Technical and moral support by lower-echelon personnel who were familiar with industrial dynamics.

This second factor was especially important. I found it difficult as an outsider to develop a model, collect data, and carry out the remainder of the project without considerable support at middle and top levels of management. Ultimately the success of the project will be, and should be, judged by its contribution to company profitability. But success of an industrial dynamics project is more likely if company personnel are informed and personally committed to it."

Wright (17) in his study of the Scannell Trucking Co. also makes the point that without involving management in the approach there is little likelihood of success. "Our initial implementation effort failed. We tried to see results of the study instead of the modelling process itself. We learned that to effect an implementation we needed to teach the Industrial Dynamics methodology and present the model formulation. Management could then see the sense and point of view of our operating recommendations While we were convinced that the recommended changes were worth-while, the operating people were not. We had

not provided them with a conceptual framework for judging our work and for confidently accepting our proposals ... A great virtue of Industrial Dynamics is its basic simplicity. We were able to sit down with operating executives who were high school graduates and explain enough about feedback systems to teach them the model and to sell the model suggestion ... Our work became their model and the new policy suggestions were adopted as their recommended changes."

Similar comments can be made concerning the P.D. and M.D. models. By the structure of Strip Mills Management Services, the models have been developed with some contact with the appropriate departments but not in close contact with Works or Divisional senior management. The models have been reported together with the results. It has been difficult to generate interest in the results because the method is virtually unknown to senior managers.

It appears that I.D. is not a particularly useful O.R. tool. It is a Management rather than Management Services tool. It studies the dynamics of causal mechanisms in the same way that financial accounting studies cash flow.

Specifically it appears that I.D. particularly requires the involvement because:

1. Senior managers understand better than most people in the organisation, how feedback relationships are likely to affect their decisions.
2. Senior managers are used to considering aggregated actions and feedback relationships. Few of the relationships modelled in the P.D. and M.D. models are simple. They consist of a number of factors which have been grouped

together and treated as a single variable or decision. The identification of these prime groups is fundamental to an I.D. study because otherwise the model would be too complex.

3. The studies tend to be Works or Division wide. They rarely relate to a single department. The authority and support of senior management is needed if inter departmental rules and procedures are to be discussed and refined. Implementation of I.D. results are particularly difficult because they tend to be concerned with altering procedures to improve the overall system performance rather than a single area.
4. It appears that to obtain confidence in the approach management need to accept the structures being modelled. The presentation of a "black box" model regardless of comparative or "validation" data is difficult to accept.

It would appear that I.D. is relevant to planning and development exercises where the dynamics of the market or production capability are of prime importance. The simulation effort need be small (two man/months for a 50 variable model) but the selection of the appropriate aggregated variables and feedback loops is paramount. An understanding of the principle mechanisms involved by senior managers seems essential.

8.4.2 Prior Knowledge of the System Behaviour and its Cause

It appears from this study that a useful I.D. model cannot be produced until both a behaviour can be recognised and its cause known. When the I.D. model has been built it will confirm or disprove this behaviour. Attempts to construct a model without a

firm idea of the causes of the behaviour have been unsuccessful. This is probably because the chance of hitting upon the appropriate aggregated variables and decisions rules is extremely small without some means of reducing the boundary of the system being modelled.

An I.D. study should start with the intention of determining dynamic behaviour and its causes. When the model is built it will indicate the sensitivity of the behaviour to these relationships and lend insight into how the behaviour can be modified. I.D. acts as a means of focusing senior managers attention upon the potential for modifying a known system behaviour.

In the M.D. study it was accepted that stockholding by manufacturers and merchants worsened the ordering variations. Further it was thought that Divisional stockholding could reduce the effect on production by introducing a buffer stock. This study showed that the buffer stock also reduced the delivery time which effectively removed the variation in orders created by manufacturer and merchant stocks. While the cause of the amplification of orders was known the potential reduction in the order amplification by Divisional stockholding was not appreciated.

8.4.3 Specifying Relationships as Tables

Relationships can be expressed in the models by equations or tables. Since most of the variables represent aggregated variables (total sheet steel tonnages delivered) each aggregate relationship represents a number of similar but not identical relationships. In this study and some of the more recent I.D. studies (5) these relationships have been represented by tables.

Tabular data has been found useful because it has been possible to include more factors. For example in the P.D. model

the relationship between the stock being scheduled and the production rate is represented by a table of values. The table is constructed from the superposition of four curves; schedulers preferred rate (to maintain an adequate stock from which to schedule), rolling pattern constraint, maximum rate permitted by handling capacity and the mill rolling capacity. It appears that because the variables are aggregated it is difficult in practice to specify a simple algebraic relationship. As the relationship became better understood curves, often derived from a number of superimposed curves, can be defined. In this study it was found useful to use dimensionless measures in curves, suitably scaling the output with a constant. By this means small changes in a relationship can be adjusted by scaling the constant while retaining the shape of the curve.

8.5 Difficulties with the I.D. Approach

I.D. requires close contact with senior management which undoubtedly limits its application. Beyond this restriction there were found a few other difficulties with the simulation process; aggregation of decisions and variables, abruptly changing variables, item identification and the recognition of omitted feedback paths.

8.5.1 Aggregating Decisions and Variables

It is common in I.D. to link actions to observations, to decisions and back to an action in a simple control system sequence. It is usual in I.D. simulations to postulate simple decision variables; normally a single variable with simple decision rules operating continuously and smoothly. For example, the customer forecast of future consumption is based in the M.D. model on a single variable; the current consumption of steel. It is not

practical to attempt to sub-divide the consumption rate into a range of products because each product requires its own flow path. The model equations have to be repeated for each flow path and inter-relating equations generated.

Subdividing the production stream in any of the I.D. models in this study tended to increase the model size very considerably. The M.D. model was extended to identify orders and production to two customer groups; merchants and consumers. The P.D. model also identified Hot Rolled Coil for sale and for further production. Further subdivisions of the products were found impractical because of the problems of relating a number of flow processes with continuously acting decision rules.

Multiple product flow systems which use related facilities are difficult to simulate using the I.D. approach even though they may have the appearance of I.D. models; feedback and essentially continuous flow and control.

8.5.2 Abruptly Changing Variables

I.D. assumes an essentially smoothly changing variable formulation. Rapid changes in variables particularly discontinuities, introduce high frequency disturbances and potential inaccuracies in the fixed step integration procedure. The effect of high frequency disturbance and the potential inaccuracy in the Euler integration method were both found to be minimal in this study.

Care has to be taken in setting up the model that any rapid changes in a variable do not create inaccuracies in the model. It appears from this study that because the systems modelled are concerned with people and industrial organisations they have a

structure that is insensitive to computational accuracy and high frequency disturbances. For example, the orders received rate is highly variable, on a week to week basis, but the orders are held as orders-in-hand which smooths out the weekly fluctuations. Each week approximately 10% of the week's orders are corrections to previous orders. The order handling system is insensitive to variations in the orders received and the precise calculation of the level of orders.

8.5.3 Item Identification

I.D. and other CSSLs are event rather than item oriented. They are able to simulate the timing of an event but do not recognise individual items. This is fundamental because it implies that multiple attributes cannot be assigned to a single material flow path. If a flow path is represented by the tonnage of steel flowing through the plant it is not possible to align variations in the tonnage with the actual width, gauge or quality of the steel.

This problem created difficulties with the P.D. model when it was desired to simulate the effects of wide orders on cold mill stocks. I.D. models are not suitable for simulations where multiple products (or multiple attributes of the same product) are to be recognised even though the process may appear to be a flow process.

8.5.4 Omission of Feedback Paths

Feedback is generated primarily in I.D. models by information paths rather than material flows. (The P.D. model includes scrap recycling but is unusual in this respect.) The material flows

are relatively easy to identify and easy to check because they are conservative flow paths. The information paths are difficult to verify and depend heavily on the means of aggregating both the variables and decisions.

Simulating these feedback networks appears worthwhile, however, because it concentrates effort on recognising the prime factors involved in the decision and illustrates the behaviour of causal relationships that could otherwise only be guessed. The problem arises in simulating new procedures or policies. Totally new situations appear to be outside the range of I.D. simulations because one has to anticipate the new feedback and detail its action. I.D. appears to be primarily useful in illustrating how changes to existing procedures can modify the existing behaviour.

8.6 An Alternative Reason for the Success of I.D. Studies

Some of the I.D. studies appear to have made a major contribution to the business (11,17). These successes can be attributed to the philosophy of I.D., to its use of some fundamental principles and the insight generated by simulating the system and refining the detail of the model. There can be little doubt that as a means of simulating the effects of policy decisions, using a continuous system simulation language, I.D. has made a major contribution. It has removed the traditional sequence;

- . View the system as a "servo" control system.
- . Prepare a "program" in the form of interconnected analog computer elements.
- . Code the analog computer representation in a CSSL.

I.D. uses a flowchart notation, linked to the DYNAMO language, which is independent of control theory, analog computer terms or

digital computer programming (other than algebraic equations).

An alternative suggestion can, however, be made to why I.D. has been successful. It could be suggested that these successes were in part due to:

- . The pressure of effort exerted on senior management to examine the dynamic behaviour of the business and to see how it may be changed.
- . The effort of M.I.T. staff and graduate students (at least nine people, including Forrester, worked on the Sprague study).
- . The companies studied have been small and there has been potential for easily altering manning policies and investment decisions.
- . The problems and their solutions had usually been considered previously. I.D. appears to have illustrated these problems in a new light, possibly giving an aura of originality to the solutions.
- . The studies were usually conducted with the authority of the President of the company which must have helped considerably in obtaining resources and assistance for the study.

It must be repeated that I.D. is unusual in providing a notation, philosophy and simulation language that is user oriented and directed at policy decisions and their consequence. In the area of policy decisions it appears able to encourage insight into an area of potentially high return. It cannot be used without management involvement and the simulation aspect must be viewed as a tool used during the analysis processes rather than as the purpose of the study.

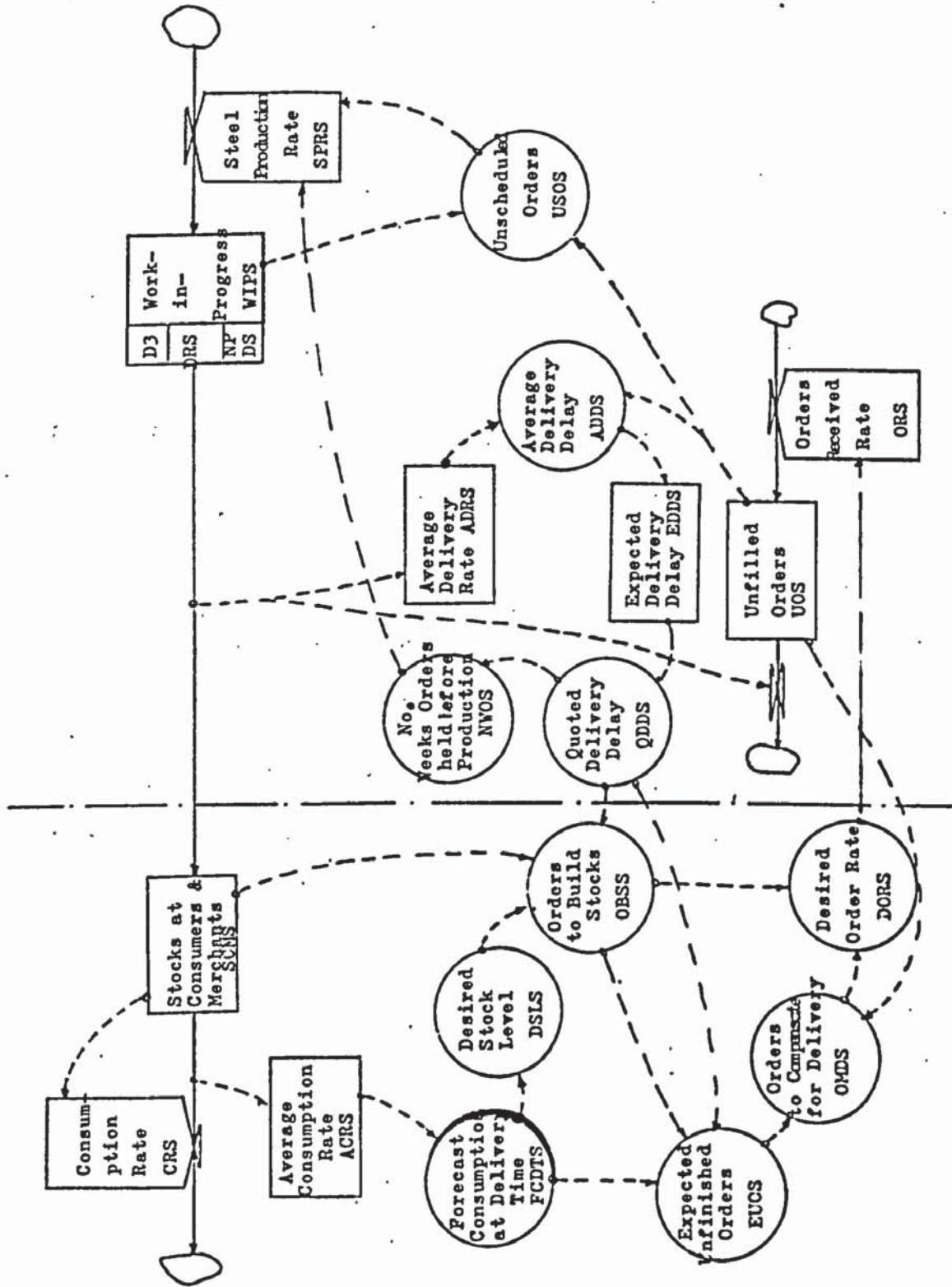
The Market Dynamics Model simulates sheet steel sales for Strip Mills Division. The flow diagram in Appendix 1.2 shows the production and delivery of steel and the stocks of steel held by the market. The market forecasting and ordering procedures are simulated together with the Division's handling of orders and delivery quotation.

The diagram has been simplified to aid understanding; constants have been omitted and the market forecast is shown as a single auxiliary symbol. The forecast consumption variable consists of alternative procedures selected by a switch.

"Valve like" symbols indicates rates of flow. Rectangles indicate level variables; integrations. Circles indicate auxiliary variables which form part of the information network and form part of the "rate of flow" computation.

Each mnemonic is listed in Appendix 1.3 together with a brief description and the units in which the variable is expressed. The units are; Tonnes (T), Tonnes per Week (T/W), Years (Y), Weeks (W) or are dimensionless (D). Names which appear in the model listing in Appendix 1.4 and which are reserved by the simulation language, DYNAMO, are described as "DYNAMO Terms". These names are control variables or special functions. Two user routines (or MACRO's) are used in this model; BOX and SRA. They both compute accurate totals of rates of flow during a period. BOX is used for the seasonal cycle forecast and SRA to generate quarterly and yearly average rates of flow for comparisons with data. Variables associated with BOX or SRA are described as "User MACRO Variables".

The model equations can be compiled using DYNAMO II (Version 4). A, R and L equations are sorted and executed each iteration by DYNAMO. N equations are used only during the first iteration. S equations (and those following the NOTE card "Supplementary Equations") are used only for output purposes.



Mnemonics	Description	Units
ACRS	Average Consumption Rate	T/Y
ADDS	Average Delivery Delay	Y
ADRS	Average Delivery Rate	T/Y
AECS	Amplitude of "Economic Consumption Cycle"	T/Y
AFPS	Average Forecasting Period	Y
ASCS	Amplitude of Seasonal Consumption Cycle	T/Y
BOX	User MACRO; Sums consumption for Forecasting	-
BSFS	Buffer Stock Factor	D
CRCS	Constant Rate of Consumption	T/Y
CRS	Consumption Rate	T/Y
CTAOMDS	Constant Time to Adjust Orders in Manufacturer	Y
DCRS	Desired Consumption Rate	T/Y
DECS	Duration of Economic Cycle	Y
DELAY3	DYNAMO Term; Function Simulating 3 Levels	-
DORS	Desired Order Rate (No Random Element)	T/Y
DRS	Delivery Rate	T/Y
DSIS	Desired Stock Level	T
DT	DYNAMO Term; Iteration Interval	Y
EDDS	Expected Delivery Delay	Y
EUOS	Expected Unfinished Orders	T
FCDTS	Forecast Consumption at Delivery Time	T/Y
FFPS	Fixed Forecast Period, Linear Projection	Y

Mnemonics	Description	Units
FLFS	Fraction of Lead Time in Forecast Period	D
FMCLTS	Fraction of Market Concerned with Lead Time	D
IN	User MACRO Term; Input to BOX	T/Y
L	User MACRO Term; Summed Value in BOX	T
LA to LF	User MACRO Terms; Levels of Quarterly Forecast	Y
LENGTH	DYNAMO Term; Finish Time of Simulation	Y
LTFS	Linear Trend Prediction Forecast	T/Y
MAX	DYNAMO Term; Function Selects Maximum	-
MCRTS	Multiplier of Consumption Rate Table	D
MIN	DYNAMO Term; Function Selects Minimum	-
NORMRN	DYNAMO Term; Function, Normal Distribution	-
NPDS	Normal Production Delay	Y
NSCMS	Initial Value of Consumer/Merchant Stocks	T
NWOS	Number Weeks of Orders (Expressed in Years)	Y
NWUSS	Number Weeks Use Held as Stocks	W
NYWS	Number Years from which Seasonal Cycle Computed	Y
OBSS	Orders to Build Stocks	T/Y
OMDS	Orders to Cover Manufacturing Delay	T/Y
ORS	Orders Received Rate	T/Y
ORSDS	Order Rate Standard Deviation	T
PACRS	Previous Average Consumption Rate	T/Y
PLOT	DYNAMO Term; Indicates Plot Variables	-

Mnemonics	Description	Units
PLTPER	DYNAMO Term; Plot Interval	Y
PRINT	DYNAMO Term; Indicates Print Variables	-
PRTPER	DYNAMO Term; Printing Interval	Y
PULSE	DYNAMO Term; Function Creates Pulse	-
QACRS	Quarterly Average Consumption Rate (Output)	T/Y
QADRS	Quarterly Average Delivery Rate (Output)	T/Y
QAORS	Quarterly Average Orders Rate (Output)	T/Y
QDDS	Quoted Delivery Delay in Years	Y
QDDWS	Quoted Delivery Delay in Weeks	W
QPS	Quarterly Period for Averaging Output Rates	Y
R	User MACRO Term; Depletion of SRA	T/Y
RA to RF	Rate of Depleting Quarterly Forecast Values	T/Y
RUN	DYNAMO Term; Causes Execution of Model	-
SAMPLE	DYNAMO Term; Function Sampling a Value	-
SATFS	Seasonably Adjusted Trend Forecast	T/Y
SAROS	Selects Constant or Variable Value of OMDS	D
SCMS	Stocks of Consumer and Merchant Stocks	T
SFMS	Switch for Forecasting Methods	D
SIN	DYNAMO Term; Function Generating a Sine Curve	-
SLFS	Stock Level Factor, E.O.Q. Stocks	$T^{\frac{1}{2}} \cdot Y$

Mnemonics	Description	Units
SMOOTH	DYNAMO Term; Function, Exponential Smoothing	-
SPRS	Steel Production Rate	T/Y
SQRT	DYNAMO Term; Function, Square Root	-
SRA	User MACRO; Sums Quarterly or Yearly Rates	-
SWTCH	DYNAMO Term; Selects one of two Values	-
T	User MACRO Term; Time to Sum Output Rates	Y
TA	User MACRO Term; Time to Sum Forecast Rates	Y
TABEL	DYNAMO Term; Function, Table Values	-
TACRS	Time to Average Consumption Rate	Y
TADD5	Time to Average Delivery Delay	Y
TADRS	Time to Average Delivery Rate	Y
TAMDS	Time to Adjust Orders in Manufacture	Y
TCRS	Table of Consumption Rate Values	T/Y
TIME	DYNAMO Term; Independent Variable	-
TRMCS	Table; Number Weeks Orders for Scheduling	W
TPACRS	Time to Average Previous Average Consumption	Y
TSCRS	Table Generated, Steel Consumption Rate	T/Y
UOS	Unfinished Orders	T
USOS	Unscheduled Orders	T
VCS	Variance in Consumption during Lead Time	(T/Y) ²
VLS	Variance in Lead Time	Y ²

Mnemonics	Description	Units
WIPS	Work in Progress	T
WPCFS	Work in Progress at Consumers, Factor	T ⁻¹
YACRS	Yearly Average Consumption Rate	T/Y
YADRS	Yearly Average Delivery Rate	T/Y
YAORS	Yearly Average Orders Received Rate	T/Y
YPS	Yearly Period for Average Output Rates	Y
£D	User MACRO Term; Depletion of SRA MACRO	T/Y
£L	User MACRO Term; Level of SRA MACRO	T

```

MACRO BOX(IN,JK,L,K)
NOTE MECHANISM APPROXIMATING A DYNAMO I BOX CAR
N      L=IN*TA
L      L.K=L.J+DT*(IN,JK-BOX,JK)
R      BOX.KI=SAMPLE(L.K/TA,TA,L.K/TA)
MEND
MACRO SRA(R,JK,T,K)
NOTE SAMPLED RESET AVERAGE
L      FL.K=FL.J+DT*(R,JK-SD,JK)
N      FL=R*T
R      SD.KL=PULSE(FL.K/DT,0,T,K)
A      SRA.K=SAMPLE(FL.K/T,K,T,K,FL.K/T,K)
MEND
NOTE STEEL PRODUCTION SECTOR
R      DR.S.KL=DELAY3(SPRS,JK,NPDS)
L      WIP.S.K=WIP.S.J+DT*(SPRS,JK-CFS,JK)
N      WIP.S=CR.S*NPDS
C      NPDS=0.115 (6 WEEKS)
R      SPR.S.KL=USOS.K/(NWOS.K-NPDS)
A      USOS.K=LOS.K-WIP.S.K
A      NWOS.K=TABHL(TNWOS,ODDS.K*52,2,14,41/52)
J      TNWOS=7,7,10,14
N      NWOS=0.192
L      LOS.K=LOS.J+DT*(CRS,JK-DRS,JK)
N      LOS=DCR.S*NWOS
R      DRS.KL=DRS.K+SAMPLE(NCRMRN(0,CRSCS),0.02,0)
C      DRSD.S=0
L      ADR.S.K=ADR.S.J+DT*(DRS,JK-ACRS,JI)/TADFS
N      ADR.S=DCR.S
C      TADR.S=0.25
A      ADD.S.K=LOS.K/ADR.S.K
A      EDDS.K=SMOOTH(ADD.S.K,TADD.S)
C      TADD.S=0.25
A      ODDS.K=MAX(NPDS,EDDS.KI)
L      SCMS.K=SCMS.J+DT*(DRS,JK-CRS,JK)
N      SCMS=N*SCMS
C      NSCMS=900E3
L      ACR.S.K=ACR.S.J+DT*(CRS,JK-ACRS,JI)/TACRS
N      ACR.S=CRS
C      TACRS=0.25
L      PACRS.K=PACRS.J+DT*(ACRS,JI-FACRS,JI)/TPACRS
N      PACRS=CRS
C      TPACRS=1
A      LTF.S.K=ACRS.K+AFP.S.K*(ACRS.K-FACRS.K)/TACRS
A      AFP.S.K=FLF.S*ODDS.K+FFPS
C      FFPS=0.06
C      FLF.S=0.6
R      RA.KL=RE,JK+(CRS,JK-RE,JK)/(MYWS*TA)
N      RA=DCR.S
R      RB.KL=BOX(RA,JK,LA,K)
R      RC.KL=BOX(RB,JK,LB,K)
R      RD.KL=BOX(RC,JK,LC,K)
R      RE.KI=BOX(RD,JK,LD,K)
R      RF.KL=BOX(RE,JK,LE,K)
C      TA=0.25

```

C NYWS=5 (5 YEARS)
 A SCFS.K=LD.K/TA
 A SATFS.K=(LA.K/TA)+(LD.K/LE.K)
 A FC)TS.K=SWITCH(ACRS.K,0,SFMS-1)
 X1 +SWITCH(LTFS.K,0,SFMS-2)
 X2 +SWITCH(SCFS.K,0,SFMS-3)
 X3 +SWITCH(SATFS.K,0,SFMS-4)
 C SFMS=1
 N =C)TS=DCRS
 A DLS.K=WPCFS*FC)TS.K+SLFS*SCRT(FC)TS.K)
 X1 +FMCLTS*Q)DS.K*FC)TS.K
 X2 +BSFS*SQRT(FC)TS.K*FC)TS.K+VLS+C)DS.K*VCS)
 C WPCFS=0.04
 C SLFS=70
 C FMCLTS=0.5
 C VLS=0.0016
 C VCS=4E9
 C BSFS=2
 A DRS.K=MAX(0,OBSS.K+FC)TS.K+(MDS.K)
 A OBSS.K=(DLS.K-SCMS.K)/Q)DS.K
 A EU)S.K=(FC)TS.K+OBSS.K)*C)DS.K
 A D)MDS.K=(EU)S.K-U)S.K)/TAC)MDS.K
 A TAC)MDS.K=SWITCH(CTAC)MDS,C)DS.K,SAR)S)
 C CTAC)MDS=0.13
 C SAR)S=1
 NOTE STEEL CONSUMPTION - AN EXCESSIVE VARIABLE
 R CRS.KL=MIN(SCMS.K/DT,DCRS.K)
 A DCRS.K=CRCS+A)CS*SIN(6.283*TIME.K)
 X1 +A)CS*SIN(6.283*TIME.K/DECS)
 X2 +M)RTS*SAMPLE(I)CRS.K,0.25,T)CRS.K)
 A T)CRS.K=TAB)I(T)CRS,TIME.K,0.16,0.25)
 C CRCS=0
 C A)CS=0
 C DECS=5
 C M)RTS=4000
 T T)CRS=705.4,738.5,592.3,592.7,597.8,599.7,
 X1 562.3,591.1,622.1,664.5,583.2,629.3,641.2,
 X2 691.3,658.9,743.7,737.9,778.1,661.5,740.0,
 X3 809.9,806.9,663.1,690.3,818.4,796.0,703.3,
 X4 619.4,745.0,754.8,640.2,772.0,814.7,809.7,
 X5 742.6,813.8,919.0,907.1,781.7,744.9,897.8,
 X6 863.1,792.8,765.2,903.8,880.4,810.3,837.8,
 X7 894.7,984.4,877.2,1046.7,895.984,877,1047,
 X8 895,984,877,1047,895,984,877,1047,895
 C DT=0.01
 C LENGTH=16
 C PR)PER=0.25
 C PL)PER=0.1
 NOTE SUPPLEMENTARY EQUATIONS AND OUTPUT CONTROL CARDS
 S Q)DWS.K=Q)DS.K*52
 A NKUSS.K=SCMS.K*52/Q)CRS.K
 A Y)CRS.K=SRA(CRS.K,Y)PS.K)
 A Y)DRS.K=SRA(DRS.K,Y)PS.K)

```

A      YAORS.K=SRA(NRS. JK, YPS. K)
A      YPS.K=1
A      QACRS.K=SRA(CRS. JK, QPS. K)
A      QADRS.K=SRA(NRS. JK, QPS. K)
A      QADRS.K=SRA(URS. JK, QPS. K)
A      QPS.K=0.25
PRINT CRS,DRS,ORS,SCMS,WIPS,FCOTS,UOS,DSL, ADDS
PRINT ACRS,PACRS,SPRS,NWUSS,CACRS,QADRS,QADRS
PRINT GDDS,EDDS,OBSS,EUOS,OMDS,YACRS,YADRS,YADRS
PRINT QDDWS,RF,USOS
PLOT  CRS=C,QACRS=1,CRS=C,QACRS=2,CFS=D,CACFS=3
X1     SPRS=P(N,*)/SCVS=S,WIPS=w(N,*)/NWUSS=N(N,*)
PLOT  SCMS=S,DSL=L,WIPS=w(N,*)/QDDWS=C(O,*)/
X1     CRS=*,FCOTS=F,NRS=D,SPRS=F,CFS=D(O,*)
RUN   U.K. SHEET STEEL - SS04

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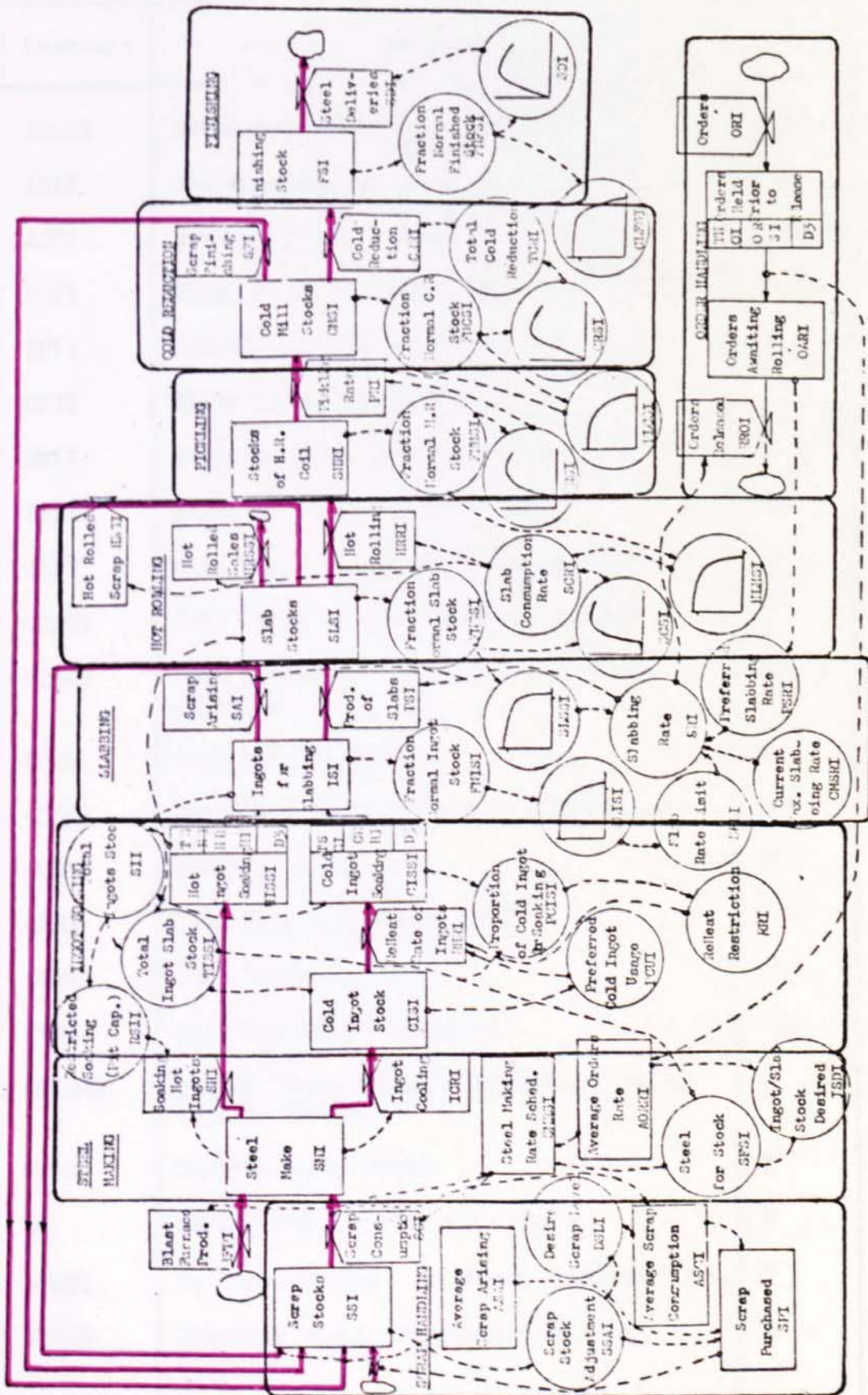
The Production Dynamics Model simulates the material flow and control procedures in a strip mill. The flow diagram in Appendix 2.2 shows the conservative material flow from scrap handling to steel delivery. Steel is delivered as Hot Rolled or Cold Reduced Coil.

The diagram has been simplified to aid understanding; constants have been omitted and descriptions are not attached to table related variables. Where one variable is related to another by an arbitrary function, specified by a table, the relationship has been shown by a curve and the variable name description omitted.

"Valve like" symbols indicate rates of flow. Rectangles indicate level variables; integrations. Circles indicate auxiliary variables which form part of the information network and form part of the "rate of flow" computation.

Each mnemonic is listed in Appendix 2.3 together with a brief description and the units in which the variable is expressed. The units are; Tonnes (T), Tonnes per Week (T/W), Tonnes per Week per Week (T/W/W) or are dimensionless (D). Names which appear in the model listing in Appendix 2.4 and which are reserved for use by the simulation language, DYNAMO, are described as "DYNAMO Terms". These names are control variables and special functions.

The model equations can be compiled using DYNAMO II/Version 3 or 4). A, R and L equations are sorted and executed each iteration by DYNAMO. N equations are used only during the first iteration. S equations are used only for output purposes.



Mnemonic	Description	Units
AORRI	Average Orders Received Rate	T/W
ASAI	Average Scrap Arising	T/W
ASCI	Average Scrap Consumption	T/W
BFPI	Blast Furnace Production	T/W
BP1I	Slabbing Breakdown Period (1)	W
BP2I	Slabbing Breakdown Period (2)	W
BS1I	Slabbing Breakdown Start (1)	W
BS2I	Slabbing Breakdown Start (2)	W
CISI	Cold Ingot Stocks in Stocking Yard	T
CISSI	Cold Ingot being Reheated (Soaked)	T
CLFSI	Cold Reduction Limited by Finishing Capacity	T/W
CISI	Cold Mill Stocks	T
CMSRI	Current Maximum Slab Rate (Breakdowns)	T/W
CORI	Constant Order Rate	T/W
CRHI	Cold Ingots Reheated Rate	T/W
CRRI	Cold Reduction Rate	T/W
CRSI	Cold Reduction Scheduled	T/W
DELAY3	DYNAMO Term; Function creating a delay with three levels	-
DSLI	Desired Scrap Level	T
DT	DYNAMO Term; Iteration Interval	W
FNCSI	Fraction Normal C.R. Stock for Reduction	D
FNFSI	Fraction Normal Finished Stock for Dispatch	D
FNESI	Fraction Normal H.R. Stock for Pickling	D

Inemonic	Description	Units
FHISI	Fraction Normal Ingot (Soaked) for Slabbing	D
FHSSI	Fraction Normal Slabs for Hot Rolling	D
FSHRI	Fraction for Sale of H.R. Coil	D
FSI	Finishing Stock; C.R. Coils and Sheets	T
FYI	Finishing Yield	D
HISSI	Hot Ingots Soaking (Directly Heated Ingots)	T
HLHSI	Hot Rolling Limited by H.R. Stocking Capacity	T/W
HRHI	Hot Ingots Reheated Rate	T/W
HRRI	Hot Rolling Rate (for Cold Reduction)	T/W
HRSI	Hot Rolled Scrap Rate	T/W
HRSSI	Hot Rolled Sales Rate	T/W
HTI	Height of Step Input Function	T/W
ICRI	Ingot Cooling Rate	T/W
IPRI	Total Ingot Production Rate	T/W
ISDI	Ingot Slab Stock Desired	T
ISI	Ingots Awaiting Slabbing	T
IYI	Ingot Yield	D
LENGTH	DYNAMO Term; Simulation Finish Time	W
ICRSI	Maximum Cold Reduction Rate (Mill Limitation)	T/W
IHRRI	Maximum Hot Rolling Rate (Mill Limitation)	T/W
IPRI	Maximum Pickling Rate (Mill Limitation)	T/W
MSDI	Maximum Steel Deliveries (Dispatch Rate)	T/W
MSI	Maximum Steel being made	T

Mnemonics	Description	Units
MSPCI	Maximum Soaking Pit Capacity	T
MSRI	Maximum Slabbing Rate (Mill Limitation)	T/W
MSR1I	Maximum Slabbing during Breakdown 1	T/W
MSR2I	Maximum Slabbing during Breakdown 2	T/W
MCSI	Normal Cold Mill Stock	T
MFSI	Normal Finishing Stock	T
MHSI	Normal Hot Rolled Stock	T
MISI	Normal Ingots Awaiting Soaking	T
MORNERD	DYNAMO Term; Function creating Random Numbers	-
MSSI	Normal Slab Stock	T
MWCSI	Number of Weeks Use Held as Slab Stocks	W
MWSDI	Number of Weeks Use Ingot Slab Stock Desired	W
OARI	Orders Awaiting Rolling	T
ORI	Orders Received	T/W
ORSI	Orders Released for Rolling	T/W
PCISI	Proportion of Cold Ingots in Soaking Pits	D
PCUI	Preferred Cold Ingot Usage	T/W
PLCSI	Pickling Rate Limited by C.R. Stocking	T/W
PLOT	DYNAMO Term; Indicates Plot Variables	-
PLTPER	DYNAMO Term; Plotting Interval	W
PRI	Pickling Rate	T/W
PRINT	DYNAMO Term; Indicates Print Variables	-
PRTPER	DYNAMO Term; Print Interval	W
PRSI	Pickling Rate Scheduled	T/W

Incononics	Description	Units
PSCI	Preferred Proportion of Cold Ingots in Soaking	D
PSI	Production of Slabs	T/W
PSRI	Preferred Slabbing Rate	T/W
RAMP	DYNAMO Term; Function creating growth variable	-
RHERI	Reheat Rate of Ingots from Cold	T/W
RRI	Reheating Restricted	T/W
RROI	Rate of Rolling Orders	T/W
RSII	Restricted Soaking due to Pit Capacity	T/W
RUN	DYNAMO Term; Causes Execution of Model	-
SAI	Slab Scrap Arisings	T/W
SAMPLE	DYNAMO Term; Function Sampling Variables	-
SCI	Scrap Consumption Rate	T/W
SCRI	Slab Consumption Rate	T/W
SCSI	Slab Consumption Scheduled	T/W
SCSMI	Fraction Scrap Consumed in Steel Making	D
SDI	Steel Deliveries (Dispatch Rate)	T/W
SDOI	Standard Deviation of Order Rate	T/W
SE1I	Slabbing Breakdown Extent (1)	T/W
SE2I	Slabbing Breakdown Extent (2)	T/W
SFI	Scrap created during Finishing Processes	T/W
SFSI	Steel for Stock	T/W
SHI	Soaking of Hot Ingots	T/W
SHRI	Stocks of Hot Rolled Coil for Cold Reduction	T
SII	Total Ingot Stocks	T

Mnemonic	Description	Units
SLISI	Slabbing Limited by Ingot Stocks	T/W
SLPI	Slope of Optional Ramp Input Demand	T/W/W
SLSI	Slab Stock Level	T
SLSSI	Slabbing Limited by Slab Stocking	T/W
SII	Steel in Process of Manufacture	T
SMOOTH		
SMRSI	Steel Making Rate Scheduled	T/W
SPI	Scrap Purchasing Rate	T/W
SRI	Slabbing Rate	T/W
SRLI	Slabbing Rate Limitation	T/W
SSAI	Scrap Stock Adjustment	T/W
SSI	Scrap Stock Level	T
SSTI	Start of Step Input Demand	W
STEP	DYNAMO Term; Function creating step ingot	-
STI	Start of Ramp Input Demand	T
SYI	Slabbing Rate Yield	D
TABLE		
TAORI	Time to Average Orders Received	W
TASIRI	Time to Adjust Steel Making Rate	W
TASRI	Time to Adjust the Scrap Stock Level	W
TBISI	Time to Build Ingot-Slab Stocks	W
TCLFSI	Table of Values, C.R. Limited by Stocking	D
TCRI	Total Cold Reduction	T/W
TCRSI	Table of Values for C.R. Scheduled	D
THLMSI	Table of Values for H.R. Limited by Stocking	D

Mnemonic	Description	Units
THOI	Time to Hold Orders Prior to Release to Works	W
TIME	DYNAMIC Term; Independent Variable	W
TISSI	Total Ingot and Slab Stock	T
TISPI	Time to Load Soaking Pit	W
TPLSSI	Table of Values for Limiting Pickling	D
TPPI	Time to Purchase Scrap	W
TPRI	Table of Values for Pickling Schedule	D
TRCII	Time Preferred to Reduce Cold Ingot Stocks	W
TROI	Time Preferred to Hold Orders	W
TRSMI	Time to Reduce Steel Make by Unloading Cold Ingots	W
TSAI	Total Scrap Arising	T/W
TSCI	Time to Soak Cold Ingots	W
TSCSI	Table of Values for Slabbing Schedule	D
TSDI	Table of Values Determining Delivery Rate	D
TSHI	Time to Soak Hot Ingots	W
TSLISI	Table of Values for Ingot Limited Slabbing	D
TSLSSI	Table of Values for Slabbing Limit	D
TSSAI	Time to Adjust Scrap Stocks	W
TSMI	Time to Produce Ingots	W

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NOTE ORDER HANDLING
R   ORI.KL=CORI+RAMP(SLPI,STI)+STEP(HTI,SSTI)
X1  +SAMPLE(NORMRN(0,SDDI),1,0)
C   CORI=50000
C   SLPI=200,STI=100
C   SSTI=100,HTI=5000
C   SDDI=10000
R   ORSI.KL=DELAY3(ORI.JK,THOI)
C   THOI=4
L   OARI.K=OARI.J+DT*(ORSI.JK-RROI.K)
N   OARI=ORI*TROI
C   TROI=2
R   RROI.KL=SRI.K
A   PSRI.K=OARI.K/TROI
NOTE SLABBING AND INGOT STOCKS
L   CISI.K=CISI.J+DT*(ICRI.JK-RHRI.K)
N   CISI=0
S   IPRI.K=SHI.JK+ICRI.K
R   ICRI.KL=MAX(0,(SMI.K-MSI)/TRSMI)
C   MSI=2000
C   TRSMI=0.05
R   SHI.KL=MAX(0,MIN(RSII.K,SMI.K/TWSMI))
C   TWSMI=0.025
R   HRHI.KL=DELAY3(SHI.JK,TSHI)
C   TSHI=0.03
L   HISSI.K=HISSI.J+DT*(SHI.JK-HRHI.K)
N   HISSI=PSRI*TSHI
A   PCUI.K=CISI.K/TRCII
C   TRCII=0.5
R   RHRI.KL=MAX(0,MIN(RSII.K,MIN(PCUI.K,RRI.K)))
N   RHRI=0
R   CRHI.KL=DELAY3(RHRI.JK,TSCI)
C   TSCI=0.1
L   CISSI.K=CISSI.J+DT*(RHRI.JK-CRHI.K)
N   CISSI=0
A   RSII.K=(MSPCI-SII.K)/TLSPI
C   MSPCI=3500
C   TLSPI=0.001
L   ISI.K=ISI.J+DT*(HRHI.JK+CPhi.JK-PSI.JK-SAI.JK)
N   ISI=NISI
A   TISSI.K=SII.K+CISI.K+SLSI.K
A   SII.K=ISI.K+HISSI.K+CISSI.K
A   RRI.K=MSPCI*(PSCI-PCISI.K)/TSCI
C   PSCI=0.2
A   PCISI.K=CISSI.K/SII.K
A   SRI.K=MAX(0,MIN(SRLI.K,PSRI.K))
A   SRLI.K=CMSRI.K*MIN(SLSSI.K,SLISI.K)
A   SLISI.K=TABLE(TSLISI,FNISI.K,0,2,0.4)
T   TSLISI=0,0.4,0.75,0.95,0.90,0.85
A   FNISI.K=ISI.K/NISI
C   NISI=750
A   SLSSI.K=TABLE(TSLSSI,FNSSI.K,0,2,0.4)
T   TSLSSI=1.5,1.4,1.3,1.2,0.8,0
R   PSI.KL=SRI.K*IYI
R   SAI.KL=SRI.K*(1-IYI)
C   IYI=0.88
A   CMSRI.K=SE1I.K+SE2I.K

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A      SE1I.K=SAMPLE(MSR1I,BS1I,MSRI)
X1     +SAMPLE(MSRI-MSR1I,BP1I+BS1I,0)
A      SE2I.K=SAMPLE(MSR2I-MSRI,BS2I,0)
X2     +SAMPLE(MSRI-MSR2I,BP2I+BS2I,0)
C      MSR2I=0,BS2I=21,BP2I=0.6
C      MSR1I=0,BS1I=3.5,BP1I=0.4
C      MSRI=65000 TONS/WEEK
NOTE STEEL MAKE
L      SMI.K=SMI.J+DT*(SCI.JK+BFPI.JK-SHI.JK-ICRI.JK)
N      SMI=ORI*TWSMI
A      SMRSI.K=SMOOTH(AORRI.K-ICRI.JK+SFSI.K,TASMRI)
C      TASMRI=2
C      NWSDI=1
A      SFSI.K=(ISDI.K-TISSI.K)/TBISI
C      TBISI=1
A      ISDI.K=AORRI.K*NWSDI
A      AORRI.K=SMOOTH(ORSI.JK,TACRI)
C      TACRI=13
R      BFPI.KL=SMRSI.K*(1-SCSMI)
R      SCI.KL=SMRSI.K*SCSMI
C      SCSMI=0.32
NOTE SCRAP HANDLING
L      SSI.K=SSI.J+DT*(SPI.JK-SCI.JK+SAI.JK+HRSI.JK+SFI.JK)
N      SSI=DSL I
A      DSLI.K=ASCI.K*NWCSI
C      NWCSI=2.5
A      ASCI.K=SMOOTH(SCI.JK,TASRI)
A      ASAI.K=SMOOTH(SAI.JK+HRSI.JK+SFI.JK,TASRI)
C      TASRI=13
A      SSAI.K=(DSLI.K-SSI.K)/TSSAI
C      TSSAI=13 WEEKS
R      SPI.KL=MAX(0,SMOOTH(SSAI.K+ASCI.K-ASAI.K,TPPI))
C      TPPI=13
S      TSAI.K=SAI.JK+HRSI.JK+SFI.JK
NOTE HOT ROLLING AND FINISHING
L      SLSI.K=SLSI.J+DT*(PSI.JK-HRRI.JK-HRSI.JK-HRSSI.JK)
N      SLSI=NSSI
A      FNSSI.K=SLSI.K/NSSI
C      NSSI=25000
A      SCRI.K=MHRI*MIN(SCSI.K,HLHSI.K)
A      SCSI.K=TABLE(TSCSI,FNSSI.K,0,2,0.4)
T      TSCSI=0,0,0.75,0.95,0.90,0.80
C      MHRI=60000
A      HLHSI.K=TABLE(THLHSI,FNHSI.K,0,2,0.4)
T      THLHSI=1.2,1.2,1.1,1,1,0
R      HRRI.KL=SCRI.K*SYI*(1-FSHRI)
R      HRSSI.KL=SCRI.K*SYI*FSHRI
R      HRSI.KL=SCRI.K*(1-SYI)*(1-FSHRI)
C      FSHRI=0.55
C      SYI=0.96
L      SHRI.K=SHRI.J+DT*(HRRI.JK-PR I.JK)
N      SHRI=NHSI
A      FNHSI.K=SHRI.K/NHSI
C      NHSI=25000

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R      PRI.KL=MPRI*MIN(PRSI.K,PLCSI.K)
T      TPRI=0,0,0.75,0.95,0.90,0.80
A      PRSI.K=TABLE(TPRI,FNHSI.K,0,2,0.4)
A      PLCSI.K=TABLE(TPLSSI,FNCSI.K,0,2,0.4)
T      TPLSSI=1.5,1.4,1.2,1,0.6,C
C      MPRI=25000
L      CMSI.K=CMSI.J+DT*(PRI.JK-CRRI.JK-SFI.JK)
N      CMSI=NCSI
A      FNCSI.K=CMSI.K/NCSI
C      NCSI=35000
R      SFI.KL=TCRI.K*(1-FYI)
A      TCRI.K=MIN(CRSI.K,CLFSI.K)*MCRSI
A      CRSI.K=TABLE(TCRSI,FNCSI.K,0,2,0.4)
T      TCRSI=0,0,0.75,0.95,0.90,0.80
A      CLFSI.K=TABLE(TCLFSI,FNFSI.K,0,2,0.4)
T      TCLFSI=1.5,1.4,1.3,1.2,1.1,0
C      MCRSI=25000
R      CRRI.KL=TCRI.K*FYI
C      FYI=0.88
L      FSI.K=FSI.J+DT*(CRRI.JK-SDI.JK)
N      FSI=NFSI
A      FNFSI.K=FSI.K/NFSI
C      NFSI=35000
R      SDI.KL=MSDI*TABLE(TSDI,FNFSI.K,0,2,0.4)
T      TSDI=0,0.35,0.75,0.95,0.85,0.75
C      MSDI=25000
NOTE  CONTROL STATEMENTS
C      DT=0.005
C      LENGTH=52
N      TIME=-5
C      PRTPER=0
C      PLTPER=0.5
PRINT ORI,SRLI,FSI,OARI,CMSRI,SDI,SAI,SFI
PRINT CISI,SMRSI,ICRI,SPI,SHI,BFPI
PRINT SMI,SSAI,SCI,HRHI,SRI,RHRI,SSI,CRHI
PRINT ASAI,ASCI,RSII,ISI,SLSI,SII
PRINT HRRI,PSI,HRSI,RROI
PLOT  SCI=C,BFPI=B,SRI=*,ORI=0,ICRI=I,SHI=S
X1    IPRI=P,RHRI=R(0,80000)/CISI=Y(0,40000)
PLOT  SPI=P,SCI=C,SAI=S,HRSI=H,SFI=F,
X1    TSAI=A(0,20000)/SSI=*(0,60000)/SPI=2(0,*)
PLOT  ORI=0,SDI=D,SRI=S,HRHI=H,SMI=M,RROI=*(0,*)/
X1    OARI=A(0,*)/RSII=I(0,*)
PLOT  PSI=S,HRHI=H,PRI=P,CRRI=C,SDI=D(0,*)/SLSI=L,
X1    SHRI=R,CMSI=M,FSI=F(0,*)
PLOT  HRHI=H,CRHI=C,PSI=S(0,*)/ISI=A,SII=T,CISSI=I,
X1    HISSI=R(0,*)
RUN   PKSM04

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AUTHOR	BRIEF NAME	COMPUTER IMPLEMENTATION	DATE	FEATURES	
Morhouse et al (50)	-	-	1950	Paper on Electro-analog simulation in economic dynamics	
Selfridge (51)	-	IBM 704	1955	Digital analog simulation	
Anderson & Johnson (59)	NIDA	IBM 704	1956	Digital integration simulation	
Lesh (60)	DEP 1	DATATRON 204	1958	Small digital computer	
Hurley (6)	DEP 1	IBM 704	1959	Rewrite on larger machine	
Stein et al (62)	ASTRAL	IBM 704	1958	FORTTRAN generated, automatic equation sorting	
Theodoroff (63)	DYANA	IBM 704	1958	FORTTRAN engineering CSSL	
Bennet	} See Pugh (23)	SIMPLE	IBM 704	1958	Macro expanding, I.D. models
Fox		DYNAMO	IBM 704	1959	Equation forms and checks improved
Hurley & Skiles (64)	DYSAC	CDC 1604	1961	Block oriented, extensive functions	
	BLOC		1964	Series of similar compilers	
Janoski (65)	COBLOC	CDC 1604/3600	1966	Hybrid simulator, logical blocks	
Vebber	FORBLOC			DYSAC to FORTRAN Translator	
Hurley	HYBLOC	IBM 7090		Hybrid simulation	
Rideout & Tavernini (66)	MALBLOC	IBM 7040 UNIVAC 1107	1965	Uses MAD language	
Gaskill et al (67)	DAS	IBM 7090	1962	Programming ease, translated into assembler but without sorting	
Harnet et al (68)	MIDAS	IBM 7090	1963	Widely used, sorting of equations, variable step size	
Sansom (69)	MIMIC	IBM 7090	1965	FORTTRAN algebra plus blocks. Direct compilation into M/C code	

AUTHOR	BRIEF NAME	COMPUTER IMPLEMENTATION	DATE	FEATURES
Hughes et al (70)	SAM	Mercury	1966	U.K. - Autocode analog simulation
Dinely et al (71)	DALDAS	KDF 9	1966	U.K. - ALGOL based
Syn & Wyman (72)	DSL	IBM 7090, 7040 1130, 1800 360 Series	1964	IBM supported, widely used, available on main IBM computers
IBM	CSMP	1130, 360 1370	1967	CSMP/360, CSMP III widely used, latter with extensive facilities
<p>Simulation Software Committee (53) of Simulation Council, Inc., propose CSSL standard: Communication language for Continuous System Simulation</p>				

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