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THE DYNAMICS OF GROWTH OF A SMALL COMPANY

by

DAVID JOHN HOWARD

B. Eng., McGill University
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Signature of Author ______________________
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Certified by ______________________
Thesis Supervisor

Accepted by ______________________
Chairman, Departmental Committee on Graduate Students

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Submitted to the Department of Electrical Engineering on January 16, 1961, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

During the stages of birth and early growth of a new company, the policies of its managers are critical in determining success or failure. Although each new company is a special case, most have many elements and structures in common, and have, therefore, similar kinds of problems. Among these are the allocation of resources to the various activities within the organisation, and the timing of the allocations which will produce the best results. A study is made of a typical company situation with the object of creating a vehicle with which the structure and policies of such a company may be analysed.

Using the methods of Industrial Dynamics, a dynamic non-linear (in the engineering sense) mathematical model is constructed to show the company as an information-feedback system. A particularly successful new research-oriented electronics company is used as a guide in the construction. Since a mathematical solution is not feasible, the company behaviour is simulated under hypothetical conditions by running the model on a digital computer. The bulk of the work presented is devoted to finding and defining the important elements of the company structure, and the mechanisms which link them. The results of a sample run are discussed.

Thesis Supervisor: Professor Jay W. Forrester
Title: Professor of Industrial Management.

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I The Problem

The problems of managing a company and deciding on its policies are complex and subtle, and require a constant re-evaluation if continuous control is to be excercised. Any general approach to solving these problems, therefore, is necessarily also complex, and must allow for time-varying quantities in the solution.

It may be sufficient in particular isolated cases to formulate an inventory re-order rule which will simultaneously minimise the cost of inventory and the cost of run-outs. This is a static approach, and the results are valid only for those conditions obtaining when the rule was formulated; it may be sufficient for practical purposes. However, the function of senior management is to know the behaviour of the separate parts, and to devise for the parts policies which are consistent with the overall objectives of the company. In the vernacular of the electrical engineer, management is responsible for setting the parameter values and time constants in the black boxes of a system in such a way that the overall behaviour with time of the system is consistent with specifications. Finding the best possible static solution to a problem, such as a particular inventory, is not necessarily acceptable from this point of view, because it may set up undesirable side effects in other parts of the organisation, and more often than not the nature of this induced behaviour is not understood locally. Furthermore, it is a truism that the behaviour of any feedback system containing delays is largely dependent on the relative sizes of the delays, and that any intelligent decision made within the system must consider them. A general approach to the problems of company management, therefore, must be based on an overall study of the time-varying interactions between the constituent parts of the structure[3].

The most obvious application of the engineering feedback system analogy is to an established company, say a manufacturing company, neither growing nor dying but involved in routine daily operations. According to implicit or overt decisions, orders are received and processed, finished goods are shipped, materials are ordered and received, labour is employed and laid off, capital equipment is purchased and retired, and money is received and disbursed. Superimposed on all these activities is an information flow pattern which consists of the data which are the sources of decisions, and the data describing the results of the decisions. This might be termed the steady state situation, in spite of the fact that some variables may be very active; a more perilous definition might be 'dynamic steady state'.

The analogy is also applicable to the transient situation, which is the birth and growth of a new company. Beginning with an a priori concept of the future structure of the organisation, one can say that all the variables are present but most have zero values. The initial conditions might include a small group of people, a sum of money, and a set of objectives which incidentally define, to a greater or lesser degree, the framework which the company will assume. The company then grows into the structure defined. The problem now becomes the establishment of policies which will guide the company as smoothly or as profitably or as quickly as possible in the attainment of its stated objectives. The approach is similar to that for an established company because the essences of the two problems are fundamentally the same: the control of the behaviour of an information-feedback system.

There are certain differences between the transient and the steady state situations, but these are concerned with the way that attention is divided among the different activities of the company. For example, an established company might want to choose between two pieces of new equipment and might make the decision on the basis of the long-term return on investment, regardless of the size of the investment. The new company might be faced with the same choice, but would probably decide on the basis of how quickly results could be obtained with a minimum investment, operating on the principle that funds will be more plentiful later and credit is tight now. A more important difference between the two situations is to be found in the effects of the quantity and timing of management supervision. In the new company the investment of time and effort by management in a certain activity can produce immediate and dramatic results. In the older company the effects of such management attention are not disseminated as quickly through the system, and the absence of it will not necessarily bring severe or rapid consequences.

The present study is concerned with a typical new company situation. An attempt is made to define a structure which includes the important elements present in the real system, and which will exhibit, when simulated, behaviour which is plausible in the light of experience gained so far.

II The Approach

Industrial Dynamics is a formalised approach to the study of industrial and economic systems[4]. Through its application, the detailed structure of a system emerges in such a way as to emphasise the nature of the relationships existing between the various parts, enabling management to analyse quickly and economically the effects of any proposed policy. The procedure employed is, briefly, as follows.

The area to be studied is defined as carefully as possible. Care must be taken to ensure that no variable is considered exogenous if its value is in fact partially or completely determined be the behaviour of the system under study. A period of familiarisation follows to allow the structure to be defined, and work then begins on the formulation of the model. The first set of variables to be recognised are the 'levels'; these are inventories, backlogs, bank balances, etc., including all those quantities which would continue to have values if all activity were brought suddenly to rest. The levels are then joined together by flows, or 'rates', which include money, materials, finished goods, manpower, orders, and capital equipment. Delays are then inserted in the flows where appropriate, creating new levels in the process. The final stage in the formulation is the most subtle: the decision mechanisms controlling the rates of flow are determined. These decisions make use of fixed parameters and information generated elsewhere in the system, and in this way the information flow pattern is added to the model. The equations for these rates are sequential (i.e., non simultaneous) in character.

A run on a model of this kind comprises a series of complete solutions of all the equations present, the series being long enough to cover a predetermined number of months or years of system operation. Each solution is separated in time from the last by an interval which is a small fraction of the shortest delay encountered in the model. The results of runs are analysed and parameters, decisions and structure are changed until further runs yield behaviour which is realistic in a qualitative sense; that is to say, the frequency spectra, oscillation periods, and phase and amplitude relationships generated by the model should agree with what is known about the real world. When confidence has been gained in the model by these means, this model may be used to analyse the effects of whatever changes might be contemplated in the real system. A more general benefit to be gained from the model is that by the application of the principles of feedback-control system analysis the areas of weakness and sensitivity may be located.

The Industrial Dynamics method has been applied in the recent past, and is currently being applied, to a number of hypothetical and actual situations. These studies include: a production-distribution system of manufactured goods[1,2,11]; a situation dealing with the marketing of a dairy product; the manufacturing and marketing of a food product derived from crops; the steam turbine industry and its relationship with the electrical utility industry; the manufacturing problems associated with a particular line of high-quality electronic components[8,9]; the general problem of the management of research and development[10]; and the manufacture of commercial aircraft, to mention a few.

A special-purpose compiler, DYNAMO[5,6,7], has been developed by the Industrial Dynamics Group to generate these models on the IBM 704 and 709 computers. DYNAMO accepts instructions and equations in any of approximately seventy standard forms, and by recognising the forms generates pre-established codes for their solution. It also recognises some functional forms (e.g., TABLE and DELAY3 used in Chapter 2) for which it generates the necessary equations as well as the codes for solving them. The method of presenting the formulations in Chapter 2 has been determined in some cases by the demands of DYNAMO.

Equations are divided into a number of classes, depending on the nature of the variables they define. The equations developed in Chapter 2 have been labelled as follows:

A - Auxiliary

C - Constant

L - Level

N - Initial value or computed constant

R - Rate.

CHAPTER 1

Description of the Company.

The company situation studied in this report is to some extent hypothetical, but is largely based on a new electronics company founded three years ago in Massachusetts. It was started by a nucleus of two or three highly competent men, and after two years employed roughly eighty people. Nine months after it was founded it broke even and began to show a profit; one year later it showed a loss for a short while, and then reverted to being a singularly successful operation. That this could happen in the absence of any changes in basic policy and in apparent contradiction of the current efforts of the company was intriguing, from an academic viewpoint at least, but this kind of behaviour, among others, is not difficult to explain in the frame of reference suggested by the Industrial Dynamics approach.

The company was started by two men. They had a good engineering background and better than average experience. They had ideas for several products, and some of these were so clear that the research and development work might be said to have been done. All that was left to be done was the final design. The men were relatively well known in their field, and the market was, for all practical purposes, unlimited.

The capital was provided by an investing corporation, a site was chosen, a few more qualified men were enlisted, and the company was born.

The type of product initially chosen was what is known as a digital building block. This includes square-wave generators, counters, buffer amplifiers, current sources, and other units designed to fit into a variety of digital electronic systems. The units were all relatively simple in conception, and were chosen primarily for this reason. The objectives of the company regarding its products are, however, much broader than the list of initial products would indicate. The talent was available to enable the company to expand into all kinds of digital information-processing systems, including computers and their components. Furthermore, it was hoped that the research and development function could be expanded to the point where it could become the dominant activity; that is, the company would become more and more involved with special projects.

With a knowledge of these plans it is possible to define the structure into which the company will probably develop. Four main areas of activity are indicated: engineering, production, sales, and management, the last including accounting and general administration.

The engineering group perform work which can be roughly divided into three sub-activities. The first is the creation of new product ideas. The second, allied to the first, is the screening of ideas which come from other areas, such as the customers. The third is the conversion of acceptable ideas into designs, which is the most easily measurable of the functions performed, and which may be considered for accounting purposes as productive of revenue, particularly if the ideas are patented.

The function of the production department is to convert designs into finished goods. This production is clearly dependent on the existence of designs, and the rate of production is indirectly a function of the number of completed designs.

The sales sector of the company is engaged in finding customers and generating orders. In order to function, the sales group must be able to offer designs and samples, and its selling effectiveness is enhanced by the number of ideas and designs the company has, as well as by the size of its inventory and, by inference, its ability to deliver. In defining the function of the sales force the nature of the customer must be considered. This can be hypothesised from a consideration of the product to be sold, and will be characterised by a long acceptance delay. Furthermore, since the product is assumed to be of high quality and good design, the aggregate of all potential customers will send orders in proportion to the amount of selling effort (publicizing and demonstrating) expended by the company. This assumption is supported by the acceptance criteria applied to the product in the first place.

The management activity of the company assumes the role of coordinator of effort. Initially, management exists alone, and the president and vice-president make the designs, build the prototypes, and find the customers. As the size of the staff increases, the managers divide their time among the various activities, tending to emphasize their attention where it appears to be needed most. Until the company has reached some stage of quasi stable operation, possibly several years after formation, the management does very little in the way of administration, policy-making, or overall control, but spends most of its time actively working in the various departments. This allocation of management time is possibly the greatest single problem encountered by a company of this type.

A number of other problems face a new company, some of them being peculiar to new companies, others being ubiquitous. One problem concerns the acquiring and training of new personnel. It is commonly accepted that the value of an employee is an increasing function of the time and money spent on finding him; a new company, whose management is fully occupied with daily operations, must face the problem of allocating time (or money, or both) to this function. There are also alternatives to be faced in the internal organisation of the company which can, for instance, be functionally or project-oriented. In the first case a department performs an operation on an article and passes it onto the next department. In the second case, a group is assigned a project and is made responsible for all phases from design to marketing. A recurring problem concerns the choice of projects or products on the basis of the type of investment required for each. Some products require a high initial investment and, after a gestation period, produce sustained revenue. Other products require little initial investment, a greater investment just prior to marketing, but may produce revenue for only a short period. One further problem should be mentioned for it occurs consistently in research-oriented organisations: it is the problem of whether to capitalise money spent on research, or whether to charge it to current expenses. Each alternative has both advantages and disadvantages which depend not only on the current operating condition of the company but on the direction of its development and on its policies.

These are the kinds of problems which arise in the course of company growth. When a model is to be built to analyse a company situation, the choice of questions to be asked will determine the scope of the model. The obverse statement is axiomatic: one cannot ask of a model questions it was not designed to answer.

CHAPTER 2

Development of the Model.

I Introduction

As the model was constructed, two concepts were particularly difficult to define. The first concerns quantification of invested effort, and the second concerns the measurement of work done in terns of the finished product. These will be discussed before the model is developed.

The process of including a labour force in a model is commonly not difficult, because generally it is only in the most prominent area of activity that the labour force is of interest. In a factory making sub-assemblies, for instance, it is the production line labour which is least stable and most expensive; administrators, accountants, and clerks would be classed as overhead. The hiring and firing policies are the same for all workers because all their jobs are subject to the same forces. In the case of the growth situation mentioned here, however, the processes are more complex. In the first place, all four areas of activity (engineering, production, sales and management) are of interest. There is no single activity so prominent that it overshadows the rest, although there may be differences in importance. Since the nature of the work done in each sector differs from the others, there is no common productivity factor; hence the labour force must be split up and the parts accounted for separately. Furthermore, since the demand for labour is determined by different criteria in each sector, it may be necessary to formulate up to four separate hiring and firing policies. The situation is further complicated by the fact that managers are assumed to have a higher productivity than the others, and to affect the productivity of others by investing time in any particular sector. The formulation, if taken along these lines, is extremely complex.

A simpler approach is to define the concept of effective effort, and to measure it in terms of man-hours per week. Effective effort is hired in one place into a pool of unallocated effort, from where it is allocated to the various functions within the company, on the basis of existing demand. Individual people are not considered. The effort is completely fluid, in that it can be allocated in any proportions and reallocated in different proportions without the necessity of explicitly firing some people and hiring others. This is to a large extent justified in a new company by the assumption that the first officers and employees will be talented and flexible, and will do whatever work demands most loudly to be done. Effective effort, therefore, is the aggregate result of the direct work done by the officers and employees in a department, and the effect that the managers have on the productivity by their encouragement and coaching of the workers. Thus the problem of accounting for different types of labour wanted at different times to do different types of work has been simplified, the price being the loss of individuality of the workers and the consequent loss, perhaps, of the one-to-one correspondence with reality of each element in the model. The essence of the problem, however, is the allocation of effort and money; the people are incidental.

The second fundamental difficulty to be mentioned is that of accounting for the output of each department. What are the aggregate units that flow through a company which designs and manufactures only a line of hundred-dollar amplifiers one month, but adds a one-hundred-thousand dollar computer the next month. The productivities of the labour force will vary with a large number of input variables. One approach, used in some types of models, is to reduce all goods to their dollar equivalents, and to say that each department adds value at some rate to the goods. This is not satisfactory in a situation where there is a diversified line of products going through the same department, and where the value of each line is increased by different amounts. Since the distribution of products is not constant, further complications arise. The greatest objection, however, to using the dollar common denominator is that it is not dollars which are flowing, but ideas, designs, finished goods and orders for them.

Since the model will not be initially concerned with how each department reacts to each product line, the simplest approach is to define a basic unit of product. Thus, one unit of ideas might be defined as corresponding to a certain flip-flop oscillator. This gives rise to one design, which gives rise to as many units of production as are ordered. One unit of orders, or one order, is for one unit of finished product. On this scale a magnetic core memory tester might be worth fifty units of ideas, giving rise to fifty designs, and if a customer wanted to buy one he would send in fifty orders. A small computer might be worth a thousand units of ideas, and so on. The problem is now one of scaling each prospective product to fit the model; this is not of interest in the first stages of model formulation.

II Framework of the Model

The formulation of the model is best approached by defining a framework of all levels (backlogs, inventories, etc.) of interest. Once this is done, the scope of the problem is automatically determined. The levels are those variables which would continue to have real values if all activity were to come to a stop.

Figure 1 at the end of this section is a diagram of this framework. Starting at the point where the idea for a product enters the orbit of the company, the first level encountered is the backlog of available ideas. This variable shall be known as BAI. The dimensions are idea units as described in section I above. The contents of the backlog are those ideas which have been accepted by some screening process external to the model, and which are available for exploitation but are as yet unexploited.

The input to the level is a rate of generation of ideas, which rate may be considered an exogenous variable until a screening mechanism is introduced, and the output is the rate at which designs are started. This equation is written:

BAI.K = BAI.J + (DT)(RGI.JK - RSD.JK) 1,L

where

BAI - Backlog of Available Ideas (units)(1000)*
RGI - Rate of Generation of Ideas (idea units/wk)
RSD - Rate of Starts of Designs (units/wk)

The DT which appears in the equation is the solution interval, which exists because the equations of the model are solved at discrete instants of time. DT should be short enough so that its size does not affect the numerical stability of the model. Since the shortest delay represented in this system is of the order of a week, a value of DT = 0.1 weeks is perfectly acceptable.

The above equation states that the backlog of ideas at the present instant of time (.K) is equal to its value at the last time it was calculated (.J) plus the inflow minus the outflow of ideas over the intervening period (.JK). The inflow and outflow are the rates (units/time) multiplied by the solution interval DT.

Following the cycle of the idea through to the finished product

*Where numbers are included in parentheses following the definition of a variable, they are the initial conditions or parameter values chosen for preliminary runs.

the next level is that of ideas in the process of being converted into designs. The designing process is assumed to be simply a third-order exponential delay, and whenever a flow of something suffers a delay a level is formed. The level of in-process designs is known as LPD:

LPD.K = LPD.J + (DT)(RSD.JK - RCD.JK) 2,L

where

LPD - Level of in-Process Designs (units)(0.0)
RSD - Rate of Starts of Designs (units/wk)
RCD - Rate of Completion of Designs (units/wk)

Clearly the input to the level is the rate at which designs are started and the output is the rate at which they are completed.

As the designs are completed they become part of the file of current work. The file is labelled LWD and is defined by:

LWD.K = LWD.J + (DT)(RCD.JK - RAD.JK) 3,L

where

LWD - Level of Working Designs (units)(0.0)
RCD - Rate of Completion of Designs (units/wk)
RAD - Rate of Attrition of Designs (units/wk)

The output of the level of working designs is the rate at which the designs become obsolete.

The existence of designs makes possible production which is initiated at some rate to be discussed later. The production process imposes a delay on the flow of materials, and this causes another level, that of goods in process.

$$LGP.K = LGP.J + (DT)(RSP.JK - RCP.JK) \quad 4,L$$

where

LGP - Level of Goods in Process (units)(0.0)
RSP - Rate of Starts of Production (units/wk)
RCP - Rate of Completion of Production (units/wk)

Finished goods flow to an inventory from where they are shipped to the customer.

$$IFG.K = IFG.J + (DT)(RCP.JK - GSC.JK) \quad 5,L$$

where

IFG - Inventory of Finished Goods (units)(0.0)
RCP - Rate of Completion of Production (units/wk)
GSC - Goods Shipped to the Customer (units/wk)

Goods are shipped to the customer according to the orders he has placed. There is some delay in filling the orders due to processing, and at any given time there is therefore a backlog of unfilled orders:

$$BUO.K = BUO.J + (DT)(RRO.JK - GSC.JK) \quad 6,L$$

where

BUO - Backlog of Unfilled Orders (units)(0.0)
RRO - Rate of Receipt of Orders (units/wk)
GSC - Goods Shipped to the Customer (units/wk)

The input to the backlog is the rate at which orders are received, and the output that at which orders are filled; that is, the rate at which goods are sent out.

Within the customer sector there is a delay to the orders. The rate at which the customer initiates potential orders is related to the effort that the company makes to sell the product, but a delay exists while the customer investigates the product and approves the purchase. For convenience this delay is labelled a transit delay, and the level of orders in transit is created:

OTC.K = OTC.J + (DT)(RIO.JK - ROE.JK) 7,L

where

OTC - Orders in Transit from Customer (units)(0.0)
RIO - Rate of Initiation of potential Orders (units/wk)
ROE - Rate of Orders Entering the market (units/wk)

The second set of levels in the model accounts for the effective effort invested in the company. The first such level encountered is the effective effort in training or in the process of being absorbed. The input is the rate at which it is hired, and the output is the rate at which it is absorbed.

EET.K = EET.J + (DT)(EEH.JK - EEA.JK) 8,L

where

EET - Effective Effort being Trained (man-hrs per wk)(0.0)
EEH - Effective Effort being Hired (man-hrs per wk/wk)
EEA - Effective Effort becoming Available (man-hrs per wk/wk)

The dimensions of these variables appear to be inconsistent with the definitions of levels and rates, since the level EET has dimensions of man-hours per week. The time units in the denominator, however, do not indicate a rate as defined here; 'forty man hours per week' does not mean that man-hours are flowing anywhere at a speed of forty per week, it simply represents a man (or woman). On the other hand, the effort being hired EEH represents a number of people flowing into the organisation at a certain rate; that is, EEH man-hours per week are flowing in each week. 'Man-hours per week', therefore, represents a level, while 'man-hours per week/week' represents a rate.

When the effort is absorbed into the company it goes initially to the pool of unallocated effort.

EEU.K = EEU.J + (DT)(EEA.JK - EEL.JK - EECE.JK - EECP.JK -EECS.JK)   9,L

where

- EEU - Effective Effort Unallocated (man-hrs per wk)(200.0)
- EEA - Effective Effort becoming Available (man-hrs per wk/wk)
- EEL - Effective Effort Leaving (man-hrs per wk/wk)
- EECE - Effective Effort, Change in allocation to Engineering (man-hrs per wk/wk)
- EECP - Effective Effort, Change in allocation to Production (man-hrs per wk/wk)
- EECS - Effective Effort, Change in allocation to Sales (man-hrs per wk/wk)

EEA is always an input because it is always positive or zero. Similarly EEL, the effort leaving the company, is always an output because it is always positive or zero. The effort flowing to the various sectors, however, may be positive (here defined as flowing to the sectors) or negative (defined as flowing from the sectors). The effort left unallocated is presumed to contain the effort required for administration and accounting functions.

The amounts of effort allocated to the three sectors are defined by the following three level equations:

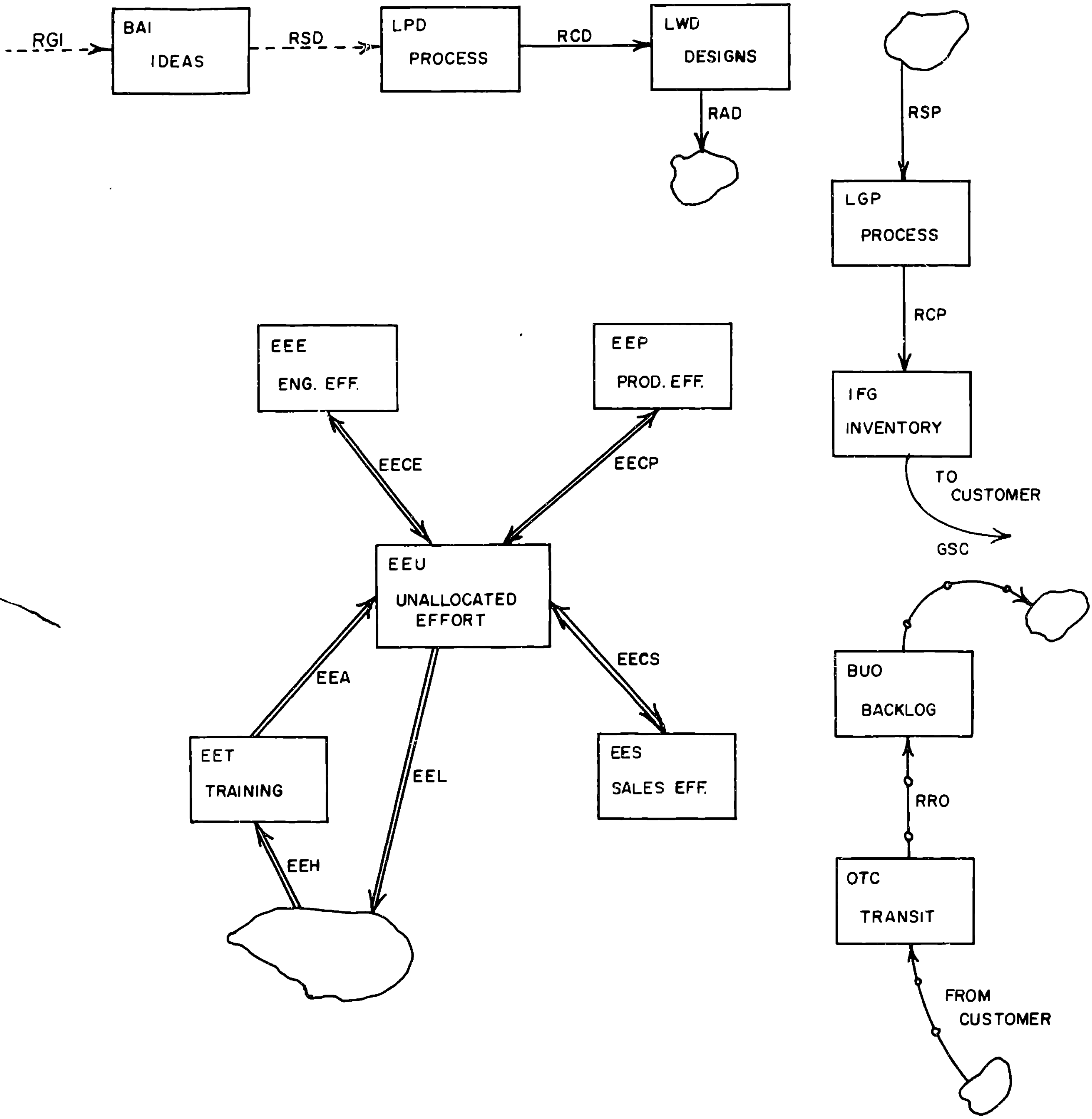


FIGURE I FRAMEWORK OF THE MODEL

EEE.K = EEE.J + (DT)(EECE.JK) 10,L

EEP.K = EEP.J + (DT)(EECP.JK) 11,L

EES.K = EES.J + (DT)(EECS.JK) 12,L

where

EEE - Effective Effort at Engineering (man-hrs per wk)
EECE - Effective Effort, change in allocation to Engineering (man-hrs per wk/wk)
EEP - Effective Effort at Production (man-hrs per wk)
EECP - Effective Effort, Change in allocation to Production (man-hrs per wk/wk)
EES - Effective Effort at Sales (man-hrs per wk)
EECS - Effective Effort, Change in allocation to Sales (man-hrs per wk/wk)

This completes the definition of the levels in the model. The rates which flow between them must now be added.

III The Management Sector

The management sector includes the unallocated effort and the hiring and firing mechanisms. The unallocated effort EEU is the time available for administrative work and for looking for new employees, and when expressed as a fraction of total effort invested is a measure of the need for more people. With a view ultimately to forming a hiring rate, the following two auxiliary variables are defined:

EETOT.K = EEU.K + EEE.K + EEP.K + EES.K 13,A

where

EETOT - Effective Effort, TOTal in all sectors (man-hrs per wk)
EEU - Effective Effort Unallocated (man-hrs per wk)
EEE - Effective Effort at Engineering (man-hrs per wk)

EEP - Effective Effort at Production (man-hrs per wk)
EES - Effective Effort at Sales (man-hrs per wk)

and

EEUF.K = EEU.K/EETOT.K 14,A

where

EEUF - Effective Effort Unallocated, Fraction of total effort
EEU - Effective Effort Unallocated (man-hrs per wk)
EETOT - Effective Effort, TOTal for all sectors (man-hrs per wk)

EETOT is a theoretical point which is approached as the need for more effort approaches infinity; this would be of the order of eighty or a hundred hours per week per man. Since the company will work longer than a forty-hour week on the average, the normal state of allocation will be when the unallocated effort is about equal to the sum of the effort in engineering, production and sales, or when EEUF is about 0.5.

The hiring rate will be based on this variable EEUF, the fraction of time which is unallocated. A very small EEUF, near zero, means that everyone in the company is being forced to work very long hours, in spite of pressures to unallocate time from the sectors, and there simply is no time to spend searching for new staff. When EEUF is roughly between 0.25 and 0.5, the managers are very busy but can make enough time to do some hiring. If EEUF is greater than, say, 0.6, there is not enough work to keep everyone busy and the tendency is to want to fire people. As the curve passes from a desire to hire to a tendency to fire, there is some flattening of the curve in the sense that there is an area where the motivation is not strong enough to justify action. This curve is denoted by THGF (total hiring and firing goal, fraction of total effort), and is shown in figure 2.

The vertical scale is set through a combination of argument and trial and error. The peak of desired hiring comes at EEUF = 0.3125, or when management is working a fifty-five hour week; a longer work week means less time available, so the hiring is necessarily limited, and a shorter week means that the desire to hire is not as strong. THGF is expressed as a fraction; thus the maximum on the curve of THGF = 0.25 means that the most effort which could be desired at any time would be twenty-five percent more than is currently employed. The minimum of THGF = -1.0 at EEUF = 1.0 means that if there is no work for anyone, it is desired to lay off the entire staff. The curve is defined for purposes of computer simulation by the following table function:

THGF.K = TABLE(THGFT, EEUF.K, 0.0, 1.0, 0.0625) 15,A

THGFT* = 0/0/.01/.125/.22/.25/.225/.13/.03/0/-.08/-.225/-.425/-.625/-.78/-.92/-1.0 16,C

where

THGF - Total Hiring and firing Goal, Fraction of total effort
THGFT - Table of values for defining THGF (the asterisk indicates to the computer that a string of constants follows)
EEUF - Effective Effort Unallocated, Fraction of total effort

The number of new man-hours desired is the fraction THGF multiplied by the total effort.

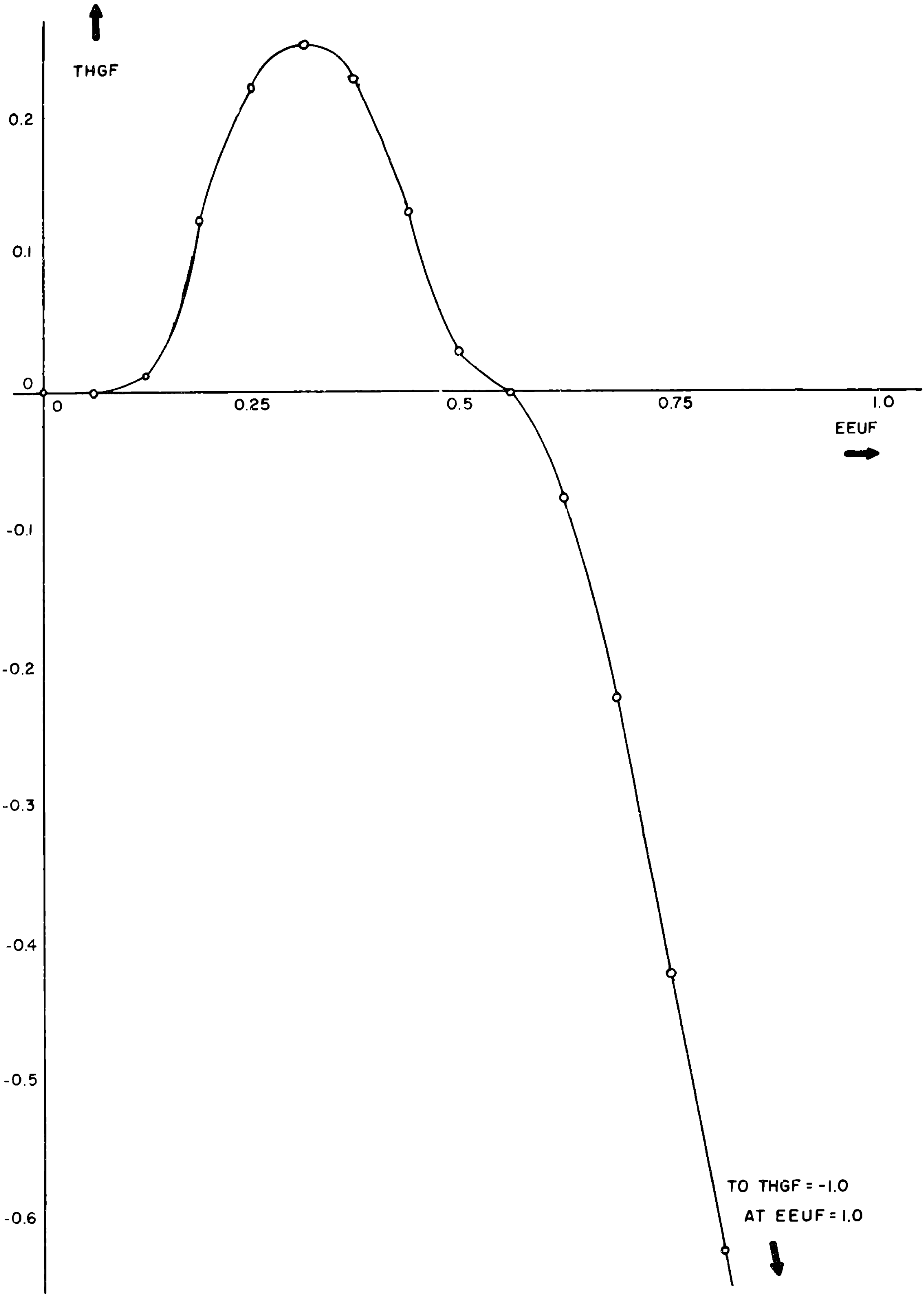


FIGURE 2 TOTAL HIRING AND FIRING GOAL

THG.K = (THGF.K)(EETOT.K) 17,A

where

THG - Total Hiring and firing Goal (man-hrs per wk)
THGF - THG as a fraction of total effort
EETOT - Effective Effort, TOTal in all sectors (man-hrs per wk)

THG is the total number of man-hours per week desired; management must now decide on the interval over which they wish to accomplish the change, and the hiring rate (or firing rate) is the total desired effort divided by this delay. In other words, the resulting rate HIR is that rate which would hire THG units of effort in TCH weeks.

HIR.K = THG.K/TCH 18,A

where

HIR - HIRing rate trial (man-hrs per wk/wk)
THG - Total Hiring and firing Goal (man-hrs per wk)
TCH - Time Constant for Hiring (weeks)(8.0)

If the hiring goal is negative, the inference is that the company wishes to fire effort; the firing equation is similar to HIR, but the time constant will not necessarily be the same as for hiring. The firing rate, then, is:

FIR.K = THG.K/TCF 19,A

where

FIR - FIRing rate trial (man-hrs per wk/wk)
THG - Total Hiring and firing Goal (man-hrs per wk)
TCF - Time Constant for Firing (weeks)(6.0)

The actual hiring and firing rates mentioned in paragraph II may now be defined:

$$\text{EEH.KL} = \begin{cases} \text{HIR.K} & \text{if THGF.K gte } 0.0^{*} \\ 0.0 & \text{if THGF.K lt } 0.0 \end{cases} \qquad 20, \text{R}$$

where

EEH - Effective Effort being Hired (man-hrs per wk/wk)
HIR - HIRing rate trial (man-hrs per wk/wk)
THGF - Total Hiring and firing Goal, Fraction of total effort

The equation for effort being fired must be modified slightly owing to the unique conditions which might exist at the start of the life of a company. Before any departments are formed the bulk of the effort is unallocated because it is not actively engaged in any of the functions defined for the three sectors. EEUF is therefore high, which the hiring and firing rule interprets as a desire to fire. To guard against the possibility that all the managers will be fired before they are given an opportunity to do any work, the firing equation is made dependent on inventory in the following way: firing may not be instituted unless inventory is finite.

$$\text{EEL1.K} = \begin{cases} 0.0 & \text{if THGF.K gte } 0.0^{*} \\ \text{FIR.K} & \text{if THGF.K lt } 0.0 \end{cases} \qquad 21, \text{A}$$

$$\text{EEL.KL} = \begin{cases} \text{EEL1.K} & \text{if IFG.K gte } 0.0 \\ 0.0 & \text{if IFG.K lt } 0.0 \end{cases} \qquad 22, \text{R}$$

where

EEL - Effective Effort Leaving (man-hrs per wk/wk)
FIR - FIRing rate trial (man-hrs per wk/wk)
THGF - Total Hiring and firing Goal, Fraction of total effort
IFG - Inventory of Finished Goods (units)

---

* gte means 'greater than or equal to'; lt means 'less than'.

In the previous section there was mentioned a delay in the absorption of effort. This hiring delay, a third-order exponential delay[4], is representative of a class used in this model, and is best defined by its impulse response (figure 3). For purposes of computer simulation it is defined by a functional equation for the output rate and (optionally) by the equation for the level in the delay.

EET.K = EET.J + (DT)(EEH.JK - EEA.JK) 8,L

EEA.KL = DELAY3(EEH.JK, TEEA) 23,R

where

EET - Effective Effort in Training (man-hrs per wk)
EEH - Effective Effort being Hired (man-hrs per wk/wk)
EEA - Effective Effort becoming Available (man-hrs per wk/wk)
TEEA - average Time delay for EEA (weeks)(6.0)

Associated with the level of unallocated effort is a desire to allocate effort to itself, or to unallocate from the sectors. Management wishes to reserve time for administrative functions as well as for hiring and there is a natural desire to shorten the work week when it is too long. Conversely, if the sectors are operating in such a manner that they do not require (or at least think that they do not require) further effort of any kind, then there is a tendency for the unoccupied people to go out and look for work; i.e., management itself generates a desire to allocate. This behaviour is described by the variable RAEE, the resistance to the allocation of effort, figure 4. If the unallocated fraction EEUF is small, the resistance to further allocation is high. Theoretically if EEUF is zero, RAEE is infinite. At some value of EEUF, say about 0.5, the resistance

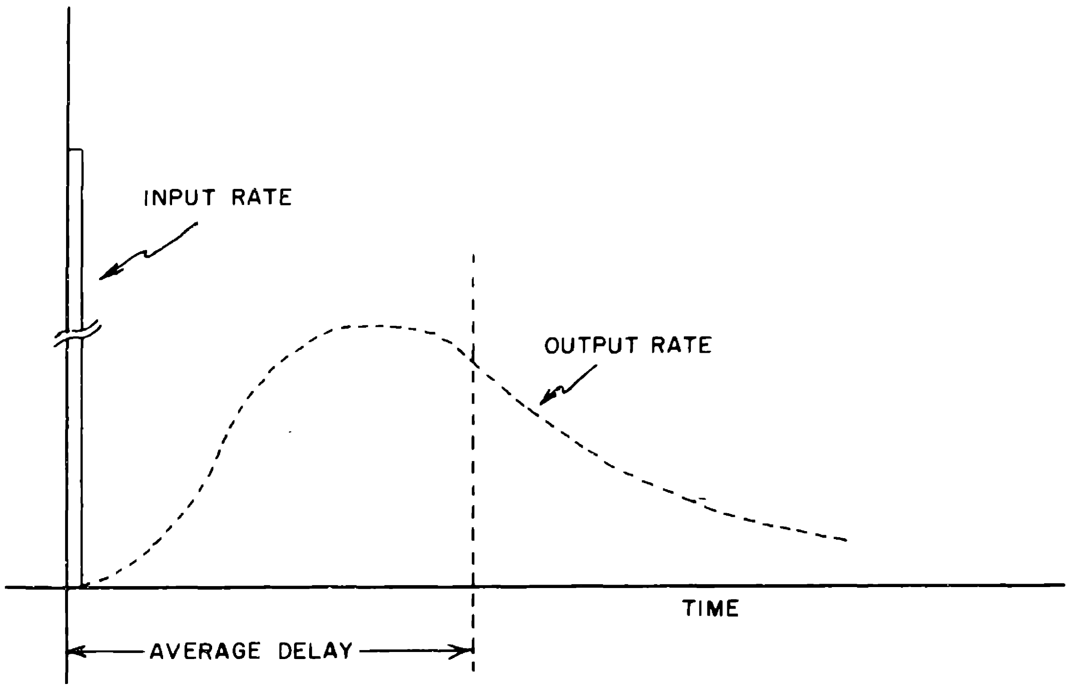


FIGURE 3 IMPULSE RESPONSE OF A THIRD-ORDER DELAY

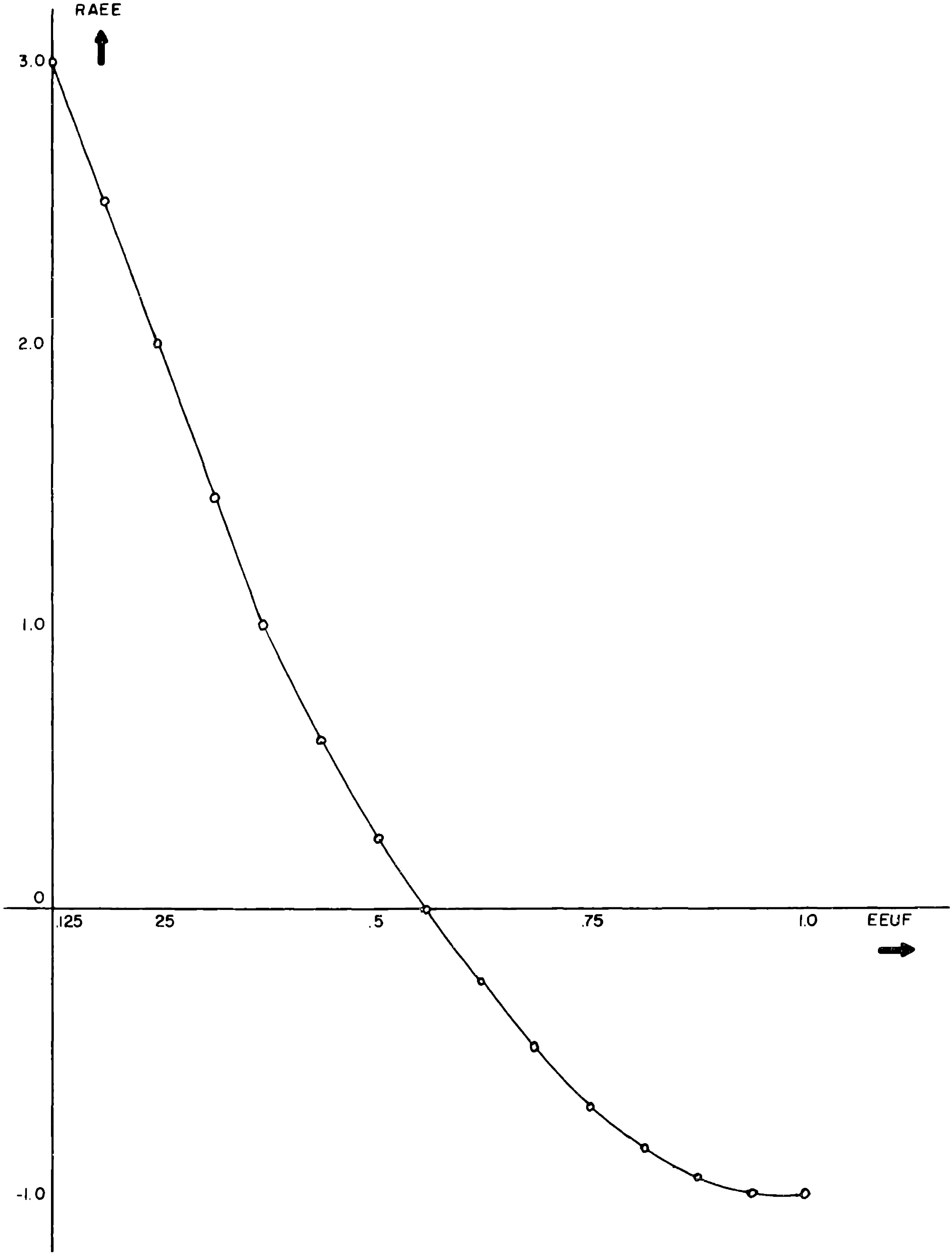


FIGURE 4 RESISTANCE TO THE ALLOCATION OF EFFORT

to allocate is zero; the managers are busy enough that they will not actively go out and look for extra work, but not so busy that they will object to allocating more of their time if there is a demand. As EEUF increases, indicating idle time, the resistance to allocate becomes negative. The curve describing this behaviour is shown in figure 4; the scale of RAEE is for the present arbitrary.

For the purpose of computer simulation the curve is defined by the following equations:

RAEE.K = TABLE(TRAE, EEUF.K, 0.125, 1.0, 0.0625) 24,A

TRAE* = 3/2.5/2/1.45/1/0.58/.25/0/-.25/-.48/-.66/-.84/-.93/-1/-1 25,C

where

RAEE - Resistance to the Allocation of Effective Effort
TRAE - Table for defining RAEE
EEUF - Effective Effort Unallocated, Fraction of total effort

IV Engineering Sector

Beginning with the ideas-designs path, the first variable encountered (figure 6 at the end of this section) is the rate of generation of ideas RGI. Until such time as a screening mechanism for ideas is included in the model, RGI may be an exogenous variable. For purposes of preliminary computer runs, it is set equal to zero and the backlog of ideas is assumed to contain initially a number of ideas.

The backlog of ideas is depleted as designs are started. The designing process works independently of other company operations, and the rate is dependent only on the effort allocated, subject to the restriction that there exist some ideas to work on. This restriction is recognised by defining a limiting rate RSDL, the rate which would exhaust the idea backlog in the next computational interval. The rate at which designs are started is then defined as follows:

RSDT.K = (EEE.K)(PRE) 26,A

RSDL.K = BAI.K/DT 27,A

RSD.KL = RSDT.K if RSDL gte RSDT 28,R
= RSDL.K if RSDL lt RSDT

where

RSD - Rate of Starts of Designs (units/wk)
RSDT - RSD, Trial rate (units/wk)
RSDL - RSD, Limiting rate (units/wk)
EEE - Effective Effort at Engineering (man-hrs per wk)
PRE - PRoductivity at Engineering (units/man-hr)(0.05)
BAI - Backlog of Available Ideas (units)

As was indicated in the previous section the design process is assumed to behave like a third-order delay. The level and output rate are defined by:

LPD.K = LPD.J + (DT)(RSD.JK - RCD.JK) 2,L

RCD.KL = DELAY3(RSD.JK, TRCD) 29,R

where

LPD - Level of in-Process Designs (units)
RSD - Rate of Starts of Designs (units/wk)
RCD - Rate of Completion of Designs (units/wk)
TRCD - average Time delay for RCD (weeks)(15.0)

The finished designs flow into the level of working designs (equation 3,L), and gradually become obsolete. This effect is included by assuming that a fixed fraction of the existing designs are continuously flowing out of the level. The attrition rate is defined by:

RAD.KL = LWD.K/TRAD 30,R

where

RAD - Rate of Attrition of Designs (units/wk)
LWD - Level of Working Designs (units)
TRAD - Time constant for RAD (weeks)(200.0)

This equation 30,R states that at any instant the rate at which designs become obsolete is 1/TRAD of the contents of the level. If this rate were constant from some instant of time, it would deplete the level to zero in TRAD weeks.

To complete the engineering sector it is necessary to define the mechanism used to allocate effort from the unallocated pool. One technique is indicated by the conditions found in the typical real situation, and that is to compare the desire for effort with the resistance to allocate, and to allocate (or unallocate) accordingly. This infers that it is necessary to find for each sector a scream quotient or crisis factor or, as it is named here, a demand factor, in order to measure the loudness of the demands. This demand factor is based on the amount of effort allocated to engineering as a percentage of total effort; a desired percentage is defined and compared with the actual percentage. The desired percentage ENEP is made a constant for present purposes:

ENEP.K = CPERE 31, A

where

ENEP - Effort Needed at Engineering, Percentage of total effort (%)
CPERE - Constant PERcentage of total effort needed at Engineering (%) (20.0)

The actual percentage is easily defined:

EEEP.K = (EEE.K)(100.0)/EETOT.K 32, A

where

EEE - Effective Effort at Engineering (man-hrs per wk)
EEEP - EEE, Percentage of total effort (%)
EETOT - Effective Effort, TOTal in all sectors (man-hrs per wk)

The ratio of the desired and actual percentages is formed:

EPRE.K = EEEP.K/ENEP.K 33, A

where

EPRE - Effort Percent Ratio at Engineering
EEEP - Effective Effort at Engineering, Percent of total effort (%)
ENEP - Effort Needed at Engineering, Percent of total effort (%)

The demand factor will vary with the percent ratio as follows. When EPRE is zero, the demand factor EDFE will be a maximum. When EPRE = 1.0, the demand factor will have some small value representing the fact that even when the proper effort has been allocated, there is always a desire for a little more; questions need answering, encouragement is needed, etc. When EPRE is greater than 1.0, the demand factor drops gradually to zero. It never goes negative because there is never pressure from within the sector to unallocate effort. The curve generated by this argument is shown in figure 5. The scales are, again, a combi-

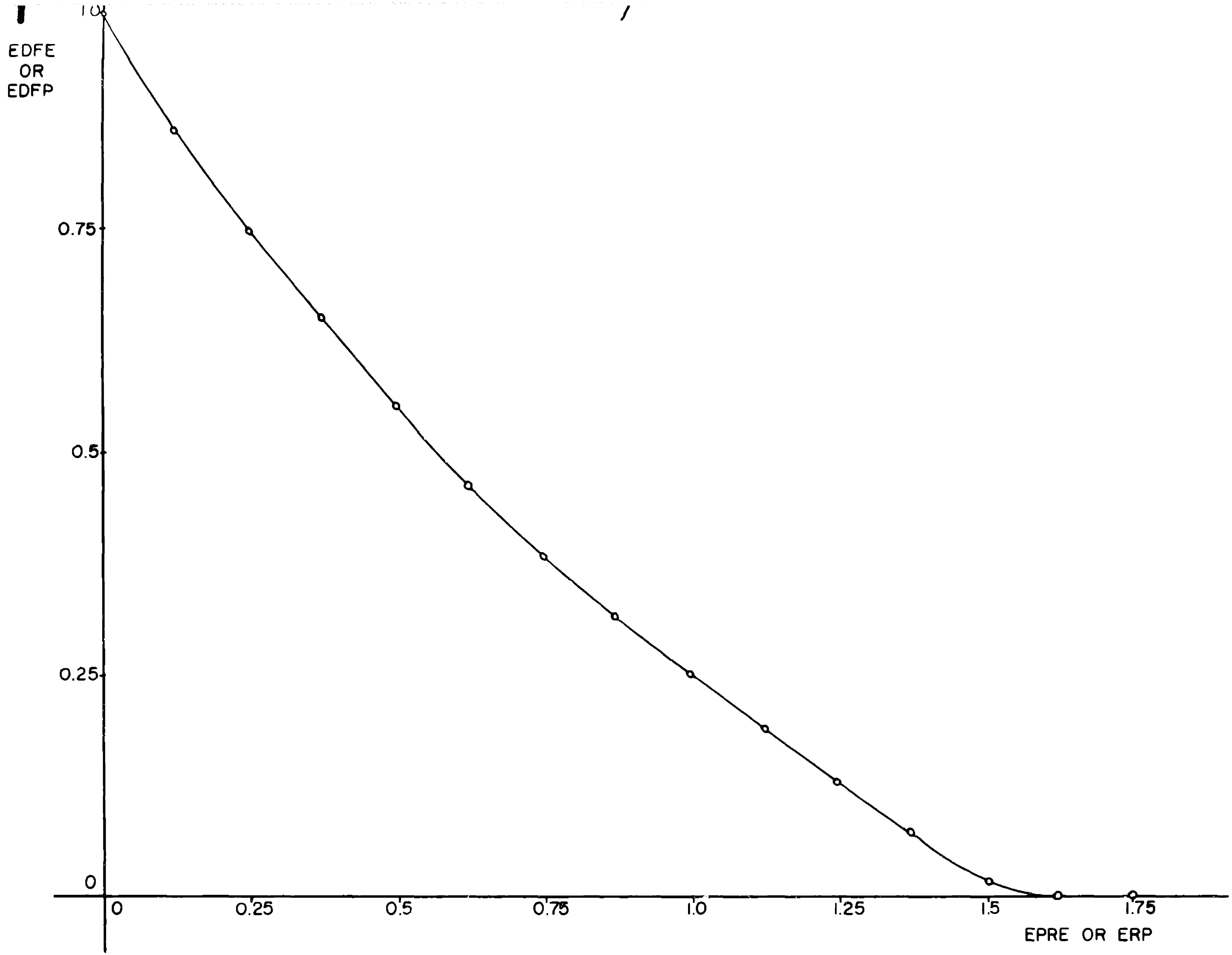


FIGURE 5 DEMAND FACTOR AT ENGINEERING AND PRODUCTION

nation of argument and trial and error, and are set so as to be consistent with the resistance to allocate, figure 4. The function defining the demand factor is shown below. Note that EPRE1 is the same as EPRE, the percent ratio, but is restricted to lie between zero and 1.75 so that it does not exceed the limits of the table function.

```
EPRE1.K  =  EPRE.K             if 1.75 gte  EPRE.K          34,A
         =  1.75               if 1.75 lt   EPRE.K

EDFE.K  =  TABLE(EDFTA, EPRE1.K, 0.0, 1.75, 0.125)          35,A

EDFTA*  =  1/.87/.75/.65/.55/.47/.38/.315/.25/.18/.125/.07/
           .01/0/0                                          36,C
```

where

EPRE - Effort Percent Ratio at Engineering
EDFE - Effort Demand Factor at Engineering
EDFTA - Table for defining EDFE

The allocation rate for effort to engineering may now be defined. The total amount of effort to be allocated is based on the difference between the demand factor and the resistance to allocate (EDFE - RAEE). This number which varies between the approximate limits of 1 and -1 operates on some fraction, say FRE, of the unallocated time. This amount of effort is divided by a time constant to set the rate at which the effort is to flow, the time constant being the desired time for the adjustment of the levels.

```
EECET.K  =  (EDFE.K - RAEE.K)(FRE)(EEU.K)/TCEE              37,A
```

where

EECET - Effective Effort, Change in allocation to Engineering, positive Trial rate (man-hrs per wk/wk)

EDFE - Effort Demand Factor at Engineering
RAEE - Resistance to the Allocation of Effective Effort
FRE - Flow Rate factor at Engineering (0.33)
EEU - Effective Effort Unallocated (man-hrs per wk)
TCEE - Time Constant for Effort change at Engineering (weeks)(12.0)

If the resistance to allocate is greater than the demand factor, effort will flow back to the pool of unallocated effort. The rate of flow is similar to equation 37,A, but is based on the actual allocation to engineering.

EECEN.K = (EDFE.K - RAEE.K)(NRE)(EEE.K)/TCNE   38,A

where

EECEN - Effective Effort, Change in allocation to Engineering, Negative trial rate (man-hrs per wk/wk)
EDFE - Effort Demand Factor at Engineering
RAEE - Resistance to the Allocation of Effective Effort
NRE - Negative flow Rate factor at Engineering (0.5)
EEE - Effective Effort at Engineering (man-hrs per wk)
TCNE - Time Constant for Negative effort change at Engineering (weeks)(12.0)

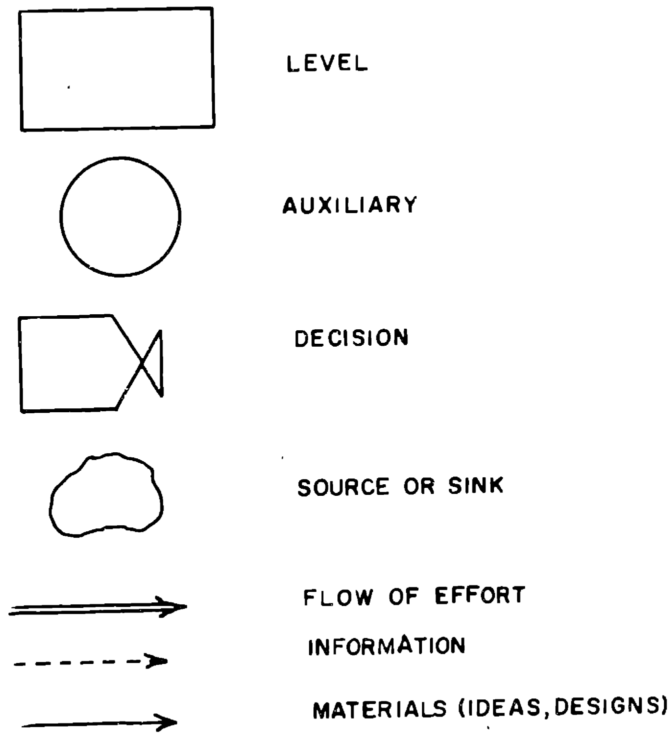
The actual flow rate between the unallocated pool and the engineering sector depends on whether or not the demand factor is greater than the resistance to allocate:

EECE.KL =	EECET.K	if EDFE.K gte RAEE.K	39,R
=	EECEN.K	if EDFE.K lt RAEE.K	

where

EECE - Effective Effort, Change to Engineering (man-hrs per wk/wk)
EECET - EECE, positive Trial rate (man-hrs per wk/wk)
EDFE - Effort Demand Factor at Engineering
RAEE - Resistance to the Allocation of Effective Effort
EECEN - EECE, Negative trial rate (man-hrs per wk/wk)

LEGEND


LEVEL
AUXILIARY
DECISION
SOURCE OR SINK
FLOW OF EFFORT
INFORMATION
MATERIALS (IDEAS, DESIGNS)

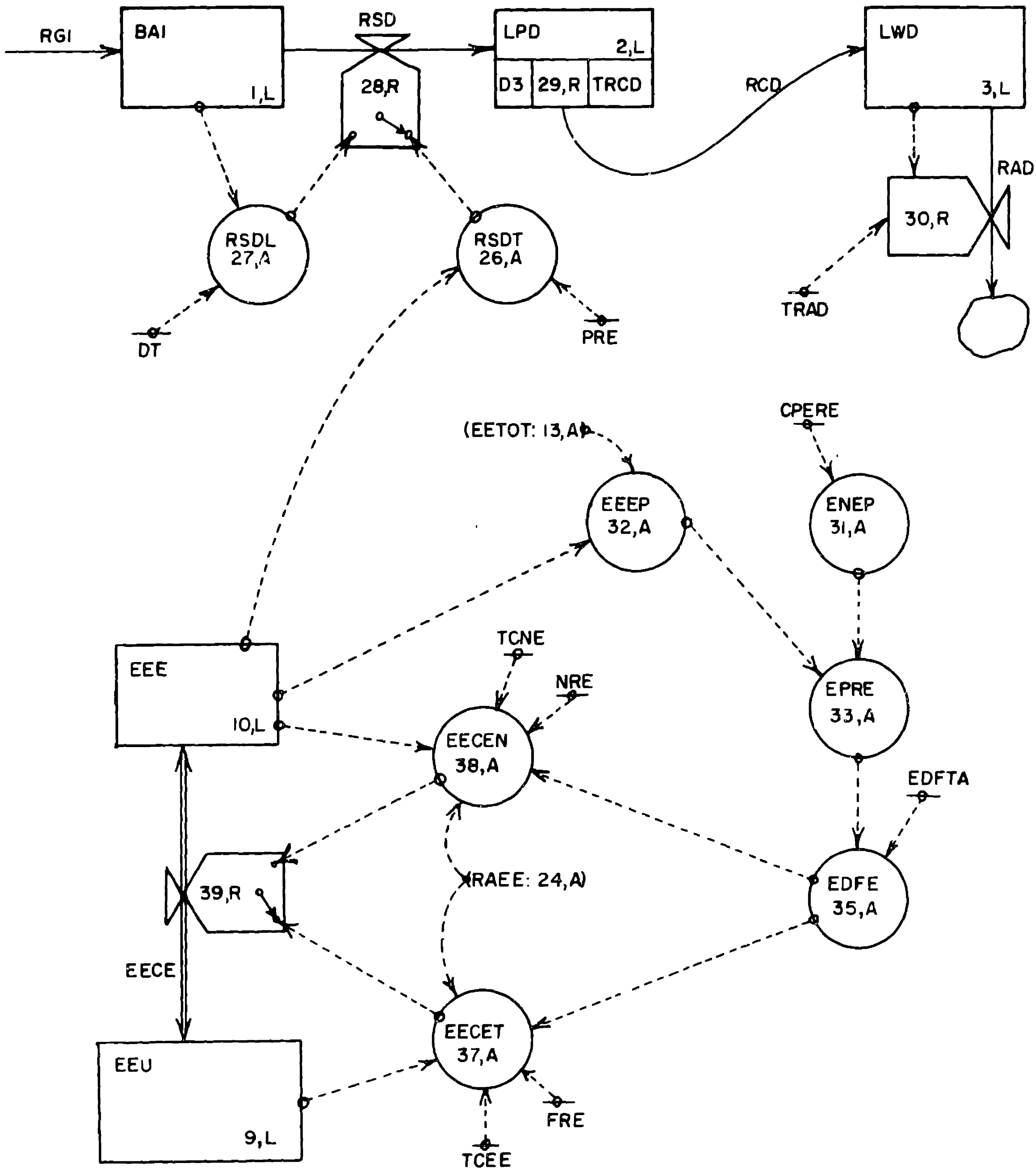


FIGURE 6 ENGINEERING SECTOR

V Production Sector

Figure 8 at the end of this section is a flow diagram of the sector. The rate of production starts is determined by the effort invested in the sector. The number of designs available limits this indirectly in that it controls the desired value of production starts and therefore the allocation of effort. The production rate is:

RSP.KL = (EEP.K)(PRP) 40,R

where

RSP - Rate of Starts of Production (units/wk)
EEP - Effective Effort at Production (man-hrs per wk)
PRP - PRoductivity at Production (units/man-hr)

The production process is also assumed to behave like a third-order delay:

LGP.K = LGP.J + (DT)(RSP.JK - RCP.JK) 4,L

RCP.KL = DELAY3(RSP.JK, TRCP) 41,R

where

LGP - Level of in-Process Goods (units)
RSP - Rate of Starts of Production (units/wk)
RCP - Rate of Completion of Production (units/wk)
TRCP - average Time delay for RCP (weeks)(3.0)

The finished goods flow into inventory, IFG, as defined by equation 5,L.

A variable which is important in determining the allocation of effort is the desired inventory IFGD. The basic element of IFGD is some number of weeks (TIFG) times smoothed sales per week (RROS). There is an additive term, however, which is necessary particularly in the beginning to provide some samples before there is a record of sales. After enough designs have been made to support a reasonable amount of business, the samples cease to increase with designs and become constant (figure 7). The additive term is defined by the following equations:

$$IFGD1.K = (LWD.K)(NOS) \qquad 42,A$$

$$IFGDM = (ENDS)(NOS) \qquad 43,N$$

$$IFGDA.K = \begin{cases} IFGDM & \text{if } LWD.K \text{ gte } ENDS \\ IFGD1.K & \text{if } LWD.K \text{ lt } ENDS \end{cases} \qquad 44,A$$

where

IFGD - Inventory of Finished Goods Desired (units)
IFGDM - IFGD, Maximum necessary for samples (units)
IFGDA - IFGD, Additive term (units)
LWD - Level of Working Designs (units)
NOS - Number Of Samples required per design (5.0)
ENDS - ENough DeSigns (units)(10.0)

Two other variables may be defined. The first is the desired inventory given the existing number of designs, IFGD, and the next is the desired level for the condition of enough designs; the latter quantity, IFGDS, is used for sales purposes. The inventory ratio is also defined here.

$$IFGD.K = (RROS.K)(TIFG) + IFGDA.K \qquad 45,A$$

$$IFGDS.K = (RROS.K)(TIFG) + IFGDM \qquad 46,A$$

$$INR.K = IFG.K/IFGDS.K \qquad 47,A$$

where

IFG - Inventory of Finished Goods (units)
IFGD - IFG Desired (units)
IFGDA - IFGD, Additive term (units)
IFGDS - IFGD for Sales only (units)
IFGDM - IFGD, Maximum necessary for samples (units)(50.0)
RROS - Rate of Receipt of Orders, Smoothed (units/wk)
TIFG - Time constant for IFG (weeks)(5.0)
INR - INventory Ratio

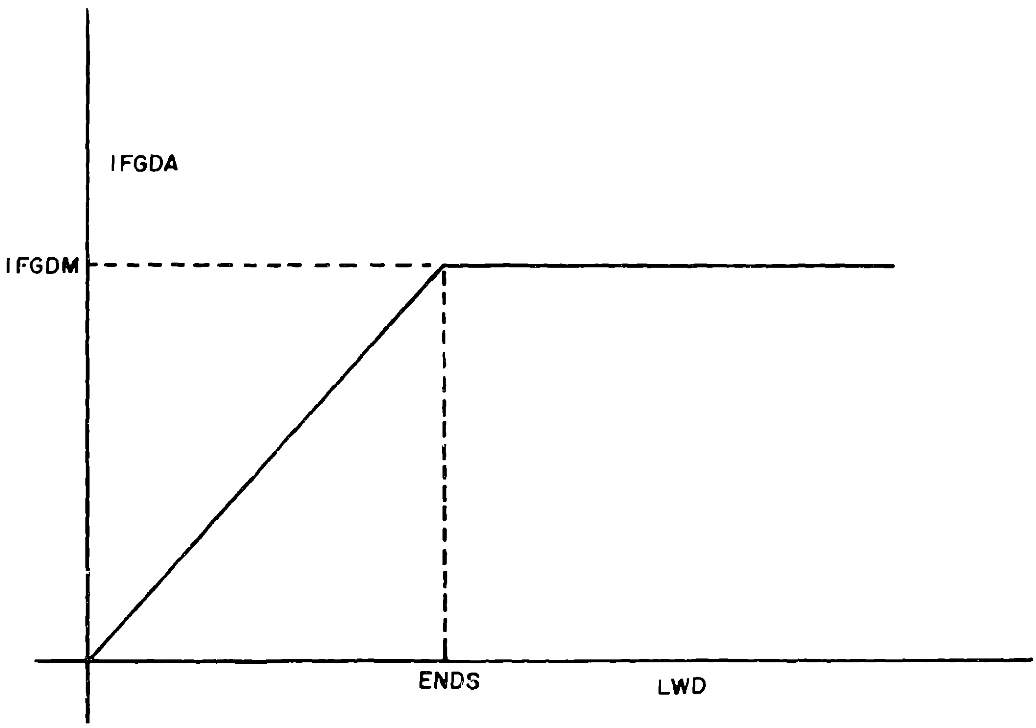


FIGURE 7 REQUIRED SAMPLES

A factor affecting sales is the delay in filling orders. One way of formulating this is given in section 7 of reference 11, and is as follows:

DDG.K = DDGM + (DDGN)(IFGD.K/IFG.K) 48,A

where

DDG - Delay in the Delivery of Goods (weeks)
DDGM - DDG, Minimum for order handling (weeks)(1.0)
DDGN - DDG, Normal due to stock runouts, etc. (weeks)(6.0)
IFG - Inventory of Finished Goods (units)
IFGD - IFG Desired (units)

Equation 48,A defines two elements in the order-filling delay. DDGM is simply a minimum handling delay. The second term adds a normal delay DDGN if inventory is equal to desired inventory, and adds more or less depending on whether desired inventory is greater than or less than actual.

The instantaneous shipping rate from the company is based on the size of the order backlog BUO and the above delay DDG; it is limited in the extreme by the absolute size of inventory.

GSCT.K = BUO.K/DDG.K 49,A

GSCL.K = IFG.K/DT 50,A

GSC.KL = GSCT.K if GSCL.K gte GSCT.K 51,R
= GSCL.K if GSCL.K lt GSCT.K

where

GSC - Goods Shipped to the Customer (units/wk)
GSCT - GSC, Trial rate (units/wk)
GSCL - GSC, Limiting rate (units/wk)
BUO - Backlog of Unfilled Orders (units)
DDG - Delay in the Delivery of Goods (weeks)
IFG - Inventory of Finished Goods (units)

The remainder of the production sector is concerned with the allocation of effort; a desired production rate is defined to yield a needed level of effort on which the allocation rate shall be based.

Production is required to meet three objectives: incoming orders must be filled, and the backlog and inventory must be adjusted to their desired levels. Three desired production rates are therefore defined. These are self-explanatory except for the inventory adjustment rate; it is undesirable to produce for inventory if there are no designs, so a clipping function is introduced.

RSPO.K = RROS.K 52,A

RSPB.K = (BUO.K - BUOD.K)/TBP 53,A

RSPI.K = (IFGD.K - IFG.K)/TIP 53,A

RSPIA.K = 0.0 if 0.0 gte LWD.K 54,A
= RSPI.K if 0.0 lt LWD.K

RSPD.K = RSPO.K + RSPB.K + RSPIA.K 56,A

where

RSPD - Rate of Starts of Production Desired (units/wk)
RSPO - RSPD for filling orders (units/wk)
RSPB - RSPD for adjusting Backlog (units/wk)
RSPI - RSPD for adjusting Inventory, trial rate (units/wk)
RSPIA - RSPD for adjusting Inventory, Actual rate (units/wk)
RROS - Rate of Receipt of Orders, Smoothed (units/wk)
BUO - Backlog of Unfilled Orders (units)
BUOD - BUO Desired (units)
IFG - Inventory of Finished Goods (units)
IFGD - IFG Desired (units)
TBP - Time constant for Backlog adjustment through Production(wks)(6.0)
TIP - Time constant for Inventory adjustment through Production (weeks)(6.0)
LWD - Level of Working Designs (units)

In order to achieve this production goal, effort is needed:

ENP.K = RSPD.K/PRP 57,A

where

ENP - Effort Needed at Production (man-hrs per wk)
RSPD - Rate of Starts of Production Desired (units/wk)
PRP - Productivity at Production (units/man-hr)

The effort ratio at production is calculated as :

ERP.K = EEP.K/ENP.K 58,A

where

ERP - Effort Ratio at Production
EEP - Effective Effort at Production (man-hrs per wk)
ENP - Effort Needed at Production (man-hrs per wk)

The demand factor for effort is based on the effort ratio in the same way as in the engineering sector; in fact, the same curve is used (see figure 5). ERP1 and ERP2 are defined below in order to restrict the effort ratio to lie between the limits of 0.0 and 1.75.

ERP1.K	= ERP.K	if 1.75 gte ERP.K	59,A
	= 1.75	if 1.75 lt ERP.K	
ERP2.K	= ERP1.K	if ERP1.K gte 0.0	60,A
	= 0.0	if ERP1.K lt 0.0	

EDFT.K = TABLE(EDFTA, ERP2.K, 0.0, 1.75, 0.125) 61,A

EDFTA* = 1/.87/.75/.65/.55/.47/.38/.315/.25/.18/.125/.07/.01/0/0 36,C

where

ERP - Effort Ratio at Production
EDFP - Effort Demand Factor at Production
EDFTA - Table defining EDFT

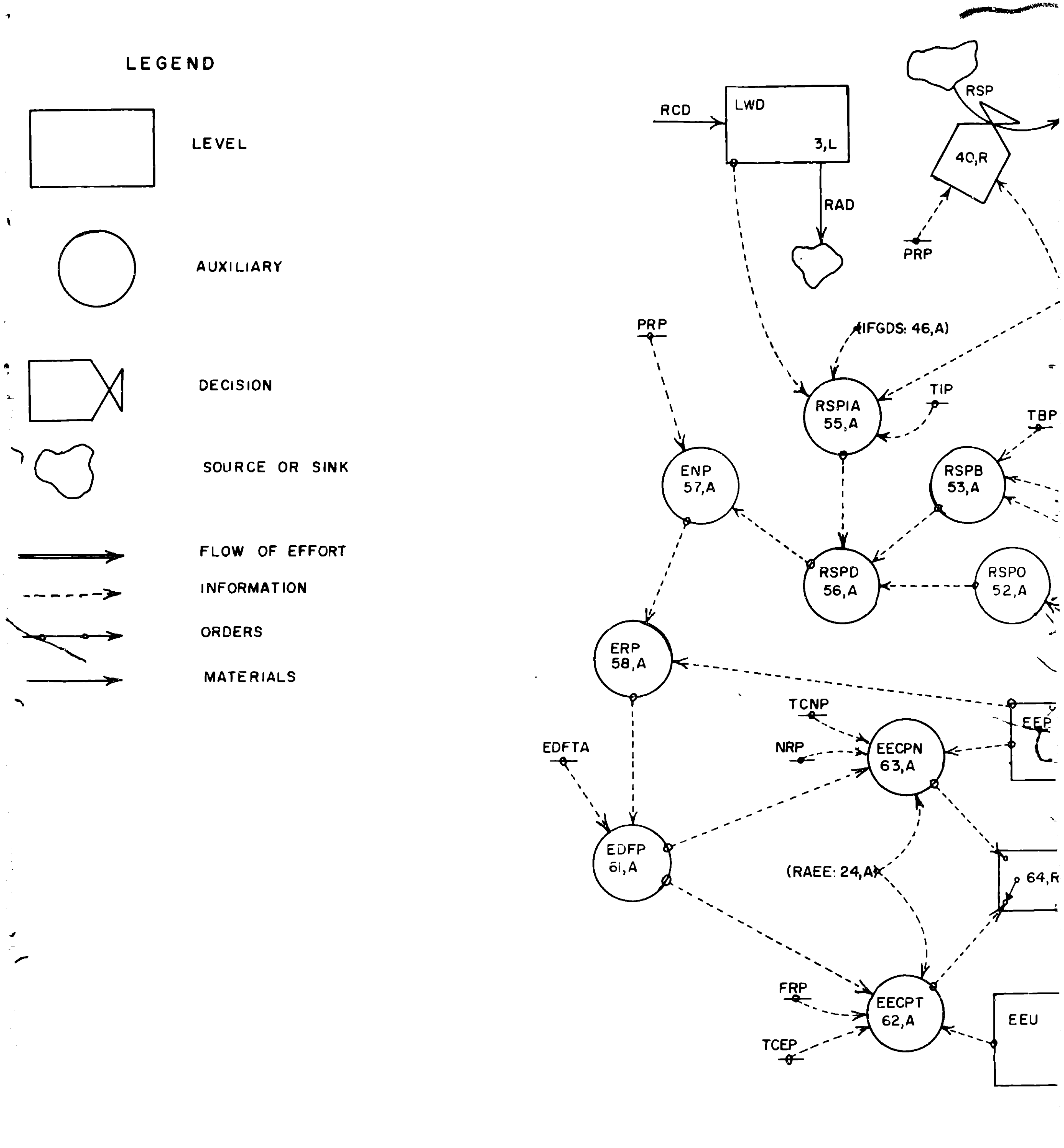


FIGURE 8 PRODUCTION SE

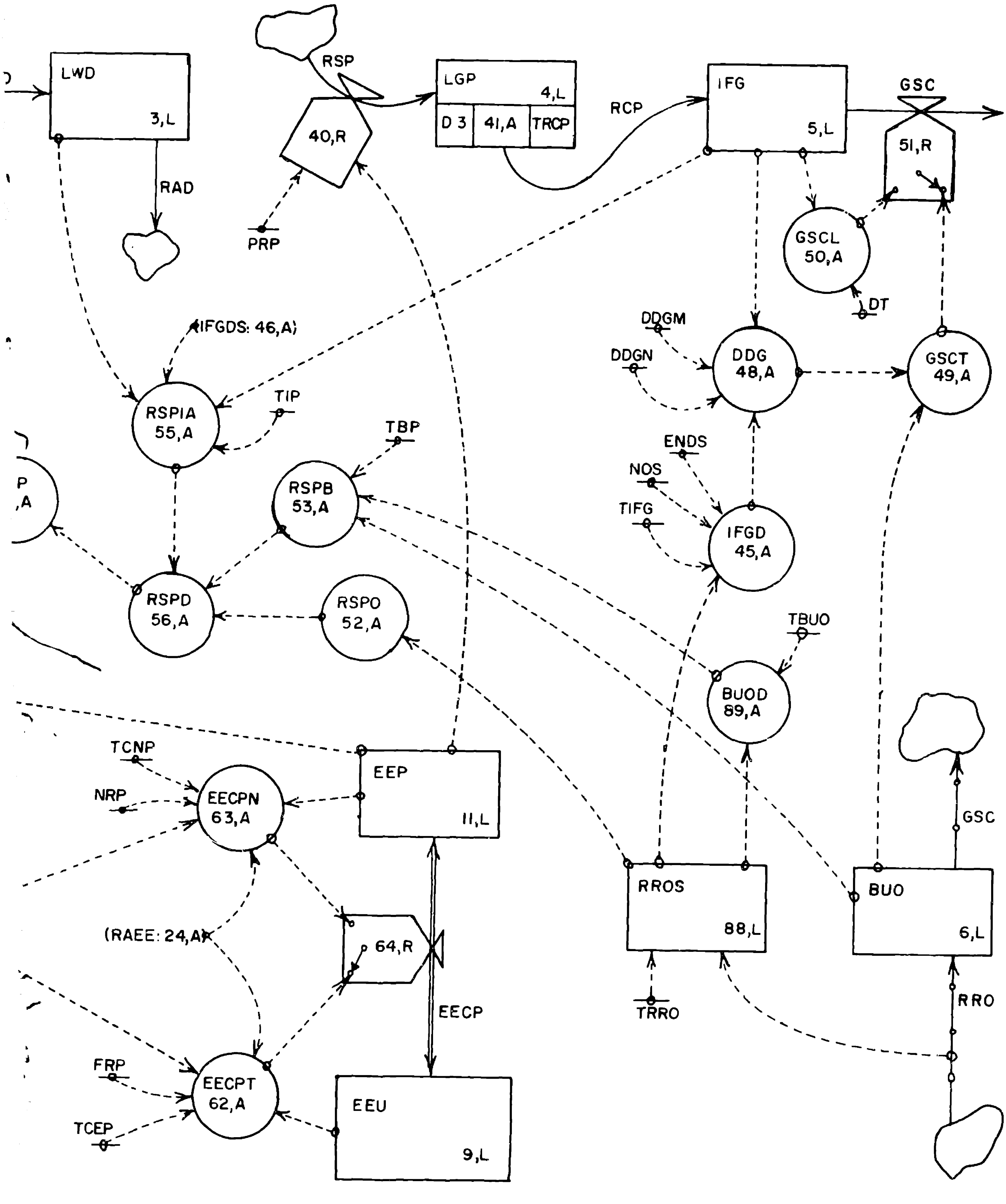


FIGURE 8 PRODUCTION SECTOR

The rate of change of effective effort to the production sector is defined in the same way as for the engineering sector, equations 37,A through 39,R.

EECPT.K	= (EDFP.K - RAEE.K)(FRP)(EEU.K)/TCEP		62,A
EECPN.K	= (EDFP.K - RAEE.K)(NRP)(EEP.K)/TCNP		63,A
EECP.KL	= EECPT.K	if EDFP.K gte RAEE.K	64,R
	= EECPN.K	if EDFP.K lt RAEE.K	

where

EECP - Effective Effort, Change in allocation to Production (man-hrs per wk/wk)
EECPT - EECP, positive Trial rate (man-hrs per wk/wk)
EECPN - EECP, Negative trial rate (man-hrs per wk/wk)
EDFP - Effort Demand Factor at Production
RAEE - Resistance to the Allocation of Effective Effort
FRP - Flow Rate factor at Production (0.33)
NRP - Negative flow Rate factor at Production (0.5)
EEU - Effective Effort Unallocated (man-hrs per wk)
EEP - Effective Effort at Production (man-hrs per wk)
TCEP - Time Constant for Effort change at Production (weeks)(5.0)
TCNP - Time Constant for Negative effort change at Production (weeks)(5.0)

This completes the description of the production sector equations.

VI Sales Sector

Figure 12 at the end of this sector is a flow diagram of the sector. The function of the sales group is to generate orders from the customers; they do this by investing effort in finding customers who want the products offered.

$$RGO.KL = (EES.K)(PRS.K) \quad 65,R$$

where

RGO - Rate of Generation of Potential Orders (units/wk)
EES - Effective Effort at Sales (man-hrs per wk)
PRS - PRoductivity at Sales (units/man-hr)

The productivity here, unlike the other sectors, is defined as a variable because the variations are more marked and more important. It will vary with invested effort EES. When EES is small, notably at the beginning, then PRS will be high because it is likely that the few people involved are more competent than the average, and that they will concentrate on choice customers who are sure to buy. As EES increases, however, the salesmen tend to be relatively less competent and they must spread their efforts out over more companies with less likelihood of selling every time. This behaviour is like a first-order exponential:

$$PRS.K = (\text{max. } PRS)e^{-EES.K/\text{constant}}$$

The maximum value of PRS, however, itself varies with the number of designs LWD, increasing sharply with LWD for the condition of few designs and changing slowly with LWD when there are many. Thus:

$$\text{Max. } PRS = (\text{max. possible } PRS)(1 - e^{-LWD.K/\text{constant}})$$

where 'max. possible PRS' is a theoretical maximum implying optimal conditions. Inserting plausible values for the constants, PRS becomes

$$PRS.K = (PRSMX)(1 - e^{-LWD.K/ENDS})\, e^{-EES.K/200} \quad 66,A$$

where

PRS - PRoductivity at Sales (units/man-hr)
PRSMX - PRS, MaXimum possible (units/man-hr)(1.0)

LWD - Level of Working Designs (units)
ENDS - ENough DeSigns (units)(10)
EES - Effective Effort at Sales (man-hrs per wk)

The equations for the allocation of effort to the sales sector are similar to those in the other sectors. The effort needed, as a percentage of total effort, is a constant percentage modified by functions of designs and inventory:

ENSP.K = (CPERS)(FLWD.K)(FIV.K) 67,A

where

ENSP - Effort Needed at Sales, Percentage of total effort (%)
CPERS - Constant PERcentage of effort at Sales (%)(30.0)
FLWD - Function of the Level of Working Designs
FIV - Function of InVentory

The way in which the effort needed is dependent on designs is shown in figure 9. When there are more than enough designs, then LWD does not affect the effort required to sell them, and FLWD = 1.0. If there are fewer, proportionately less effort is needed. If there is less than one design, as much effort is needed as if there were one. In equation form:

FLWD1.K = LWD.K/ENDS 68,A

FLWDT.K	= FLWD1.K	if ENDS gte LWD.K	69,A
	= 1.0	if ENDS lt LWD.K	
FLWD.K	= FLWDT.K	if LWD.K gte 1.0	70,A
	= 1/ENDS	if LWD.K lt 1.0	

where

LWD - Level of Working Designs (units)
FLWD1 - Function of LWD between 1.0 and ENDS
FLWDT - Function of LWD for LWD greater than 1.0
FLWD - Function of LWD
ENDS - ENough DeSigns (units)(10.0)

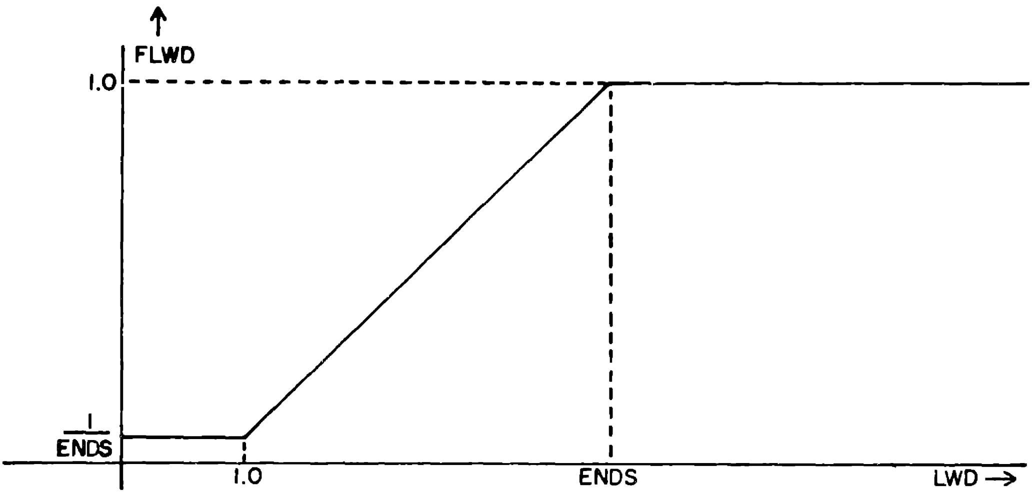


FIGURE 9 FUNCTION OF DESIGNS FOR EFFORT ALLOCATION

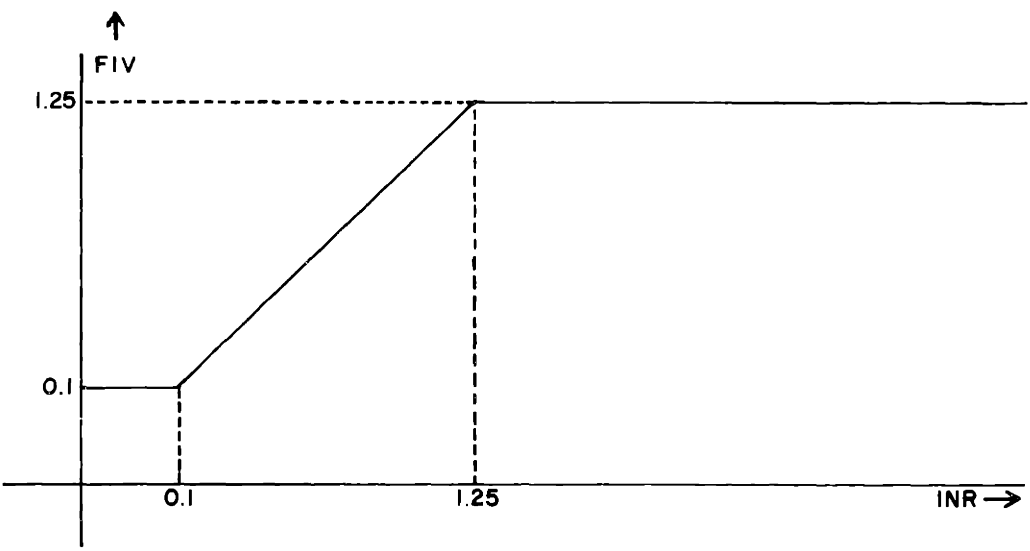


FIGURE 10 FUNCTION OF INVENTORY FOR EFFORT ALLOCATION

The function of inventory FIV which also multiplies the percentage of effort needed depends on the inventory ratio INR (equation 47,A) in the manner shown in figure 10. When the actual inventory equals the inventory desired for sales, then INR = 1.0 and the condition of inventory does not affect the need for effort. When the inventory ratio is greater than (arbitrarily) 1.25, the extra effort required to sell is fixed at 1.25 times the normal requirement. When INR is less than 1.25 but greater than (arbitrarily) 0.1, at least 0.1 of the effort normally required is still needed. The equations describing this curve, figure 10, are:

```
FIVT.K  =  INR.K          if INR.K gte 0.1          71,A
        =  0.1            if INR.K lt  0.1

FIV.K  =  FIVT.K          if 1.25 gte INR.K         72,A
       =  1.25            if 1.25 lt  INR.K
```

where

FIV - Function of Inventory
INR - INventory Ratio

The effort needed (equation 67,A) is the product of the constant percentage CPERS, the function of inventory and the funvtion of designs. In the particular case where there are more than enough designs and inventory equals desired inventory, then the effort required is the constant percentage CPERS.

The percentage of total effort actually at sales is given by:

```
EESP.K  =  (EES.K)(100.0)/EETOT.K                           73,A
```

and the effort percent ratio is

EPRS.K = EESP.K/ENSP.K 74,A

where

EES - Effective Effort at Sales (man-hrs per wk)
EESP - EES, Percentage of total effort (%)
EETOT - Effective Effort, TOTal in all sectors (man-hrs per wk)
EPRS - Effort Percent Ratio at Sales
ENSP - Effort Needed at Sales, Percent of total effort (%)

As in the other sectors, the demand factor at sales EDFS is a decreasing function of the effort percent ratio EPRS (see figure 11). Since management is more sensitive to sales, however, in matters concerning the allocation of effort, the maximum of the present curve is higher.

As before, the percent ratio is restricted to lie in the region between 0.0 and 1.75; to this end EPRS1 is defined.

EPRS1.K = EPRS.K if 1.75 gte EPRS.K 75,A
= 1.75 if 1.75 lt EPRS.K

EDFS.K=TABLE(EDFTB, EPRS1.K, 0.0, 1.75, 0.125) 76,A

EDFTB* = 2/1.7/1.43/1.15/.93/.71/.53/.36/.25/.18/.13/
.098/.06/.03/0 77,C

where

EPRS - Effort Percent Ratio at Sales
EDFS - Effort Demand Factor at Sales
EDFTB - Table for defining EDFS

The rate of allocation of effort is defined in the same way as in the other two sectors:

EECST.K = (EDFS.K - RAEE.K)(FRS)(EEU.K)/TCES 78,A

EECSN.K = (EDFS.K - RAEE.K)(NRS)(EES.K)/TCNS 79,A

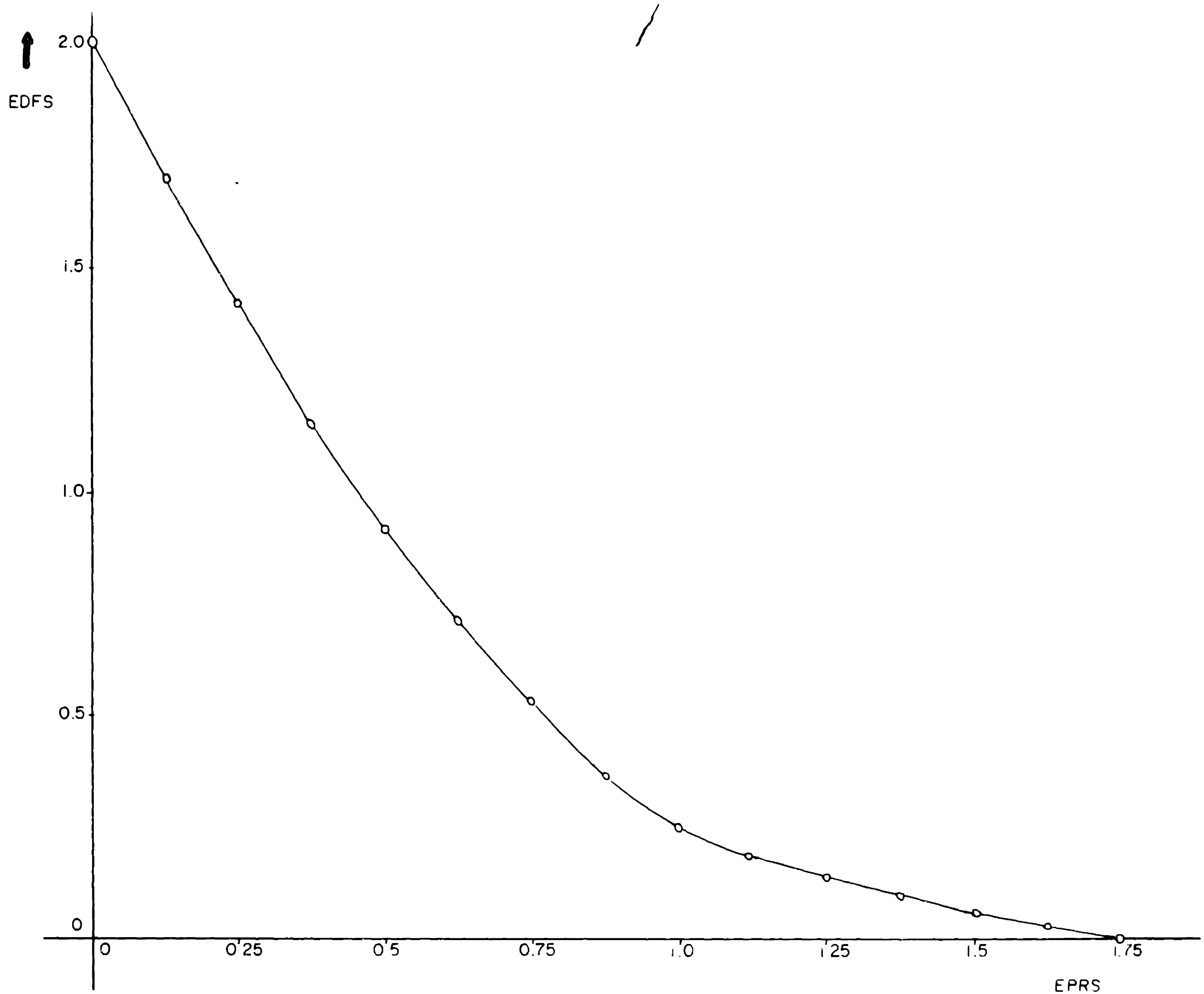


FIGURE 11 SALES EFFORT DEMAND FACTOR

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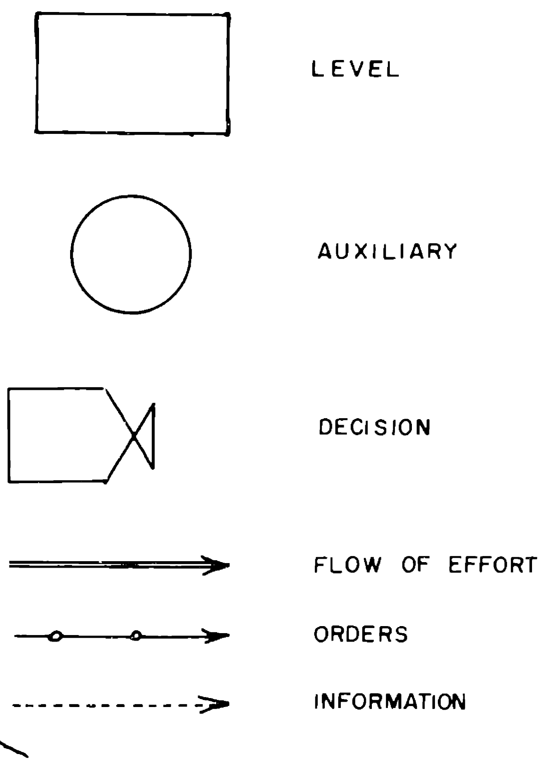

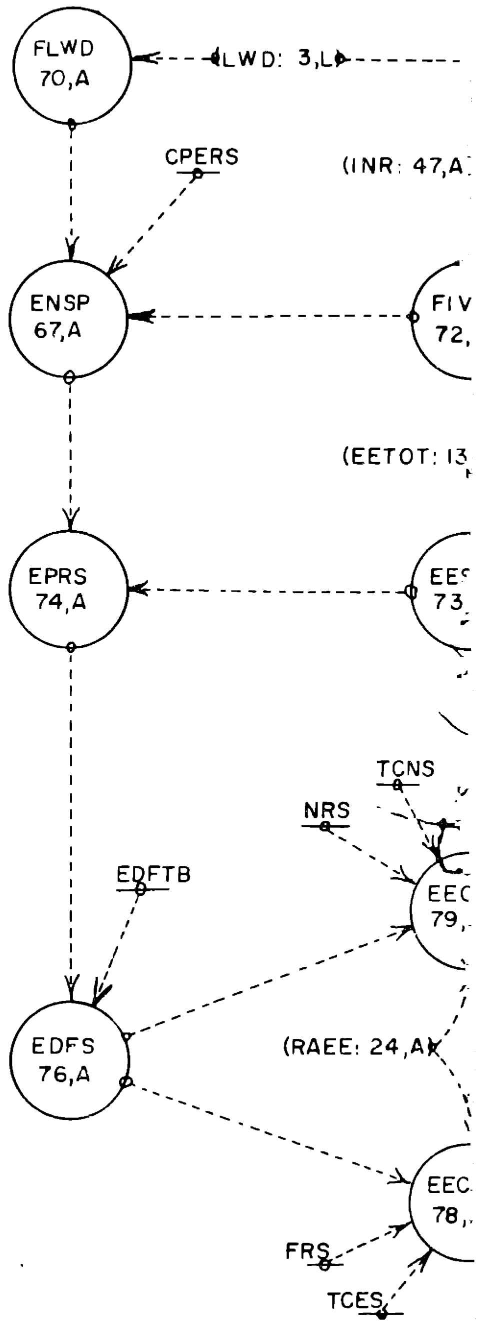

FIGURE 12 SALES SE

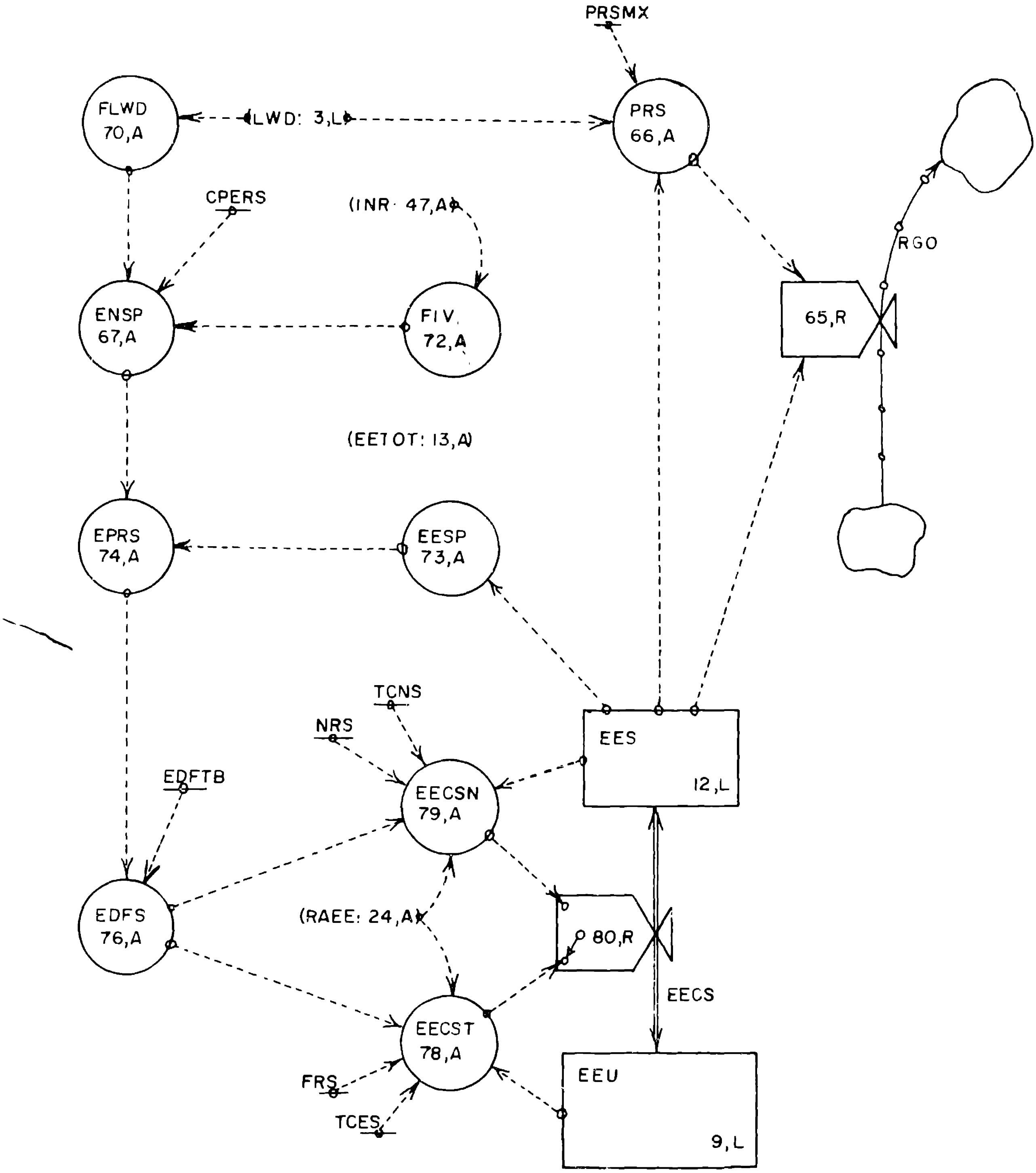

FIGURE 12 SALES SECTOR

EECS.KL	= EECST.K	if EDFS.K gte RAEE.K	80, R
	= EECSN.K	if EDFS.K lt RAEE.K	

where

EECS - Effective Effort, Change in allocation to Sales (man-hrs per wk/wk)
EECST - EECS, positive Trial rate (man-hrs per wk/wk)
EECSN - EECS, Negative trial rate (man-hrs per wk/wk)
EDFS - Effort Demand Factor at Sales
RAEE - Resistance to the Allocation of Effective Effort
FRS - Flow Rate factor at Sales (0.33)
NRS - Negative flow Rate factor at Sales (0.5)
EEU - Effective Effort Unallocated (man-hrs per wk)
EES - Effective Effort at Sales (man-hrs per wk)
TCES - Time Constant for Effort change at Sales (weeks)(8.0)
TCNS - Time Constant for Negative effort change at Sales (weeks) (8.0)

This completes the description of the sales equations.

VII The Customer

Pressure is exerted on the customer by the company in the form of potential orders generated. The reactions of the customer are based on his satisfaction factor, which in turn is based on the company's designs, and on the delay the company exhibits in filling orders. For a flow diagram of the sector see figure 13 at the end of this section.

The satisfaction factor is the ratio of the company's designs to the industry average, and arbitrarily less than 1.5:

CSFT.K	= LWD.K/IALD		81, A
CSF.K	= CSFT.K	if 1.5 gte CSFT.K	82, A
	= 1.5	if 1.5 lt CSFT.K	

where

CSF - Customer Satisfaction Factor
CSFT - CSF, Trial factor
LWD - Level of Working Designs (units)
IALD - Industry Average Level of Designs (units)(30.0)

The rate of potential orders initiated by the customer is given by:

RIO.KL = (RGO.JK)(CSF.K) 83, R

where

RIO - Rate of Initiation of Orders by the customer (units/wk)
RGO - Rate of Generation of potential Orders (units/wk)
CSF - Customer Satisfaction Factor

The orders thus initiated enter a delay representing the period of examination of samples, approval of the purchase, and choice of supplier.

OTC.K = OTC.J + (DT)(RIO.JK - ROE.JK) 7, L

ROE.KL = DELAY3(RIO.JK, TROC) 84, R

where

OTC - Orders in Transit from the Customer (units)
RIO - Rate of Initiation of Orders by the customer (units/wk)
ROE - Rate of Orders Entering the market (units/wk)
TROC - average Time delay for ROE (weeks)(20.0)

The fraction of the market which goes to the company is based on the delivery delay relative to the usual delay. (This formulation is not particularly apposite, but until a customer can look at competitors in the model it will be sufficient.) This fraction decreases from 1.0 with increasing delay, and when the delay is at its usual value some fraction of the orders will go elsewhere because the company's usual delay is not necessarily the shortest available. The following formulation results:

$$FOF.K = e^{-DDG.K/DDGMN} \qquad 85,A$$

$$DDGMN = DDGM + DDGN \qquad 86,N$$

where

FOF - Fraction of Orders to the Factory
DDG - Delay in the Delivery of Goods (weeks)(equation 48,A)
DDGM - DDG, Minimum for order handling (weeks)(1.0)
DDGN - DDG, Normal for stock runouts, etc. (weeks)(6.0)
DDGMN - DDG, usual (weeks)(7.0)

The orders received by the company are given by RRO. The smoothed rate is also defined here.

$$RRO.KL = (FOF.K)(ROE.JK) \qquad 87,R$$

$$RROS.K = RROS.J + (DT)(1/TRRO)(RRO.JK - RROS.J) \qquad 88,L$$

where

RRO - Rate of Receipt of Orders (units/wk)
RROS - RRO, Smoothed (units/wk)
TRRO - Time constant for smoothing RRO (weeks)(12.0)
FOF - Fraction of Orders to the Factory
ROE - Rate of Orders Entering the market (units/wk)

Based on smoothed orders, a desired backlog is defined as TBUO weeks of smoothed sales:

$$BUOD.K = (RROS.K)(TBUO) \qquad 89,A$$

where

BUOD - Backlog of Unfilled Orders Desired (units)
RROS - Rate of Receipt of Orders Smoothed (units/wk)
TBUO - Time constant for desired Backlog of Unfilled Orders (weeks) (5.0)

Finally, the rate of generation of ideas is defined as zero (see section IV).

$$RGI.KL = 0.0 \qquad 90,R$$

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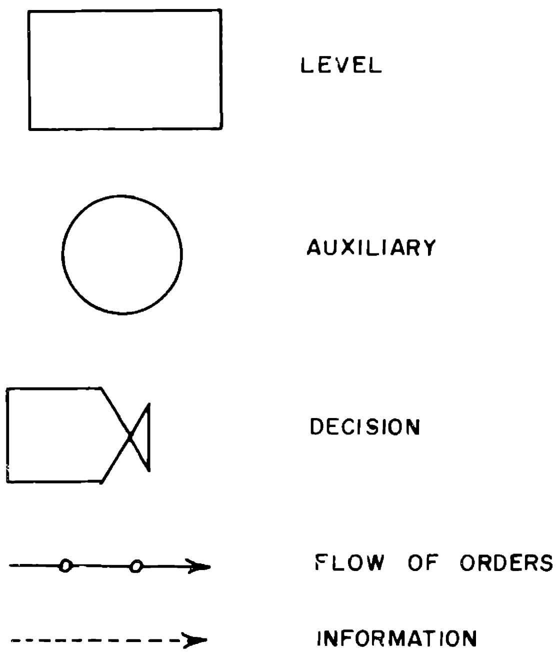


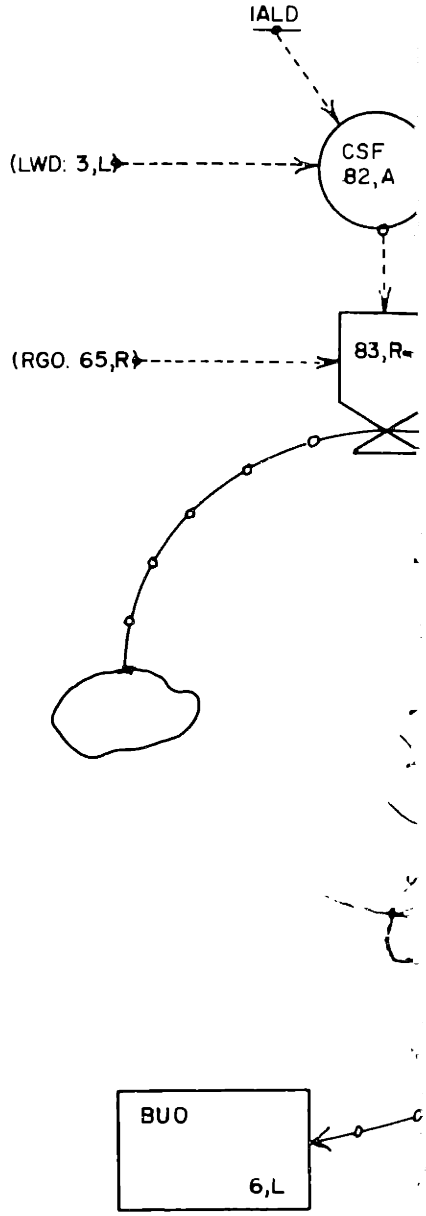


FIGURE 13.

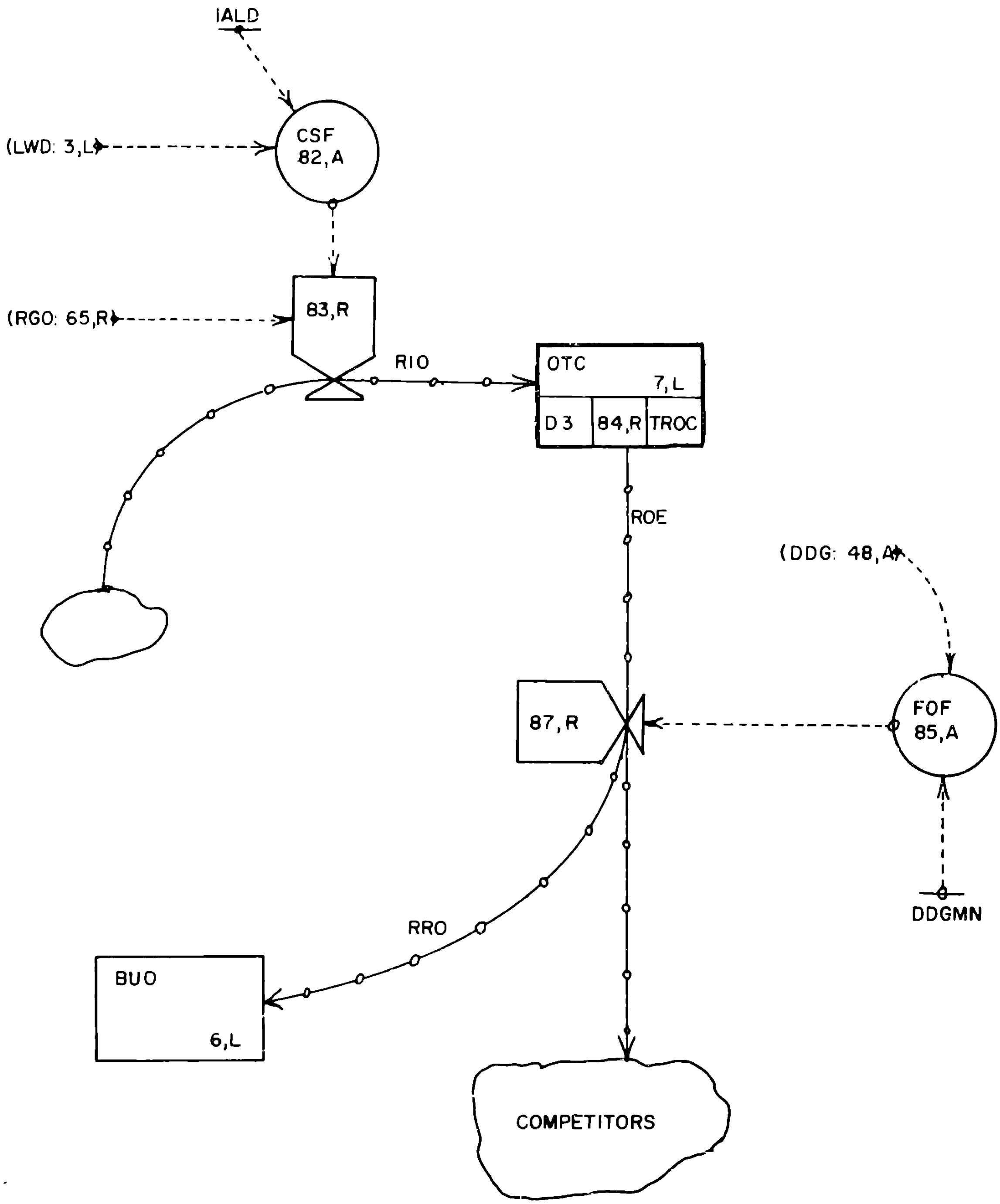


FIGURE 13. THE CUSTOMER

CHAPTER 3

Some Results and Conclusions.

I Error in Formulation of Sales Productivity

A study of the model as formulated reveals a number of shortcomings; some areas should be developed further, some formulations should be altered, and some parameter values should be reconsidered. One error in particular is described here.

The equation for the rate of potential orders generated is:

$$RGO.KL = (EES.K)(PRS.K) \qquad 65,R$$

Also:

$$PRS.K = (PRSMX)(1 - e^{-LWD.K/ENDS})\, e^{-EES.K/200} \qquad 66,A$$

where

RGO - Rate of Generation of Potential Orders (units/wk)
EES - Effective Effort at Sales (man-hrs per wk)
PRS - PRoductivity at Sales (units/man-hr)
LWD - Level of Working Designs (units)

By inserting 66 into 65, reducing to the continuous case, and by rewriting the variables more simply, the following is obtained:

$$y = a x e^{-bx}$$

The level of designs is assumed constant. Differentiating,

$$y' = a e^{-bx} - a b x e^{-bx} = a e^{-bx}(1 - bx).$$

This equation has a zero at $x = 1/b = 200$, indicating that the slope of orders as a function of sales effort changes sign. The second derivative is

$$y'' = -ab\,e^{-bx}(1 - bx) - ab\,e^{-bx} = -ab\,e^{-bx}(2 - bx)$$

Solving at $x = 1/b$, this yields

$$y'' = -ab\,e^{-1}$$

Now, b is always positive, and since LWD is positive, so is a. Hence the second derivative is negative, indicating that RGO reaches a maximum at EES.K = 200, or when there are roughly four men in the sales sector. If more effort is added, the total sales generated decrease. The regrettable conclusion is that the formulation for PRS was too hasty. A possible solution is to add 1.0 to the second exponential term so that it does not converge to zero. The productivity equation would then be

$$PRS.K = (PRSMX)(1 - e^{-LWD.K/ENDS})(1 + e^{-EES.K/200}).$$

This would require that PRSMX and the constant 200 be re-evaluated.

II Discussion of a Sample Run

A run (number 1317 in the Industrial Dynamics Group files) was submitted for solution using the parameters and initial conditions noted in the previous chapter. The run covers two hundred weeks of company operation, and took 4.6 minutes on the IBM 709 computer installed in the Massachusetts Institute of Technology Computation Center. Figure 14 is a sample page of the equations as printed out by the computer. Figures 15, 16, and 17 show some of the plotted results of the run, and figure 18 is a sample page showing the first twenty weeks of printed output.

The system was started empty except for two hundred man-hours per week in the unallocated effort level EEU and one thousand units of ideas in the idea backlog BAI. This corresponds to two or three people who bring to the company ideas in sufficient quantity to build, say, a small special-purpose digital computer, or a line of building blocks.

On figure 15 are plotted quantities according to the following code:

U - EEU, the unallocated effort
E, P, S, - EEE, EEP, EES, the effort at the three sectors
1, 2, 3 - EECE, EECP, EECS, the allocation rates to the sectors
H, F - EEH, EEL, the hiring and firing rates.

The scales were unfortunately not well chosen, but it is nevertheless possible to see that effort was allocated to all three sectors. The printed results show that the allocation was made roughly in the ratio 4: 11:3 for engineering, production, and sales, respectively, which stresses the production sector. This is not plausible at the beginning of the company's life. At about 150 weeks the sales effort becomes predominant; this is to be expected, since there comes a stage when the preliminary organisational and production problems subside, and sales are stressed. No firing is done in this run, and total effort grows continuously. The hiring rate increases to 14.5 man-hours per week/week at 78 weeks (about one man every six weeks), then decreases as a crisis in production occurs (discussed below), then continues to increase. At 100 weeks the total effort corresponds to about eleven people, which is a low figure reflecting unrealistic productivity factors in the formulation.

In figure 16 the symbols are as follow:

R - RIO, the rate of initiation of orders
O - RRO, the rate of receipt of orders
P - RSPIA, the desired production rate for inventory
D - RSPD, the total desired production rate
M - RSP, the actual production rate.

Production begins very early in the company's life; this is part of an error mentioned above and discussed below. The sales effort performs its function, and at about 20 weeks the rate of initiation of orders begins to flow. This is followed by the growth of RRO which remains fairly steady. The rate of production starts, after being too high for a period, settles down at about the level of incoming orders.

At about 120 weeks the effort at sales reaches the 200 mark and continues to rise. As was noted in section I of this chapter, this is the signal for the orders generated to fall off; that this happens is reflected in the decline of RIO at about 150 weeks.

The code for figure 17 is the following:

X, Y, Z - EDFE, EDFP, EDFS, the demand factors
R - RAEE, the resistance to allocate effort.

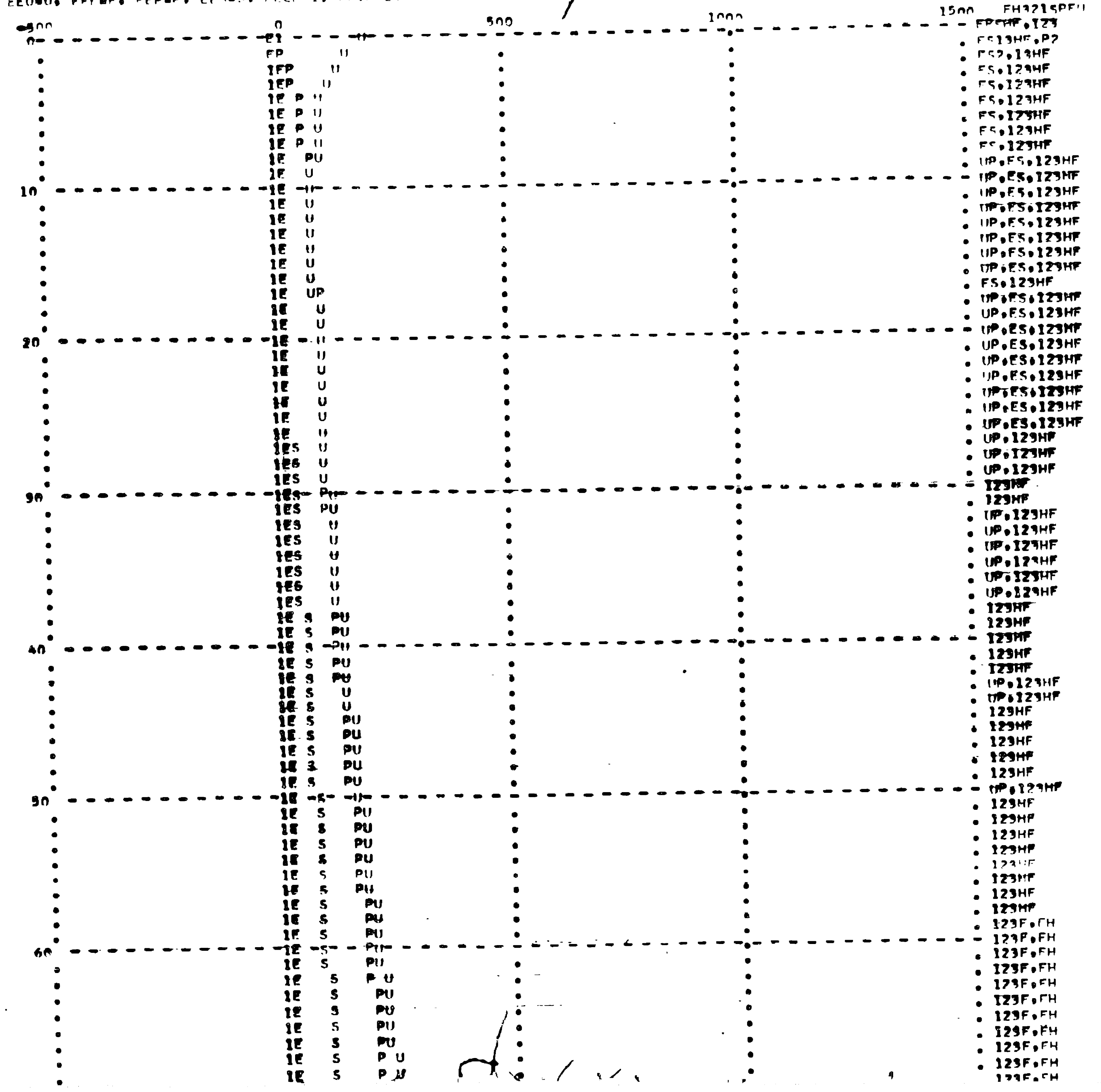
RAEE starts at -1 because all the effort is initially unallocated (see figure 4). It rapidly rises, however, as allocation takes place. The engineering demand factor behaves reasonably, starting high but falling off as effort is allocated to the sector. The production demand factor (plotted as Y), however, does not behave plausibly, and this is probably the cause of several other effects noted in this run, including the shape of the EDFS curve (plotted as Z). EDFP starts at its maximum and remains there until the 78th week when it goes suddenly to zero. Thereafter it behaves plausibly. This error is explained as follows. When effort is initially allocated to production, actual inventory becomes greater than desired inventory, making the desired production rate negative (equations 54,A and 56,A). Since RSPD is negative, so is ENP, the effort needed at production (equation 57,A), and so is the effort ratio ERP (equation 58,A). The clipping equation 60,A re-defines ERP as zero, and the table function of figure 5 produces a demand factor which is equal to 1.0. This results in more allocation to the production sector, which simply aggravates the problem. After 80 weeks sustained orders cause the desired production rate rapidly to become positive, so that the effort ratio ERP moves from a negative value rapidly through zero to a value greater than 1.75, which is the limit of the demand factor table; this causes the demand factor to drop to zero. Effort is unallocated from the sector until the demand factor begins to rise normally. The consequent increase in the unallocated effort causes the hiring rate to decrease temporarily, and this effect can be seen in figure 15.

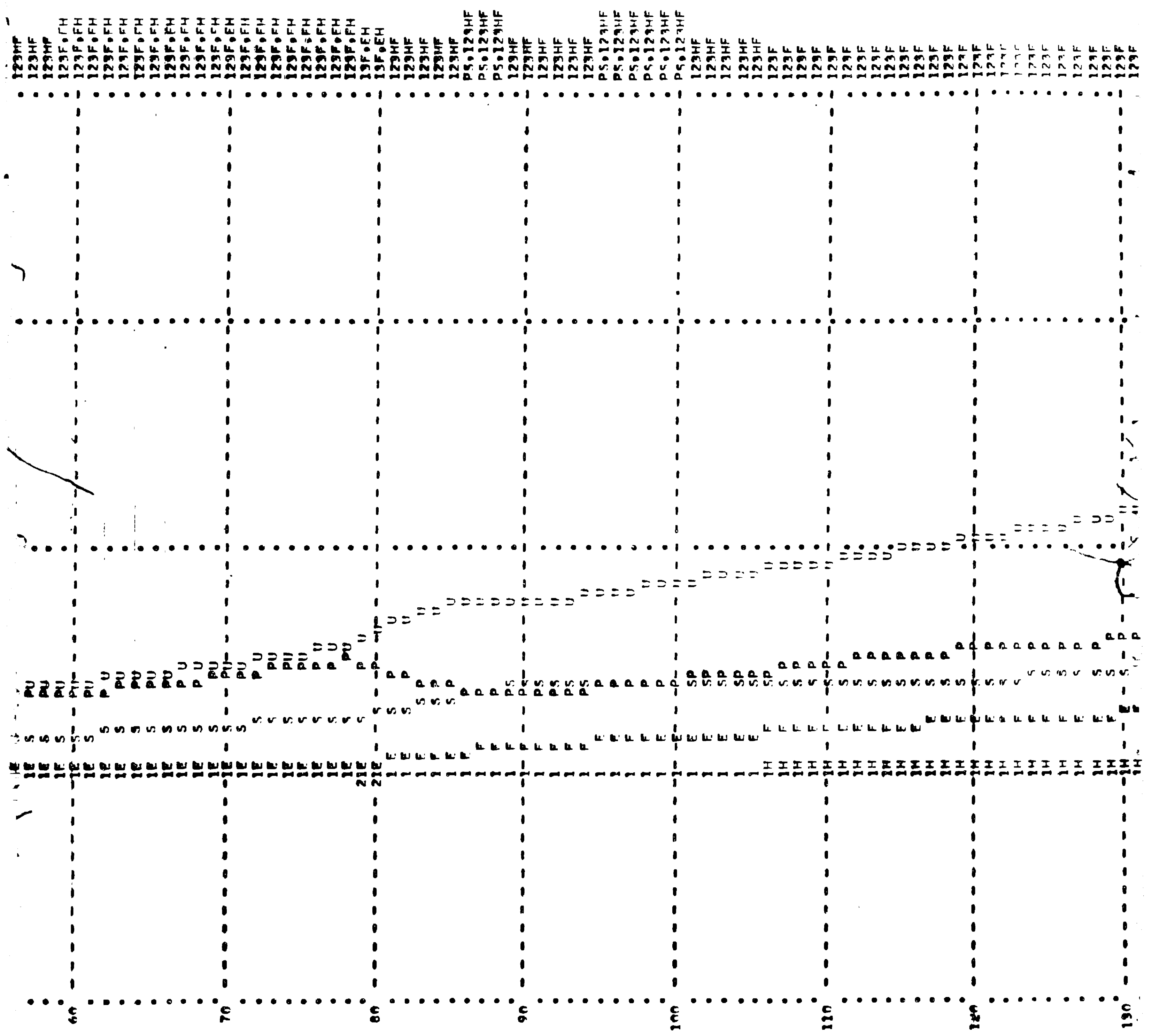
```
51A   TPRS1.K=CLIP(FPRS.K,1.75,1.75,FPRS.K)          LIMITER FOR TABLE
39A   FDES.K=TABLE(FDETB,FPRS1.K,0.0,1.75,.125)      DF AT SALES

          CHANGE IN EFFORT ALLOCATION AT SALES
46A   EFCST.K=(PRS)(DFRAS.K)(EFU.K)/((TCPS)(1.0)(1.0))
46A   EFCSN.K=(NRS)(DFRAS.K)(EFS.K)/((TCNS)(1.0)(1.0))       NEG RATE
7A    DFRAS.K=FDES.K-RAEF.K                           DF-RESISTANCE ,SALES
51A   EFCS.K=CLIP(EFCST.K,EFCSN.K,FDES.K,RAEF.K)

                              CUSTOMER.
        EQUATIONS FOR CUSTOMER SATISFACTION FACTOR.
51A   CSF.K=CLIP(CSFT.K,1.5,1.5,CSFT.K)              CUST SAT FACTOR
20A   CSFT.K=LWD.K/IALD

12R   RIO.KL=(RGO.JK)(CSF.K)                          ORDERS INITIATED.
1L    OTC.K=OTC.J+(DT)(RIO.JK-ROF.JK)                 ORDERS IN TRANSIT.
39R   ROF.KL=DELAY3(RIO.JK,TROC)                      ORDERS ENTERING MARKET.
        EQUATIONS FOR FRACTION OF MARKET TO FACTORY.
20A   FOF1.K=DDG.K/DDGN
28A   FOF.K=(1.0)EXP(-FOF1.K)                         FRACTION.

12R   RRO.KL=(FOF.K)(ROF.JK)                          ORDERS RECEIVED.
3L    RROS.K=RROS.J+(DT)(1/TRRO)(RRO.JK-RROS.J)       ORDERS SMOOTHED.
1L    BUO.K=BUO.J+(DT)(RRO.JK-GSC.JK)                 ORDER BACKLOG.
12A   BUOD.K=(RROS.K)(TBUO)                           DESIRED BACKLOG.


                        PROFIT RATE EQUATIONS
16R   PROF.KL=(GSC.JK)(GMU)+(-DMH)(EFTOT.K)+(-BUDN)(WAG.JK)+(0.0)(0.0)
12R   WAG.KL=(DMH)(EFTOT.K)

        CONSTANTS AND INITIAL CONDITIONS.

                              MANAGEMENT.
C       EFH=5.0
C       TEFA=6.0
C       B=1.0
C       D=10.0
6N      EFE=0.0
6N      EFP=0.0
6N      EFS=0.0
6N      EFT=0.0
6N      EFH=0.0
C       EPS=1E-20
                              ENGINEERING.

C       PRF=.05
C       TRCD=15
C       IFGDM=50.0
C       NOS=5.0
C       TRAD=200
C       TRAI=100
C       TMFE=2.0
6N      LPD=0.0
6N      RSD=0.0
6N      LWD=0.0
                              PRODUCTION.
C       PRP=.1
C       TRCP=3.0
```

BEGAN PLOTTING AT 12/ 5 1749.9

INDUSTRIAL DYNAMICS, RUN NUMBER 1317DH

EEU=U, FFF=F, FEP=P, EFS=S, FECF=1, FECP=2, FECS=3, FEH=H, FEL=F

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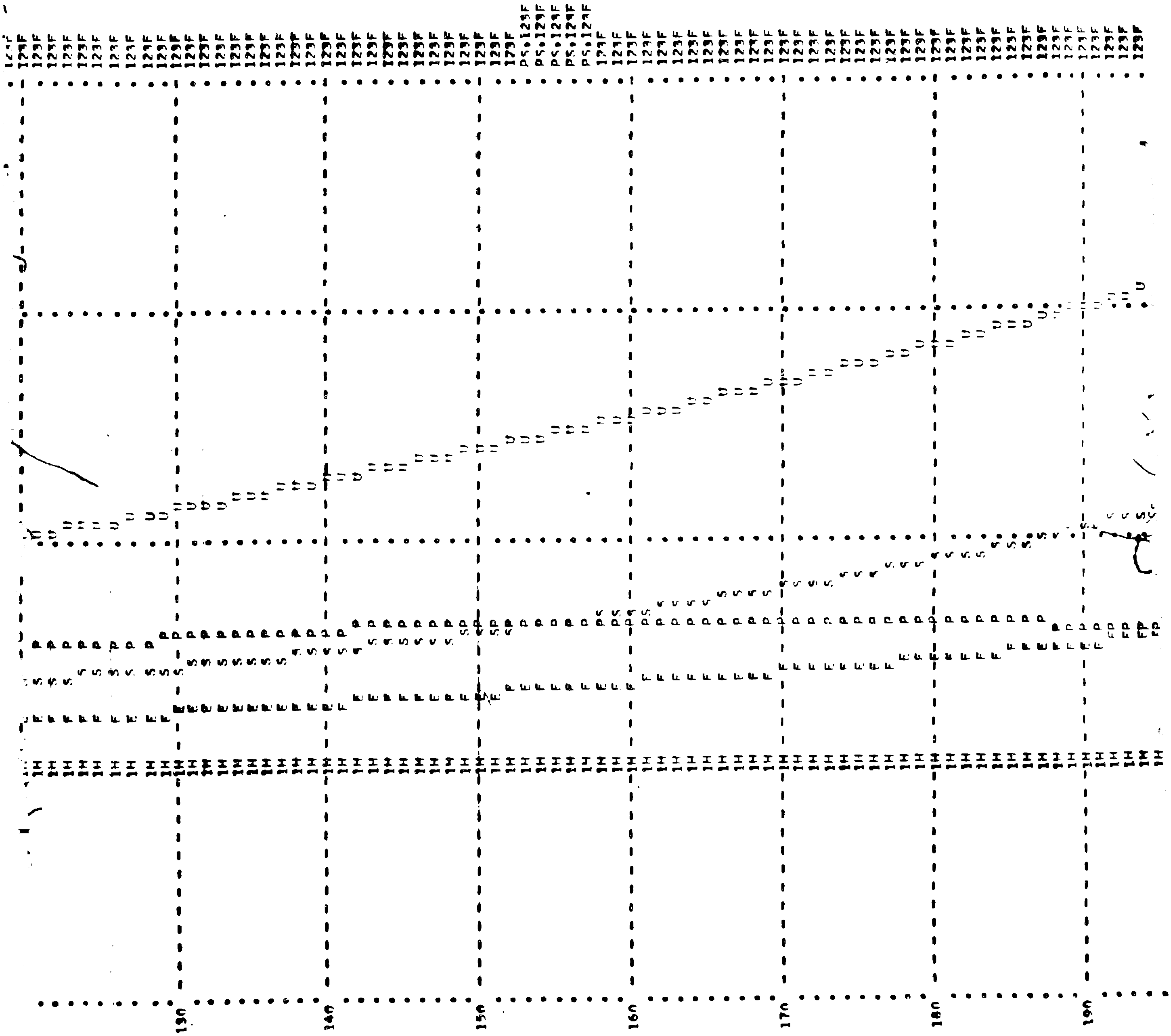

FIGURE 15

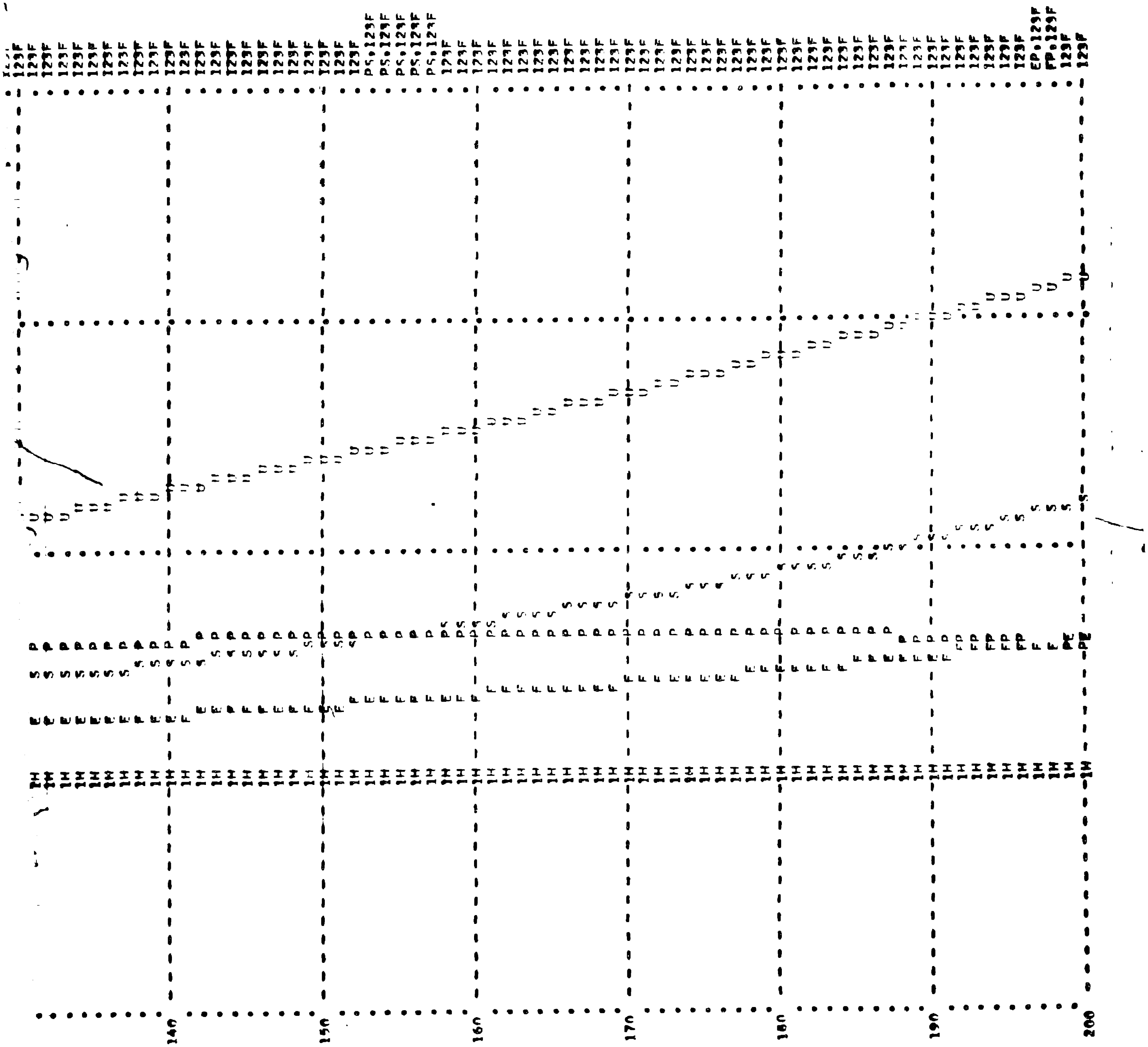

FIGURE 15

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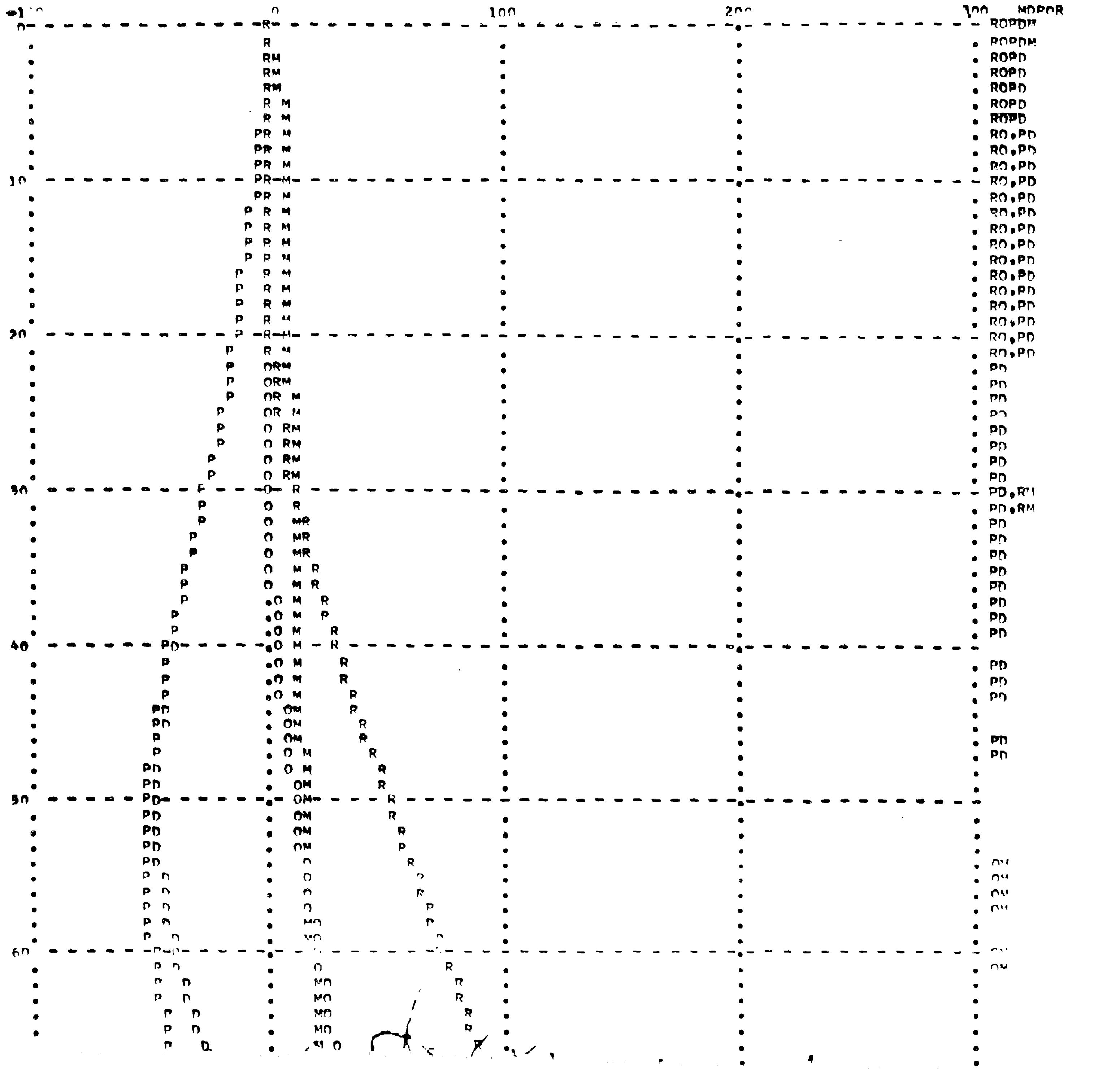
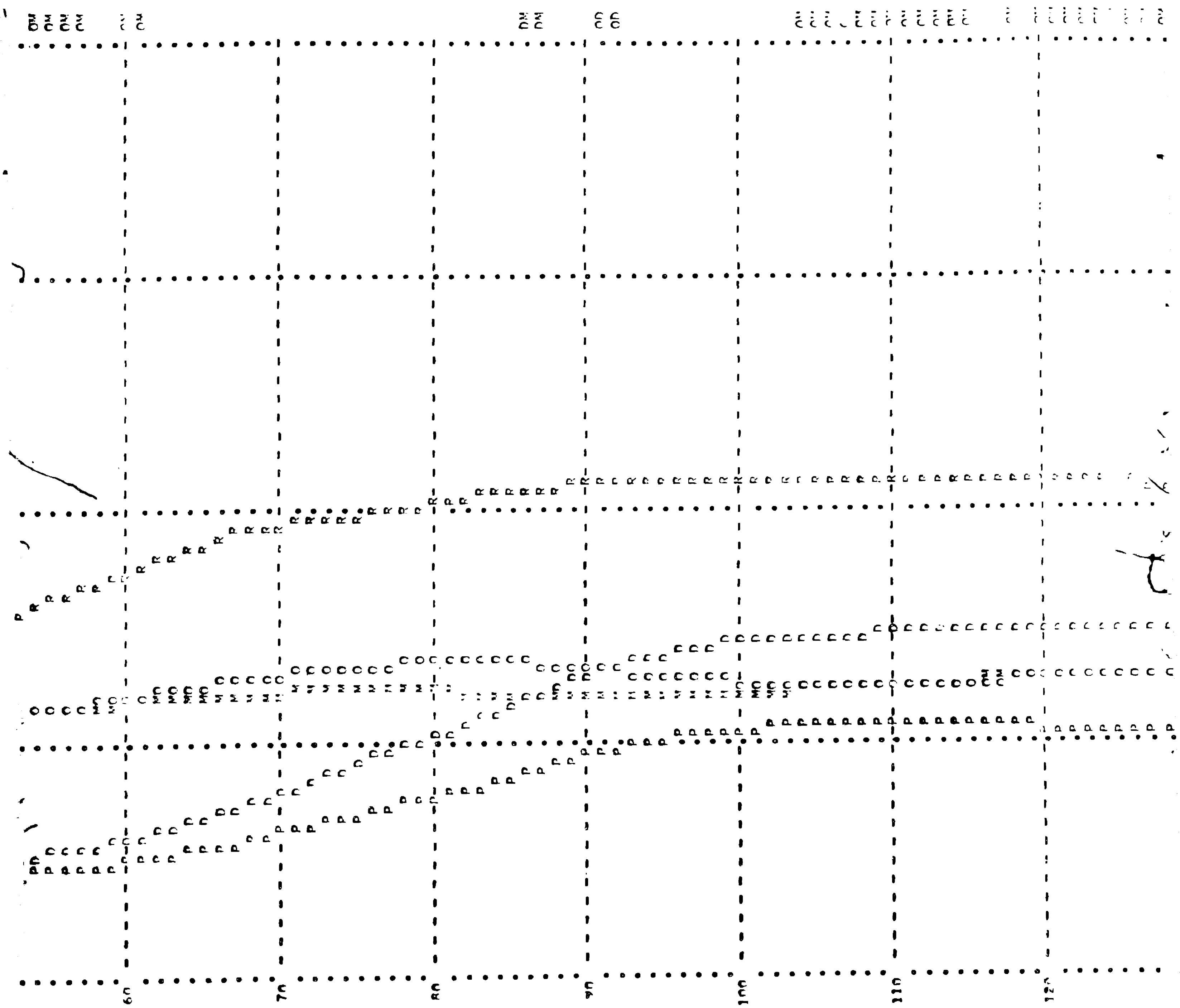
INDUSTRIAL DYNAMICS, RUN NUMBER 1327DH

RIO=R, RRO=O, RSPIA=P, RSPD=D, RSP=M

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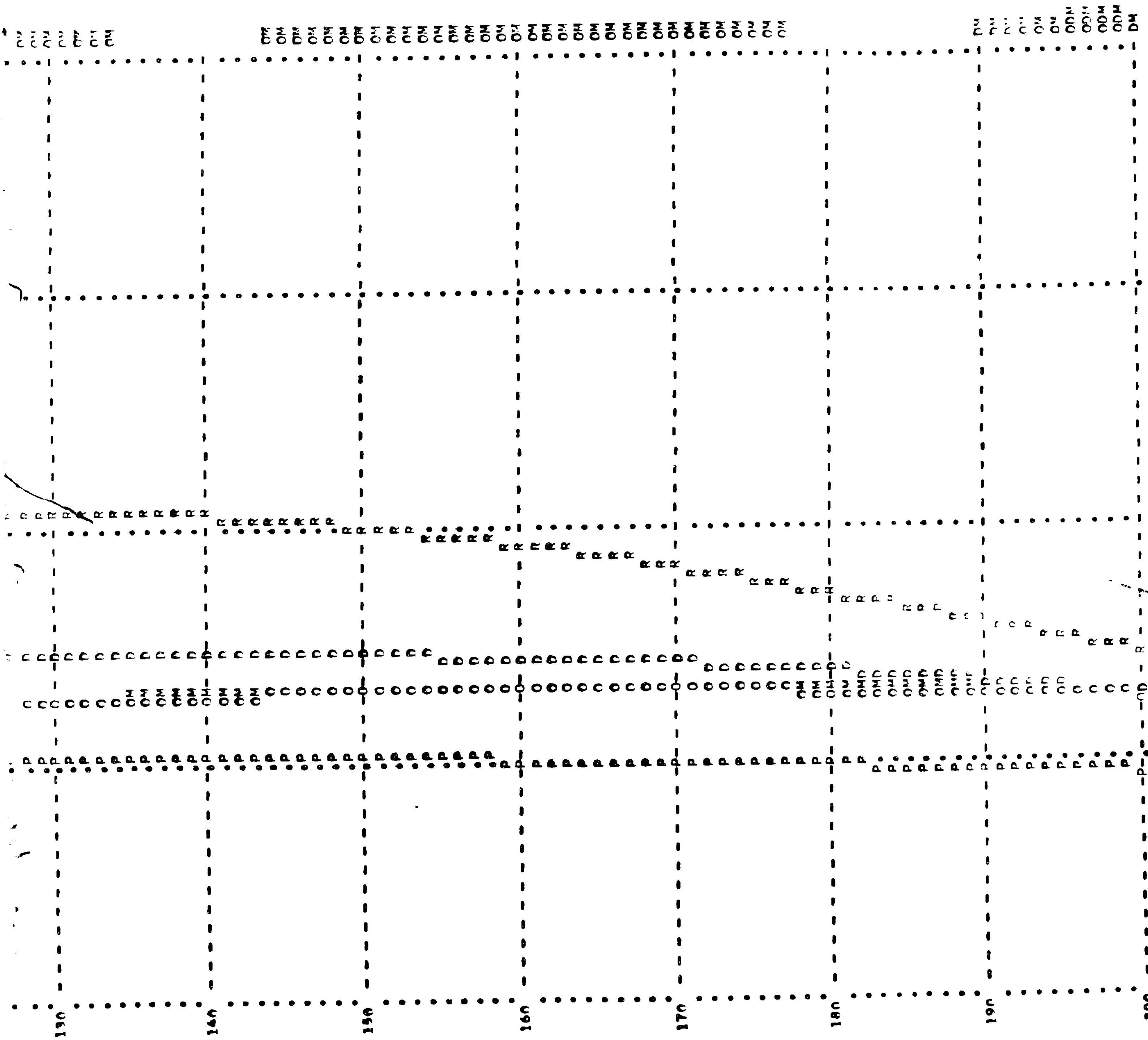

FIGURE 16

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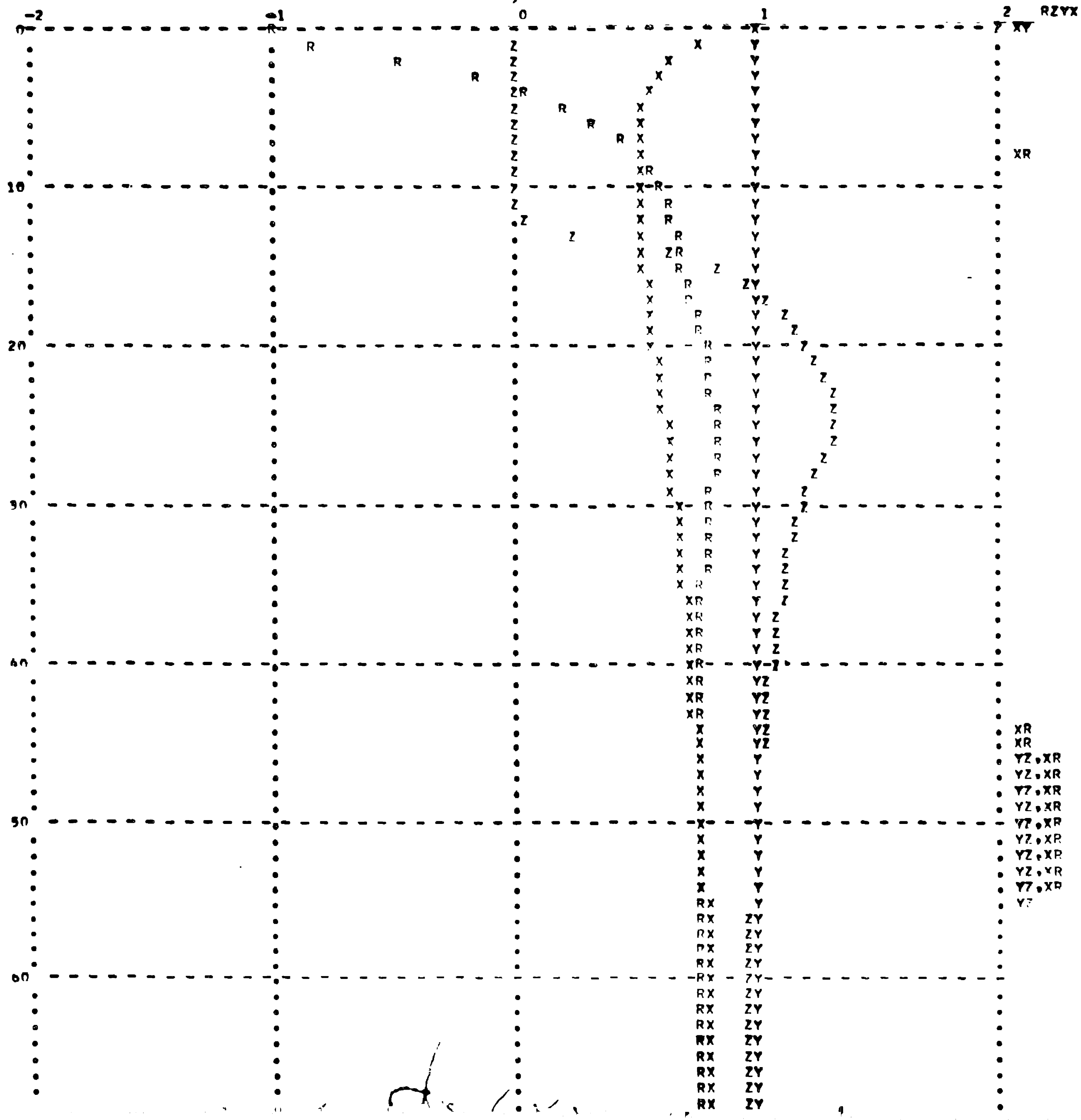
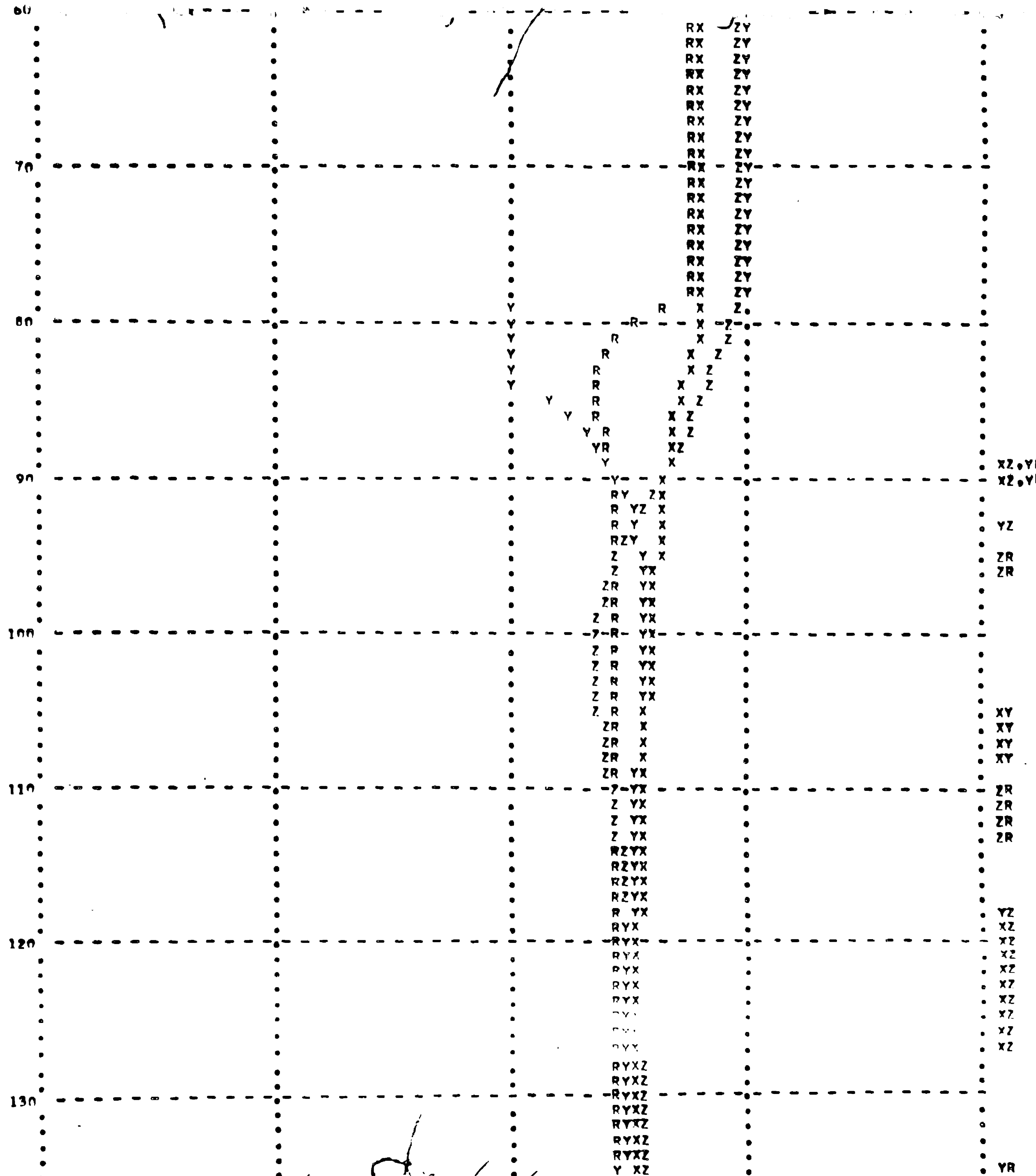
INDUSTRIAL DYNAMICS. RUN NUMBER 1317DH

FDFF=X, FDFP=Y, FDFS=Z, RAFF=R

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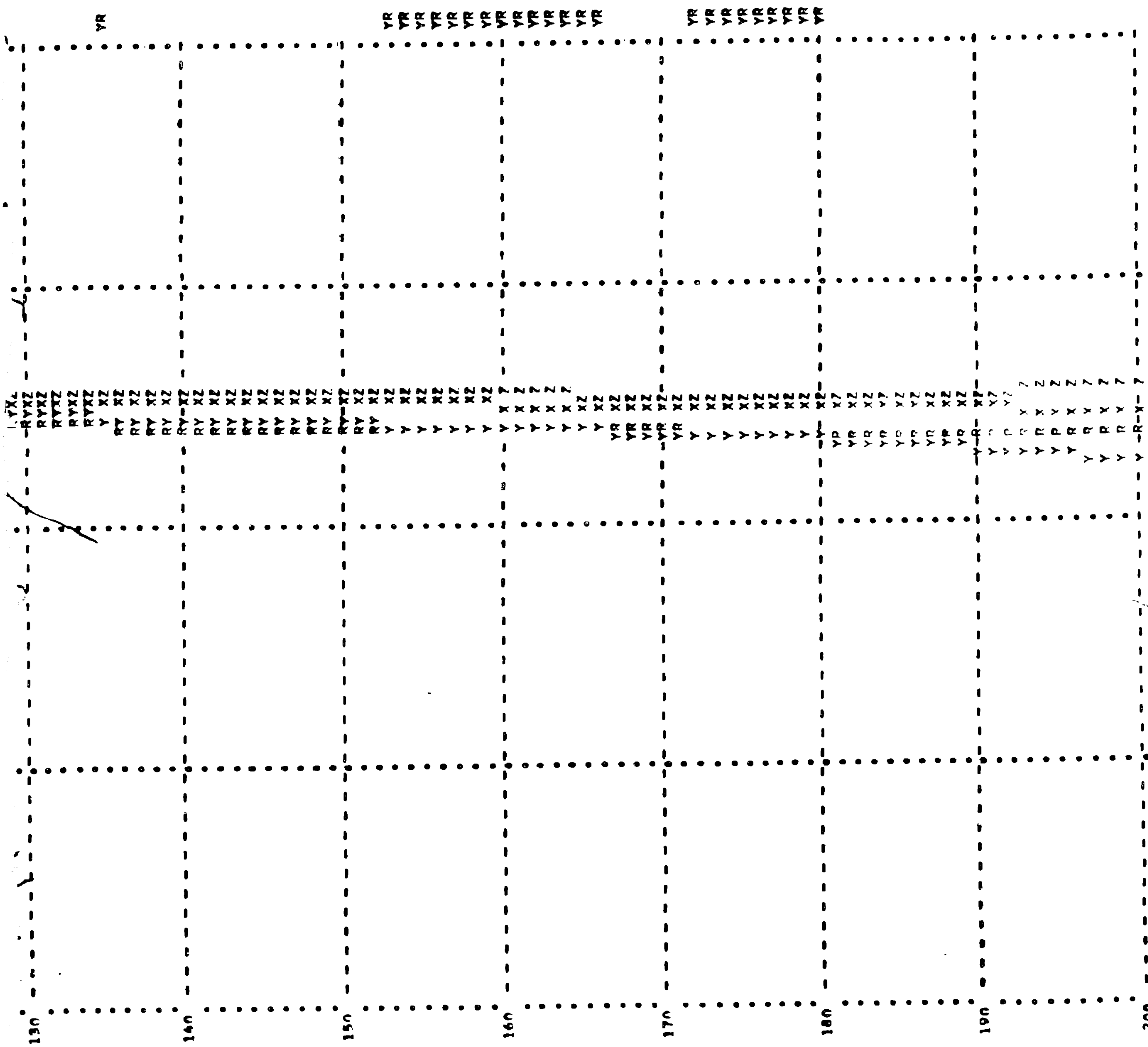

FIGURE 17

TIME	BAI RSD LWD	RSP IFG	GSC BUD	FEE FECF	FEP FECP	FES FECS	FEU	PRS FOF CSF	FPRE FNSP	E[illegible] E[illegible] E[illegible]
E+00	E+00 E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00 E+00	E+00	E+00 E+00 E+00	E+00 E+00	[illegible]
.00	1000.0 .000 .00	.000 .00	.000 .00	.00 11.000	.00 26.400	.00 24.750	200.0	.00000 .84648 .0000	.00000 .300	1. 1. 2.
2.00	999.2 .749 .00	3.519 .15	.000 .00	14.99 4.209	35.19 19.245	13.03 2.636	136.8	.00005 .82974 .0000	.37464 .300	. 1. .
4.00	997.4 1.015 .02	5.450 2.42	.000 .00	20.30 1.494	54.50 6.884	15.05 -.047	109.8	.00150 .81863 .0005	.50832 .300	. 1. .
6.00	995.2 1.113 .10	6.562 8.98	.000 .00	22.25 .509	65.62 4.940	14.70 -.296	97.1	.00893 .80217 .0032	.55724 .539	. 1. .
8.00	993.0 1.136 .31	7.283 19.21	.000 .00	22.73 .009	72.83 2.968	13.95 -.438	90.4	.02830 .78126 .0103	.56845 1.159	. 1. .
10.00	990.7 1.132 .71	7.805 31.92	.000 .00	22.64 -.088	78.05 2.287	13.02 -.491	87.2	.06408 .75758 .0236	.56331 1.915	. 1. .
12.00	988.5 1.121 1.33	8.227 46.25	.000 .00	22.41 -.129	82.27 1.972	12.03 -.466	86.7	.11738 .73301 .0444	.55094 3.695	. 1. .
14.00	986.2 1.107 2.19	8.610 61.74	.000 .00	22.15 -.137	86.10 1.874	11.44 -.036	87.8	.18550 .70909 .0729	.53370 8.100	. 1. .
16.00	984.0 1.093 3.26	8.971 78.12	.001 .00	21.86 -.156	89.71 1.687	12.42 .950	89.0	.26173 .68688 .1088	.51329 12.241	. 1. .
18.00	981.9 1.076 4.54	9.286 95.30	.003 .01	21.52 -.176	92.86 1.466	14.74 1.347	90.2	.33890 .66703 .1513	.49044 17.075	. 1. 1.
20.00	979.7 1.058 5.08	9.564 113.18	.008 .02	21.17 -.183	95.64 1.313	17.70 1.624	92.2	.41216 .64977 .1995	.46654 22.440	. 1. 1.
22.00	977.6 1.040 7.56	9.816 131.68	.019 .05	20.80 -.183	98.16 1.208	21.17 1.845	94.9	.47731 .63509 .2521	.44253 28.361	. 1. 1.

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FFP FFCP	FFS FFCS	FFU	PRS FOF CSF	FPRE FNSP	EDFE EDFP EDFS	RAFF	FFH FFL	INR FPRS	RRO DDG IFGD
E+00 E+00	E+00 E+00	E+00	E+00 E+00 E+00	E+00 E+00	E+00 E+00 E+00	E+00	E+00 E+00	E+00 E+00	E+00 E+00 E+00
.00 3.400	.00 24.750	200.0	.00000 .84648 .0000	.00000 .300	1.0000 1.0000 2.0000	-1.0000	.000 0.	.0000 .000	.000 1.0000 .00
35.19 3.245	13.03 2.636	136.8	.00005 .82974 .0000	.37464 .300	.6503 1.0000 .0000	-.4671	.000 0.	.0027 21.719	.000 1.1199 .00
54.50 6.884	15.05 -.047	109.8	.00150 .81863 .0005	.50832 .300	.5447 1.0000 .0000	.0500	.150 0.	.0485 25.124	.000 1.2008 .08
65.62 3.940	14.70 -.296	97.1	.00893 .80217 .0032	.55724 .539	.5134 1.0000 .0000	.3226	1.298 0.	.1796 19.670	.000 1.3226 .48
72.83 2.968	13.95 -.438	90.4	.02830 .78124 .0103	.56845 1.159	.5062 1.0000 .0000	.5025	2.661 0.	.3842 6.056	.000 1.4813 1.54
78.05 2.287	13.02 -.491	87.2	.06408 .75758 .0236	.56331 1.915	.5095 1.0000 .0000	.6028	3.395 0.	.6384 3.383	.000 1.6658 3.54
82.27 1.972	12.03 -.466	86.7	.11738 .73301 .0444	.55094 3.695	.5174 1.0000 .0359	.6555	3.740 0.	.9251 1.600	.000 1.8635 6.66
86.10 1.874	11.44 -.036	87.8	.18550 .70909 .0729	.53370 8.100	.5284 1.0000 .6296	.6766	3.938 0.	1.2347 .681	.001 2.0627 10.93
89.71 1.687	12.42 .950	89.0	.26173 .68688 .1088	.51329 12.241	.5415 1.0000 .9717	.7127	4.259 0.	1.5624 .476	.003 2.2536 16.32
92.8[illegible] 1.466	14.74 1.367	[illegible]	.32[illegible] .66703 .1513	.49044 17.[illegible]	.5576 1.0000 1.1156	.7540	4.646 0.	1.9058 .395	.008 2.4295 22.71
95.64 1.313	17.70 1.624	92.2	.41216 .64977 .1995	.46654 22.449	.5768 1.0000 1.2111	.7846	4.999 0.	2.2630 .348	.018 2.5868 29.93
98.16 1.208	21.17 1.845	94.9	.47731 .63509 .2521	.44253 28.361	.5960 1.0000 1.2786	.8070	5.327 0.	2.6319 .318	.041 2.7745 37.85

FIGURE 18

CONCLUSIONS

This study has shown that it is feasible to analyse a new-company situation using the Industrial Dynamics method, and further has provided a vehicle for such an analysis. The model described is incomplete, and some of the shortcomings have been mentioned. In particular there is a need for a comprehensive financial sector to enable the investment patterns of the company to be included. The effects of competing companies should be studied, but this aspect is less important than the expansion of the existing model.

Some errors in the present formulation have been pointed out, and the general nature of the required corrections has been described.

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