SOME COMPUTER APPLICATIONS IN THE DROP FORGING INDUSTRY.

by

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SUMMARY.

The cost estimating and production planning techniques at a jobbing Drop Forge were examined with a view to developing improved, computerized alternatives.

Regression analysis was used to develop mathematical models capable of predicting the production variables(i.e. flash weight and production rate) for any forging. The accuracy of the models was found to be better than that presently obtained using the traditional technique based chiefly on human experience.

A way in which this improved accuracy of prediction could result in financial benefits has been discussed. A computer simulation study was used to investigate these benefits.

The possibility of using Discriminant analysis to aid the selection of optimum production unit for any forging has been explained. This avenue of research proved fruitless due to the lack of suitable records at the study forge. An alternative approach to the hammer selection problem was briefly outlined.

A computerized production scheduling system was devised, capable of planning both Forge- and Die Shops. This computerized system was tested and found to reduce the planned lateness of late jobs by 30%, typically. This was achieved by adopting a more logical, rigorous approach to the scheduling problem.

The rôle of the developed scheduling system in an overall, fully integrated production management and control system has been assessed, together with the anticipated costs and benefits of such a fully integrated system.

TABLE OF CONTENTS.

CHAPTER. VOLUME ONE. PAGE.

VOLUME TWO.

SOME APPLICATIONS OF COMPUTERS IN THE DROP FORGING INDUSTRY

1. INTRODUCTION

1.1 The need for research in the Drop Forging Industry

Drop forging has been defined[1] as the metal-forming process in which hot metal, in the form of cut pieces or bar stock, is shaped by forging between dies which contain an impression of the shape to be formed.

In recent years forges have found life increasingly competitive, the competition coming from other, more efficient forges and also from other forms of metal shaping.

This fierce competition has forced the forger to investigate the science and technology of his process in order that he may attempt to improve it and hence maintain, or increase, his share of the potential market of forgeable products.

This thesis makes no attempt to discuss the improvements and innovations introduced due to research into the purely technical problems of manufacturing forgings. Several such types have been admirably researched by D.F.R.A. Instead, this thesis, and the investigation from which it arose, is devoted to a critical discussion of the possibility of using computers in some applications in the drop forging industry. The reason for this approach is in the fact that this appears to be an area sadly neglected by contemporary researchers, both in the drop forging and computer fields.

This research, obviously, embodies several very different disciplines; computing, metallurgy (forging), accounting and some aspects of operational research. It is for this reason that the broad approach afforded by an I.H.D. student was chosen in preference to a research student well versed in the techniques of only one discipline.

1.2 The Drop Forging Industry

The drop forging industry is split broadly into two groups, with a considerable degree of overlap and gradual transition between them. The two groups can be defined as:-

1. Jobbing Forges
2. Tied or "Long-Run" Forges.

The former group is typical of a number of the smaller/ medium sized firms found in and around the Midlands. These make forgings for a number of different customers, the quantities involved ranging from a few dozen to several thousand. The very nature of this type of work is such that a particular component may be made once for a customer, that customer then may, or often, may not require any further forgings of the same pattern.

The latter case, the tied or long-run forge, is at the other end of the scale entirely. These forges often produce the same component for the same customer for years. An example of this would be a forge producing crank shafts subsequently used on a popular model of motor car, quantities of forged crank shafts being required by the customer at regular intervals. Further examples of this category are the larger forges within an organisation, these making forgings for use inside the same organisation. The forges at the car plants of BLMC are an example.

The cost breakdown of a typical forging is given below, figure 1. From the cost "pie" it is evident that the material cost may contribute up to 50% of the overall selling price of the forging, while the production-rate dependent costs may contribute a further 35% or so.

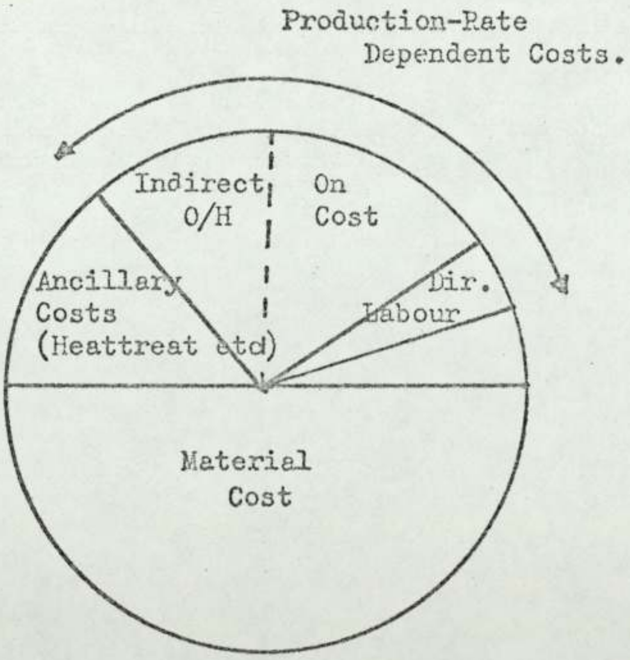


Figure 1[2] Cost "Pie"

1.3 The Firm involved in the Investigation

The firm at which this project was based is situated in the heart of the industrial Midlands. The firm has been in existence as a drop forge some thirty years, and before that it existed solely as a die manufacturer. This company falls in the transition region between the two extremes quoted in the earlier section. They produce both short run jobs for certain customers on a jobbing basis and also very long running jobs, repeated at regular intervals for other customers. For this reason it was thought that the firm chosen was ideally suited for the required investigation.

In 1960 the family business was taken over by a medium-sized industrial holdings group and since that time the Company has continued to trade in the field of medium-sized, drop-forged components with an annual turnover of about £1.5M. The spectrum of forgings produced at the firm ranges from components weighing only a few ounces to components weighing fifteen or so pounds, in materials from mild, to stainless steel. The majority of the components are for the mining and commercial vehicle industries, although a considerable number of high quality components for the aircraft industry are also manufactured there.

Forging equipment consist of 18 friction-drop hammers, both automatic and manual types, with tup weights ranging from 9cwts to 30 cwts. The larger units are served by rotary hearth pre-heating furnaces. A well-furnished die preparation shop enables the firm to produce the majority of its own die requirements. Recently, the firm has added a heat-treatment section to provide heat treatment facilities to serve both its own forge-shop requirements, and also to offer a heat treatment service to other producers of forged components.

The senior management structure at the firm follows the usual pattern for smaller firms. That is, the commercial manager, works manager and company secretary (administrative manager) are directly responsible to the general manager who is also a director of the firm. The Managing Director adopts a global rôle, all other personnel, obviously, being ultimately responsible to him for their actions.

The total work force at the firm is of the order of 200, about 70 per cent of these being directly involved in production of dies or forgings. The working day for the die shop personnel is a single shift of 7½ hours duration. The forge shop offers a slightly more complex picture, several of the units working an eight hour single shift day, whilst other units work a two, 7½ hour shift system.

2. LITERATURE REVIEW

2.1 Current research in the Industry

The introduction to this thesis noted that the past ten years have seen an acceleration of research in the drop forging industry. The basic theory and principles of drop forging have been well documented by Lange[3] Sharman[4] and Schey[5].

Tholander[6] in an early review article (1963) outlined fifteen projects which he felt would be significant in increasing man's understanding of the drop forging process. That author further suggested some form of international cooperation in the solution of these problems, to avoid duplication of research effort.

Aston et al[7] in a more recent review paper summarise the research situation so far, noting the contributions made by several authors on various forging topics. This paper indicates the main area of research undertaken by Universities, that is, investigations into the problems associated with dies and die-life, and those problems associated with the prediction and measurement of loads in forging. D.F.R.A. have extensively researched similarly related topics; both the research association and the Universities cooperating towards one common goal, to improve the understanding and technology of forging.

Jackson and Watson[8] have reported work into the operational research aspects of forging. They have indicated the low utilization of many of the hammers at the plants investigated, while Banbury and Chelsom[9], also at B.I.S.R.A., have examined alternative forging techniques.

In addition to witnessing an acceleration in Drop-Forging research, the past ten years have also been a boom time for the use of digital computers in many technical and business applications. Digital computers have the ability to perform arithmetical operations, subtraction, addition etc., with great speed and accuracy. The storage and rapid retrieval of large quantities of information (data) are further facilities offered by the modern computer, making it a valuable tool in both commerce and industry.

2.2 Specific research involving computers

The Battelle Memorial Institute has been quick to grasp the significant contribution to be obtained from the use of computers, both as a research tool and as an aid in the day-to-day functioning of a drop-forge.

In a series of research papers[10, 11], Akgerman et al report work at Battelle into computer-aided-design, (C.A.D.). C.A.D. required the co-ordinates of various cross-sections of the forging to be punched onto cards. The programme devised by Battelle then determines the number of preform operations required and the necessary die configurations, in addition to outputting optimum flash dimensions, forging load and local shrinkages. This extensive programme also generates a punched tape for subsequent die sinking by numerical controlled drafting. This last feature, production of N/C tapes, is termed "Computer-aided-manufacture", (C.A.M.) by the authors. Further examples of C.A.D. and C.A.M. are documented by a recent Department of Trade and Industry publication[12].

Barry and Aston[13], Thomas[1], Aston and Muir[14] and Litler[15] have all reported the use of computer-aided statistical analysis in investigating factors affecting die-life during drop-forging.

Several authors [16, 17, 18, 19, 20, 21] have suggested the use of computers, or computerized control systems, in controlling the forging process itself. This work, however, tends to concentrate on open die forging, particularly towards the heavier end of the weight spectrum. Little work has been reported regarding the computer control of the closed-impression, drop-forging process, due no doubt, to the less quantifiable nature of the drop-forging process, and the difficulties of expressing the process precisely, in analytical terms.

Law and Humphrey[21], as a result of their investigations into possible computer applications in the foundry industry, suggest that these could include; process control, model building by statistical analysis and computerized production scheduling.

Guest[23] in a similar preliminary investigation into the forging industry, cites the possible use of computers as an aid to the forging estimator and he, similarly, mentions the possibility of some form of computerized scheduling system. The advantages Guest claims for using such a scheduling system include:

a) Reduction in work-in-progress.

b) Increase in production.

and, c) Reduced delivery times.

In addition, the author makes a brief reference to the intangible benefits likely to accrue from the use of a computerized scheduling technique.

As a result of the various recommendations made in the literature and for reasons that will become evident in a later section (3.2), it was decided to concentrate effort in two areas:-

a) Investigations into the possible use of computerized cost-estimating techniques.

and b) Investigations into the possible use of a computerized scheduling system.

2.3 Cost estimating

Cost estimating is the procedure whereby a drop forge may predict the manufacturing cost for a forged component, and thus may tender a selling price to an enquiring customer based on this prediction.

2.3.1 Conventional technique

The technique and mechanism of this procedure have been detailed by various authorities[4, 24, 25, 26]. In an early treatise on forging, Naujoks and Fabel[24] suggest a technique for cost estimating involving the systematic break-down of the forging production, and costs involved, into discrete packages. For example, the authors recommend that material weight (and hence, cost) be computed firstly, followed by computation of labour costs etc. In this way, it is claimed, there is little risk of overlooking some item of manufacturing cost, resulting in an erroneously quoted selling price.

A publication by N.A.D.F.S.[25] states:- "It is the general custom in this country (England) to rely entirely on past experience in estimating the weight of flash, this can and does lead to wide divergencies between the estimated and actual weight." The author continues by recommending the British drop-forger to adopt the approach of Naujoks and Fabel, who report that flash weight is a function of the linear inches of flash and of the net weight of the forging.

It is unfortunate that neither authority makes any recommendations as to the method of predicting production rates, except to acknowledge that quantity made per die-setting has some effect on the ultimately achieved production rate.

A Drop Forging Association (America) estimating manual[26] recommends an estimating procedure not disimilar from that suggested by N.A.D.F.S. The former manual, however, suggests that production rates may be predicted by one of two methods:-

a) Comparison with records of past performance on similar jobs, if available.

or, b) A time-study approach, in which each element of the forging cycle is "imagined in the estimators minds-eye".

Sharman[4] makes two interesting comments regarding flash weight and production unit. Of flash weight he says: "The assessment of the flash weight may appear complex, its form usually being undefined and dependent on the accuracy of the 'use'. An even width around the periphery is extremely difficult to achieve on many shapes, and in consequence, the assessment can only be approximate".

The problem of estimating optimum production unit for any forging, gives rise to the following statement from Sharman:- "There are no set rules as to the size or weight of hammer required to make a specific forging. It is determined from experience. A certain amount of work can be imparted with a given number of blows from a specific hammer, but the same amount of work can be obtained in a fewer number of blows with a heavier unit".

Particularly of interest is the point regarding the interaction of unit size and number of blows required. This will be referred to again in appendix V.

2.3.2 Alternative techniques

Little published work regarding new techniques of cost estimating has been discovered, although the N.A.D.F.S.[27] recently attempted to highlight the possible anomalies in predicting die costs at many forges.

Teterin et al[28, 29] conducted statistical analyses of data from a number of axisymmetrical forgings with the intention of developing a mathematical procedure for estimating flash metal losses. The authors formulated a dimensionless parameter, γ which takes into account the original stock dimensions, the dimensions of the final forging and the vertical distance between the internal and external parting lines, (figure 2).

$$\gamma = \frac{Hs}{ho + hA}$$

Hs - Final height of forging.

ho - Minimum distance between flat surfaces upon which stock was resting when dies were closed.

hA - Distance between internal and external parting lines.

The investigators proposed the following, rather complex, equations for calculating flash weight.

$$Q_f = \frac{(K_1-K_2).Q}{100}$$

where;-

$$K_1 = 0.54+15.44(Q/2.2)^{-0.2} . (1+0.0075\mu)Q$$

$$K_2 = 0.7026.(1+0.01969\mu)w/t$$

and,

$$\mu = S\left(\frac{Do}{D_1}\right)^2 \gamma^2$$

Qf - Flash wt. (Lbs).

Q - Weight of forging, Net weight (Lbs).

Do - Diameter of stock.

Di - Diameter of final forging.

w - Width of flash land.

t - thickness of flash land.

S is a shape change parameter devised by the authors for axisymmetric forgings. (To maintain continuity, this factor is discussed in appendix III).

Researchers at the Battelle Institute^{30} developed the relationship suggested by Teterin et. al. and produced a computer programme in FORTRAN. The programme requires data for each corner/fillet to be input on punched cards. The programme employs a stepping procedure, using the corner/fillets as reference points, and computes several geometric values for the given forging, including:- net weight, complexity factor, flash-gap dimensions and flash weight in pounds. The authors describe four, very similar shaped, forgings and report the agreement between computed and actual flash weight (expressed as a percentage of the forging weight) as, varying between 11% compared with 12.6% and 9% compared with 18% (for actual and computed values respectively).

Battelle's work is referred to further in appendix II, in which a modification to the programme is suggested, resulting in a substantial reduction in the amount of data to be input per forging.

Various authors [28, 31, 32, 33, 34] have devised empirical formulae for calculating optimum w/t ratios based on the statistical analysis of practical or experimental data.

Vieregge[35] in a recent paper comments on the similarity of the overall trend of all the various suggested relationships, but notes that the degree of quantitative agreement is not nearly so satisfactory, (figure 3).

Tognarelli[36] conducting an investigation at an aluminium forge, reported some success in using various statistical techniques in producing models for predicting number of heats required, hammer selection, need for dummying and stock size. He examined numerous aluminium forgings and attempted to derive the relationship between several forging parameters and the dependent variables described above.

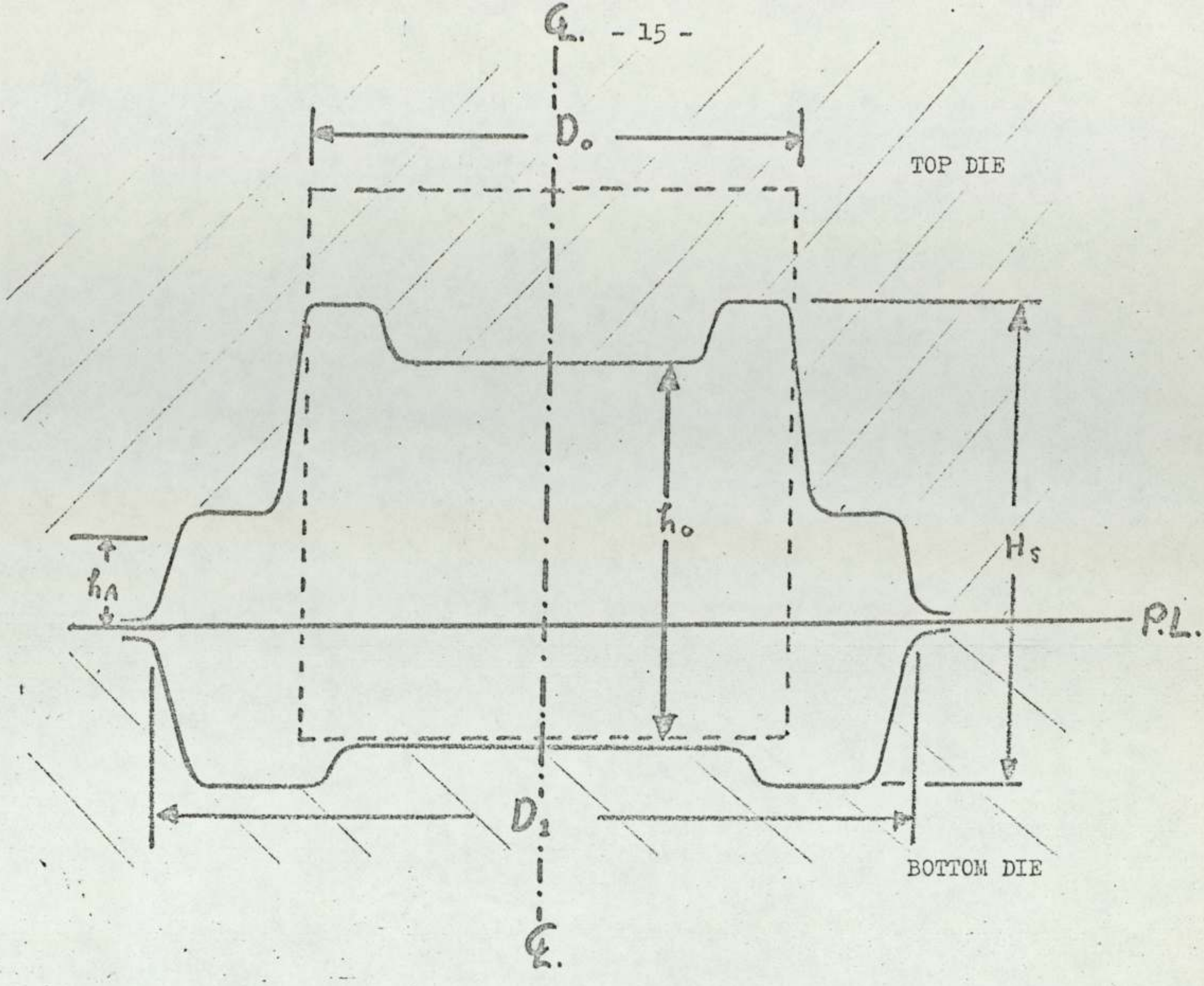


Figure 2. (After Teterin et al.[28])

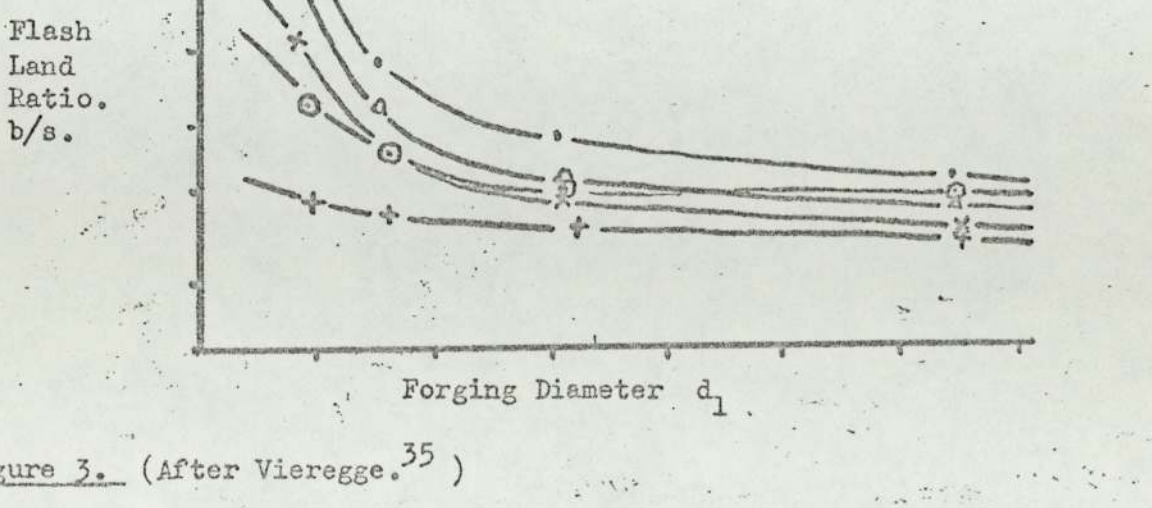


Figure 3. (After Vieregge.[35])

2.3.3 Other approaches to the estimating problem

Lyle[37], working in the sugar refining industry, and later, Bubb and Smith[38] in the food additive field, report the use of regression techniques in predicting annual costs for various work centres. The authors found that equations could be derived that would predict annual variable costs with an improved degree of accuracy when compared to the predominantly experienced-based method formerly employed. Although very different industries, and even a slightly different application, it is interesting to note the use of statistical techniques in fundamentally similar problem areas.

Simons[39] considers that any system of arriving at selling prices via the estimation of manufacturing costs (i.e. a cost-plus system) is quite unrealistic. The calculated selling price is often adjusted up or down by the managing-director in the light of his knowledge of the market position.

Jaques and Brown[40] develop this argument further and suggest that "product analysis" (i.e. the use of statistical analysis to examine the past records of quoted prices) be used to determine the relationship between price (not cost) and the physical parameters of the component offered for sale. The authors quote as an example die-castings of various shapes and sizes, the equation-predicted prices and the previously quoted (actual) prices being in close agreement.

Jaques and Brown contend that such an approach; "..... would maintain an internally consistent price structure, impossible with unit costing. With unit costing, even identical or nearly identical goods can be priced differently at different times, because personnel in the estimating department have changed".

2.4 Discussion of previous work

It is apparent from the literature that forge estimating technique has changed little since Najouks and Fabel first made their recommendations for a suitable technique over thirty years ago. There appears to be no objective way of predicting the production variables necessary for accurate estimation of manufacturing costs.

The Battelle Institute has made a start, in developing the expression for predicting flash-metal losses first suggested by Teterin et. al. This work is likely to be of limited applicability to many British drop forges. The authors concentrated on axisymmetric forgings which, at the firm involved in the study, comprise only 2% of the total component range. This work could, however, be of use to drop-forges whose work mix includes a reasonably high proportion of such forgings; flanges, hubs, discs etc.

The more usual "cost-plus" method of arriving at a selling price should be compared to the unorthodox, "value selling price" approach of Simons, and Jaques and Brown. While it is generally accepted that the Managing Director of most drop forges finds a certain degree of freedom to adjust recommended selling prices, relative to the current market trends, desirable, it is doubtful if many would welcome the product-analysis approach of these authors in the day-to-day running of forge business. Only the most enlightened of Managing Directors would have sufficient confidence in <u>any</u> "automatic" price setting technique to quote to a customer an unexpectedly low selling price, suggested by the analysis, without prior knowledge of the manufacturing "cost" for this forging.

Of the specific research published involving computers in the forging industry, Battelle's work appears to be significant. The work on C.A.D. and C.A.M. indicates a determined step away from more traditional methods and techniques. It must be remembered, however, that the workers at this Institute were involved with relatively simply-shaped, high value, aircraft forgings. The amount of input data required in the case of more complex, but lower-value, forgings (for example, automobile parts) might well hinder the use of such an approach in many British forges. In addition, the capital outlay for N/C drafting machines would almost certainly restrict their use to the largest drop-forges.

2.5 Production Scheduling

Production scheduling, or sequencing, has probably generated more research and literature than any other aspect of production management. The work may be segregated into two, broadly definable classifications: work by authors dealing with the theoretical considerations of scheduling, usually assuming an idealized and simplified problem area; and work by authors investigating a more practical solution to this problem that arises continuously in the manufacturing industries.

2.5.1 The Scheduling Problem - Theoretical considerations

The scheduling or despatching problem has been extensively documented, excellent reviews being conducted by Mellor[41], Sissons[42] and Thompson[43], Mellor defines scheduling (sequencing) as:- "The ordering of the operations on jobs at the machines, subject to routing constraints, so that the best value is obtained for some measure of efficiency".

Law and Green[44] note five approaches to the solution of the scheduling problem:-

1. Critical path analysis

A technique in which gantt charts represent the lengths of production time consumed, and the gaps between the lines, the float. Jobs having little float, get priority over more slack jobs when producing job schedules. This technique is more applicable to situations involving assemblies of parts rather than single entities, and, as such, is likely to be of little practical relevance to the Drop Forging Industry.

2. Algorithmic techniques

This technique often tends to be restricted to problems in which an optimal solution is produced for a relatively small number of jobs on a few machines. Algorithms may be described as step-by-step mathematical or mathematical/logical procedures, whereby solutions to problems are obtained.

The computation time required and the complexity of the scheduling problem in a drop forge would probably render a technique based on algorithms an unsuitable choice for a practical scheduling system.

3. Branch and Bound

'Branch and Bound', a special case of the algorithmic type, is a technique in which various 'branches' (possible solutions) of a scheduling problem are systematically investigated; 'bounds' (time span limitations) are used to discard any unsuitable branches and so prevent further fruitless search. Such systems tend to be rather complex in terms of programming instruction and extravagant with computer time.

4. Linear programming

This application of the widely-used technique of Linear programming involves the minimization of some objective function, such as total production time or number of late jobs. Linear inequality constraints ensure that no operation may be performed until the previous operation in the job sequence has been completed.

5. Simulation approach

A job shop scheduling situation may be imitated by 'modelling' the situation in the form of a simulation programme. In simulating a scheduling problem, each machine is examined in turn, and, if possible, a job loaded onto it, the 'clock' time being advanced only when no machines are capable of accepting a new job at that specific time. The conflicts between jobs competing for time on any one machine are resolved using priority rules, heuristics, or a mixture of the two.

Gere[45] defines a priority rule thus, ".......a function which assigns to each waiting job a scalar value, the minimum of which, among jobs waiting at a machine, determines the job to be selected over all others".

A system implemented at the El Segundo plant of Hughes Aircraft proposed by Bulkin et al[46], consists of a simulation type system, resolving conflict by a minimum job-slack rule. With this system, the authors claim a reduction in the proportion of late orders from 60 to 10 per cent.

Brown and Lomnicki[47] and Brooks and White[48] both describe scheduling systems based on the branch and bound algorithm. Brooks and White developed a procedure suggested by Giffler and Thomas[49] for solving the m x n scheduling problem, (where 'm' represents the number of machines and 'n' the number of jobs to be scheduled). They compared the performance of this method with schedules generated by a random rule, shortest imminent operation rule, and the largest remaining time rule. The authors cautiously report that the method could be used instead of other scheduling rules, for certain applications. They concede, however, that the computation time involved restricts the solution to unrealistically simple scheduling problems.

A system based on descrete linear programming has been devised by Manne[50]. Manne, however, did not attempt to establish the computational feasibility of his approach in the case of large-scale, realistic scheduling problems. His system was tested only on a very small number of jobs and machines.

Nicholsen and Pullen[51] proposed an algorithmic system which depends on the production of an initial feasible schedule. This feasible schedule is then improved, in terms of objective goal, by a second stage involving the movement of each job, individually, into all its possible alternative locations. The order resulting in the best overall value of objective function is chosen. The order may be further improved by a third stage, similar to the second stage except that adjacent pairs of jobs are systematically moved into new positions. The authors report an improvement of between 1.8% and 2.5% of the scheduled cost function over the manually produced schedule.

Palmer[52] devised an ingeniously simple algorithm for scheduling, but made the simplifying assumption that <u>all</u> jobs contain the same sequence of operations. Palmer suggested that priority be given to items (jobs) having the strongest tendency to progress from short to long times in the sequence of processes (operations). The author demonstrates his theory with a schematic (figure 4).

Palmer drew the conclusion that his slope-index method appeared to produce schedules fairly close to optimality in most cases, where optimality could be found (i.e. small m x n problems).

Gupta[53], reporting work on an heuristic method, claimed that his 'functional - heuristic' produced a practical solution to large scale scheduling problems that cannot be solved by exact enumeration. He concludes that the schedules produced are optimal, or near optimal, and considerably better than those produced by Palmer's method.

Wilks[54] describes work at Aberdeen in which the methods of Palmer,and Nicholsen and Pullen, together with hybrids of the two methods, were compared analytically. Wilks uses two measurements of effectiveness, computational cost and performance (as indicated by objective function). He produces a graph of the type shown in figure 5, and notes that such a relationship could form some sort of economic choice between the two algorithms.

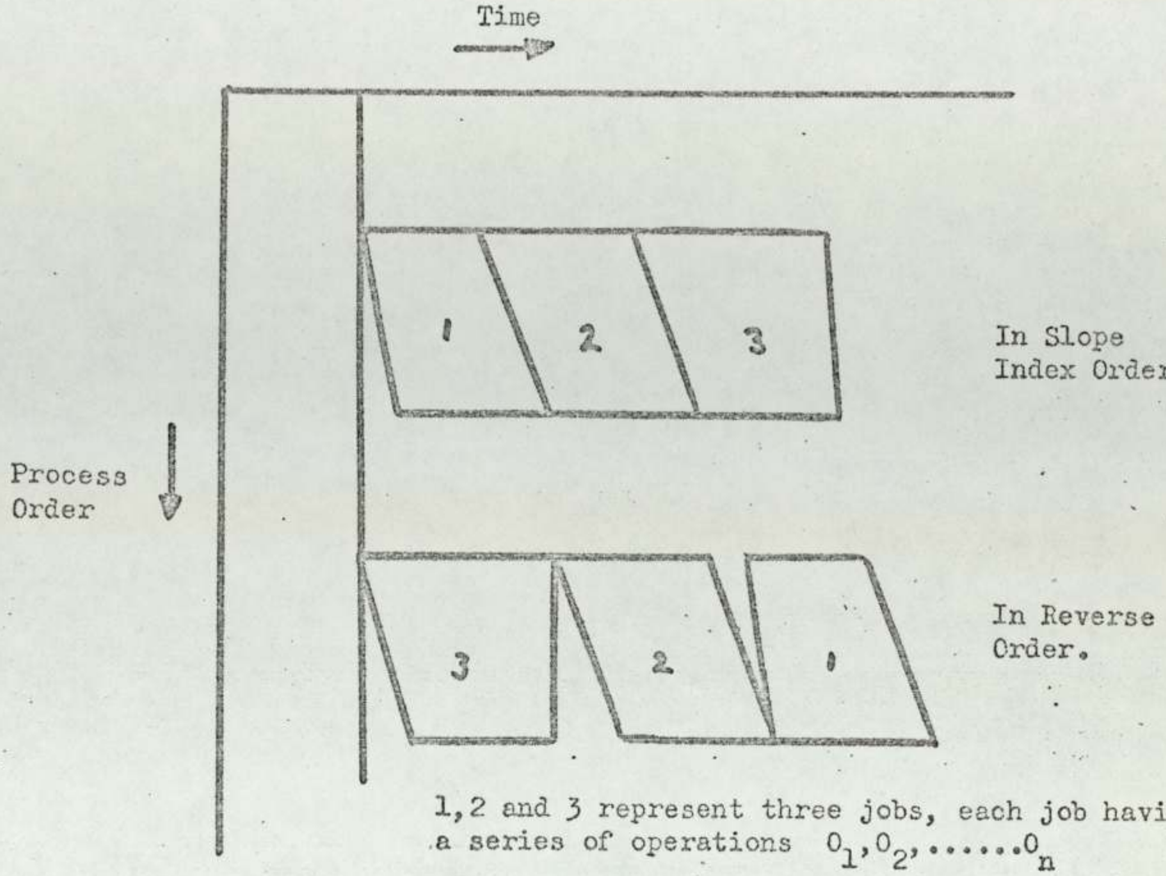
Gere[45], in an earlier article, compares various priority rules alone, and various rules in conjunction with certain heuristics or rules of thumb. Using total tardiness as an objective measure, Gere details three conclusions drawn from his investigation:-

1. "When the problem under study is the realistic one, with the goal of meeting due date commitments, then the selection of priority rule for resolving conflicts is not so important as the selection of a set of heuristics with which to bolster this rule."

2. "Hence, a simple rule should be used, e.g. job slack or shortest imminent operation."

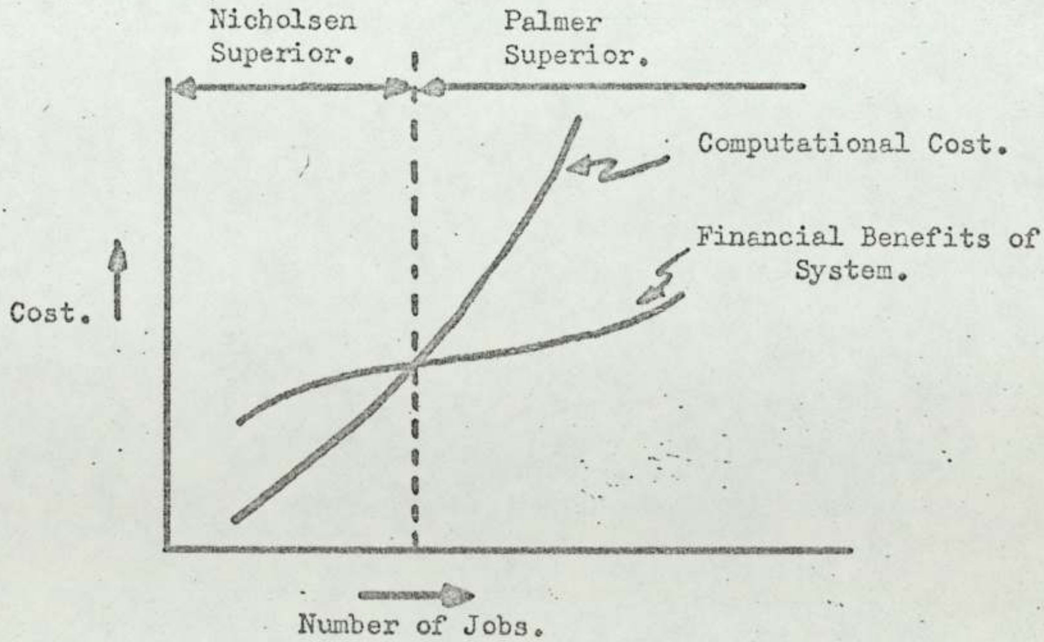
3. "Heuristics which anticipate the future progress of a schedule improve the schedule both in a statistical and practical sense. The improvement in performance is ample reward for the incremental computing cost."

Earl Le Grande[55] in a similar paper, also discusses the relative merits of various priority rules in the job shop scheduling problem. Using a simulator developed by Bulkin et al[46] at Hughes Aircraft, LeGrande's findings are summarized in Table 1, each priority rule examined being allocated a 'Total Relative Rank'.



1,2 and 3 represent three jobs, each job having a series of operations $0_1, 0_2, \ldots\ldots 0_n$

Figure 4. (After Palmer.[52])



Where , $COST = aC_2 - bC_1$;

C_1 = Cost of Comutation per sec.

C_2 = Cost-Value of Improvement of 1% over Random Sequence.

a and b are constants.

Figure 5. (After Wilkes.[54])

Priority Rule		RELATIVE RANK	
		LeGrande HIGH = BEST	Gere LOW = BEST
a	S.I.O/Min.process time per op.	8.70	120
b	Min. slack time per op/job slack per op.	8.54	73
c	First come, first served.	6.93	-
d	Earliest possible start date.	6.77	-
e	Minimum due date.	7.52	-
f	Random selection	7.40	-
g	Job slack	-	69.5
h	S.I.O-job slack ratio.	-	78
i	Job slack ratio.	-	92
j	Modified job slack ratio.	-	92.5

Table 1.

While Gere considers the performance of rules b,g,h,i and j to be similar and only rule a to be significantly different (worse) Le Grande notes that minimum process time per operation (rule a) gave better (unweighted) results than any other rule, with minimum slack time per operation (rule b) a close second. The confusion is increased by Conways results[56] of a similar investigation which, like Le Grande, proved the S.I.O (rule a) to be superior to all other scheduling rules.

Gere assumes a linear relationship between lateness cost and lateness. McNaughton[57] suggests a linear or quadratic cost function and adds that the slope of the cost function has to be decided intuitively.

Beenhaker[58] in his extensive work, adopts a more analytical approach and uses utility theory in an attempt to produce a comprehensive cost relationship for scheduling. Utility theory may be defined as being the mechanism of constructing a pay-off function by attaching quantitative values to qualitative, subjective factors.

Smith for BISRA[59] proposes a linear lateness/cost relationship, stating that a customer ceases to place an order if he receives material more than N ton-days late. (Smith was researching at a hot strip-mill). If the customer ceases to order, Smith argues that the company loses the future annual revenue which it would otherwise have obtained represented by £P. An order N ton-days late incurs a penalty of £P, therefore, Smith proposes than an order M (where $M \ll N$) ton-days late should incur a penalty of £MP/N.

Smith suggests examination of past records of annual revenue per customer in an attempt to assign a value to P and, like McNaughton, agrees that the intuitive mind of the marketing or sales manager is required in arriving at a value for N.

2.5.2 Current scheduling systems available

Various computer scheduling systems are available to the prospective user, often in the form of computer packages. A computer 'package' may be described as a computer system developed and written in such a way that it may be used in a diverse range of user industries, whilst still retaining a rigorous scheduling discipline. Ones own individual environment and requirements have to be described, in a suitable formated manner, to the package prior to using it for scheduling.

Such package systems include - W.A.S.P.[60], S.C.O.P.E.[61], C.L.A.S.S.[62], N.I.M.M.S.[63] and others.

W.A.S.P, developed originally to schedule work through U.K.A.E.A - Harwell workshops, is a system which resolves conflicts by a hierarchy of priority rules. It is a forward scheduling system, loading machines from now up to full capacity. The objective function of the WASP system is two fold, to reduce machine idle time and to keep job idle time to a minimum.

CLASS uses minimized work in progress as its scheduling philosophy. NIMMS, an ICL system, is an integrated package system, comprising a suite of programmes to cover all aspects of production control:- scheduling, stock control, financial reporting etc.

In addition to package systems, various organisations have produced their own, 'home made' scheduling systems. Law and Green[44] proposed a system based on selection by priority rule. Guest[23], in preliminary work at a drop forging firm, devised a system which similarly resolved conflicts by means of a priority rule. In contrast to the two previous references, which were never actually implemented, Muir[64] reports on a system currently performing very satisfactorily in a medium sized drop-forge. It is claimed that the scheduling system does nothing that could not be done manually, but because of the size of the problem involved and the need for rigorous adherence to the decision rules, a computerized system provides the ideal solution. Muir quotes an improvement of customer relationship, vendor-rating (measured as number of jobs delivered on time in any given period) from 50% to 95%.

2.6 Discussion of previous work on the scheduling problem

Of all the literature generated by the theoretical consideration of scheduling, Gere's work appears to be some of the most informative. Gere's suggestions regarding the need to temper priority rules with heuristics, particularly heuristics that anticipate the future progress of a schedule, will inevitably have some influence on any system developed by the present author.

Tate[65] reports on results of work he is presently conducting to compare various, implemented scheduling systems. Tate has indicated that 'home-made' systems appear to be more successful (in terms of benefits obtainable) than package systems. However, he continues by noting that they take twice as long, and are approximately eight times as expensive to set up and install as package systems.

Knight[66] found that the average time required to develop a scheduling system in the American Foundry industry was thirty three man-months, at a development cost of £12000(currency corrected). This figure for the foundry industry must be compared with Muir's experience at a drop forge. Muir has reported that development costs of £25,000 have been incurred in bringing their present system to its current state. It should be noted, however, that Muir's system performs several other major functions such as management accounting reports, invoicing etc., in addition to the main function of job scheduling.

It is apparent from the available literature that 'home-made' systems are likely to be of more practical importance to the drop-forging industry, than the more widely applicable package type systems. This opinion is consolidated by the very nature of the forging industry and the peculiarity of its member firms. The potential difficulties of adapting a formal package to exactly suit each forge's requirements would, no doubt, be considerable.

King[67] makes the point that his recent survey of computerized production control systems has revealed that the use of computers does not appear to have a significant effect in reducing the number of clerical staff employed. He does concede, however, that in some cases it may obviate the necessity for additional recruitment. This must be compared with Muir's experience in achieving a reduction in clerical staff of seven per cent by changing to a computerized system.

To put this discussion (more correctly, the whole question of scheduling)in its true perspective, it is interesting to note Mellor[41]. Mellor, in his review, cites Pounds[68], who records "his unfortunate experience of being unable to find any one in industry, who was responsible for the detailed sequencing of jobs, who recognised that he had a scheduling problem". Pounds is noted as drawing the analogy that the industrial scheduler is "being asked to get a pint out of a quart pot - and is finding no difficulty in doing so". The scheduler's protection arises from the extravagant provision of shop capacity or poor commercial performance.

Mellor adds his own comments. "Most of the accounts one hears of computer based scheduling systems, seem to concentrate on the information handling and data processing functions, and accept the existing sequencing methods as satisfactory". Mellor concludes, "Whilst real progress has undoubtedly been made with idealized, highly abstract models, this progress has not been reflected in the solution of real problems".

Part of this thesis forms a report of endeavours to produce a practical scheduling solution for use in the drop-forging industry.

3. PRELIMINARY INVESTIGATION

3.1 The Path Taken Through the Firm by a Typical Order - Problem Environment

The first stage in any prospective order from a customer is that of a quotation. In order that the customer may purchase his commodity at as low a price as possible, he places an enquiry for the same job with several drop forges simultaneously. The forges he invites to tender quotations are forges he is fairly confident will provide a satisfactorily high quality component. This knowledge is either obtained from his previous business with them or by virtue of the fact that the forge has a good reputation in the industry for high quality and good delivery performance.

The inquiry basically consists of a drawing of the required component plus such details as material specification, heat treatment required, any special tolerance or specifications applying and, of course, the quantity required. The actual details of arriving at the recommended selling price, and subsequent quoted selling price, are discussed at length in a later relevant section, 4.1.2.

The quoted selling price plus a very approximately delivery date, if applicable, are then forwarded for the prospective customer's perusal. If accepted, a firm order is placed by the customer with the supplying forge, this job then being allocated a certain production period on the required machine by the Production Control Department.

The first stage proper of production is that of ordering the steel and manufacturing the dies. In the majority of cases the dies require four/six weeks for completion whilst the ordering and supplying of steel, unless it is a very infrequently used one, is about four weeks. This means that no buffer stock of steel, as such has to be held by the firm, since in the majority of cases the dies take longer to prepare than does the arrival of the steel.

When the dies have been prepared a lead sample is submitted for the customer's approval of dimensional and general acceptability.

When the time comes for actual forging production to commence, the dies are transported to the required production unit and set in the hammer. This "setting" operation consists of ensuring that the two halves of the impressed die are correctly aligned and rigidly held in the upper, moving part of the hammer - the tup - and the lower, fixed part of the hammer - the anvil or bolster.

The dies are heated by means of a small gas torch as a preliminary step prior to actual production. This reduces the risk of cracking the dies due to brittle fracture, as might occur if the hammer were operated whilst the dies were below their brittle transition temperature.

Attainment of a suitable die temperature indicates that forging proper can commence. Some of the steel, having been meanwhile

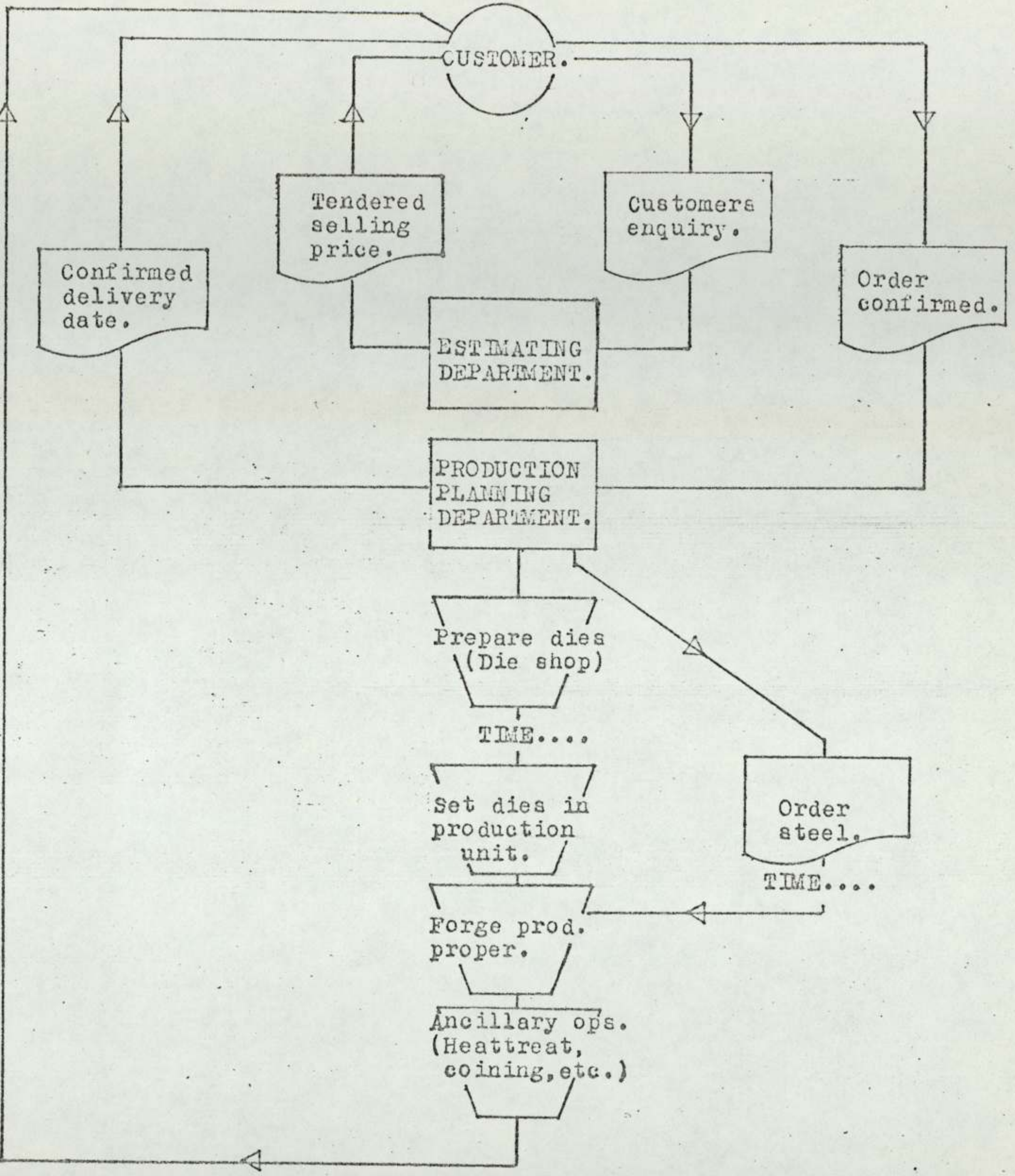


Figure 6. Path taken through Firm by a typical order - the problem environment.

transported to the production unit, is loaded into the furnace. (This furnace loading is often carried out just before the dies have reached a satisfactory temperature in order that the hammer may be used as soon as the dies are warm enough).

Production of the forged component may then be continued until the required quantity has been produced or, in some cases, plant or die failure calls a halt to the production cycle. On completion of the required quantity of forgings, the dies are removed from the unit ready for the next job. Any steel remaining is returned to the Steel Stores and the finished forgings are removed to await further treatments such as heat treatment, shot-blasting, etc., or despatching to the customer if no further treatments are required.

The above, very brief resumé of the path taken by a typical order should I hope, serve to clarify the environment of this investigation. Certain areas of the production path are discussed at length subsequently, in terms of their suitability or otherwise for possible computerization.

3.2 Areas of study chosen from consideration of the job trail

The first operation of any new (prospective) job, it has been noted, is that of evaluating a selling price for the component, which necessitates the prediction of various production variables. The present and traditional method of making such predictions is one relying heavily on the experience of the estimator. If this, or a very similar component has been produced by the firm in the recent past, then the estimator is provided with some guide to making his prediction. If, as is often the case, the enquiry represents a component new to the firm, then the estimator has no such guide, his predictions are then more than ever the results of a very subjective process.

Standard cost rates are extracted from tables or charts and, summating the various elemental costs, the estimator ultimately arrives at a selling price figure. This is a very tedious business and is one usually performed on a desk top calculator. The results are tabulated on a pre-printed "estimate" sheet, with all the inherent risks of introducing errors associated with transcribing figures from one medium to another.

It was recognised that computerisation could almost certainly be used for the second stage in estimating, that of cost arithmetic, since this represents the performance of a string of simple arithmetic operations and file keeping. In fact, since this is not unlike many other data processing applications involving the simple manipulation of supplied data, this was one application already recognised and undertaken by the groups computer personnel. This thesis will, therefore, only discuss the implications involved in such a computer application, since it is the more technical aspects of forge computerisation with which this investigation deals.

The initial stage, the prediction of production variables, was also identified as being one that might benefit from computerisation or the use of computerised techniques. The aim was to produce a firmer, more objective basis for the prediction process. It was anticipated that a more objective method might result in various benefits in addition to any increase in accuracy that might be achieved. (These benefits are discussed at length in an appropriate, later chapter).

On receipt of a firm order, the next department to be involved with the order is the production control department. This department is responsible for assigning the manufacture of the job to the 'most suitable' production period. 'Most suitable' implies that the aim of the planner is to meet, most nearly, the due-date requested by the customer within the context of other jobs competing for production time, every other job also needing its own due-date requirements satisfied.

The usual methods of planning new work is to represent the job by a ticket on a visual display board, the ticket being assigned a certain production period (represented by the position of the ticket along the horizontal axis) by a pragmatic or 'jig-saw' approach.

The production control department have also to perform a progress chasing function and maintain various production record files. The generation of paperwork necessary for efficient expediting etc., is a further task of the department.

As with estimating, this problem can be seen as comprising two closely related functions:-

a) The planning of work, assigning jobs to specific production periods

and, b) The data processing associated with each job and the department as a whole.

For most efficient use of the time available for the investigation, it was decided that research should concentrate on function a), the planning of work, since there appeared to be few set rules or guide-lines to aid the production planner[41].

The second function, b), again is an application that could be quite satisfactorily tackled by an orthodox data processing department. Due to the considerable time involved in implementing such an application (typically sixteen man-months[66]) and its inevitable uniqueness to the specific firm rather than to the industry as a whole, the salient features only will be described.

Once an alternative scheduling (planning) system had been developed it was the intention to evaluate the benefits and cost of such a computerized system compared to the more traditional approach.

The remaining links in the chain of events experienced by a typical 'job' during its involvement with the firm are unlikely to be amenable to, or benefit from, computerization, since many of these are (skilled) labour-intensive. Whilst dismissing these stages as not suitable for computerization in the context of the type and size of drop forge studied during this investigation, it should be noted that some success has been achieved in these areas by workers researching the open-die forging process, and to some extent, press forging. (see section 2.1)

Summarising, two possible areas for study have so far been isolated, namely:-

1) The cost-estimating procedure

and, 2) Production scheduling.

4. COST ESTIMATING

4.1 A Definition of Estimating in the Drop Forging Industry

In the drop forging industry, estimating is the general term given to the mechanism whereby the selling price may be quoted against a prospective customer's enquiry, before the component is actually put into production. The estimating procedure involves the prediction of various production and technical parameters. These are then used in calculating the production costs that it is anticipated will be incurred in making the part. The addition of an element to cover contribution (i.e. profit plus overhead) results in a selling price that may be quoted to the enquiring party.

This approach is, of course, the traditional "cost plus" method of arriving at selling prices. At the Firm studied, costs are calculated on a marginal costing basis as opposed to the full- or absorption costing method.

4.1.1 The Need for a Dependable Estimating Technique

In the opening chapters of this thesis, the path taken by a typical job through the Firm was detailed. The first part of this path involved the estimation of the cost of manufacture, and hence, target selling price to the customer.

The need for a reliable estimating technique can be clearly seen. The estimated cost of producing the part, and subsequently, the selling price to the customer, are based solely on the original estimate as given at the enquiry stage. If this estimate is in error on the low side (in other words, the estimated manufacturing costs are below the actual manufacturing costs incurred during subsequent production of the part), then the supplier's profit margin is likely to be drastically reduced. He may even make a loss on the job due to his quoting an erroneously low selling price to the enquiring customer. On the other hand, if the quoted price arising from the estimate is too high, then there is an increased risk that this erroneously high selling price will not be accepted by the prospective customer. He may choose to select another supplier who has quoted a lower, more realistic, selling price.

On average only three percent of all jobs quoted for, actually materialising as firm orders. This indicates the extent to which prospective customers invite several forges to tender a price for the same job. A further practice employed by the customer of forged component is to invite tenders for, not a new job, but one which is presently being produced by a supplier. The logic being, of course, that if another supplier can quote a price lower than their present supplier, then the customer can change his supplier or use the lower price as a "lever" to encourage his present supplier to lower his price; or at least, attempt to explain the discrepancy between the two prices.

The only time a customer will accept a price increase on the original quoted selling price is in the case of some increase in basic raw materials, such as steel prices. He is very reluctant indeed to accept a price increase due to factors such as increased labour rates, increased fuel oil costs etc. He will, certainly not accept any increase in price due to any error during estimating which has subsequently become evident.

Due to this understandable reluctance to accept any increase on the quoted price, the management at the Firm involved tend to direct the estimator to err on the high cost side, ensuring a slightly inflated selling price. The thought is that it is better to risk losing a job rather than make a job for a loss or very low profit margin, when this production time could have been used for the manufacture of a more profitable job. This philosophy is obviously more applicable to times of a full order book than to a recession period.

Some quotes are not accepted by the prospective customer, not because of any error in estimating technique, but since other suppliers can realistically quote lower prices. The obvious reason for this is that each supplier has certain limitations on the type of job he can make, imposed by the forging equipment he has available. A supplier quoting a lower price might well have equipment more suited to this particular job, and hence, can make the job more cheaply, with a resulting lower selling price.

A further factor that cannot be ignored is that, over the years, each drop forging firm, particularly the smaller ones, tend to gain a great deal of experience in making one specific type of job.

(The reason for this specialisation was probably originally imposed by equipment limitations.) This proficiency in a certain type of job often exhibits itself in the form of higher-than-usual production rates,low die preparation times,etc., all reflected in an overall lower selling price when compared to a firm having similar equipment but lacking the familiarity and expertise in this particular type of job.

Below is given a detailed account of the actual estimating technique employed at the firm at the present time (1972). This technique appeared to be giving a satisfactory performance in general. It was decided to examine critically every stage of the method regarding any benefits that might result from computerization, or the use of computerized techniques.

4,1,2 Present estimating technique

Estimates arrive in the estimating department at a rate of approximately 15 a day, each estimate taking on average 25 minutes to complete. The department is staffed by one man, who deals with the technological side of the estimating. The cost extension function is performed, presently, by the Company accountant, who spends approximately five minutes on each estimate. The Company propose (1972) that the cost extension function be transferred to the group's computer under the auspices of the group computer centre personnel.

New quotations generally take the form of a letter from the prospective customer stating such details as quantity required, post-forging treatment material, etc., together with a drawing of the required component. This drawing may take the form of a very good forging drawing, a machine drawing (from which a forging drawing must be constructed), or in some cases, a rough, briefly dimensioned sketch. Whatever the form of the initial drawing, almost inevitably the estimator has, in some degree, to amend the component in order to obtain a suitable drawing from which he can measure areas, volumes, etc.

Furnished with a suitable drawing, the estimator proceeds to derive the volume and hence, weight of the metal required to fill the desired forged component shape. This is the net weight of the component. The net weight calculation involves breaking the component down into simple elements of volume; such as spheres, cubes, etc. The volumes of these simple elements are calculated using traditional geometry formulae, on a desk-top calculator. The final net weight is derived by summing all the elements, plus an addition for the volume of any fillets that may be present.

The forging gross weight comprises; net weight, flash weight, bar-end loss, scale loss and a die wear allowance. Bar-end loss is a calculable quantity, based on the length of bar to be used, whilst scale loss and die wear allowance are the result of empirically derived relationships, often in the form of the addition of a simple percentage for each.

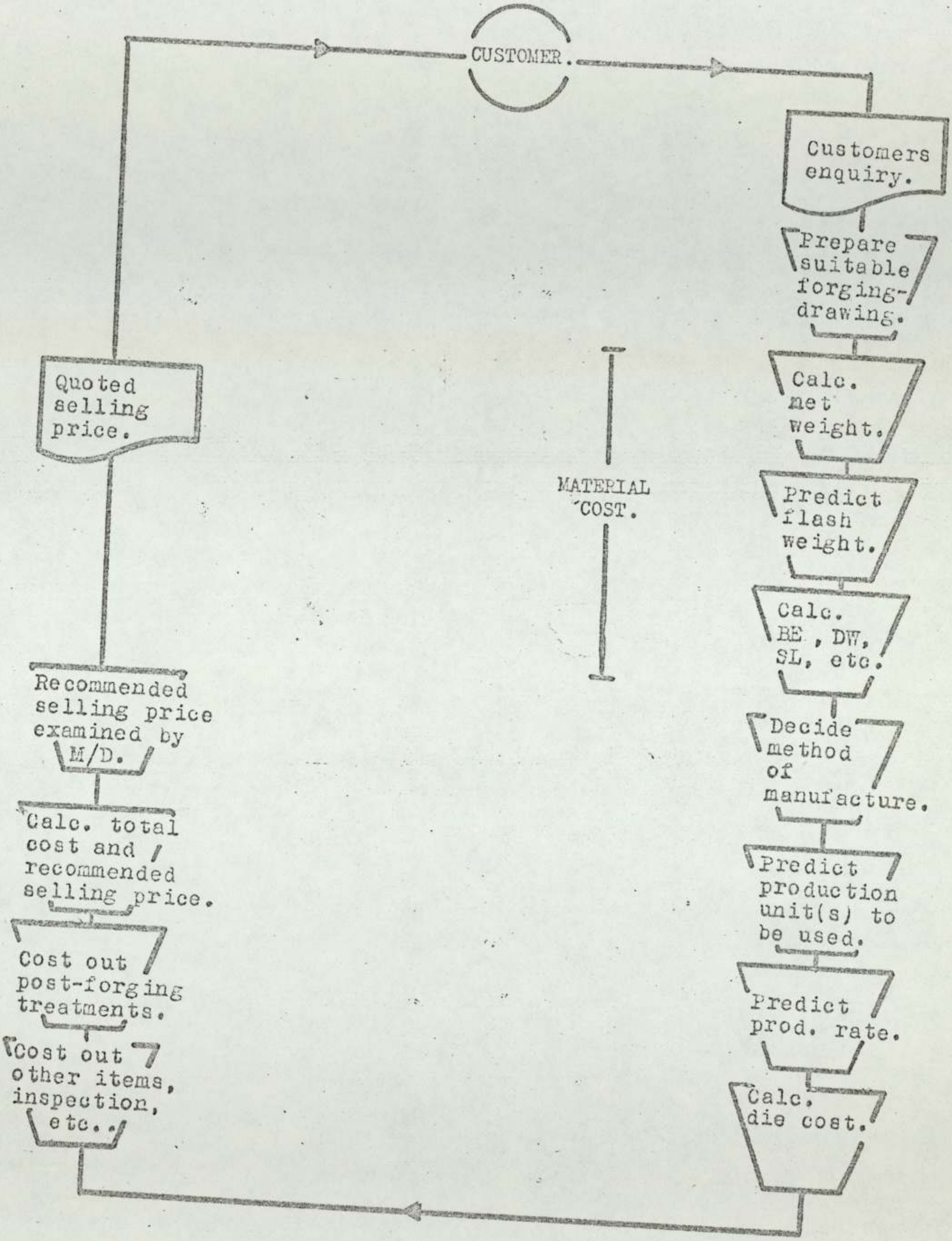


Figure 7. Schematic representation of present estimating technique.

The remaining two components, net weight and flash weight, are far more interesting. Net weight is a calculable quantity, obtained by the systematic breakdown of the component as explained previously. It was noted in the literature survey that work has been published[30] in which a FORTRAN programme, capable of calculating the net weight of an axisymmetrical component, has been developed. As yet, those authors have had little success in producing a programme capable of dealing with the far more complex non-symmetrical shapes.

Any attempt to adapt the present technique, i.e. the breakdown of one highly complex shape into several simpler shapes, is unlikely to result in any benefits. The calculation and summation of individual shapes could be automated by, for example, a computerised method. However, this would only achieve what is presently being achieved by the estimator using his desk-top calculator to evaluate these simple colume elements. What is really required is a system whereby component parameters may be input to a computer and the resulting weight of the component calculated by a computer programme. Such an investigation would require considerable time and effort (far more than is available in this research programme) to even hope to provide a feasible solution to this problem. Research at the study firm has revealed the present manual method of deriving net weight to be very reliable and unlikely to be open to any increased accuracy by alternative methods, figure 8.

Flash weight is a non-calculable quantity. Flash weight we have defined as being the excess of material over and above the net weight, required to produce adequate filling of all ribs and projections within the die cavity. This excess is exuded around the periphery of the forging at the parting plane of the two dies.

The quantity of material exuded between the contacting die faces, flash, is presently estimated on the basis of experience. By "experience" we mean that the man scans through his memory to find a similar shape component that he has dealt with in the past. Using this recollection of a similar job, he sketches around the drawing of the existing job, predicting to what extent the flash will be exuded at various points around the perimeter of the component at the parting plane.

Having drawn an outer boundary to which he expects the flash to extend, the estimator proceeds to measure the periphery of this boundary using a map-reader. He multiplies this value by, firstly, the thickness of the flash (which has a value from tables dependent upon net weight) and then multiplies again by the average width of the flash. (This is measured from the perimeter of the component proper to the perimeter of the estimated flash extension boundary.) Thus he has a value for the expected volume of flash, and, corrected for material density, the flash weight.

Initial examination of historic data indicated that the degree of accuracy of predicting flash weight was not consistent with the degree of accuracy of predicting net weight; discrepancies

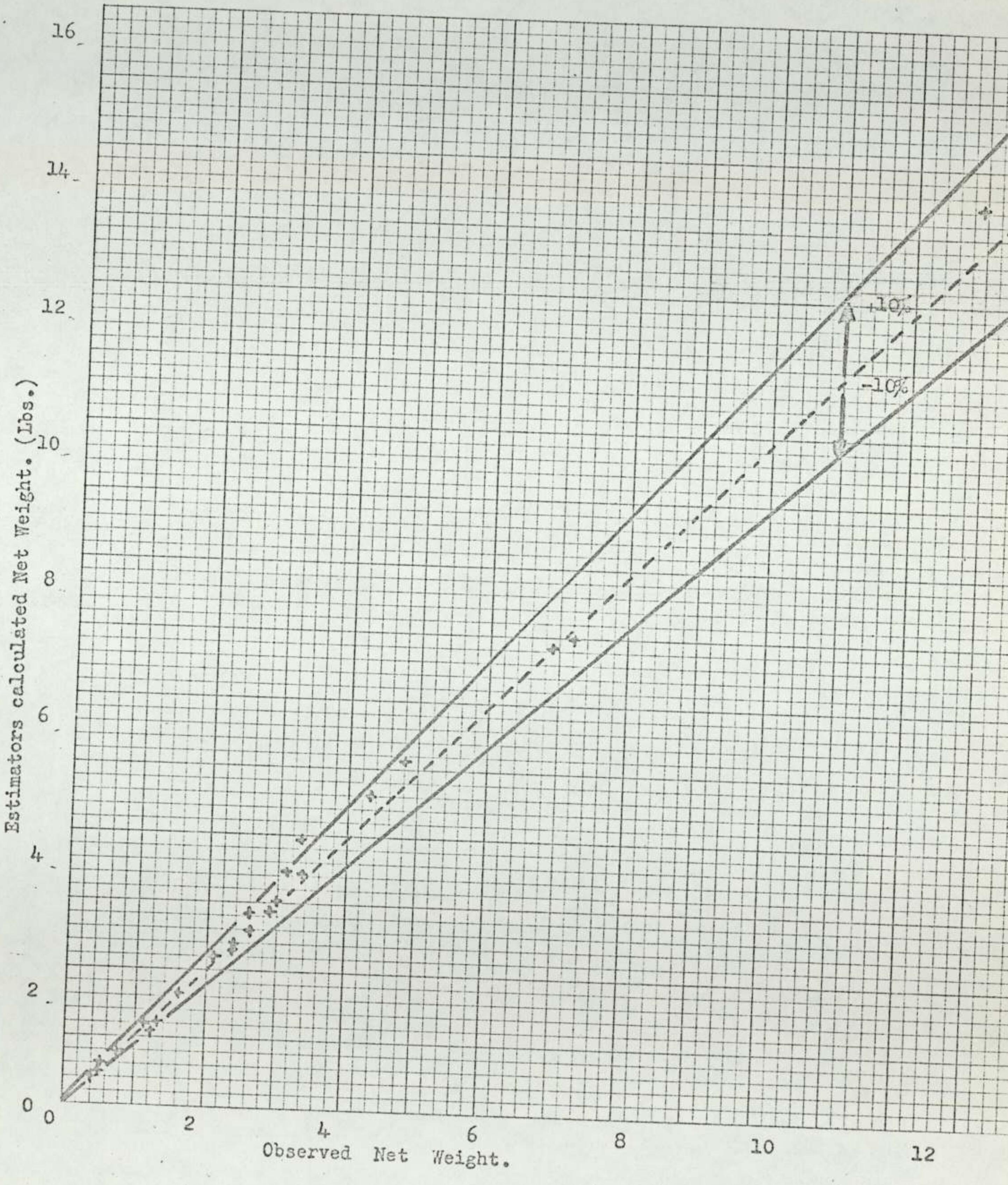

Estimators calculated Net Weight. (lbs.)
Observed Net Weight.
0
2
4
6
8
10
12
14
16
+10%
-10%

Figure 8.

between predicted and subsequently achieved value were found.

This lack of absolute accuracy suggests that the prediction of flash weight might benefit from an alternative, possibly more sophisticated, technique. An improved degree of accuracy becomes even more attractive when one remembers that material costs can contribute up to 50% of the selling price of a steel forging. Having decided that weight of material is required to make one forging, the estimator must determine what size of steel should be used, based on the largest cross-sectional area of the forging.

The method of manufacture is a further item that has to be decided before production costs can be accurately deduced. The estimator has to decide what, if any, pre-forming operations will be required. He has to decide whether any special operations such as bending, hot sizing, etc., are required. He also has to decide on what production unit the job is to be made. This choice is dictated firstly by technical requirements. The unit must have sufficient energy available to impart the required shape to the hot-metal within a reasonable number of blows. The choice of too small a unit results in an excessive number of blows being required, and hence an unsatisfactorily low production rate. A unit too large risks giving rise to reduced die life and high maintenance costs. In addition, at the Firm the larger units are burdened with higher contribution rates than are the smaller units.

In addition to choosing the unit just large enough to make a satisfactory component, the estimator must also take into account the ancillary equipment to be used. This may include pre-forming, hot-setting or bending dies, etc. The need for specialised ancillary equipment, further restricts the choice of production unit. The choice of hammer for the production of any forging, again is presently very much a matter of experience.

The layout and physical position of the impressions on the dies is another of the tasks the estimator must perform. It may be possible to make small components two at a time in the form of a double impression. The estimator must decide whether the dies are suitable for such a layout or even if the quantity of forgings required justifies the extra die sinking cost.

One key figure which the estimator must predict, is that of expected production rate. An error here has repercussions, not only on the labour costs per forging, but also on all other time-dependent costs, fuel oil, contribution, etc.

The prediction of production rates is again an experience-based decision. It involves the mental search for a similar job, or similar job characteristics, and predicting the present production rate based on this mental record.

The estimator has few rules to aid him in making his various predictions, his main guide being "experience".

In predicting production rates the man must rely almost solely on his experience, i.e. his recollection of similar shaped jobs. He may resort to examination of the historic records of these jobs to obtain the value of production rate predicted or actually achieved in these instances. In the absence of a similar shape job, the prediction of production rate becomes little more than an educated guess, an educated guess of a production variable that affects the cost calculations at almost every stage; in calculating fuel costs, labour costs, contributions etc.

Die preparation costs are estimated on the basis of the number of hours work involved and the weight of die material required.

The estimator is now in a position to sum all the various elements of production costs and to add an element for contribution, - based on a standard contribution rate per hour for the machine chosen.

Once the technology and manufacturing method for a forging have been decided, values of production rate, weights etc., predicted all that remains is a process known as the "cost-extension". This cost-extension involves extracting standard cost-figures from various files/record books for such items as steel rate per ton, fuel oil cost rate per hour etc., and substituting these, together with the production parameters previously predicted, into a standard cost evaluation routine.

This cost extension is ideally suited for computerisation, since the work is repetitive, clerical work, involving no or little original thought on the part of the operator. A computerised method would probably give benefits in a number of directions.

(a) Reduction in human participation time - freeing the worker for more demanding tasks.

(b) Speeding up of response time.

(c) Less risk of error due, for example, to looking up cost tables incorrectly in times of stress or heavy work load.

(d) Re-costing due to some standard cost change, could be performed with the minimum of effort and time. (The re-costing of all jobs for some changes in standard rate is manually a monumental task, involving weeks of clerical effort).

(e) Quotation of selling prices for various order quantities.

One very important advantage of an integrated estimating system, incorporating both sophisticated methods of predicting production variables and a fully automated costing routine, is the ease with which selling prices could be quoted for various order quantities. The customer may request selling price for quantities of say, five hundred, one thousand and five thousand forgings. The selling price that the supplier quotes to the customer will obviously be different for each of these quantities. This is explained by the large-quantity order concessions that the forger obtains from the steel supplier, increased production rates achievable with larger quantities, decreased proportion of die setting costs, etc.

With the present estimating technique, the estimator can only make experienced guesses at the effect the different order quantities will have on the respective production rates. He is again guided by any occurrence of previously similar jobs and similar batch quantities that he may recall.

The effects of differing batch quantity on the cost extension routine are, of course, calculable although tedious. An integrated estimating technique would allow both the technology and the arithmetic for any batch quantity to be determined without difficulty. Additional batch quantities, other than those requested by the customer, could be quoted enabling the customer to evaluate the desirability of placing an even larger order, since he would be in a position to see the resultant savings available with the larger order quantities.

The calculated selling price is examined by the Firm's Managing Director, who makes his adjustment up or down depending on his knowledge of the customer involved and the current market position. For example, the Managing Director may know that several other firms specialise in this type of component, and so can offer a more attractive selling price. This tempts the Managing Director to accept a lower contribution element and to cut his selling price in an attempt to break into that particular corner of the forging market.

The above account describes in considerable detail the estimating procedure adopted at one specific firm. This same approach, with minor variations, is typical of the Forging Industry.

4.2 An alternative approach - computer-aided analysis

The estimator at the study firm can examine the information available regarding a forged component and from it predict various production variables. A careful study of the available literature revealed that little had been done to improve this process. Since his approach is essentially one of examining, mentally, historical records, it was thought feasible to identify the critical component details that he examined when making his predictions. Once these critical parameters could be identified, it would be possible to produce a mathematical model to represent the prediction process in a far less abstract form.

Directly asking the estimator, or his superiors, what factors the man actually takes into account when making his predictions, brought no satisfactory answer. The man found himself unable to communicate his thought process to a second person. This is perfectly understandable when one considers that he does not work to any pattern or rules. In fact, he could not be made to deviate from his belief that it was "just a matter of experience".

His superior, however, offered a mode of working which he believed, or maybe hoped, the estimator adopted. This involved a far more analytical approach; breaking down the forging cycle into individual actions, estimating a time for each operation and summing the total time involved. Prediction of material weight was dealt with in a similar manner. This is, of course, the classical work-study approach[26], in which one tries to quantitatively analyse the individual actions contributing to some overall process.

The time and effort involved in pursuing this work study approach, however, would place a considerable strain on the time and resources available to the hard-pressed estimator (he often having to work week-ends to keep pace with the incessant inflow of new enquiries). It is perhaps not surprising, therefore, that the man adopts the quicker, though less satisfactory, subjective approach to the prediction problem.

The type of problem outlined above, the formulation of a mathematical model to represent a process not easily explained or understood, even by the people using the process, would seem to lend itself extremely well to analysis by statistical techniques.

Statistics and statistical techniques have many critics, mainly amongst people who have been the unfortunate victims of statistics used incorrectly or indiscriminately. Tempered with commonsense, however, certain statistical techniques allow the user to investigate a situation that might be impractical to investigate by more conventional experimental techniques. Several examples of the efficient use of statistical techniques have been cited in the literature review, Section 2.

4.2.1 Statistical modelling of the flash weight and production rate forecasts

The technique most suitable for this part of the investigation is that of multiple regression analysis. Briefly, the technique enables the user to determine the type and degree of correlation between some dependent variable, e.g. flash weight or production weight, and a host of possible independent variables. In this way one can build a mathematical model in which the variable to be predicted is defined as some function of the various component parameters.

4.2.1.1 Data collection

The first stage in any investigation involving multiple regression is to decide what independent variables might conceivably be correlated with the dependent variables. This done, the actual collection of data can then commence. In this investigation the data collection stage proved to be particularly tedious, since the job variables required were filed in several individual places. Constant cross referencing and collating were required. The actual job variables recorded are listed below:-

1. Production rate, achieved
2. Flash weight, achieved.
3. Batch quantity.
4. Smallest C.S.A of forging (longitudinal ANS)
5. Largest C.S.A. of forging (longitudinal ANS)
6. Area at parting plane.
7. Periphery at parting plane.

8. Volume of enclosing prism.
9. Stock C.S.A.
10. Bar length.
11. Material type, E.N. classification.
12. Net weight of forging.

First, let us consider the individual models required. In order to predict flash weight, only one model is required, since experience has shown that the unit chosen for production has little bearing on the amount of flash formed. The situation is somewhat different, however, for the production rate models. It is conceivable that the unit chosen for production could have a marked effect on the production rate subsequently achieved. This can be explained by the differing striking rates of differently-sized hammers and the smaller number of blows required on the larger hammers compared to the same forging produced on a smaller unit with less energy available per blow[4]. The differing height of tup-drop is a further factor complicating the amount of energy per blow, and hence production rate, available on various hammer units. Hence, in order to obtain a satisfactory, analytical, method of production rate prediction, individual models for each group of technologically-similar hammer units had to be devised. The alternative to producing a model for each group would have been to incorporate a "hammer factor" in one general production rate model. This hammer factor would have to be formulated as a result of extensive, and expensive, works trials in an attempt to determine the time relationship between the different hammer groups in forging various identically shaped components. In view of the expense involved, in terms of labour involvement, and die material and preparations cost, the former course of action was chosen in preference to the latter. (Note, calculated blow energy would be of limited use die to the large discrepancies often found between calculated and observed values[14].)

In any statistical analysis, it is imperative that any sample taken is a true and representative sample of the universe to which that sample is thought to belong. The usual way of attempting this is to make the sample size as large as is feasible. This has obvious drawbacks - the time involved and the fact that one is never certain when one has reached a satisfactory size. However, there are one or two devices whereby the user can ensure that the sample size is adequate for a true representation of the situation. These are discussed in the following section.

4.2.1.2 Analysis of data

Multiple regression as a model building technique is adequately described in the volumes of literature available[69, 70, 71]. The analysis of the drop-forging data was carried out on a ICL 1905 computer using a statistical package developed by I.C.L.

The use of this facility requires the data, together with details regarding the type of analysis required, to be punched onto 80 column cards and input to the computer. The packet programme itself is stored as a library programme on disc. In addition to the "raw" variables recorded from the firm's records, the statistical package offers the facility of transforming or combining, variables to generate new variables. These new variables may not be directly obtainable from records. For example, we may suspect that flash weight can best be described by, amongst other factors, the ratio of smallest C.S.A. to largest C.S.A., viewed parallel to the longitudinal axis of the bar stock. From the records, only the smallest and largest areas may be available, thus we may make use of the transformation facility to generate a third variable, namely, the ratio of the two. Similarly, other functions of variables may be generated, e.g. x^2, $\sqrt{x}$, etc., and these also analysed to determine any correlation between them and the dependent variable.

Several computer runs were required to produce the initial mathematical models. The method adopted in developing these initial models was to firstly produce a model consisting only of the variables found to be significant at the five per cent level. From this first model, further analyses were performed, adding one variable at a time into the regression set and monitoring the resulting effect on the multiple correlation coefficient and residual error terms. (These terms indicating the "goodness of fit" of the regression model to the observations). By thus adding in (or removing) one variable at a time from the regression set, it was possible to determine which factors did, and which did not, contribute to improving the fit of the model.

The models produced by this method could still possibly be improved. If we consider an equation consisting of four variables, x_1, x_2, x_3 and x_4; a plot of y versus x_1, for example, with x_2, x_3, x_4 held mathematically at some typical constant value, would be expected to give a straight line relationship of the observation points. Similarly, for plots of the variables x_2, x_3, x_4. Any deviation of the observation points from a straight line relationship is evidence that the relationship between the variable plotted say x_1, and the dependent variable, y, is not one of linearity but rather that y varies as some function of x_1.

Plotting the data in this manner for the production rate and flash weight models, did indicate some degree of non-linearity, and hence, various other functions were tried. Some of these were found to improve the fit of the equation by suitably "bending" the regression line to fit the observation points more closely.

In order to show that the data sample was truly representative of the universe from which it was drawn, the following device was used. The data was split into two roughly equal halves, so that two data "samples" resulted. Each of these samples was analysed independently and the results compared to determine any differences between the coefficients of the variables; and, indeed, which variables proved to be significant. Notable differences might suggest that the two "half-samples" were not from the same universe and would cast doubts on the suitability of the sample size proper.

A further technique employed to determine the suitability of the sample size chosen, involved a little more time and effort.

A further ten or so observations were collected and these were included with the original observations in a new analysis. Again, any notable differences in the model produced with the extra observations when compared with the model produced with the original number of observations, tends to suggest that the original number of observations collected was insufficient to be a truly representative sample.

4.2.2 The Use of Statistical Techniques for Selection of Optimum Forging Unit

As with the production rate and flash weight predictions, the estimation of the correct hammer unit on which to make any given forging presently relies heavily on experience. The man has few guide lines on which to base his prediction, his main source of information being his past personal recollection of physically similar forgings. The relative size of the forging, as described by net weight or parting plane area, is considered in a qualitative sense, if not in a quantitative one. Similarly, the complexity of the part and the degree of detail are also considered in a purely qualitative sense, particularly when making a prediction in the absence of any experience of a previous similar component.

In an attempt to identify the component characteristic controlling this choice of production unit, and to quantify their relative contributions to this choice, it was decided to employ a statistical technique known as discriminant analysis.

Discriminant analysis is a technique whereby a total observation matrix containing "m" observations of "n" variables, can be partitioned into "K groups". (Where K is less than m/2 and each group contains two or more observations). Any new observations may be assigned to one of the K groups such that the probability of assigning the observation to the wrong group is as small as possible. In an estimating context, this means that a sample of forgings (m) can be examined and the variables characteristic of the component (n) identified with respect to the hammer group (K) on which the various forgings were made. The results of such an analysis may then be used to assign any new components to a hammer group on the basis of the model so produced.

The above brief description is by no means exhaustive, a more detailed description is available from the literature[70, 71]. Discriminant analysis as a technique for investigating hammer selection, is preferred to the multiple regression analysis used in the investigation of flash weight and production rate predictions, for the following reason. Multiple regression analysis considers that a dependent variable, y, is linearly correlated with a series of independent variables, $x_1 \rightarrow x_n$, such that:

$$y = b_1 x_1 + b_2 x_2 + \dots\dots\dots\dots b_n x_n + \text{CONSTANT}$$

This type of analysis requires that the dependent variable, y, be a contiuously variable quantity, capable of assuming any value over the relevant range. This, of course, is true for both flash weight and production rate, as both variables are truly continuous. "Hammer group", however, is not a continuously varying quantity. Each group is a descrete entity, a prediction that hammer group equals 6.23 for a forging, would be completely absurd and meaningless. Discriminant analysis is ideally suited for such an investigation. The analysis attempts to identify the factors characteristic of each group. Each of the various groups is considered as an individual and discrete area into which components may be uniquely assigned on the basis of their relative values of certain, significant, independent variables.

4.2.2.1 Data Collection

The data required for discriminant analysis was not greatly different from the data that had already been collected for the investigation of flash weight and production rate. In addition to the value of various component variables:- net weight, area, etc., for discriminant analysis it was also necessary to know the 'optimum' or 'correct' choice of production unit for that forging.

At this point, it is important to consider the meaning and implication of the phrase: "the optimum or correct hammer choice".

The present procedure adopted at the firm is for the estimator, on being presented with a new job for the first time, to predict on which hammer the job should be made. In making his prediction, he considers not only the energy requirements of any particular component, but also any ancilliary equipment required (such as wide-bed press, etc.) as this factor must also influence the range of hammers suitable for production. When a satisfactory decision has been reached regarding the choice of production unit, (often in collaboration with the works manager), the remainder of the estimating method, prediction of production rate, cost extension etc., proceeds. When the time for actually making the forging arrives, the forging is inevitably made on the unit chosen at the estimating stage. Due to the time and effort involved, a smaller or larger production unit is rarely tried.

In view of the lack of recorded instances of the non-optimum prediction of hammer choice, it was impossible to obtain the identity of the truly 'optimum' hammer choice for any forging, (since the component is always made on the predicted unit, at the expense of any resulting reduction in production rate or die life). Thus, any statistical analysis could, at best, reproduce the triumphs and errors of the present manual hammer selection technique. This is clearly unsatisfactory, since improvement over the present system is impossible and we do not know whether the presently predicted hammer is the most suitable for the production of the forging or not.

We may now return to the original topic, discriminant analysis.

4.2.2.2 Analysis of Data

As with the multiple linear regression analysis, a statistica package developed by I.C.L. was used, run on the University's I.C.L. 1905 machine. The input again consisted of data (proper) and various control cards specifying type of analysis required, number of hammer group, etc.

Numerous pages of statistical output were produced by the analysis. The computer package is capable of assigning a new data matrix to respective hammer groups, the 'hits and misses' table resulting from such an analysis is given in table 2. This represents the occasions on which the 'model' predicted the correct group (hits), compared to the occasions on which the prediction was in error (misses).

Summarizing, in view of the unsatisfactory nature of the approach in not being able to improve on the manual system (due to the lack of suitable data) the reader is referred to appendix V. Here a possibly more fruitful approach is briefly outlined in the hope of providing a more satisfactory answer to the hammer selection problem.

FORECAST HAMMER GROUP	ACTUAL HAMMER GROUP					
	B	A	D	C	F	E
B	2	1	0	0	0	0
A	12	27	17	0	0	0
D	0	12	56	8	1	3
C	0	0	0	0	0	0
F	0	0	5	0	34	3
E	0	0	1	0	1	4

Table 2. "Hits and Misses" table

4.3 Details of models produced

The extensive statistical analyses conducted in this investigation resulted in the development of various mathematical models. One model describes the weight of flash produced during forging and several models describe the production rate for a given forged component.

Let us consider the models in detail, individually.

4.3.1 The Flash Weight Model

The flash weight model was found to be best described by a model consisting of four component parameters.

a) Stock area.
b) Periphery (squared).
c) Net weight.
d) Enclosing volume.

(a) Stock Area

This parameter is the cross-sectional area of the stock, bar or billet, as measured in a plane normal to be longitudinal axis of the bar/billet. This value is obviously readily available from the size of the material specified for production.

(b) Periphery (Squared)

This term is the perimeter of the forging shape, measured in the parting plane, squared. Again, this value is readily available by measurement from the component drawing, using a map reader.

(c) Net Weight

This is the weight of the finished forging, without any allowance for wastage due to bar end loss, scale loss, etc. This value, we have noted, is evaluated by breaking down the complex component shape into numerous simpler geometric shapes. This value has to be evaluated as an integral part of the costing routine and hence, its determination for the flash model requires no extra effort.

(d) Enclosing volume

This is the volume of the smallest cylinder or rectangular prism that will just enclose the component shape. This value is normally evaluated as a preliminary step in the calculation of the conventional complexity factor for subsequent use in specifying dimensional tolerances in accordance with BS 4114.

4.3.1.1 Discussion of Significant Variables

The justification for the inclusion of stock area in the flash model, is probably explained by its ability to describe to some extent the volume of material stock "offered" to the die impression. Obviously, for a given volume of impression, as the volume of stock increases so the amount of material exuded from the impression as flash wastage also increases.

The inclusion of the parameters; $(\text{periphery})^2$ and net weight, in the model is perhaps not so surprising. Najoks and Fabel[24] as long ago as 1939 recorded their opinion that flash weight was a function of net weight and the linear inches of flash (periphery).

The model has served to quantify this relationship and has shown periphery^2 to be a better description of flash weight than the linear term. (The power term indicates that the influence of periphery in controlling the amount of flash formed is greater at higher values than at lower values of the parameter). The thickness of the flash gap, it will be remembered, has a value from tables, depending upon net weight, further explaining the presence of net weight in the model. Teterin and Tornovskij[28] in proposing a model for predicting the weight of flash formed during the forging of axisymmetrical components, also include parameters to include stock size and net forging weight; while periphery enters their model indirectly via a shape complexity descriptor. (Appendix III).

A factor one might reasonably assume would markedly influence the quantity of flash produced is a quantitative statement describing the complexity and degree of detail of the shape. Complexity of shape, however, is a difficult property to describe. Several methods have been suggested , of these, only the one suggested in B.S. 4114 is of any practical significance. The method of shape description suggested by Teterin et al is only applicable to axisymmetrical type forgings, which at the study firm and many similar sized firms, contribute only 2% or so of the total tonnage of forgings produced. This factor also suffers from the disadvantage that it is somewhat difficult and time-consuming to compute manually.

Another method of quantifying shape is a classification suggested by Spies. This again is unfortunately not ideal, since experience has shown that it is difficult to decide into which classification group many of the component-shapes belong. In addition, the method does not attempt to ascribe a relative 'difficulty factor' to the categorised shapes, and hence, is not a truly quantitative method.

In an attempt to find a more suitable factor for describing complexity, several independent variables were produced by the transformation facility of the statistical computer package. The variables it was hoped might account for component shape included:-

1. Ration of smallest to largest area of the forging.
2. Ratio of smallest area to stock area.
3. Ratio of largest area to stock area.
4. Ration of area at parting plane to periphery squared.
5. Conventional complexity factor, BS 4114.

The analysis found none of the above factors to be significantly correlated with flash weight. The reason for this would seem to be that a highly complex part necessitates more pre-forming operations in order to achieve an acceptable degree of material utilisation and to enable a smaller stock size to be used than would be suggested by the largest component area. Thus, although the complexity of components may vary considerably, when the amount of pre-forming work expended on each component is taken into account, the resulting 'corrected' shape complexities will all be very similar. Only enclosing volume was present in the model, thus retaining some statement of the degree of triaxiality, or 'spread', of the component shape.

The forgeability of the steel was also found not to be significantly correlated with flash weight. This is a factor substantiated by the Firm's own observations over the years.

The model resulting from the extensive statistical analysis detailed above, can be summarized mathematically as:-

$$F = 0.22685 + 0.00095 P^2 + 0.0044 E - 0.0939 N - 0.088$$

where:-

F = Flash weight, LBS.

P = Periphery of forging at parting plane, INS.

E = Volume of enclosing prism, CU.INS.

N = Net weight of Forging, LBS.

S = C.S.A of stock material, SQ.INS.

The residual error (RE) of this model is 0.258 lbs. The residual error value allows us to put confidence limits on any estimation of the dependent variable using the full regression equation. In 95% of the predictions, the actual, observed, value will be within the range $y' \pm 1.96 \times RE$, where y' is the value predicted using the equation. (The precision or accuracy of the modes is discussed fully in following sections.)

The multiple correlation coefficient (MCC) for the model, indicating the 'goodness of fit' of the model to the observations, is 0.891. This figure is in fact the square root of the ratio of the sums of squares accounted for by regression, to the total sums of squares (due to regression and due to error). The square of the multiple correlation coefficient thus represents the proportion of the deviations accounted for by the regression model, 79.4%. The remaining 20.6% is attributable to unknown, random effects.

The contribution of each of the various independent variables in predicting the value of the dependent variable, flash weight, may be assessed by calculating the sums of squares accounted for by each independent variable, SSx_n , using the relationship:

$$SSx_n = bx_n \cdot rx_n \cdot \sigma' x_n \cdot \sigma' y \cdot (n - 1)$$

Where, bx_n = the regression coefficient of the independent variable, x_n

rx_n = the correlation coefficient between x_n and the dependent variable, y.

$\sigma' x_n$ = the Standard Deviation of the variable x_n

$\sigma' y$ = " " " " " " y

n = the number of observations on which the analysis was based.

Also, $SS_{\text{Due to reg.}} = SS_{x_1} + SSx_2 + SSx_3 - - - - - - + SSx_n$

(Derivation of the relationship is considered in Appendix VI)

For the Flash Weight model:

SS (stock area) = 33.669 = 56.8%

SS (Net wt.) = -19.238 = -32.5%

SS (Enc.Vol.) = 13.438 = 22.8%

SS (Periphery sq.) = 19.099 = 32.3%

SS (Due to reg.)	=	49.966	=	79.4%
SS (unexplained)	=	12.315	=	20.6%
SS (Total)	=	59.281		100.0%

When considering net weight alone, one might logically expect flash weight to be positively correlated with it as in general, heavier forgings produce more flash than smaller ones. When considering the effect of net weight together with several other independent variables (stock area, periphery squared etc.), however, the analysis has shown the correlation between net and flash weight to be reversed - i.e., negative.

This apparent contradiction is quite sensible when one considers what the multiple regression equation really means. One unit increase in net weight gives rise to minus 'y' units of change in flash weight, the value of all other independent variable being unchanged. (Simple linear regression does not make this stipulation.) Since stock area is one of these independent variables, it follows that, as net weight increases, so the ratio of net weight (or the volume of the die impression) to the weight or volume of stock 'offered' to the impression, also increases. It is clear that the amount of flash produced decreases as this ratio increases, since there is less excess (stock) material, over and above that required to give complete die-impression filling, to exude out as flash loss.

Algebraically, when the multiple regression coefficient of a variable is negative, but the (linear) correlation coefficient of the variable is positive, then the sums of squares resulting will inevitably be of negative sign. This is because the SSx_n relationship involves the product of bx_n and rx_n, the remaining values in the relationship being positive by definition.

If a 'pie' chart is used to display the relative contributions, then the negative sum of squares due to the variable net weight must be overlaid or subtracted from one or more of the other variables, if the total is to equal 100%. Since stock area and net weight are positively correlated with each other, it seems sensible to show the net weight contribution overlaid over part of the stock area contribution. (Although algebraically net weight is a negative contribution to the total sums of squares due to regression, it is wrong to assume that this variable could, or should, be omitted from the model. Analyses during this investigation have shown a model excluding net weight to be a poorer fit to the observations than the complete model, including it.

4.3.2 The Production Rate Models

The hammers at the Firm were divided into six groups, dependent upon maximum energy obtainable, and upon the mode of operation (i.e. manual or automatic). Both of these factors exert some influence on production rates obtainable.

Additional sub-division was necessary since the group of hammers at the top end of the energy scale could have a one-or two-man crew. The hammer grouping outlined above gives rise to 7

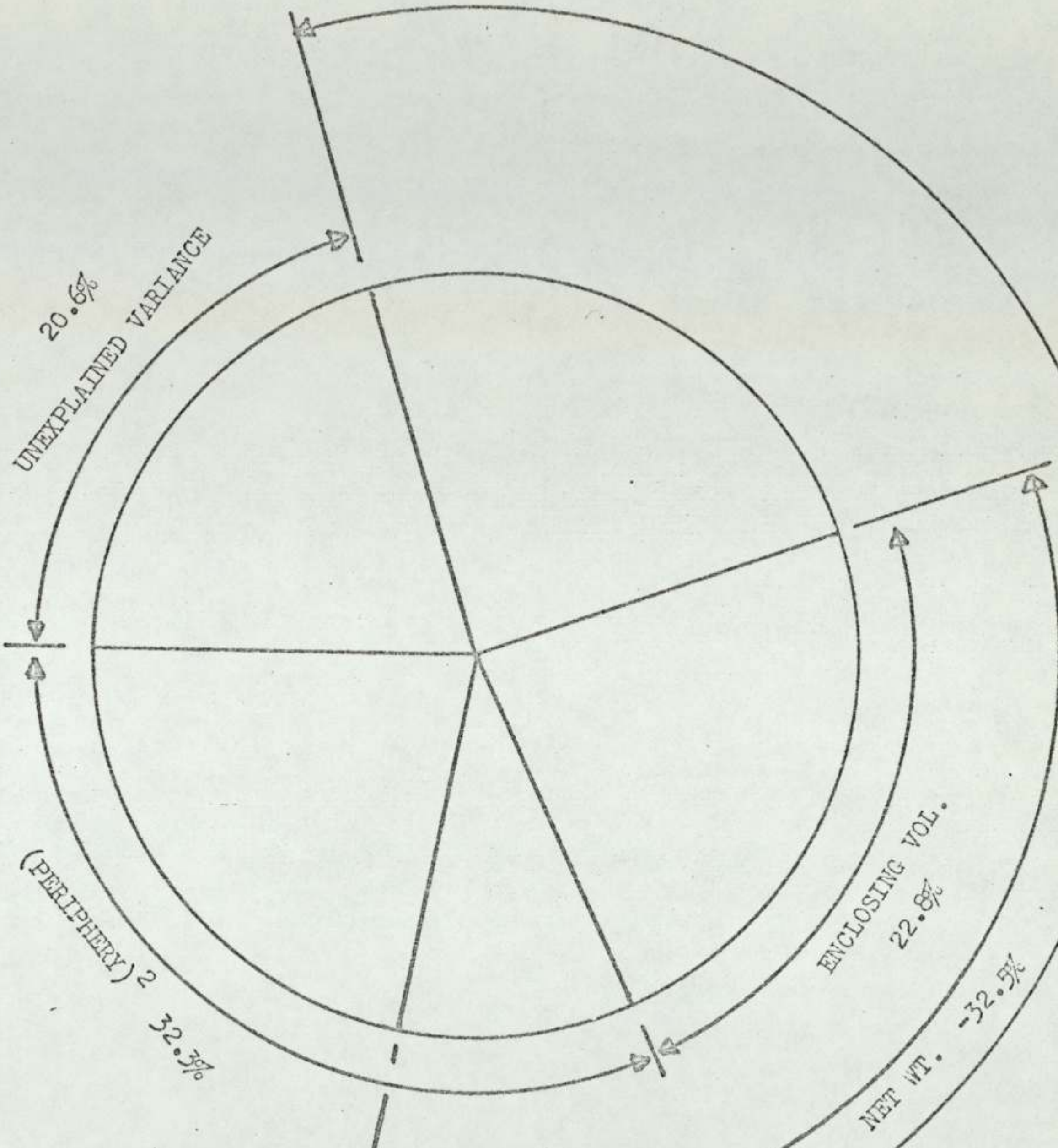


Figure 9. Contribution "Pie" For Flash Weight Model

hammer groups, with no appreciable difference in unit properties between the hammers within any one group.

GROUP	DESRIPTION/TUP WEIGHT
A	10 cwt - Manual operation
B	10 cwt - Automatic operation
C	18 cwt - Manual
D	20 cwt - Automatic
E	25 cwt - Manual
F	30 cwt - Automatic, one stamper
G	30 cwt - Automatic, two stampers.

The models produced for each of the seven hammer groups were found to fall into two slightly different categories, with regard to the significant, independent variables. Models for groups A, B, C, D and E consisted of the parameters:-

a) Stock area.
b) Periphery at parting plane.
c) Log_{10} batch quantity
d) Complexity factor. (B.S. 4114)
e) Area at parting plane.

In the larger unit group, the thirty cwt., the parameter 'area at parting plane' was not found to significantly describe the production rate. The inclusion of a factor to account for the forgeability of the stock material, however, was found to have a beneficial effect on the fit of the model to the observed values.

(a) Stock Area

As previously defined.

(b) Periphery

As previously defined.

(c) Log quantity

This value is the logarithm to the base 10 of the quantity that is to be made in one continuous run. 'Continuous' in this sense is taken to mean; not broken by the production of another job. Contingencies such as die repair, plant failures, etc., do not constitute a break.

(d) Complexity

This is the complexity factor as specified in BS 4114, that is, enclosing volume multiplied by density, all divided by net weight.

(e) Area at Parting Plane

This is the area projected by the component shape onto the parting plane.

4.3.2.1 Discussion of significant variables

It is interesting to note that of the five significant factors that comprise the production rate model, two are also present in the model predicting flash weight; namely, stock area and periphery.

Stock area is correlated with the largest cross-sectional area of the shape viewed in a direction parallel to the axis of the bar stock. If one considers the forging cycle in detail, the significance of stock area in predicting production rate becomes evident.

Break-down of Forging Cycle

The forging cycle can be thought of as consisting of the following activities:

1. Removal of stock from furnace.
2. Carrying stock from furnace to hammer.
3. Locating stock in desired position relative to the die impression.
4. Forging proper.
5. Transferring remainder of bar stock back to furnace.

(activities 1 to 5 are repeated, selecting another bar from the furnace,and so on.)

This is an over-simplification, since it ignores furnace loading when the load of bars/billets is exhausted, and also the composite nature of the activity termed "forging proper", itself comprising several individual operations. This simplified description does, however, serves to demonstrate the rôle played by stock area as a factor contributing to the prediction of production rates.

Activities 2) and 5) both involve carrying the bar stock several feet between the furnace and the hammer. Although the actual distance travelled may be only a few feet per cycle, the cumulative effect is far from negligible. Any increase in bar weight will have a deleterious effect on the production rate of any given forging. This is due to the fatigue induced in operators through repeatedly carrying several pounds of steel between furnace and hammer. When this is considered, it is perhaps not surprising that the analysis has shown the importance of stock area in predicting production rate.

The presence of an element to describe the periphery at the parting plane of the component in the flash model was explained by the fact that flash is actually formed at this plane, radiating from all points along that periphery. This explanation, of course, is not applicable to the present discussion. Periphery, however, also has the ability to describe the complexity of the part in the parting plane. A high value of periphery for a given projected area, indicates a high degree of detail, and the probable occurrence of projections/valleys in that plane. This gives rise to the metal flow problems associated with detailed shapes. The degree of metal flow required to satisfactorily fill these detailed shapes and projections influences the number of blows required, and consequently, the rate achieved.

Forgings may be ordered by the customer in quantities ranging from a few dozen to several thousand. The manufacturing batch quantity usually corresponds to the expected die life or some multiple of this figure. The batch size has a marked effect on the production rate eventually achieved in production. It has long been realised that the stamper increases his production rate with time. As he produces more and more forgings, he achieves a rhythm in his work rate. This 'learning curve' continues to rise at a decreasing rate, until there appears to be a saturation level for any given job, around which the achieved production rate fluctuates irrespective of quantity made in excess of this saturation quantity. Although this learning effect had been recognised[24, 25], it had not been quantified, or even appreciated as being a curved rather than, say, a linear response. The only way in which quantity enters the manual estimating technique at the firm is in that the man assumes a value of one thousand forgings as being a saturation value. For quantities below this, the routine is to decrease the estimated production rate by an arbitrary percentage.

The statistical analysis showed this relationship to be a logarithmic one, the production rate increasing with the logarithm of the batch quantity produced.

The value of parting-plane-projected area has been found to influence the forging load required for complete filling of the die impression[72]. In a drop forging context, where the energy available per blow is fairly fixed within groups, this can be taken to suggest that the number of blows required, other things being equal, is influenced by the parting plane area. The number of blows required has a direct effect on the production rate achieved during forging.

Complexity may influence production rate because the number of pre-forming steps, and the number of blows to achieve die filling, are both influenced by it.

Forgeability Factor

Materials forged at the studied Firm, (and indeed at many similar steel forges), include low-carbon mild steel, alloy steels and even stainless-high strength steels for aviation applications. The nature of the material stock exerts an influence on a number of process variables; die life, size of unit required, forging temperature and production rate. A forging made from a low-strength steel, for example 070M20 (En.3) mild steel, would require fewer blows to achieve the desired metal flow, than would a stronger material such as 410S21 (En.56), forged on the same sized production unit.

Thus, in order to attempt to produce a model capable of predicting production rate from various component/process details, it was necessary to describe quantitatively the forgeability of the various forging stock materials.

Several tests have been devised to determine the hot forgeability of various materials. Probably the best known is the hot torsion test[73]. This test, it is claimed, reproduces the stress system experienced by forging stock at the forging temperature. Unfortunately, published results for the En. series of steels are far from complete[74]. Results that are available refer to tests performed at a range of temperatures, which often does not include a value near the usual forging temperature of the material in question.

Tensile test results were available throughout the range of En. steels, but these referred to properties at, or near to, room temperature. These could not be equated to the performance of the material at forging temperatures.

In the absence of published data, the ideal solution appeared to be to forge samples of the various materials on a small hammer or press and measure the load required to produce a certain, known reduction in height. This, however, was not a viable solution in view of the time and equipment involved; a more immediate solution to the problem was required. A solution was found in that a "forgeability scale" had been devised by the firm in the light of their many years in the forging industry. This scale, in the range 1 to 15, was found on examination to agree with the limited amount of hot torsion data available. In the absence of any superior factor, it was decided to adopt this scale as a description of hot forgeability.

The various production rate models produced are summarized mathematically below:-

<u>GROUP A</u>

$$PR = 20.88 \, \mathrm{Log}_{10} Q + 19.3C - 21.6S - 3.8P - 2.0A + 135.4$$
$$(RE = 23.86, \; MCC = 0.794)$$

<u>GROUP B</u>

$$PR = 47.00 \, \mathrm{Log}_{10} Q - 69.4C - 25.7S - 7.5P - 7.4A + 170.4$$
$$(RE = 20.10, \; MCC = 0.915)$$

<u>GROUP C</u>

$$PR = 23.30 \, \mathrm{Log}_{10} Q + 9.4C - 12.8S - 2.1P - 0.06A + 61.2$$
$$(RE = 12.62, \; MCC = 0.820)$$

GROUP D

$$PR = 24.80 \log_{10} Q + 76.4C - 21.2S - 2.8P - 0.05A + 86.8$$
$$(RE = 14.18, MCC = 0.929)$$

GROUP E

$$PR = 16.30 \log_{10} Q + 19.7C - 4.4S - 0.8P - 0.6A + 32.7$$
$$(RE = 6.72, MCC = 0.859)$$

GROUP F

$$PR = 1.11 \log_{10} Q - 16.9C - 6.1S - 0.9P - 2.4EN + 103.0$$
$$(RE = 5.27, MCC = 0.929)$$

GROUP G

$$PR = 8.6 \log_{10} Q - 42.1C - 8.3S - 2.0P - 4.7EN + 170.5$$
$$(RE = 7.34, MCC = 0.958)$$

Where,

PR = Production rate, FORGINGS/HOUR.

Q = Quantity made per run, UNITS.

C = Complexity factor, BS4114, UNITS.

S = C.S.A. of Stock material, SQ.INS.

P = Periphery of forging at parting place, INS.

A = Area of forging at parting place, SQ.INS.

EN = Empirical, steel forgeability factor, UNITS.

(Again, the precision, or accuracy, of the models is discussed fully in following sections.)

The contribution of each independent variable to the overall production rate model can be assessed in exactly the same way as for the flash weight model. Considering any one of the groups, the variance can be analysed.

For Group 'B':

SS (stock) = 47918 = 22.6%
SS (area) = 34017 = 16.1%
SS (periphery) = 33642 = 15.9%
SS (complex) = 10524 = 5.0%
SS (log.qty.) = 51216 = 24.2%
SS (due to reg.) = 177317 83.8%
SS (unexplained) = 34353 16.2%
SS (total) = 211670 = 100.0%

In this case, the pie chart is not complicated with overlayed sectors, all contributions are positive. The contributions of the various independent variables do not differ noticeably, with the exception of the variable, complexity. Complexity contributes only 5% to the overall model. The unsatisfactory nature of many complexity factors and their inability to differentiate between certain shapes of widely differing degrees of 'easiness', has been indicated (4.3.1.1.), and may account for the relatively low contribution of this parameter.

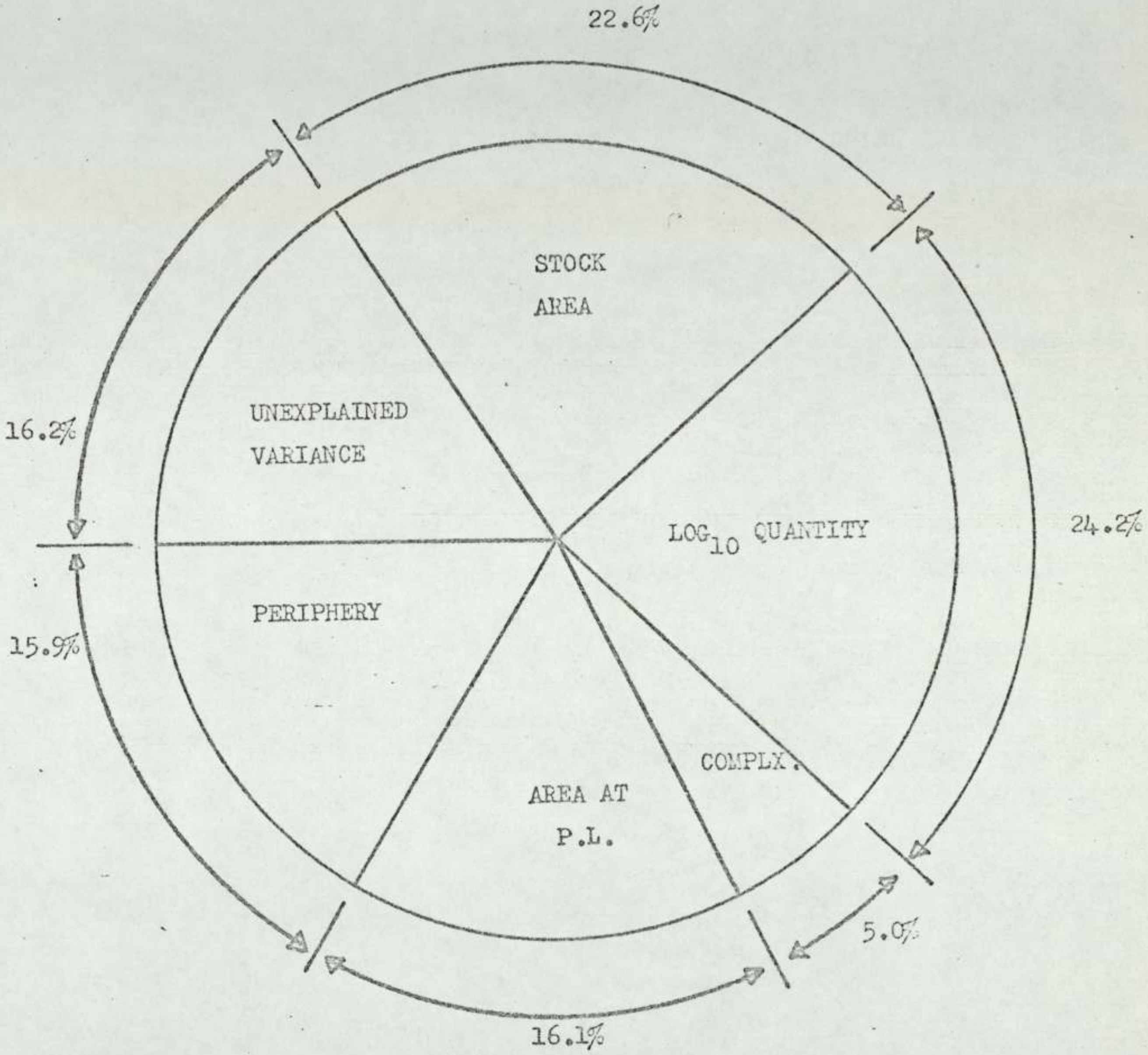


Figure 10. Contribution "Pie" for Production-Rate models

5. DISCUSSION OF MODEL TECHNIQUE

Having produced predictive models, it was necessary to compare an estimating system based on these models with one based on human experience, i.e. the present system employed at the study firm.

These two systems were compared on three different levels:-

1) Accuracy of prediction and associated benefits.
2) Method of implementation and operating cost.

and, 3) Intangible benefits.

5.1 Accuracy of Prediction

In order to compare the accuracy of the two methods, additional forgings were examined and these, together with the original forgings on which the analysis was based, were used to 'test' the two predictive methods.

In the case of the manual, experience-based method, the records were examined to find the value of dependent variable (i.e. flash weight or production ratio) predicted by the estimator when presented with the original enquiry for the very first time. This ensured that any value of, say, production rate used in the comparison, had not been 'corrected' by any knowledge of actual performance the estimator may have gained from the subsequent manufacture of the forging. Unfortunately, this was not always possible. A considerable number of observations had to be discarded as the originally predicted values had been deleted and lost when a subsequently achieved value was substituted on the record.

The parameters required by the models were extracted from the relevant information/drawings for each forging for which an estimators original prediction was available. The values of the dependent variables for each forging were calculated using a simple computer programme to perform the necessary arithmetic.

The values of dependent variables, production rate and flash weight, for each of the forgings chosen are given fully in appendix IX.

Examination of the results showed that, on the basis of the number of occurrences on which the models were nearer to the achieved value than the manually predicted value, there was little difference between the two methods. A more analytical study, however, revealed that there was a marked difference between the two techniques in terms of the spread, or variance, of the percentage errors, figure 11 . The standard deviation for the predictive models was less than that for the manual method when predicting production rates. When the methods were compared for predicting flash weights, this reduction in standard deviation was even more marked, table 3. (The implication of standard deviation as a means of measuring 'spread' is indicated in figure 11. 95% of all estimates of a variable can be expected to fall within ± 2.00, approx., standard deviations of the true achieved value.) The reduction in standard deviation values, when subjected to the F-test, was found to be significant at the one per cent level.

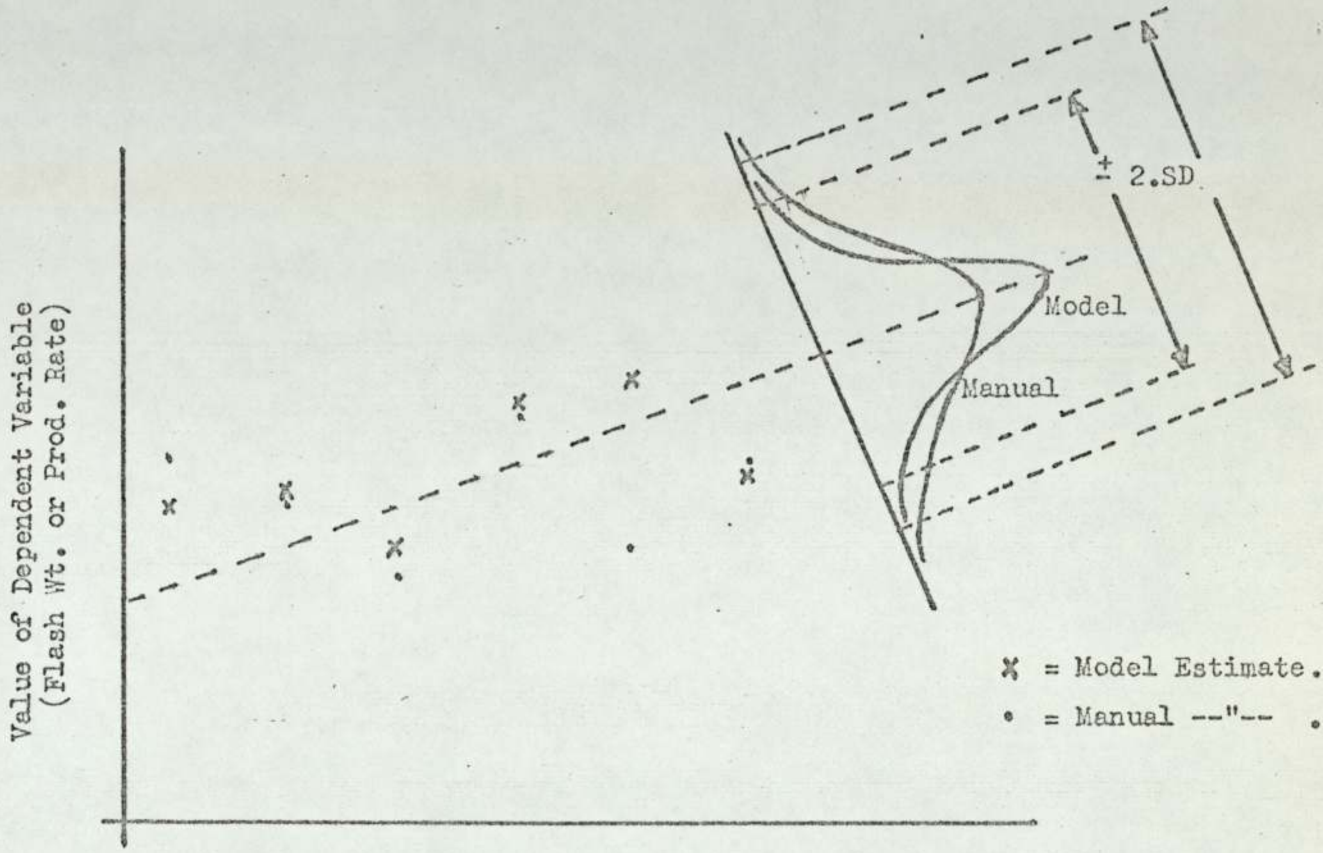


Figure 11. Schematic representation of improvement in accuracy

The comparison of the precision of the two methods has assumed that both the manually-predicted, and the model-predicted values have errors that are normally distributed.

This is certainly true for the values predicted by the models. In the case of the present manual system, however, it must be remembered that of all the estimates made, only three per cent or so are subsequently converted into firm orders.

	MEAN PERCENTAGE ERROR (Manual System)	STANDARD DEVIATION OF PERCENTAGE ERRORS	
		Manual	Models
FLASH WEIGHT PREDICTION.	21.95	46.85	34.85
PROD. RATE PREDICTION.	-7.10	20.80	16.22

Table 3. Standard Deviation and Mean Values of Percentage Error.

In the case of the other 97%, other suppliers have probably quoted lower prices, and hence, have won the order. This suggests that the jobs for which the estimator has, for example, predicted an erroneously low production rate (resulting in an unrealistically high selling price) would very likely not be accepted by the prospective customer, another supplier quoting a lower, more attractive price. The net result is that occurrences of the estimator erring on the high cost side are rarely converted to firm orders, and hence, no 'achieved' production rate or flash weight values are available for comparison purposes. Prediction errors resulting in a low selling price are not similarly 'filtered-off', such prices being more than acceptable to the enquiring customer.

This 'filtering-off' of the very high prices arising from erroneous predictions of production variables (Footnote), tends to destroy the normality of the distribution of manually predicted values available for comparison purposes, the resulting distribution being positively skewed, (Figure 12).

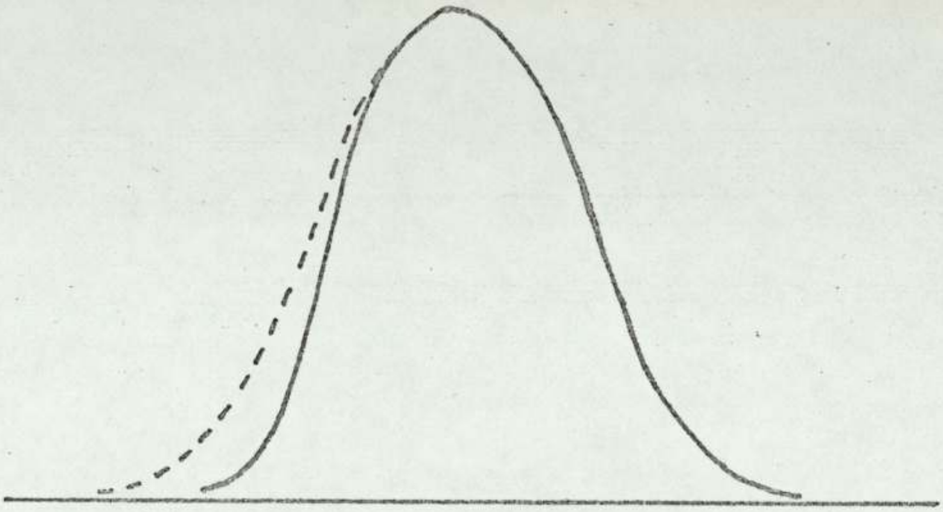


Figure 12. Skew distribution of available errors due to the discrimination of customers.

FOOTNOTE: It should be remembered that estimator errors are not the only reason for the rejection of a tendered selling price by a prospective customer, other factors were discussed briefly in section 4.1.1.

The fact that the (manual) distribution is positively skewed rather than normal, gives rise to a value of standard deviation that is lower than the one that would have been obtained had the distribution been normal. (i.e. without the 'filtering-off' effect.)

When comparing the normally distributed errors of the mathematical models with the standard deviation resulting from the present manual technique, then the comparison is inevitably prejudiced in favour of the traditional approach. The reduction in 'spread' of errors is this more marked than would be suggested by a simple comparison of the two standard deviation values.

Graphical presentation of Results

In addition to the tabulated results (appendix IX), the values of the dependent variables, flash weight and production rate, are plotted graphically in figures 13 to 20.

Figures 13a, 14a..... 20a are graphs showing the observed value of dependent variable (i.e. the value achieved during actual production) plotted against the value calculated using the relevant mathematical model. The remaining graphs, figures 13b,c,d,e; 14b,c,d,e,f;..... 20b,c,d,e,f show the value of the dependent variable plotted as a function of each independent variable individually. (The remaining independent variables in the model being held, each time, mathematically constant at some typical value.) The benefit of such plots in recognising non-linear relationship has already been indicated (section 4.2.1.2). The ability to highlight any observed values deviating widely from the norm is another important advantage of plotting the results of regression analyses, as opposed to replying solely on numerical output.

When a statistical analysis is extensive, as in this case, involving a considerable number of observation points, their plotting becomes tedious and time-consuming. In view of this, a computer programme had been developed in FORTRAN[75], in which the results of regression analysis could be plotted by computer in a matter of a few minutes. A description of this programme is given in appendix IV.

Comparison with available previous work

The reduction in the standard deviation of the percentage error, arising from the use of the flash weight model, 47 to 35%, may be compared to the limited amount of data published by Altan et al[30]. These authors used a relationship derived by Teterin and Tormovskij[28]; for axisymmetrical forgings.

Altan et al. give flash data for four very similar forgings. Examination of their results shows the standard deviation of percentage errors to be of the order of 35%. This compares with a similar value of 35% for the present author's model.

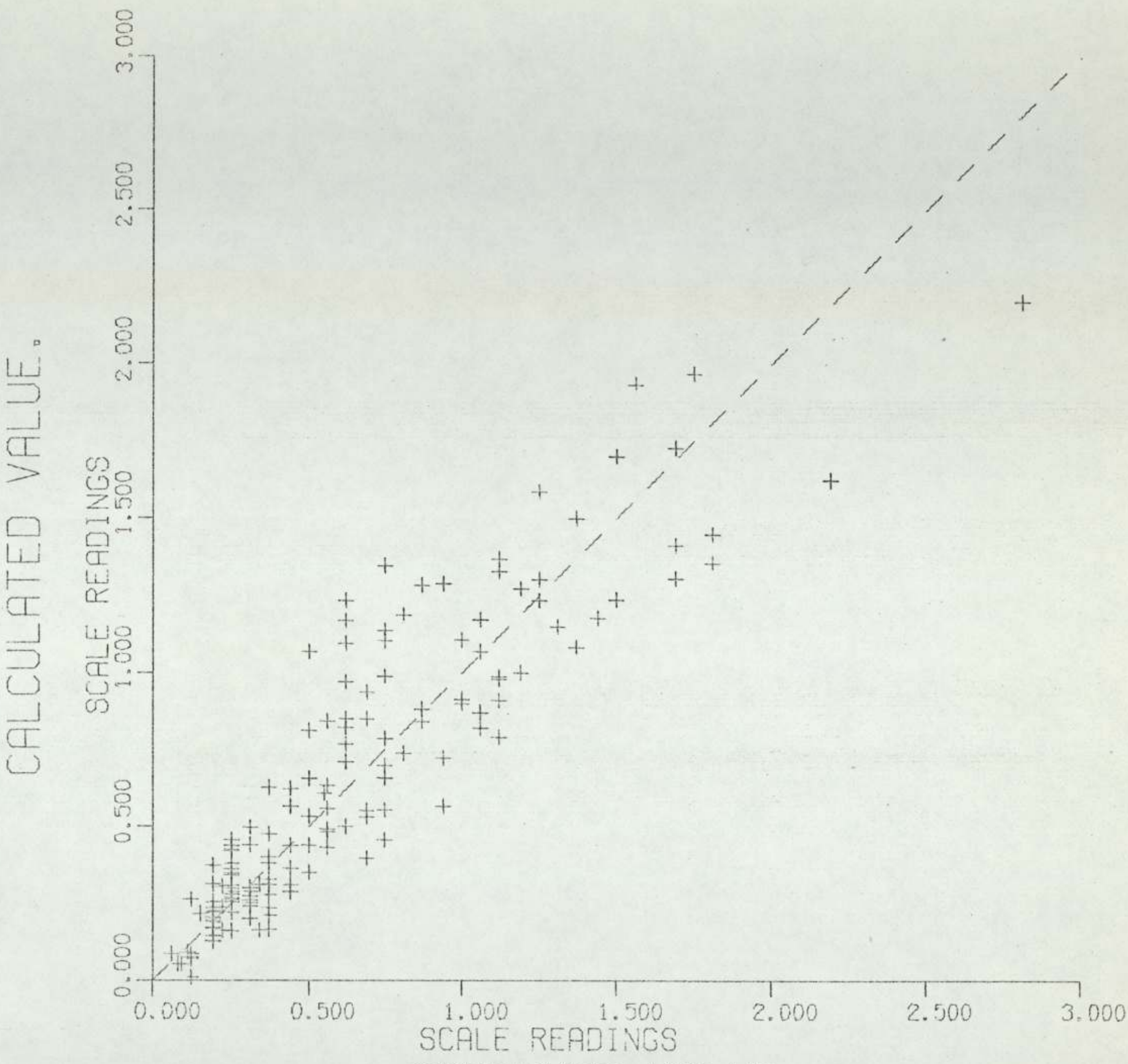


Figure 13 a.

OBSERVED V CALCULATED.

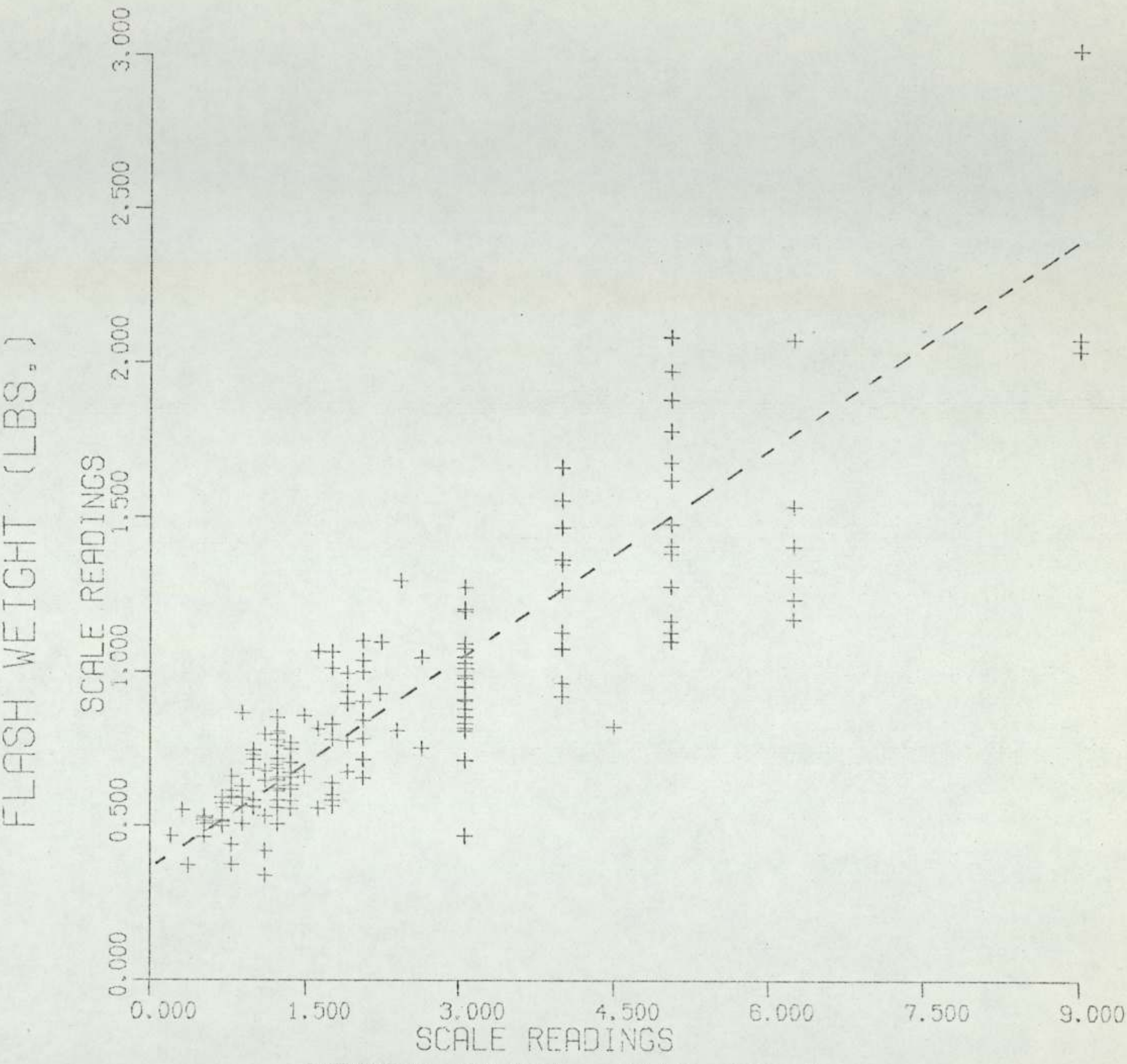


Figure 13b.

FLASH V STOCK AREA

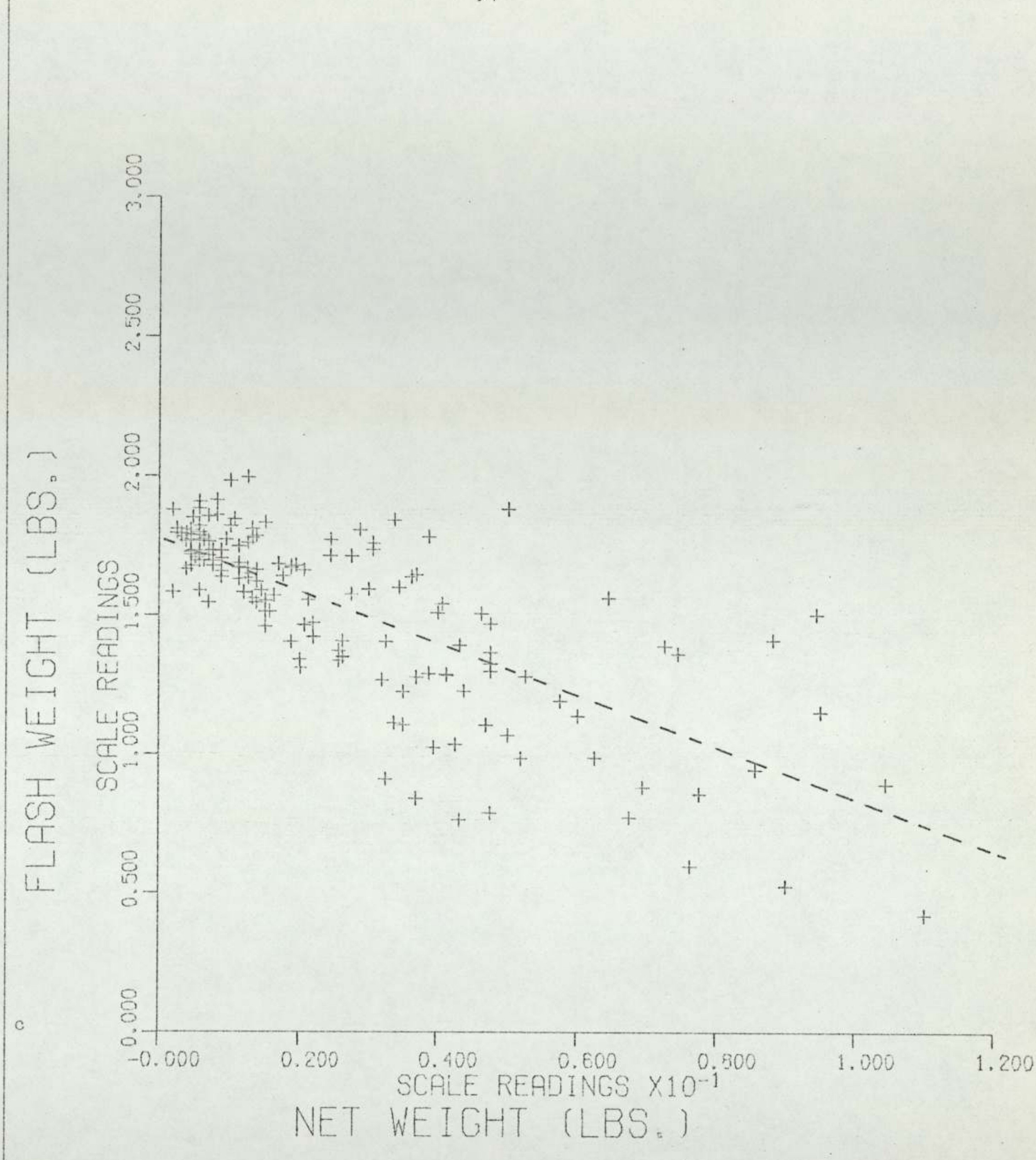


Figure 13c.

FLASH V NET WT.

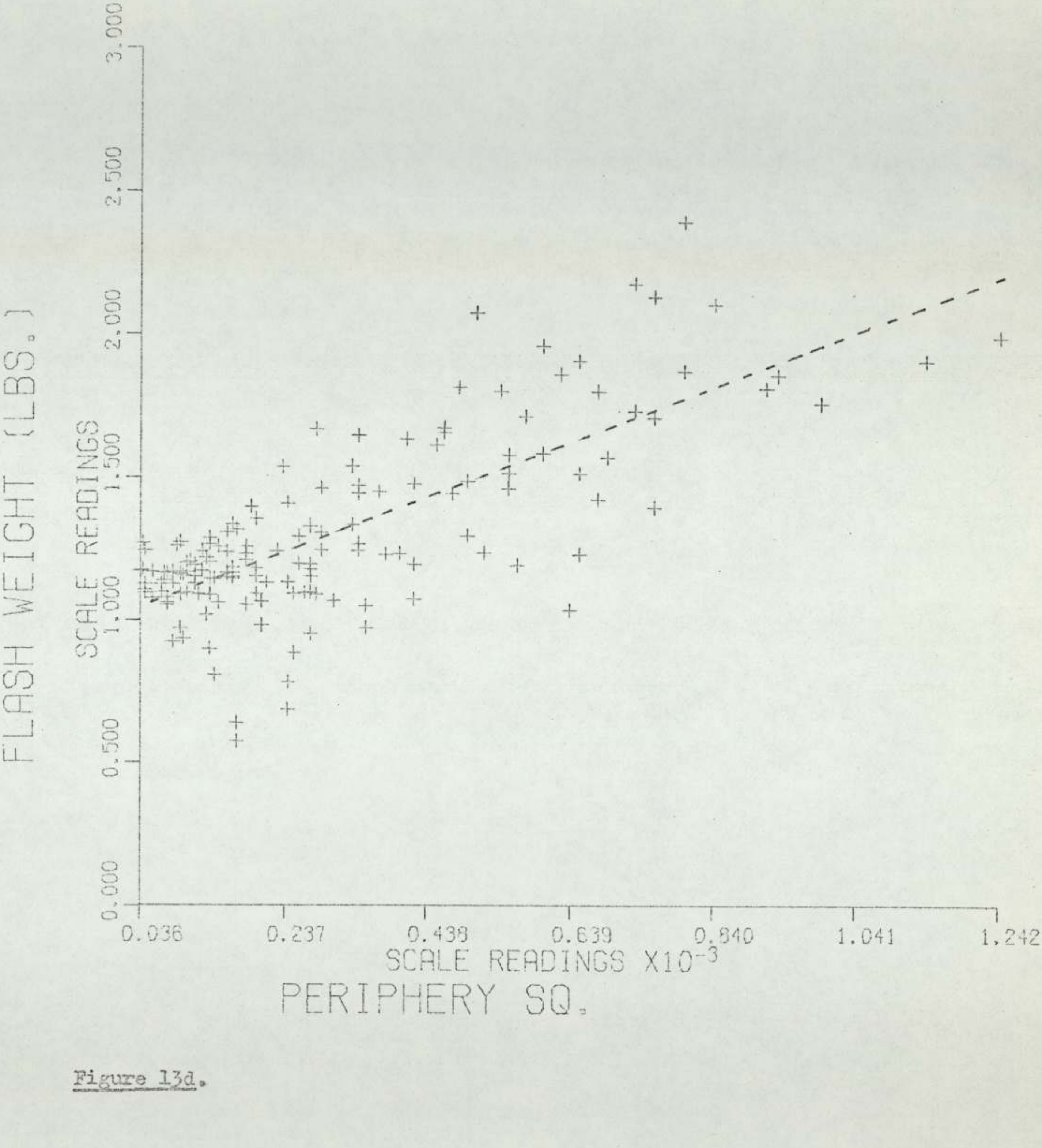


Figure 13d.

FLASH V PERIPHERY SQ.

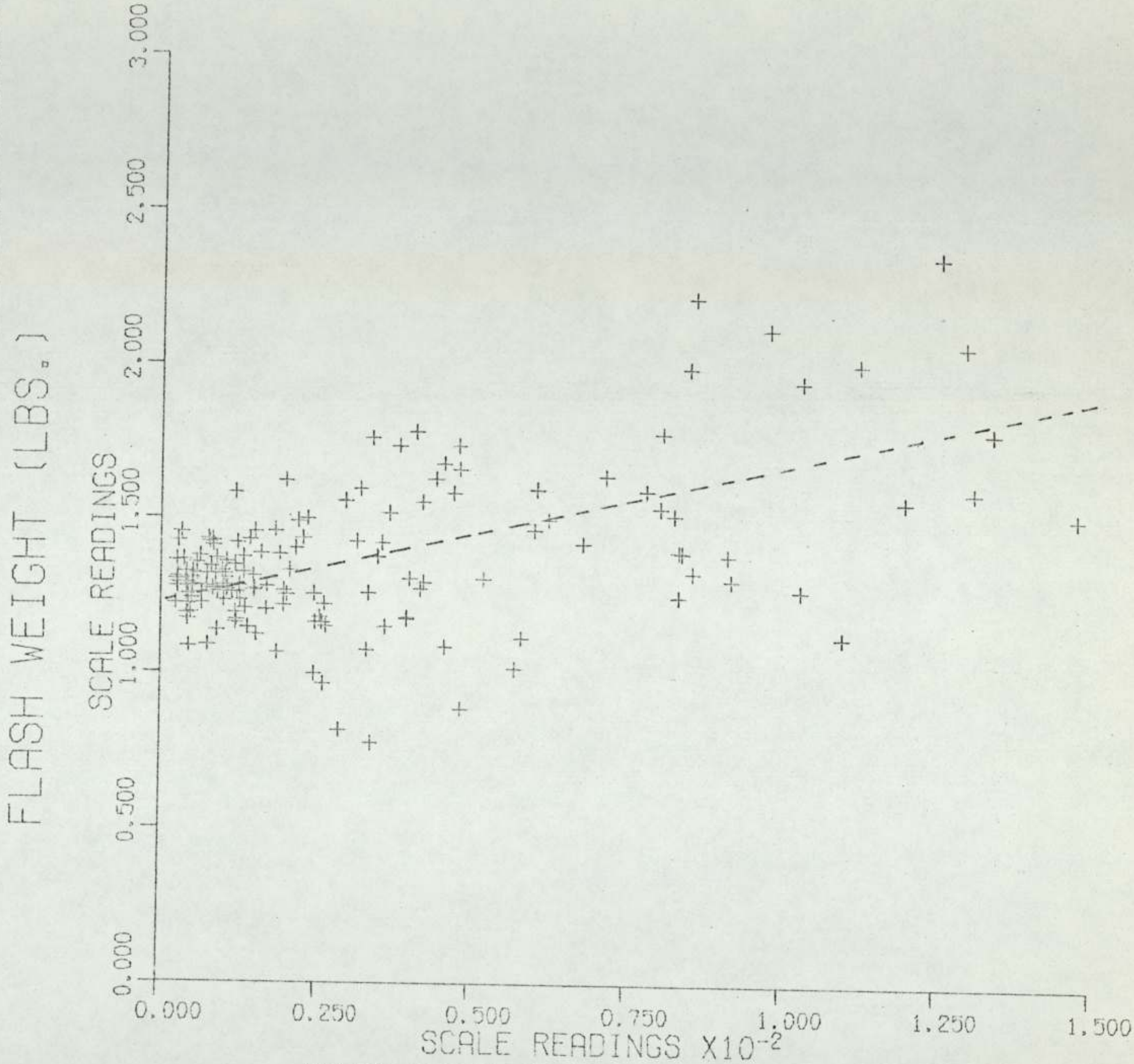


Figure 13e.

FLASH V ENC. VOL.

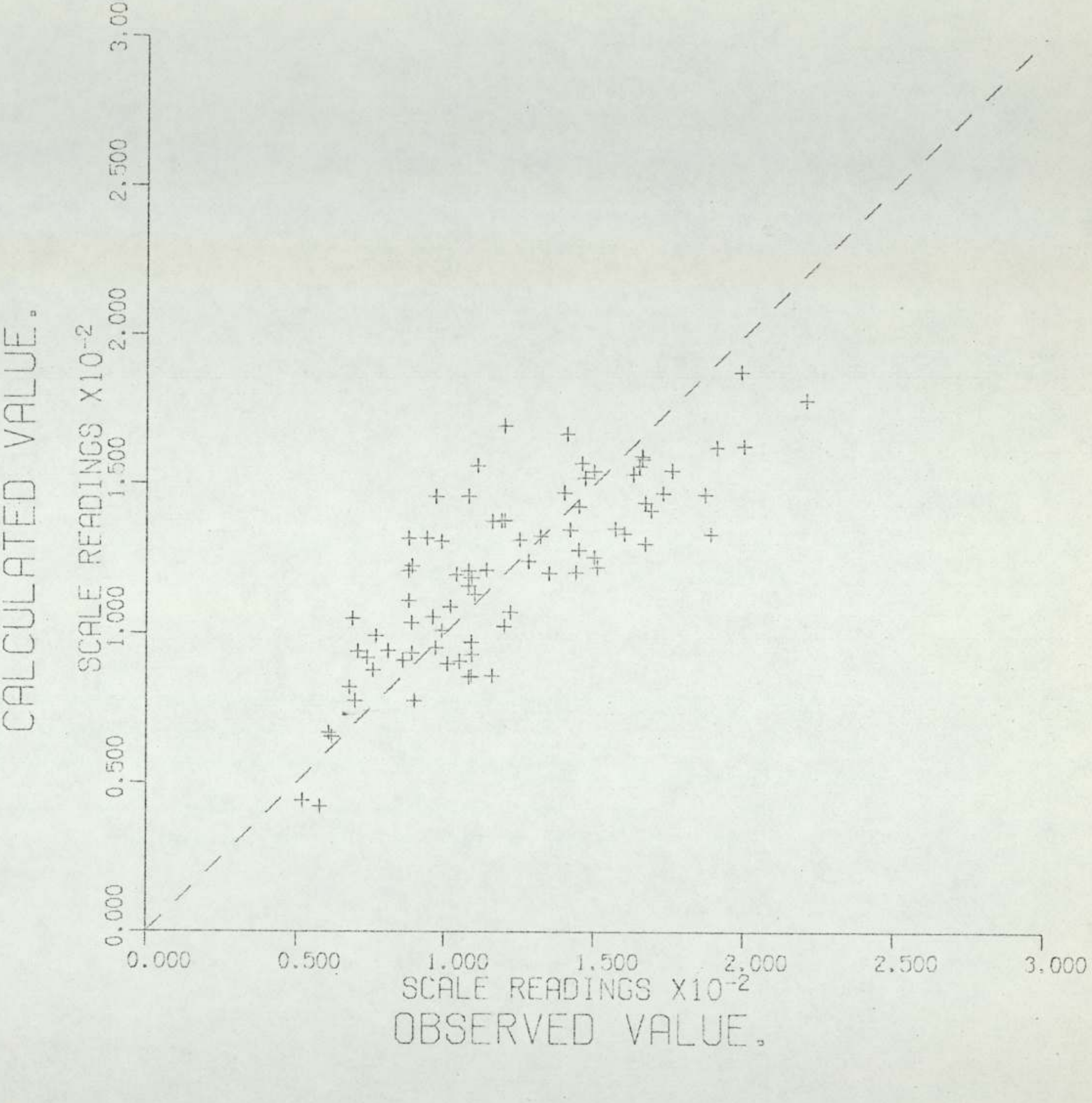


Figure 14a.

OBSERVED V CALCULATED.

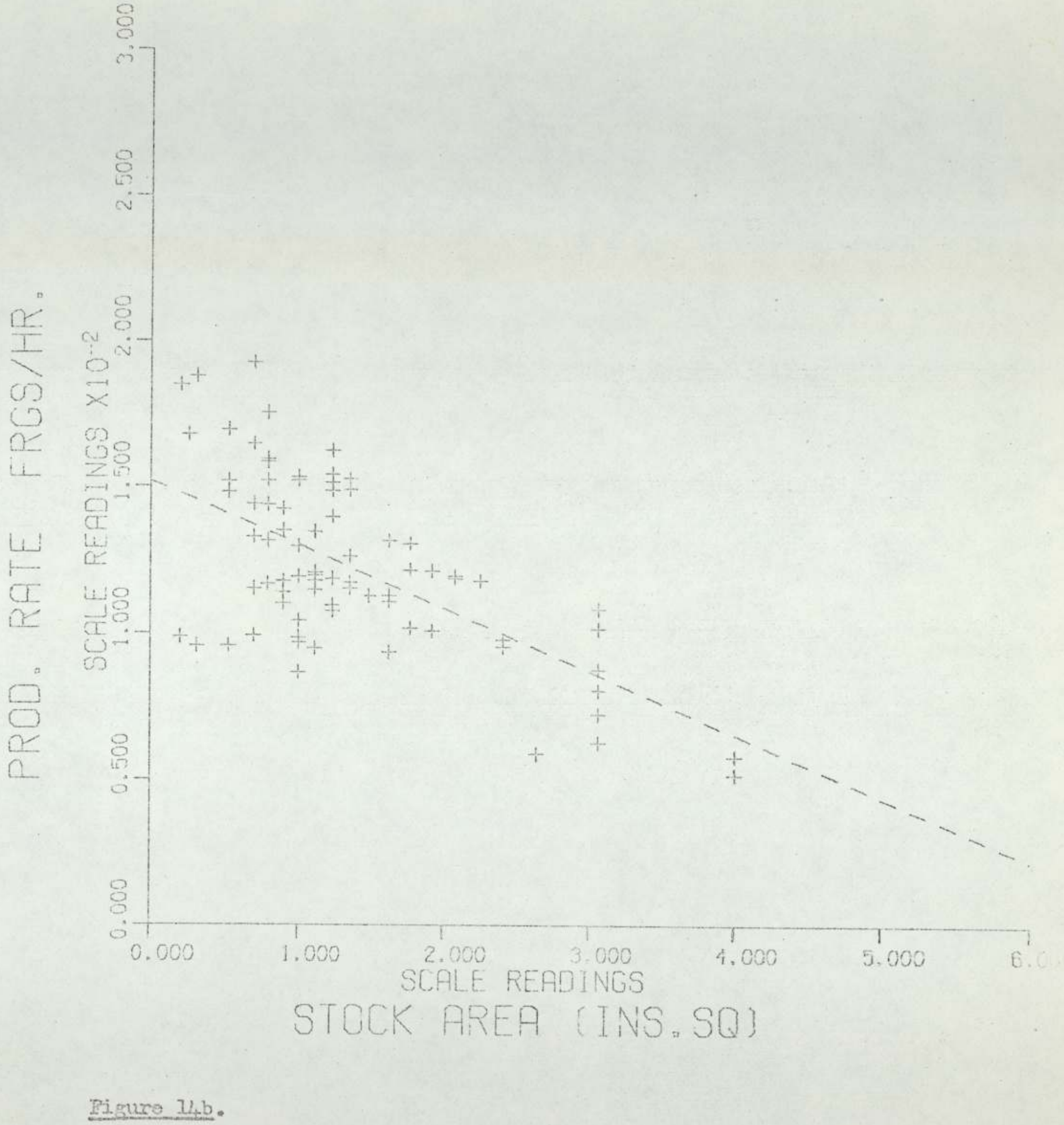


Figure 14b.

RATE V STOCK AREA

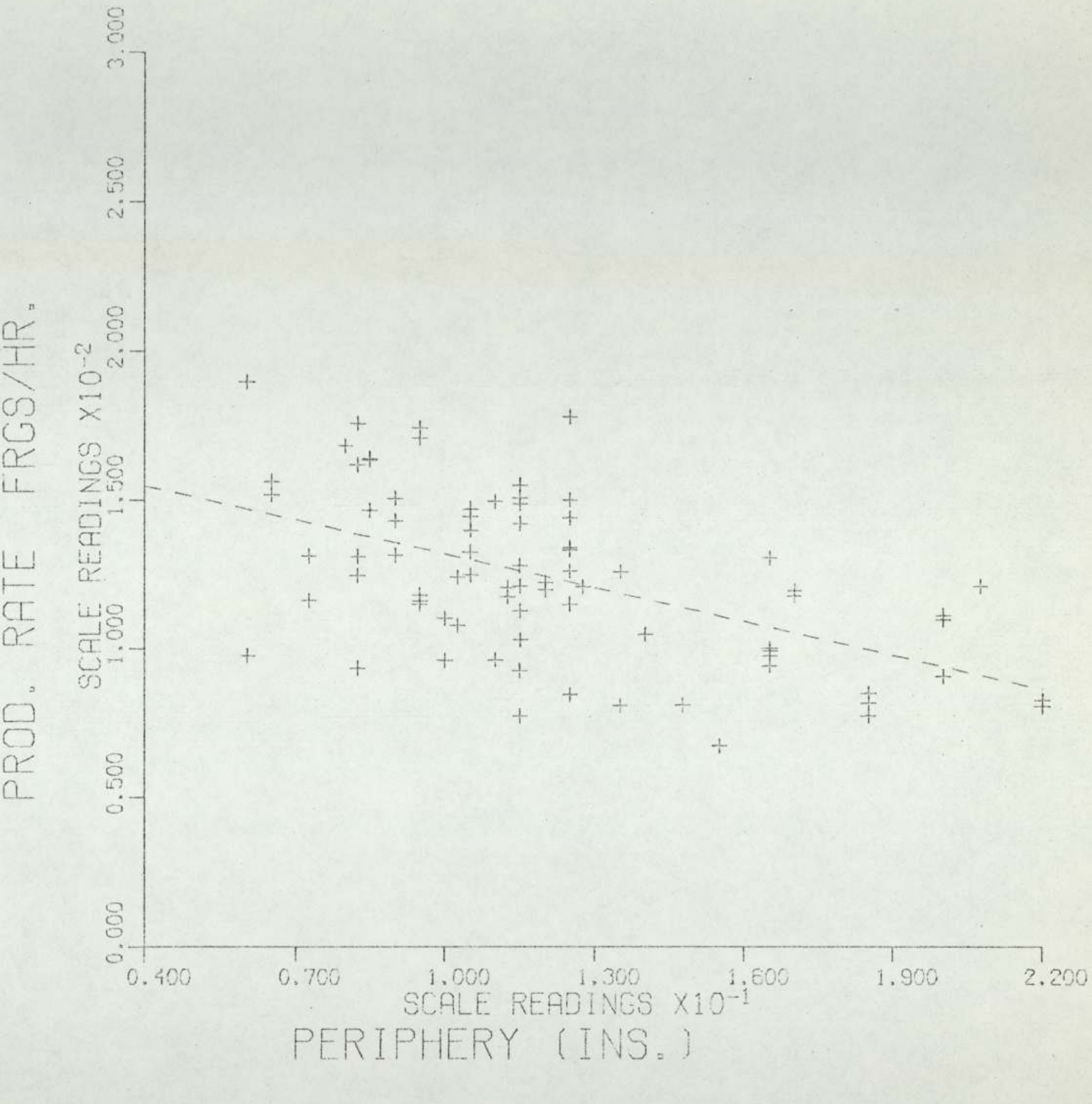


Figure 14c.

RATE V PERIPHERY

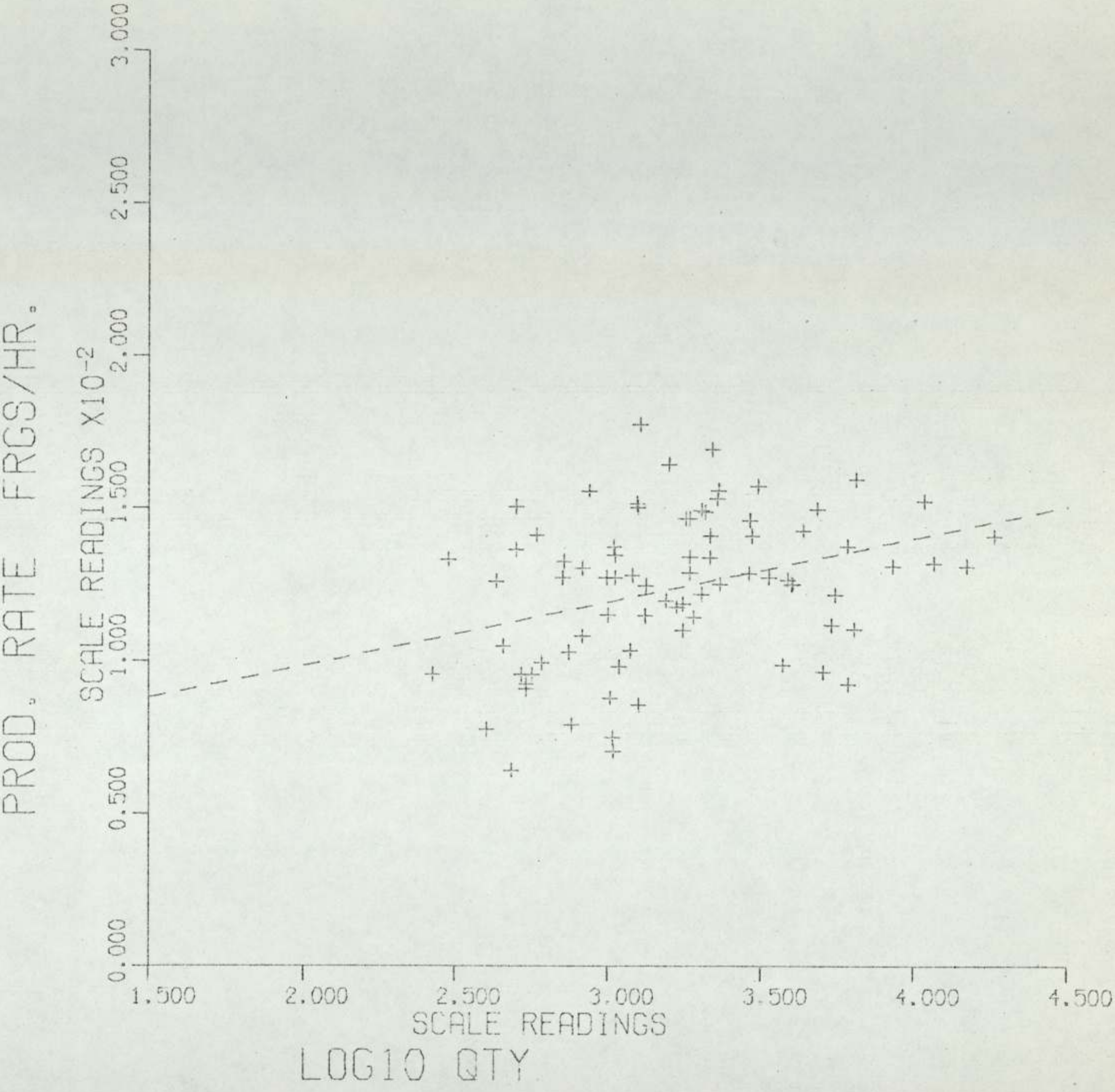


Figure 14d.

RATE V LOG10 QTY

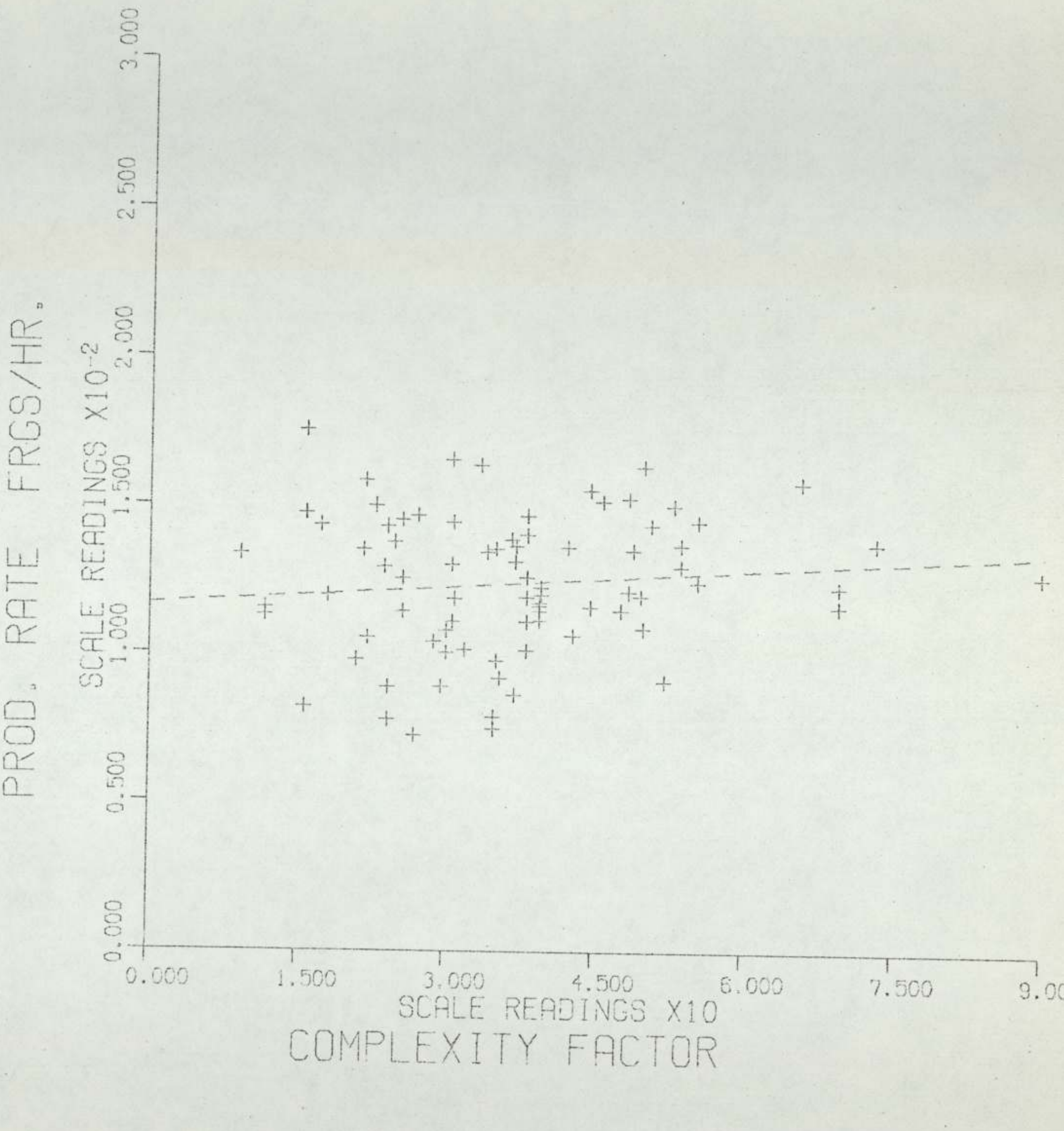


Figure 14e.

RATE V COMPLEXITY

Figure 14f.

RATE V AREA

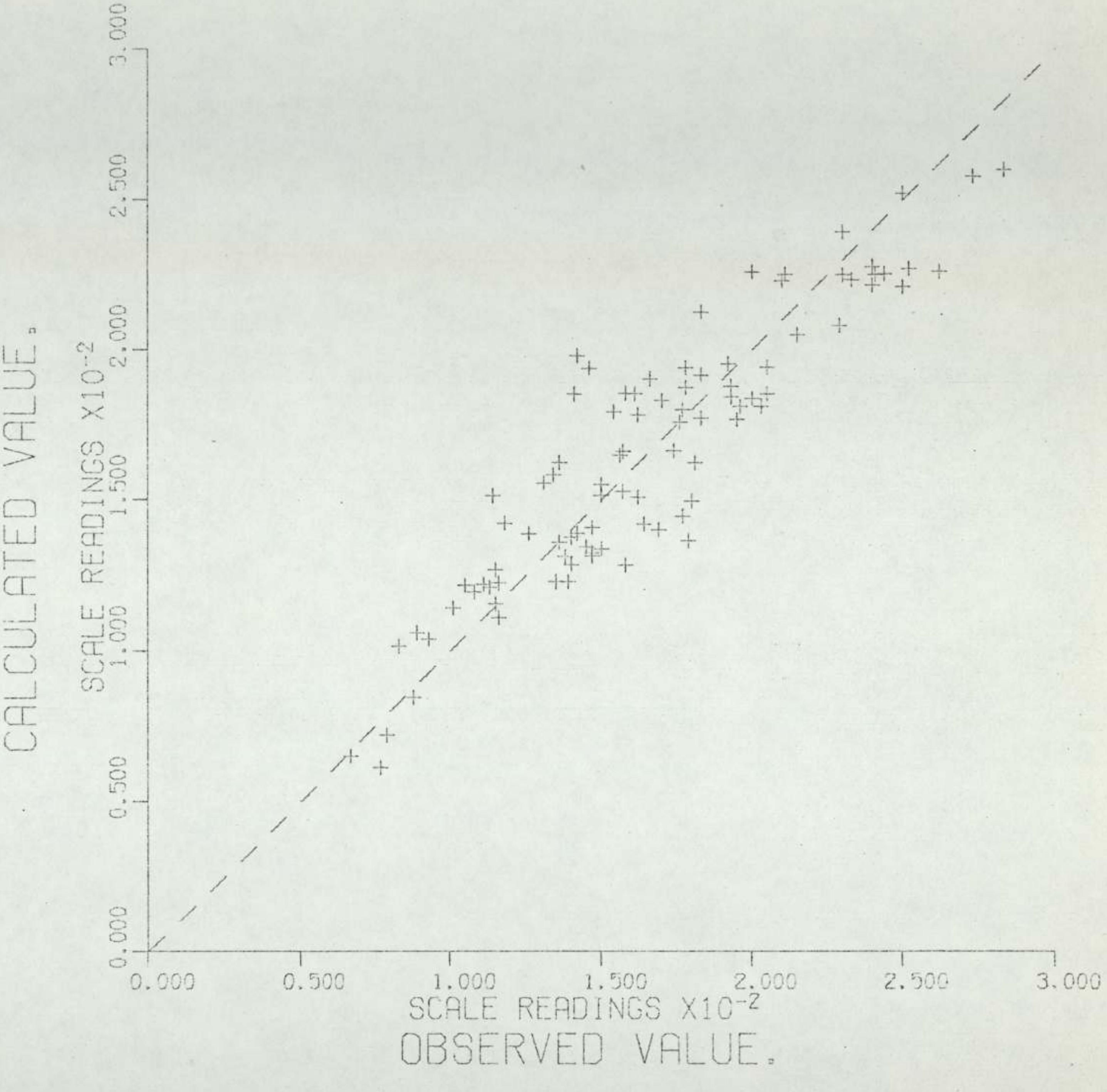


Figure 15a.

OBSERVED V CALCULATED.

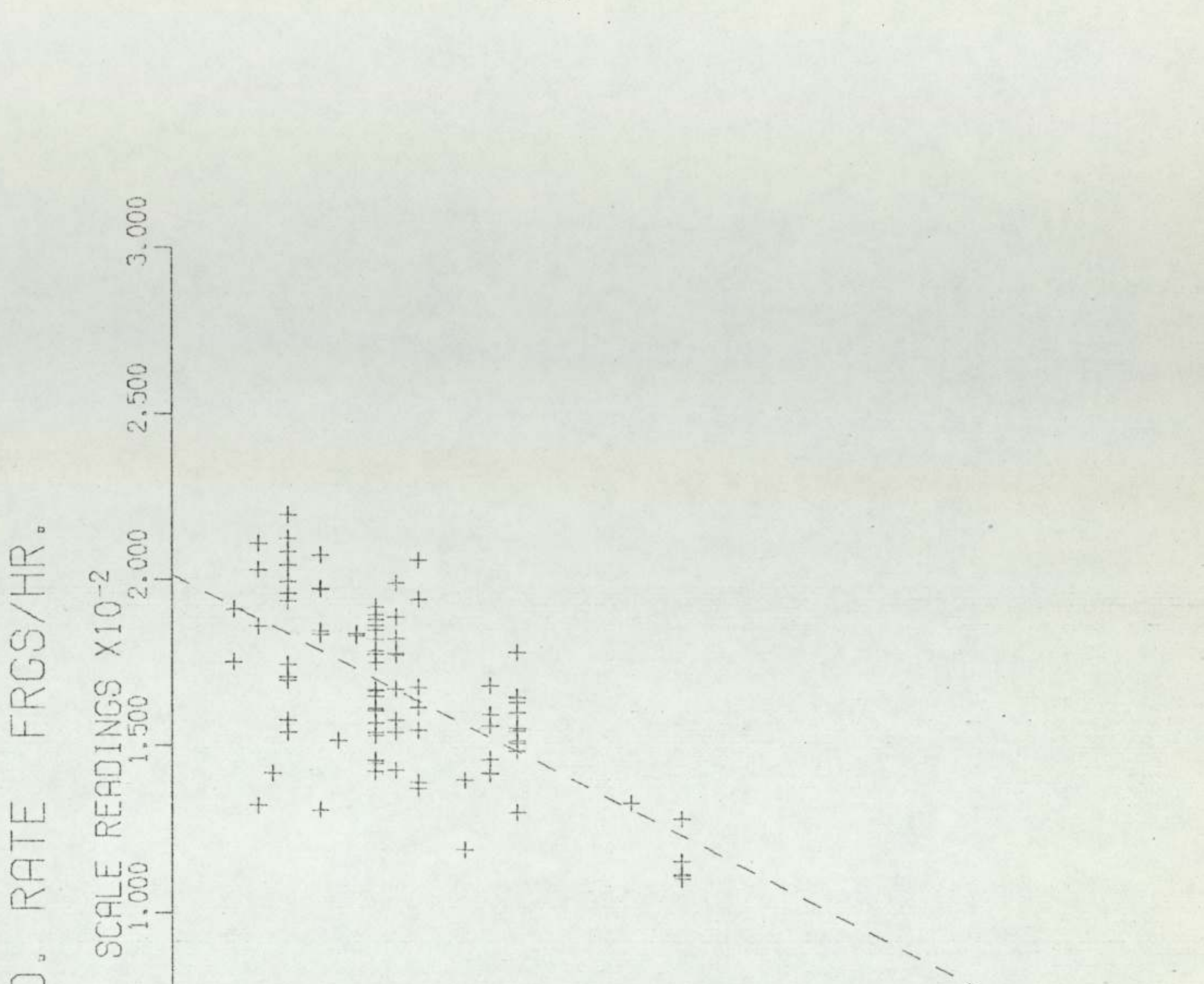


Figure 15b.

RATE V STOCK AREA

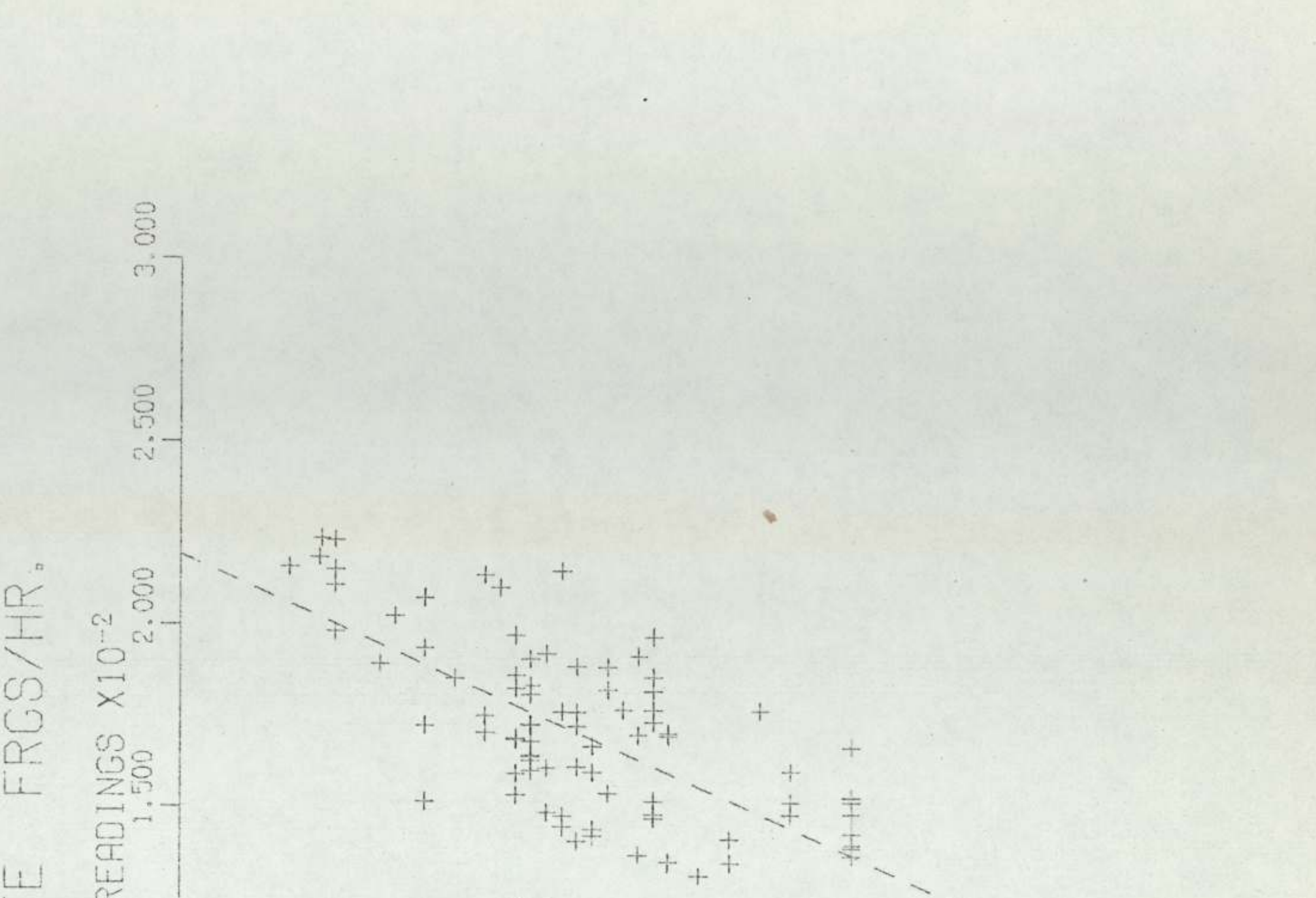


Figure 15c.

RATE V PERIPHERY

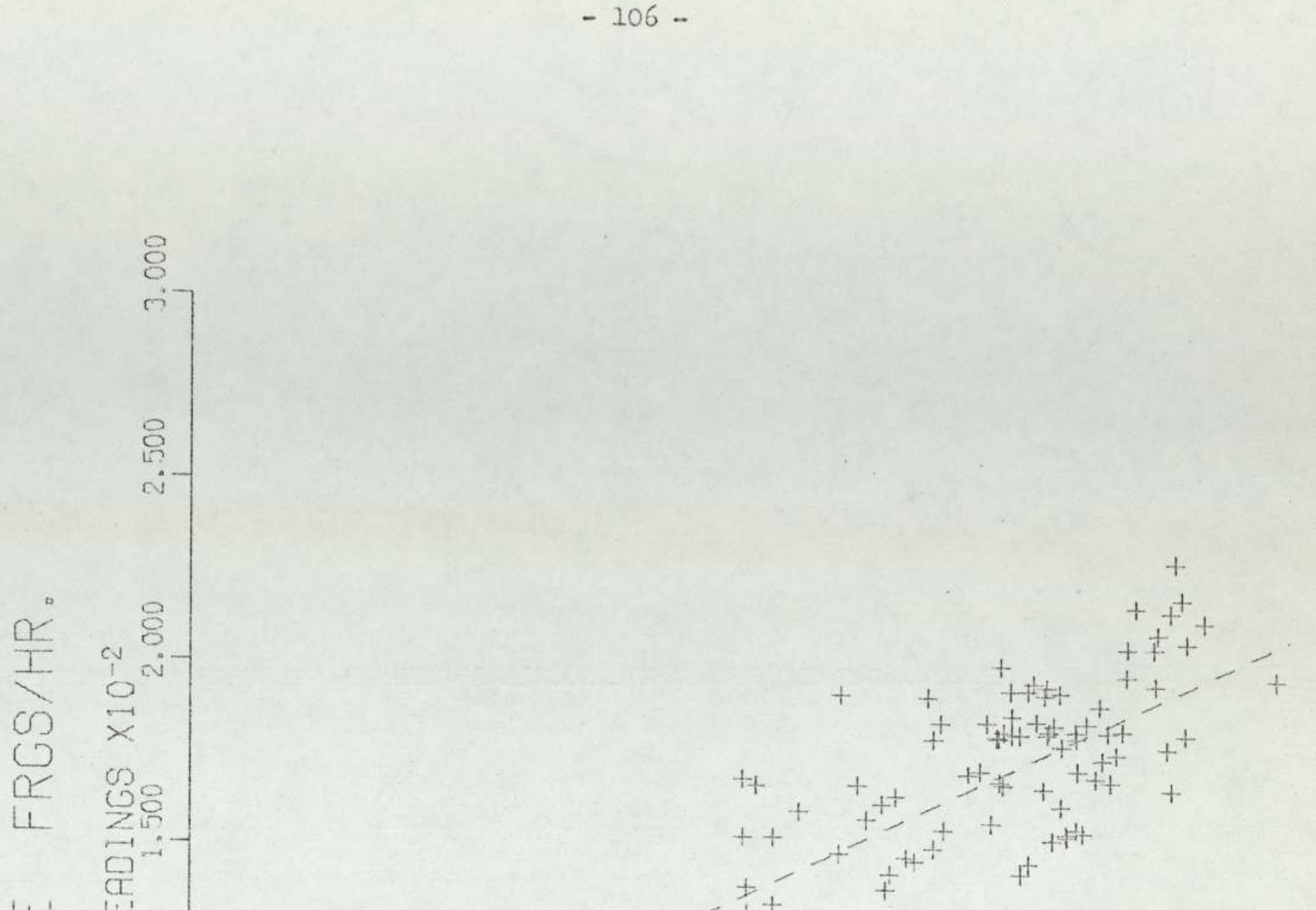


Figure 15d.

RATE V LOG10 QTY

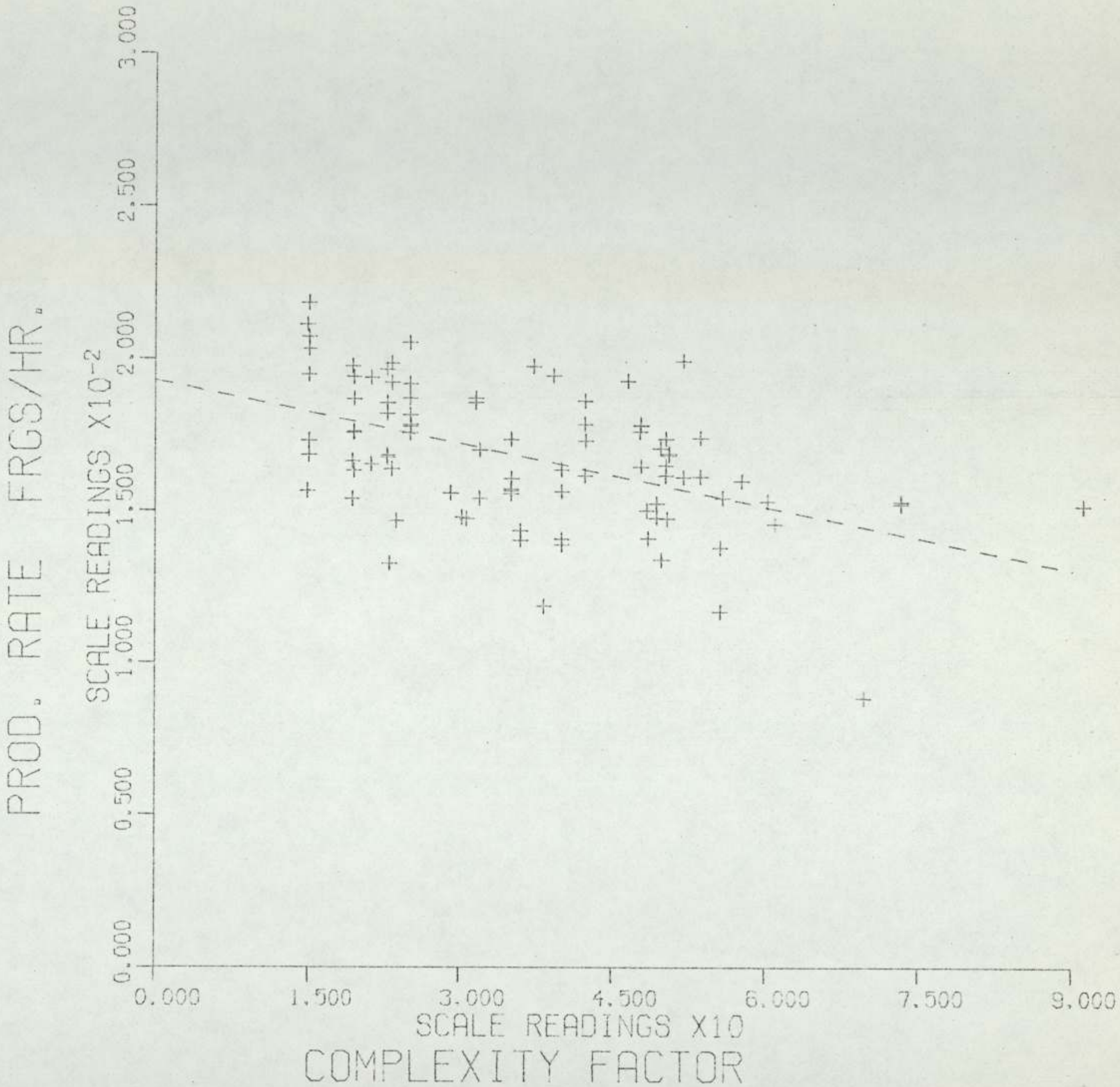


Figure 15e.

RATE V COMPLEXITY

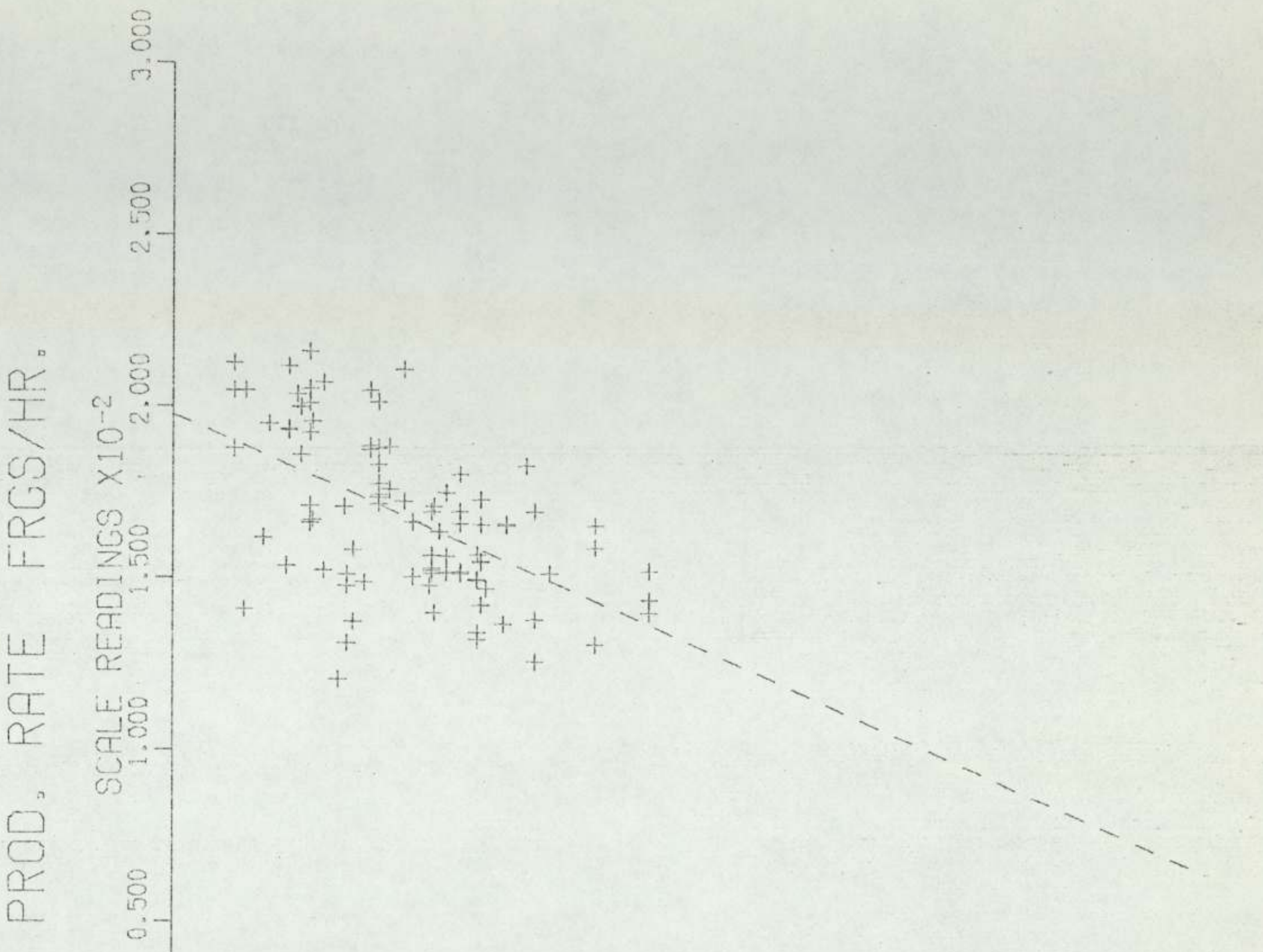


Figure 15f.

RATE V AREA

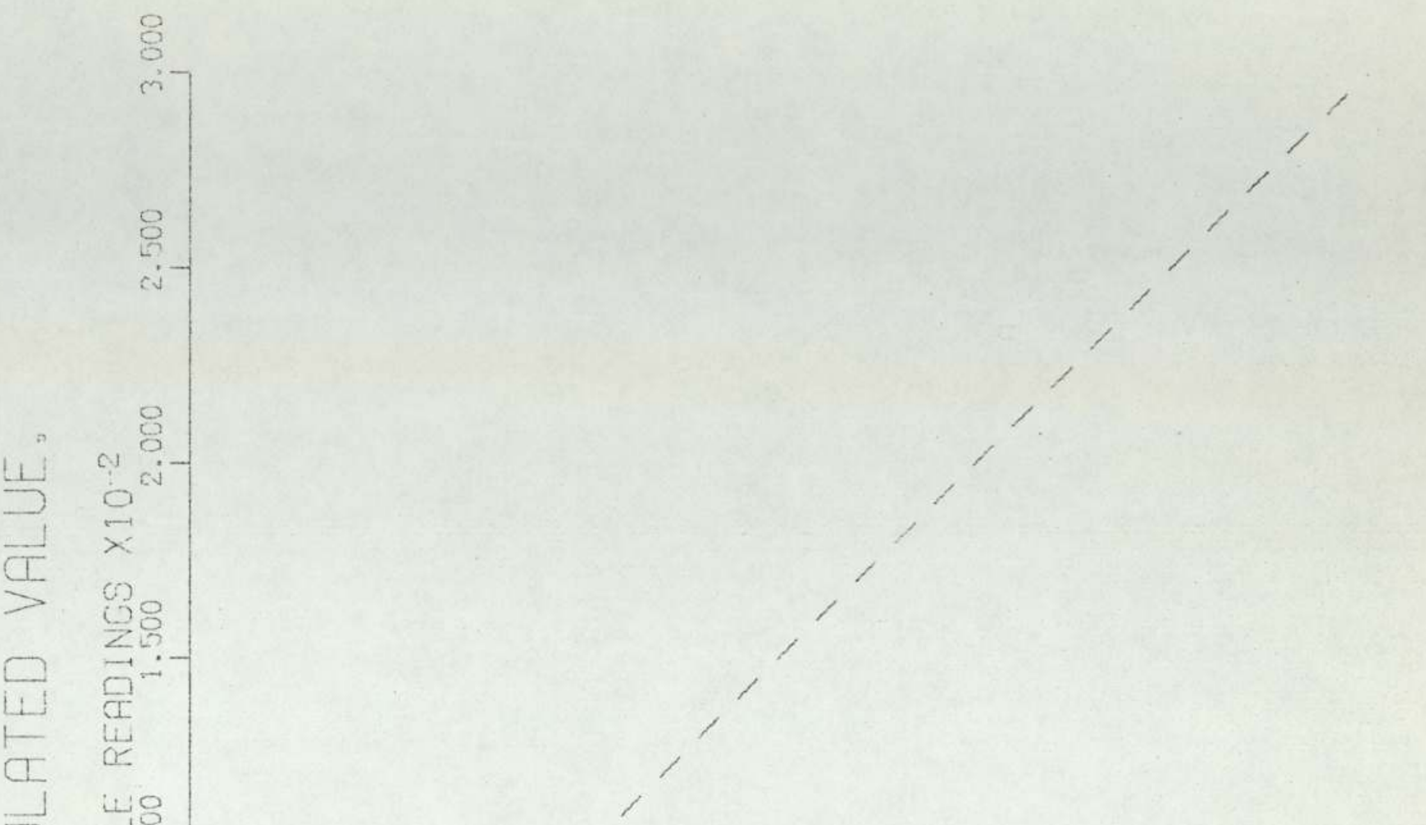
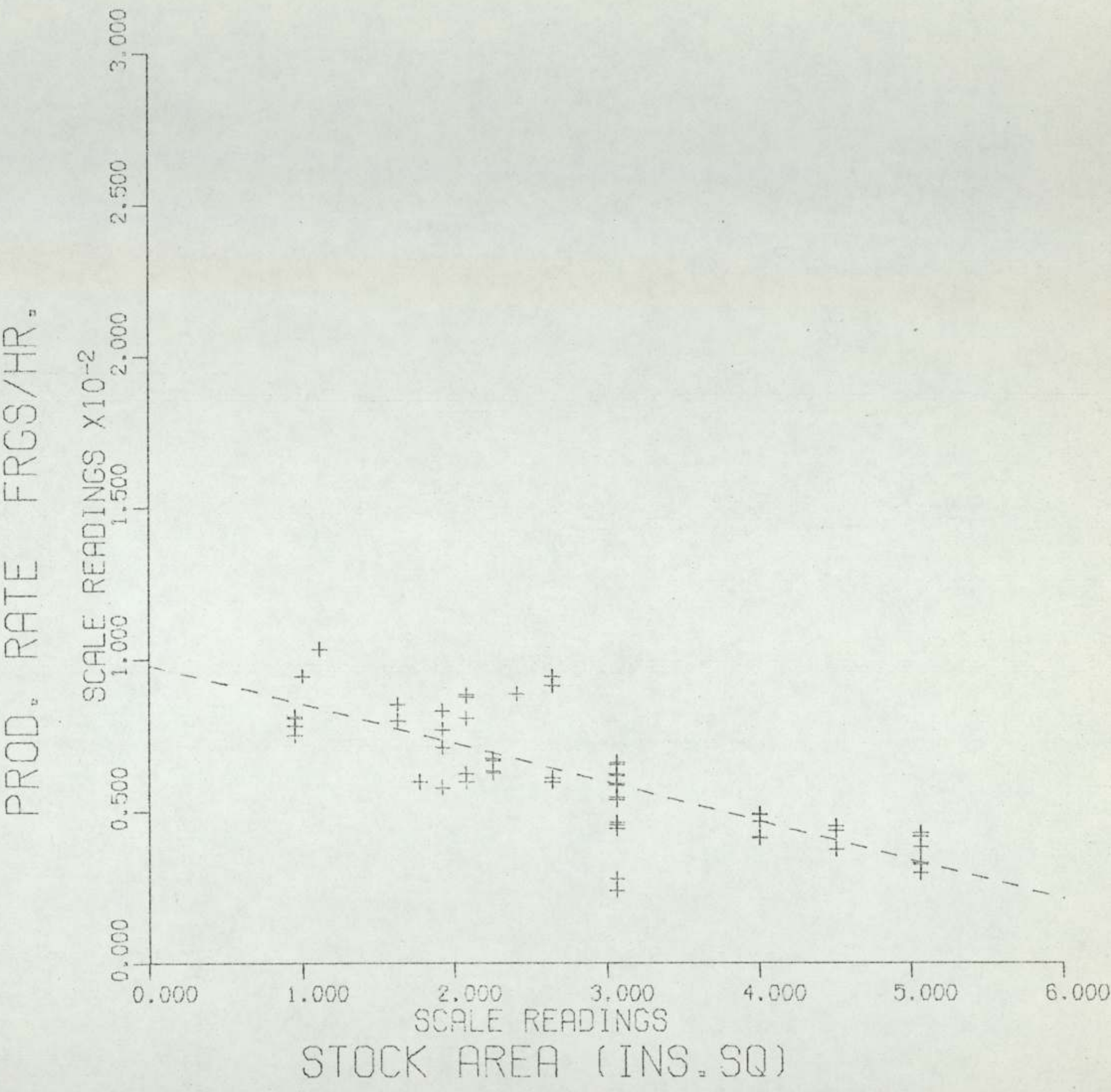


Figure 16a.

OBSERVED V CALCULATED.



<u>Figure 16b.</u>

RATE V STOCK AREA

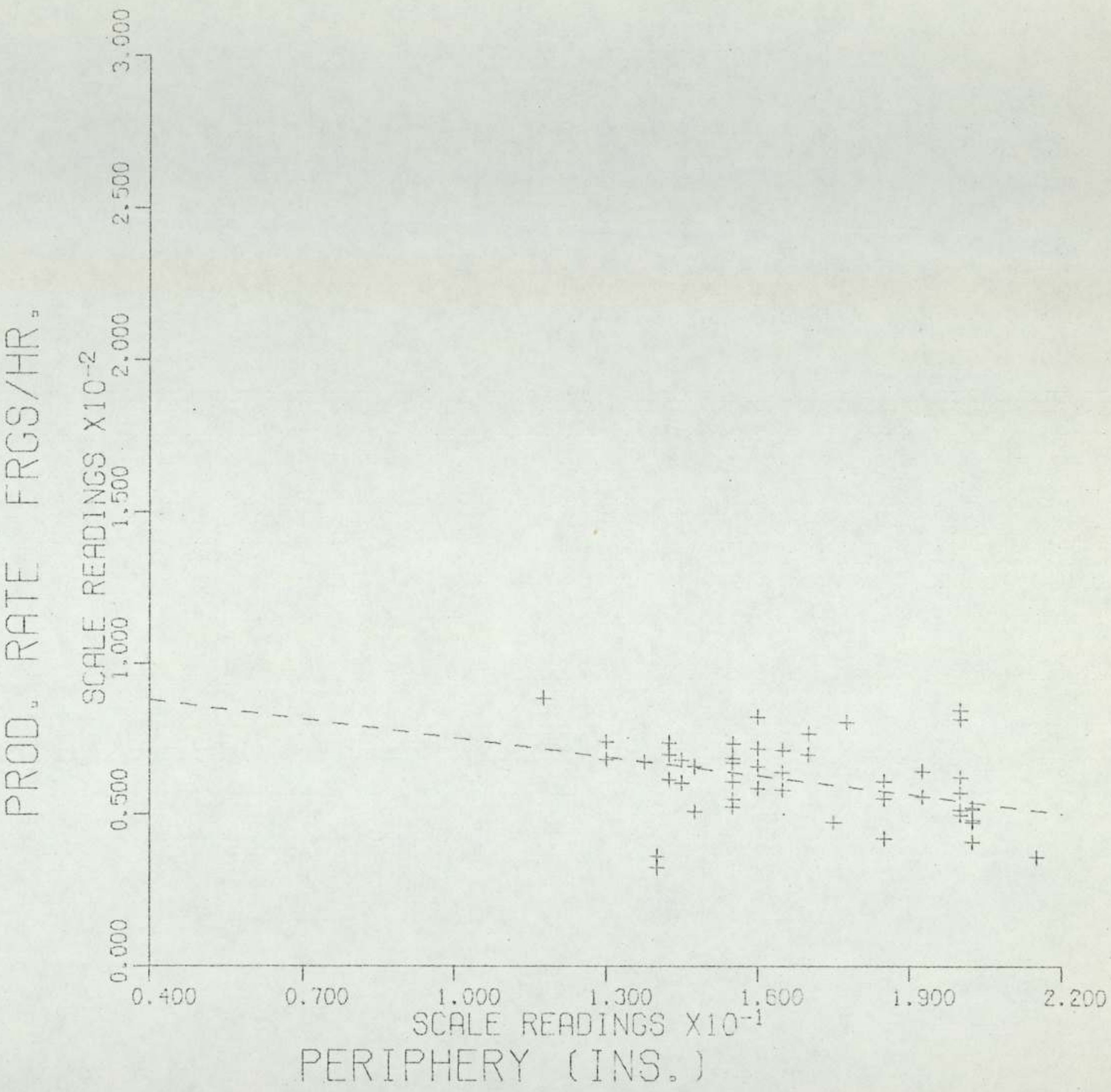


Figure 16c.

RATE V PERIPHERY

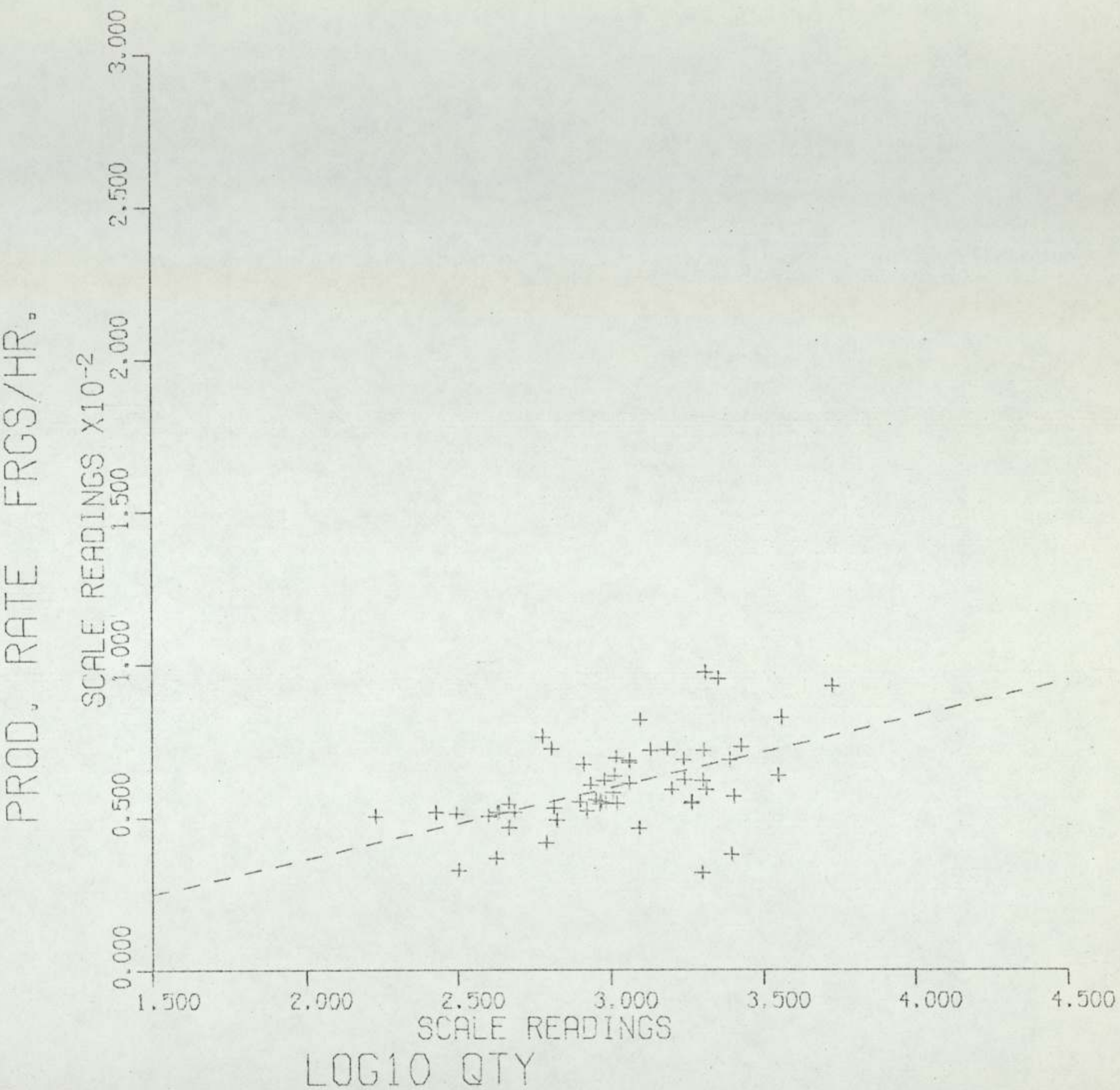


Figure 16d.

RATE V LOG10 QTY

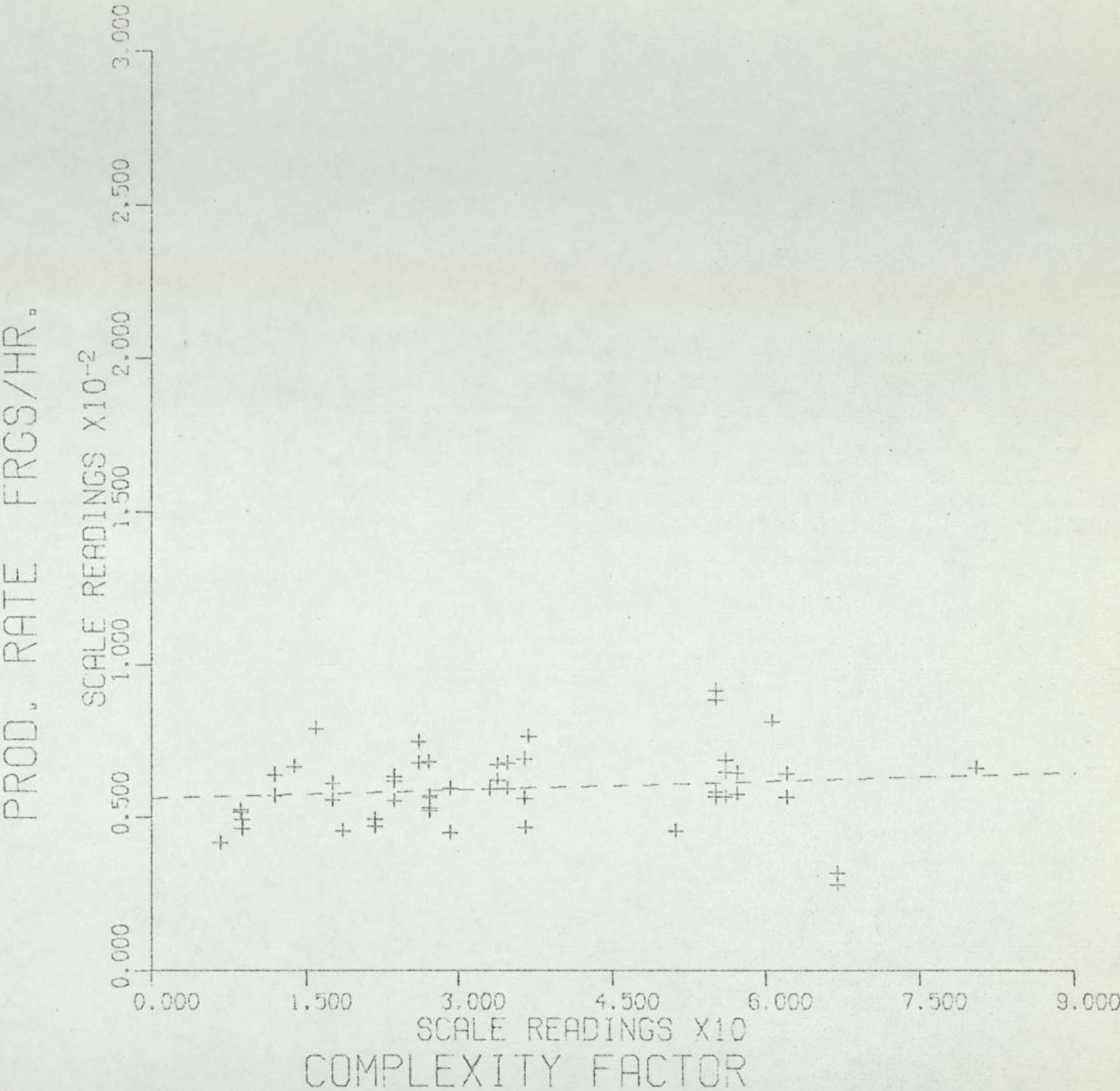


Figure 16e.

RATE V COMPLEXITY

<u>Figure 16f.</u>

RATE V AREA

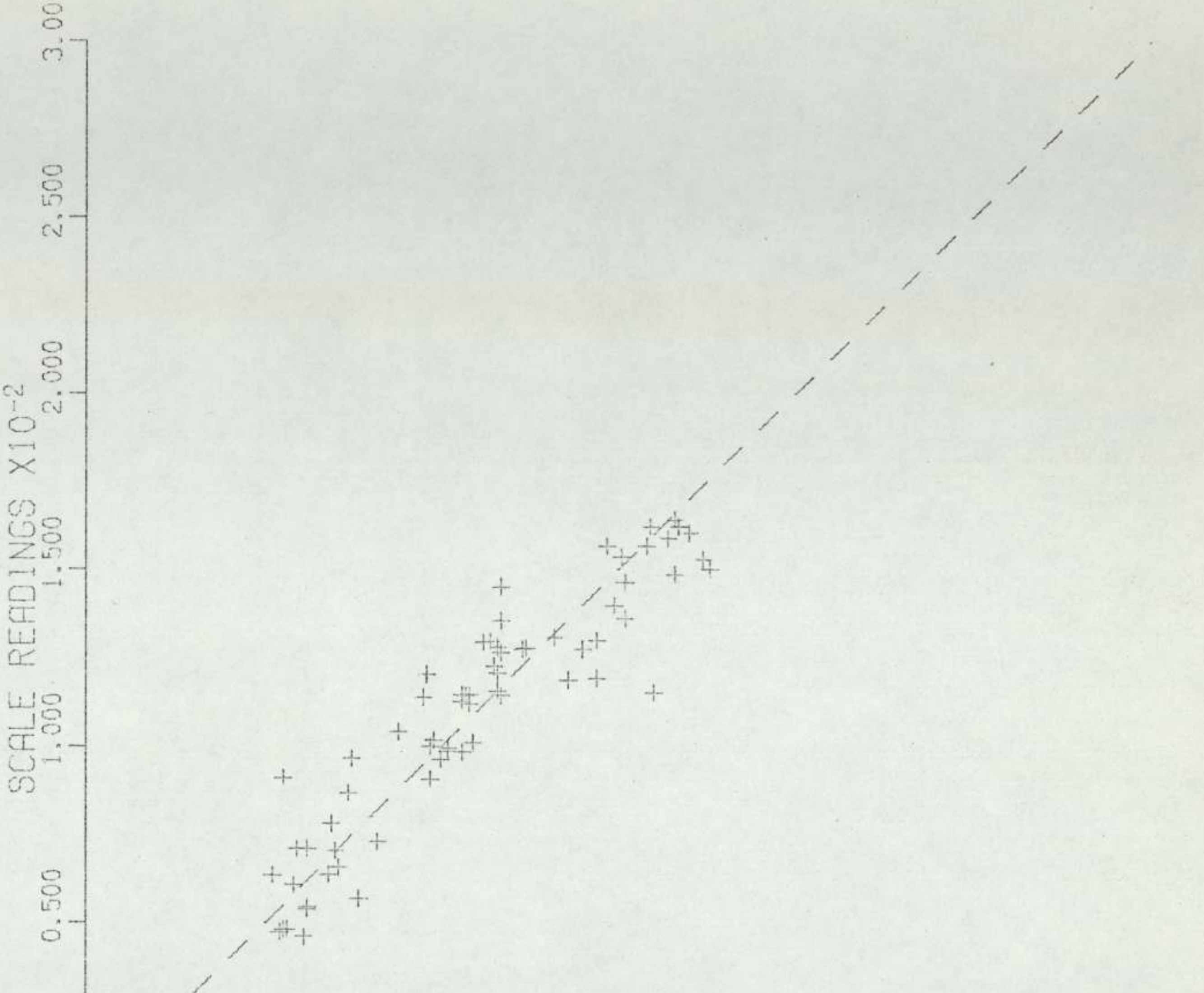


Figure 17a.

OBSERVED V CALCULATED.

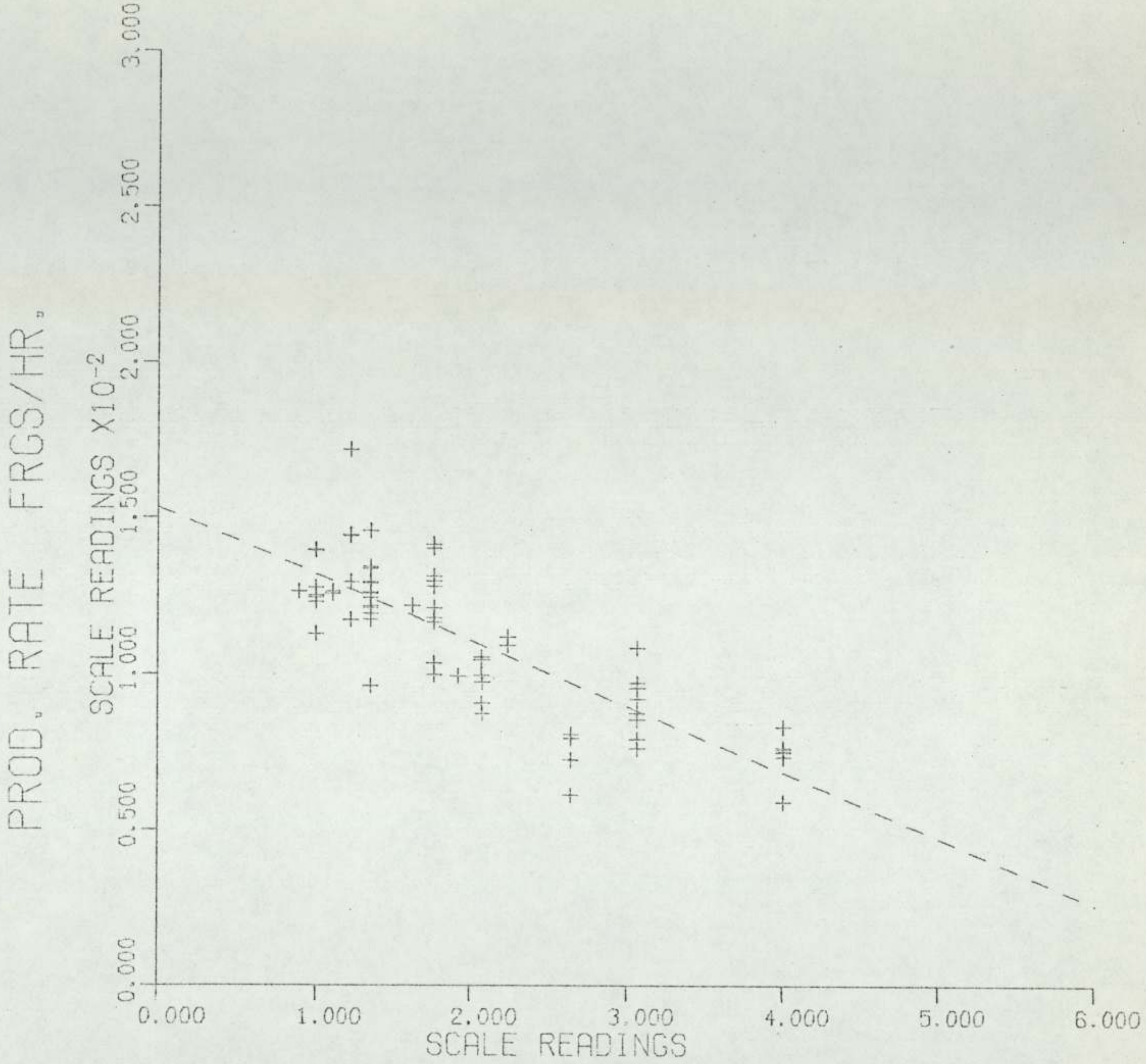


Figure 17b.

RATE V STOCK AREA

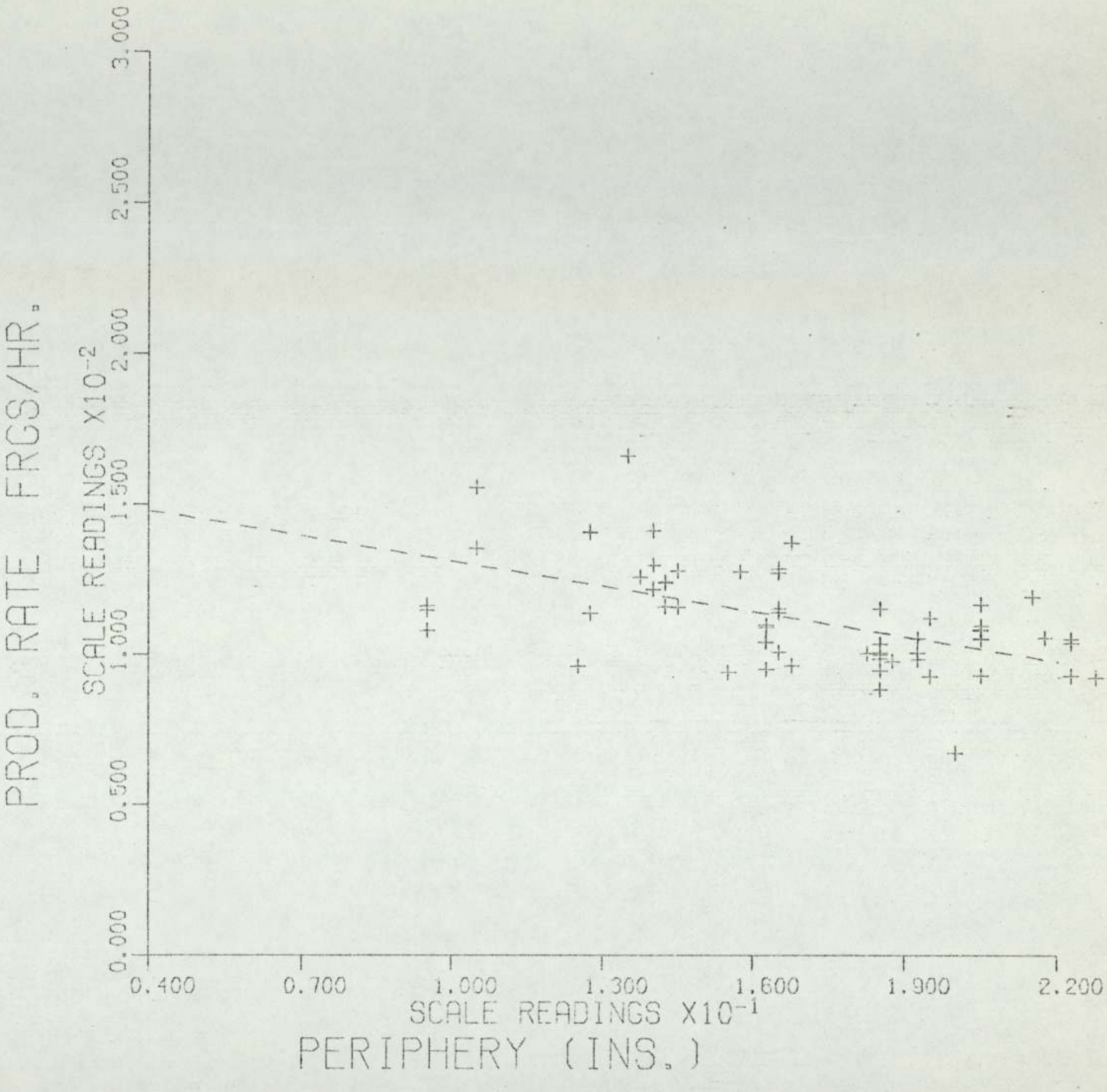


Figure 17c.

RATE V PERIPHERY

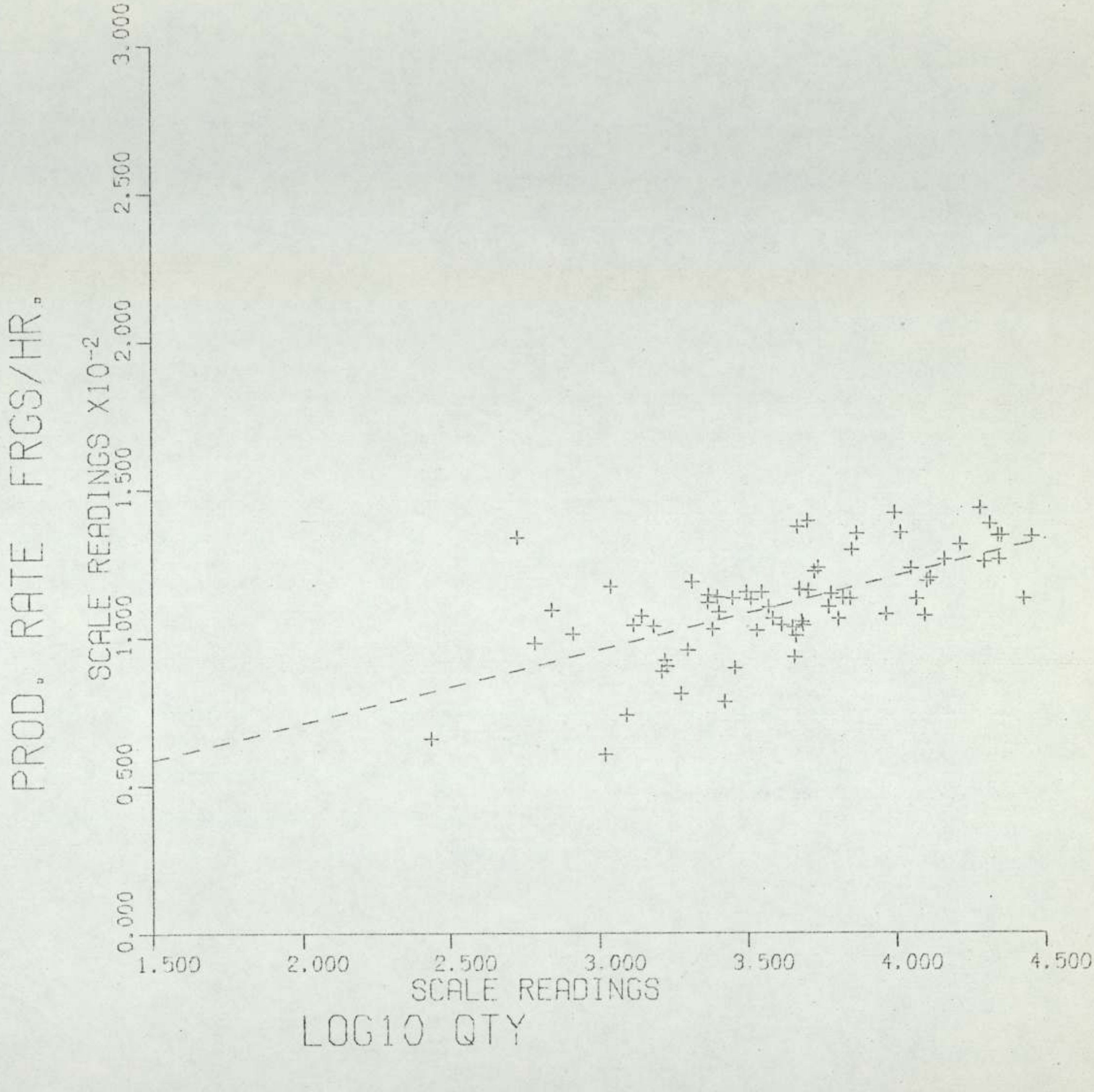


Figure 17d.

RATE V LOG10 QTY

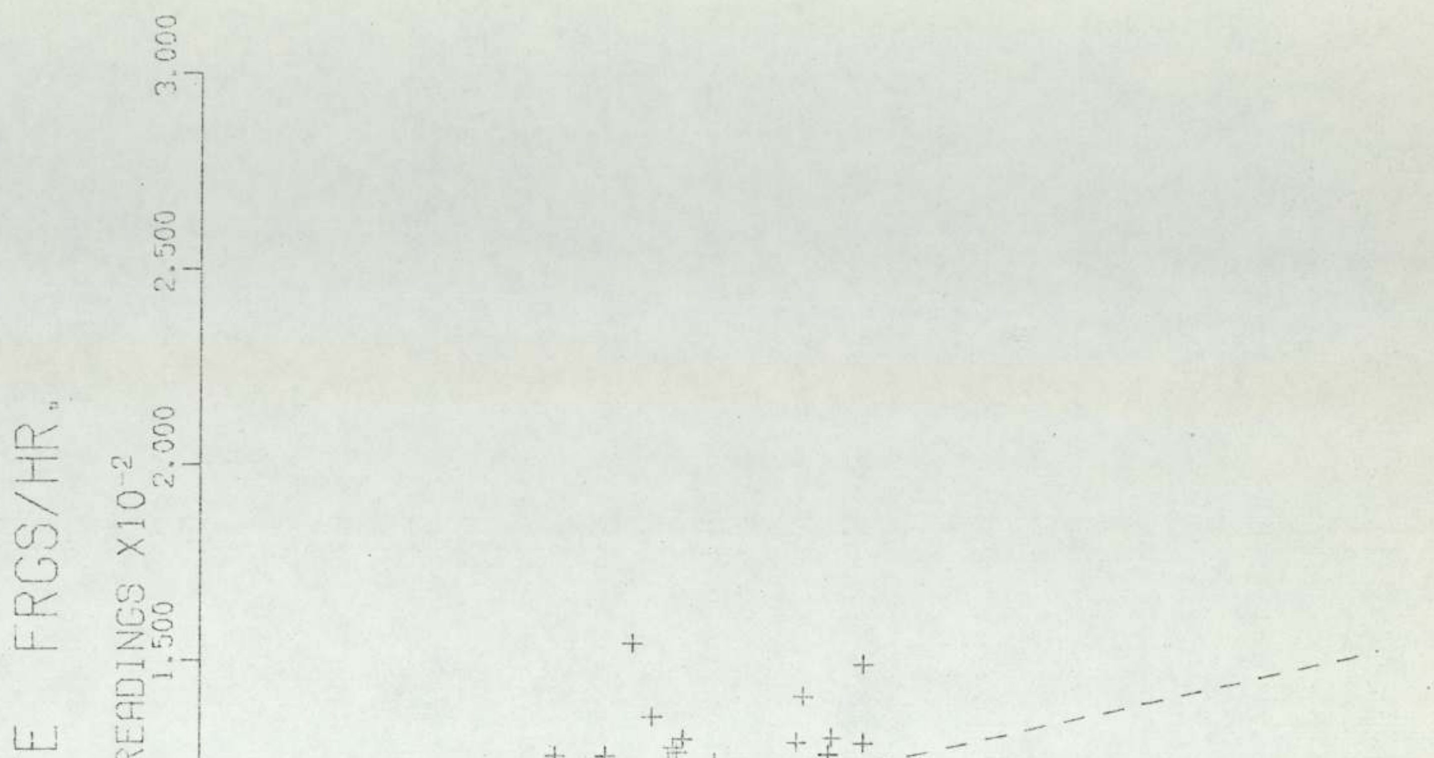


Figure 17e.

RATE V COMPLEXITY

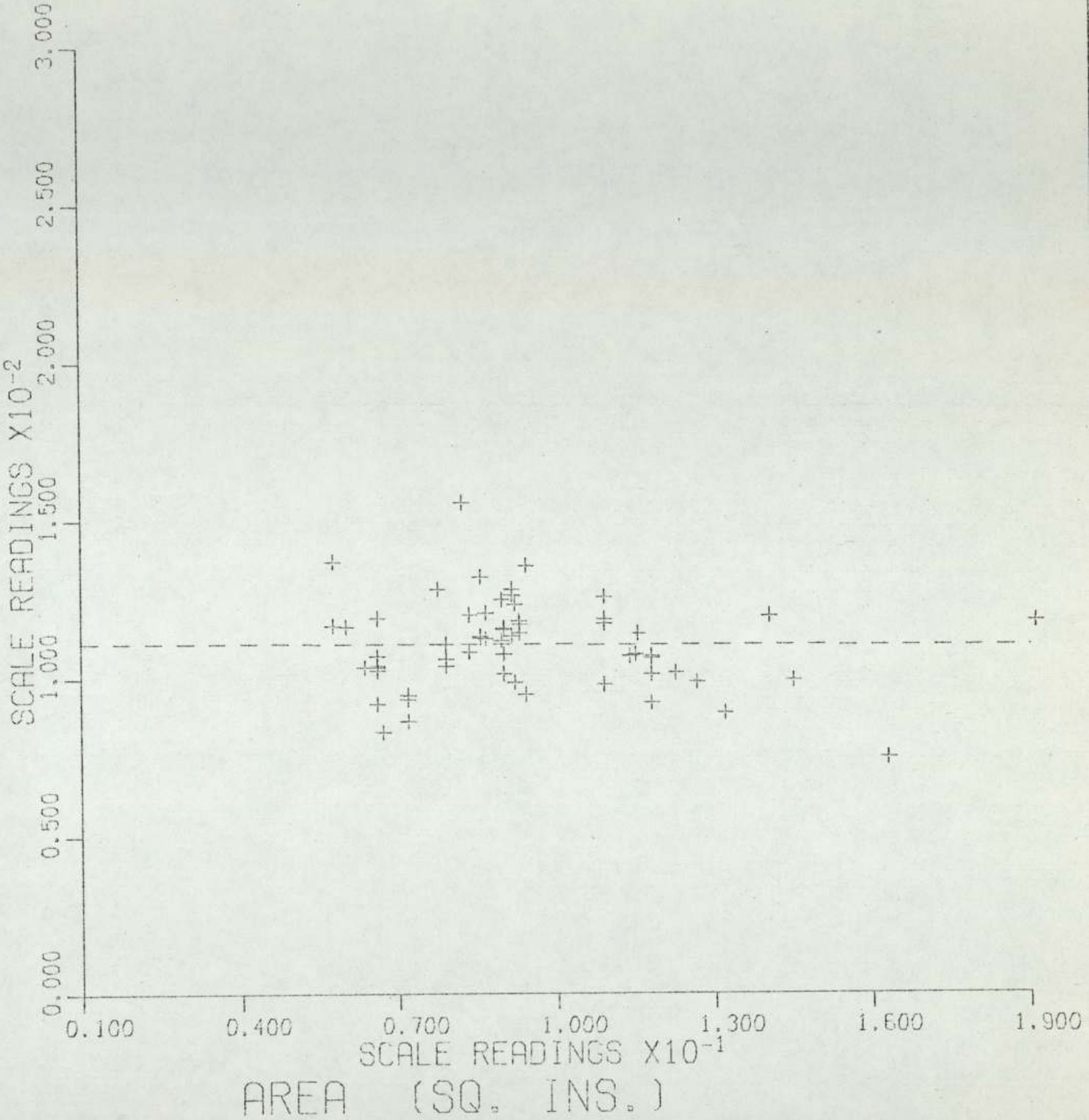


Figure 17f.

RATE V AREA

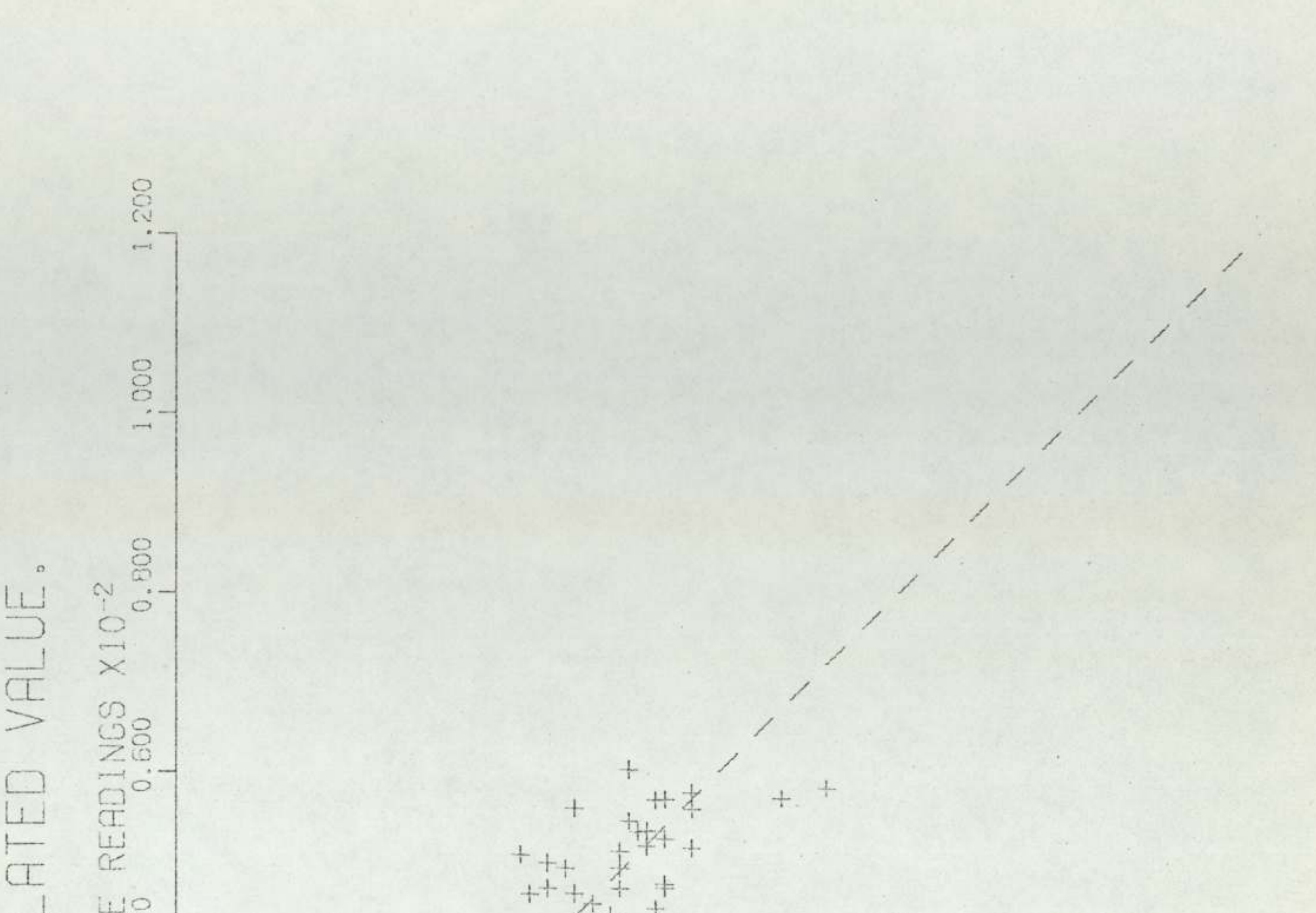


Figure 18a.

OBSERVED V CALCULATED.

Figure 18b.

RATE V STOCK AREA

Figure 18c.

RATE V PERIPHERY

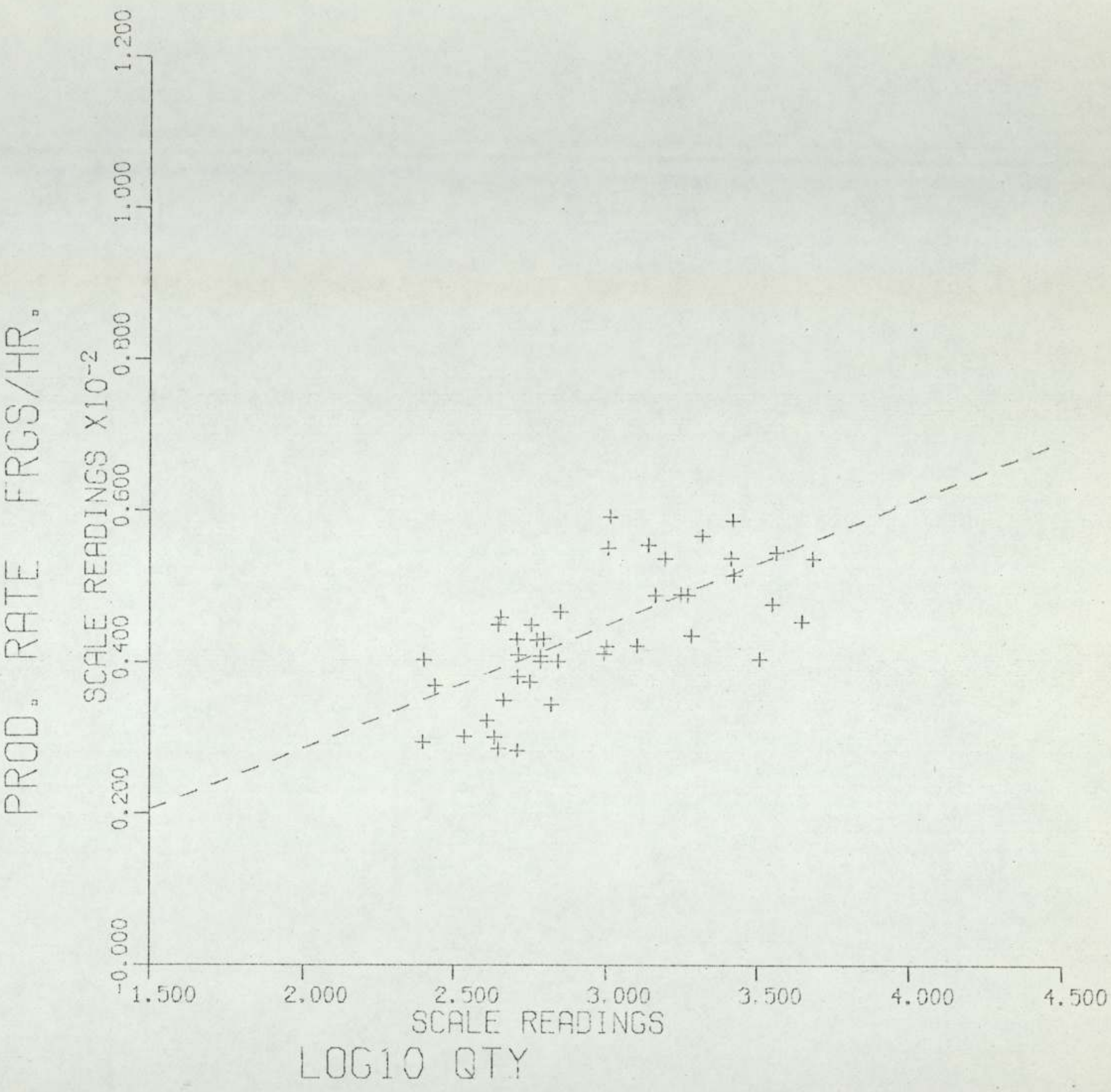


Figure 18d.

RATE V LOG10 QTY

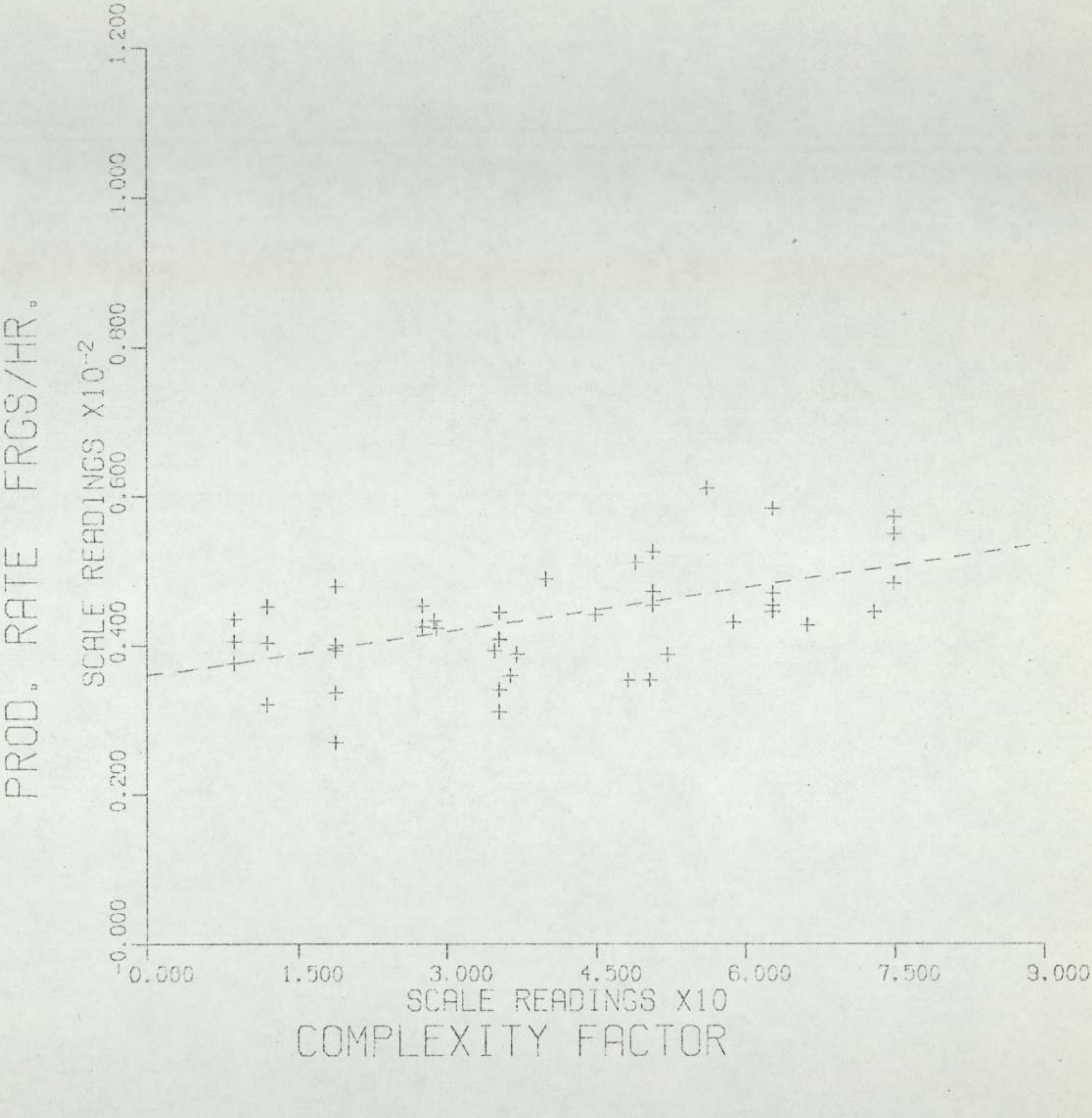


Figure 18e.

RATE V COMPLEXITY

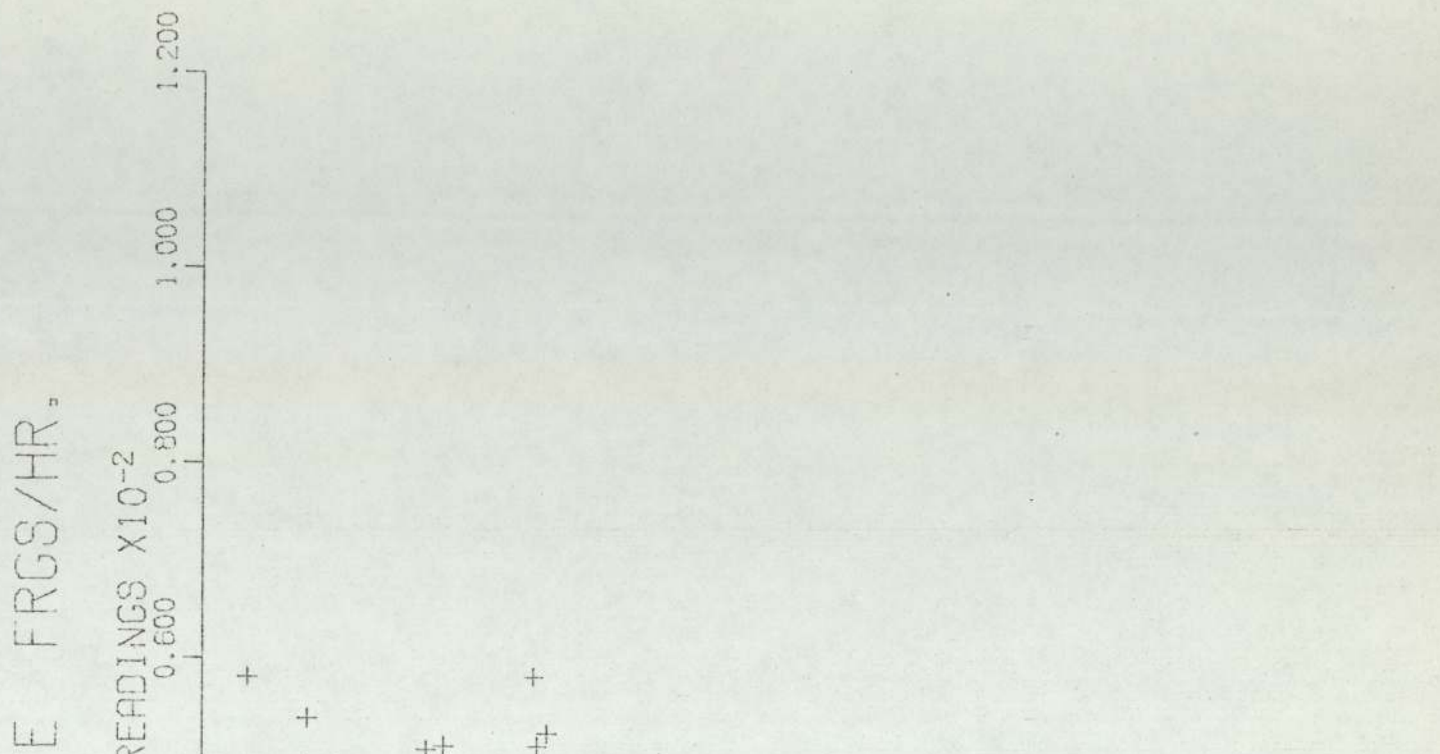


Figure 18f.

RATE V AREA

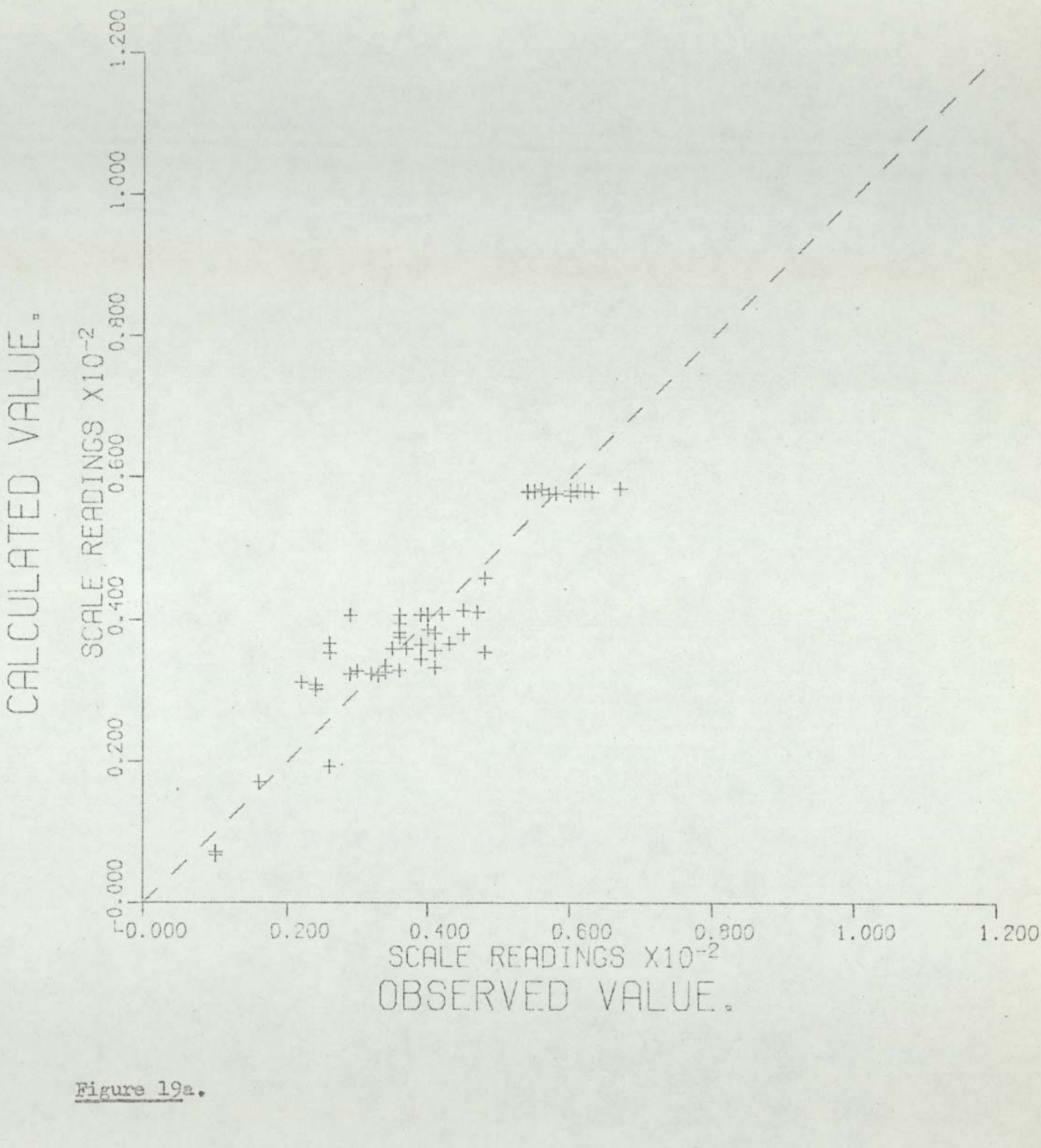


Figure 19a.

OBSERVED V CALCULATED.

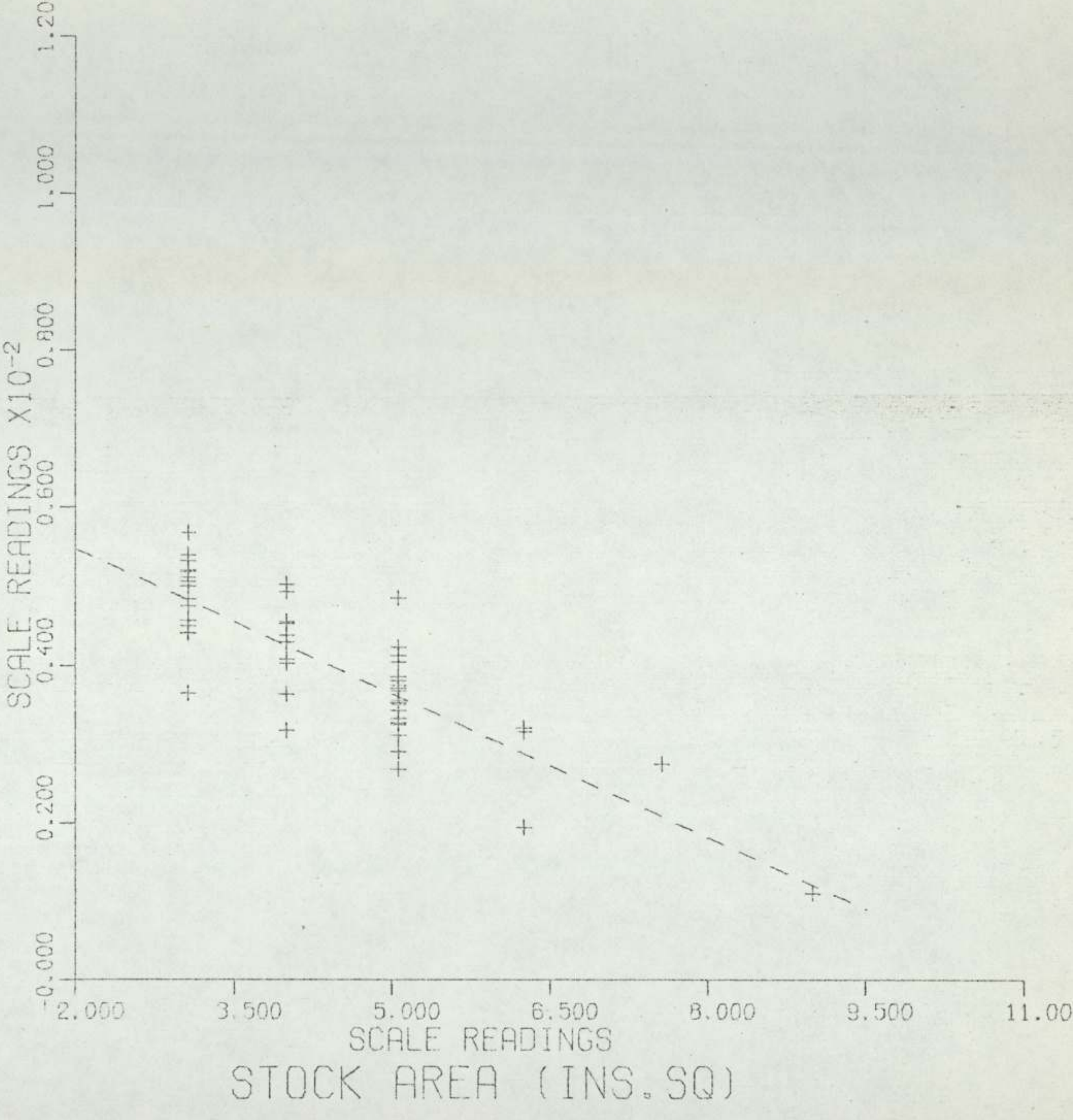


Figure 19b.

RATE V STOCK AREA

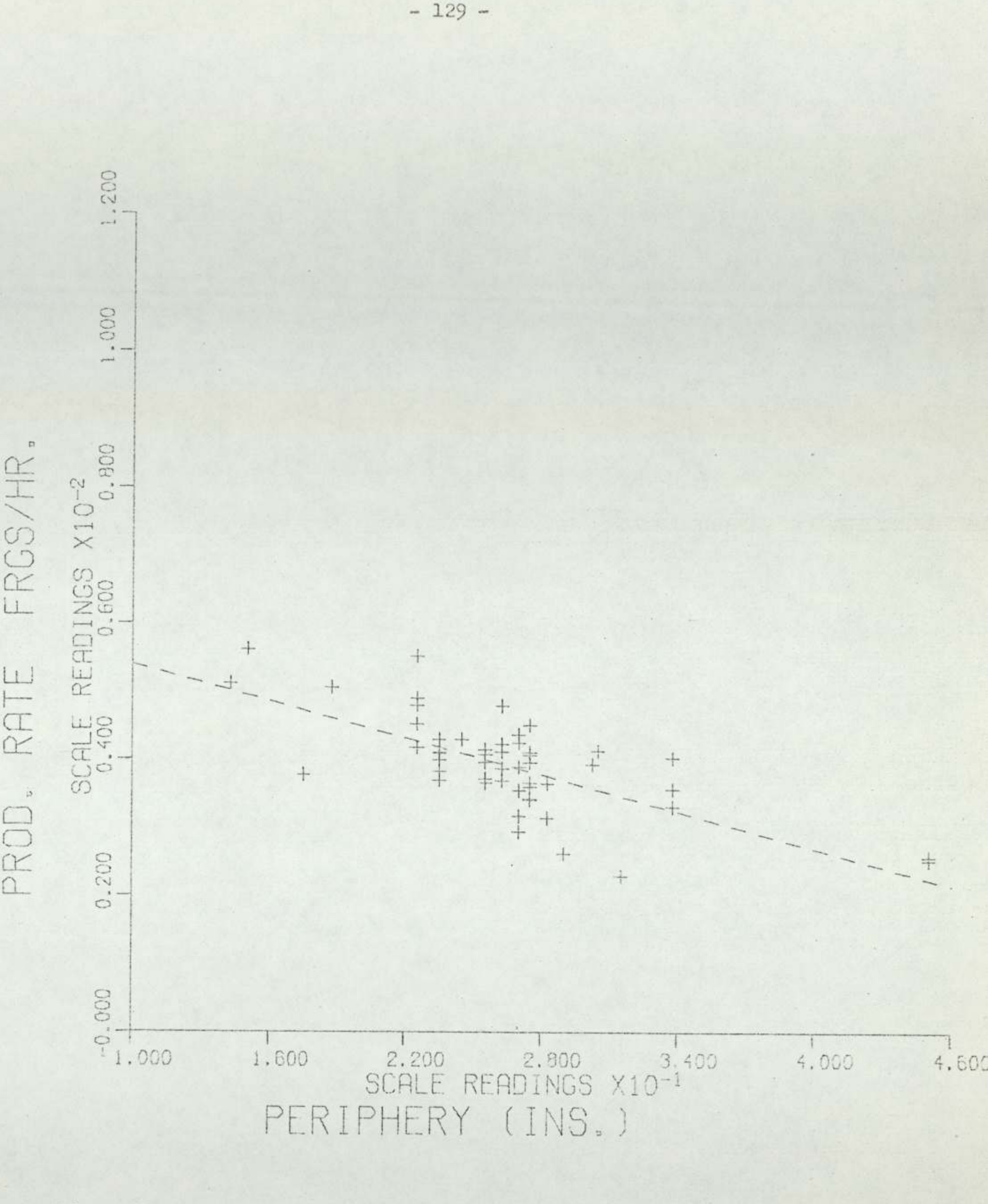


Figure 19c.

RATE V PERIPHERY

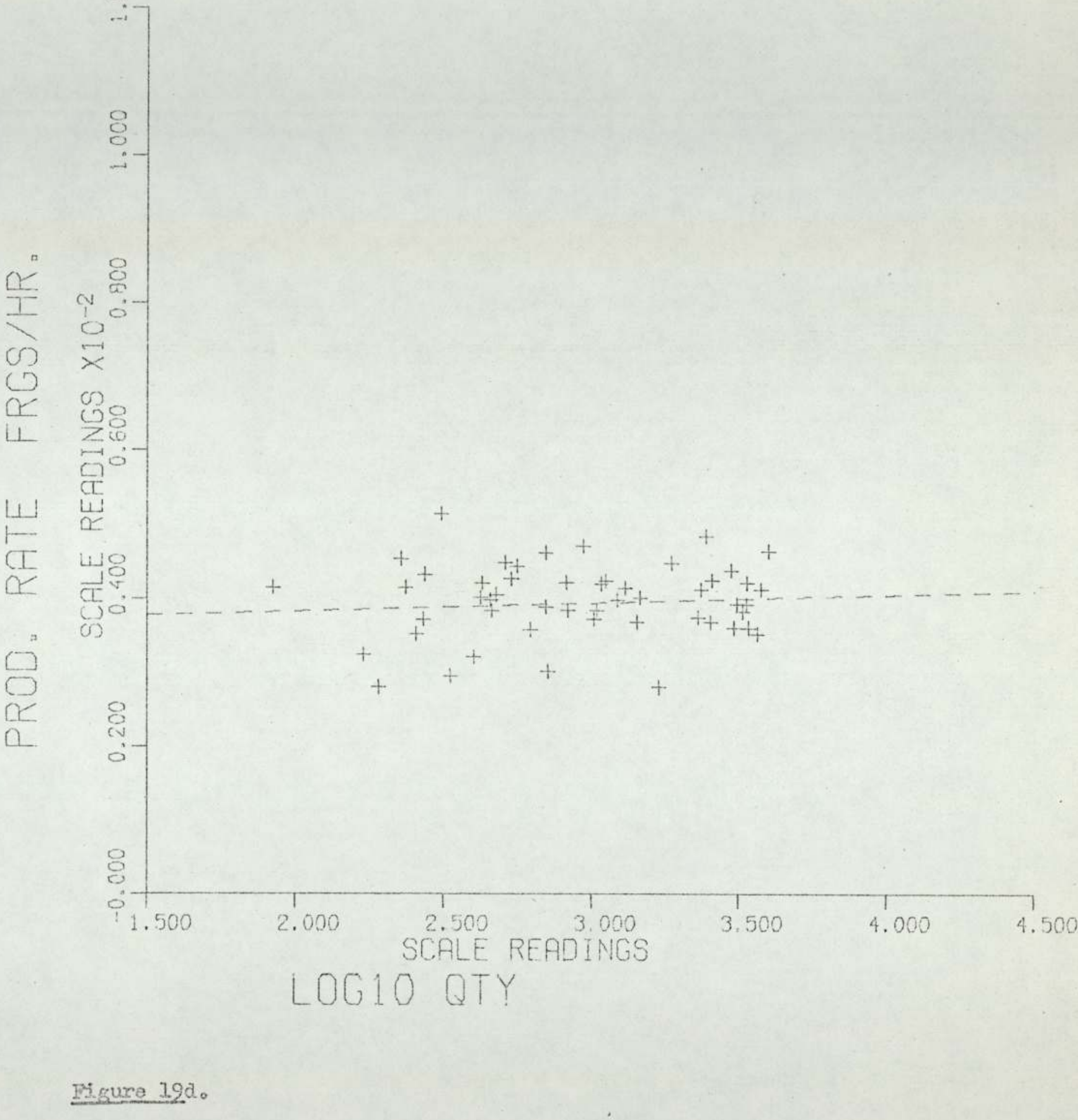


Figure 19d.

RATE V LOG10 QTY

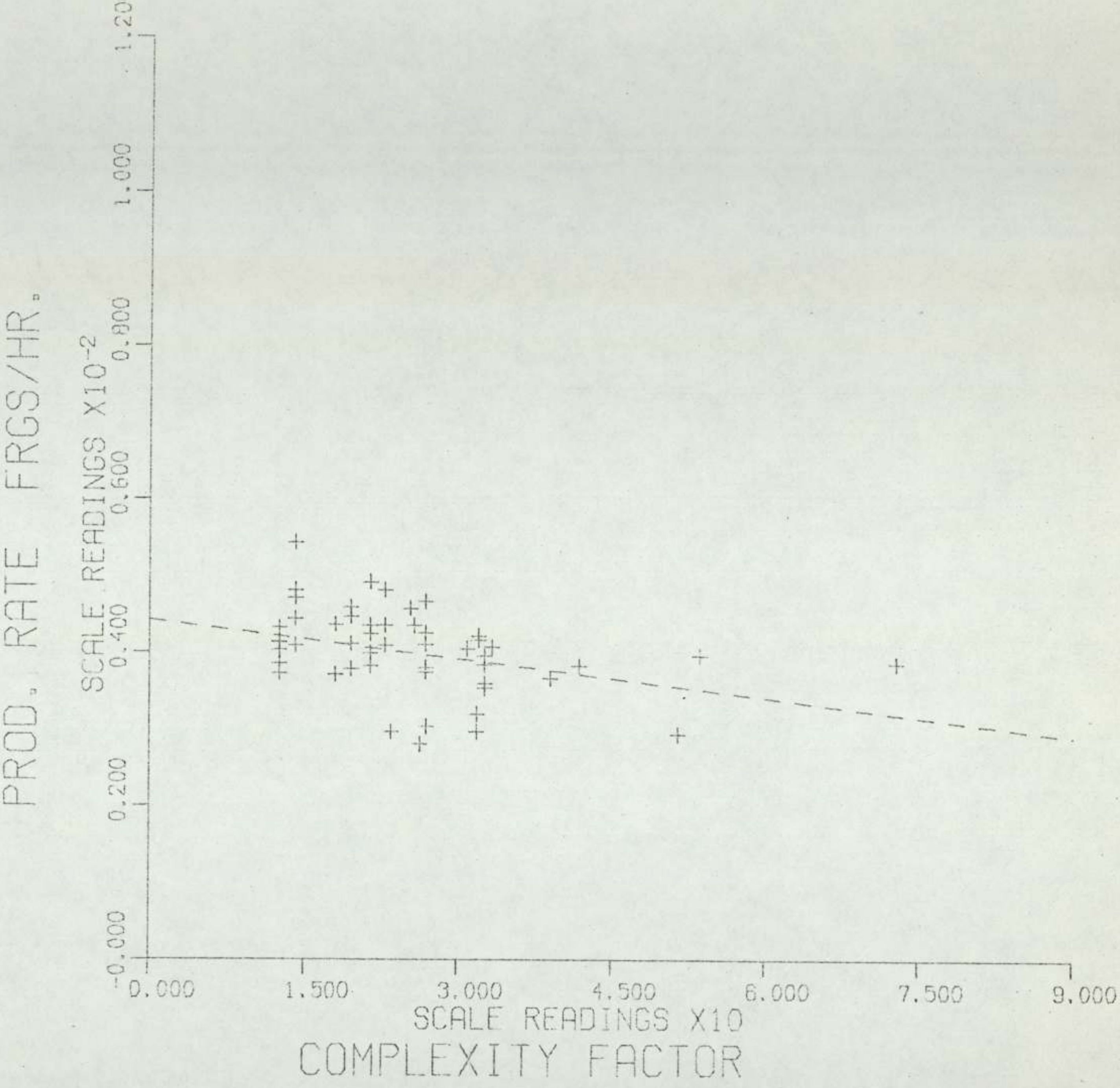


Figure 19e.

RATE V COMPLEXITY

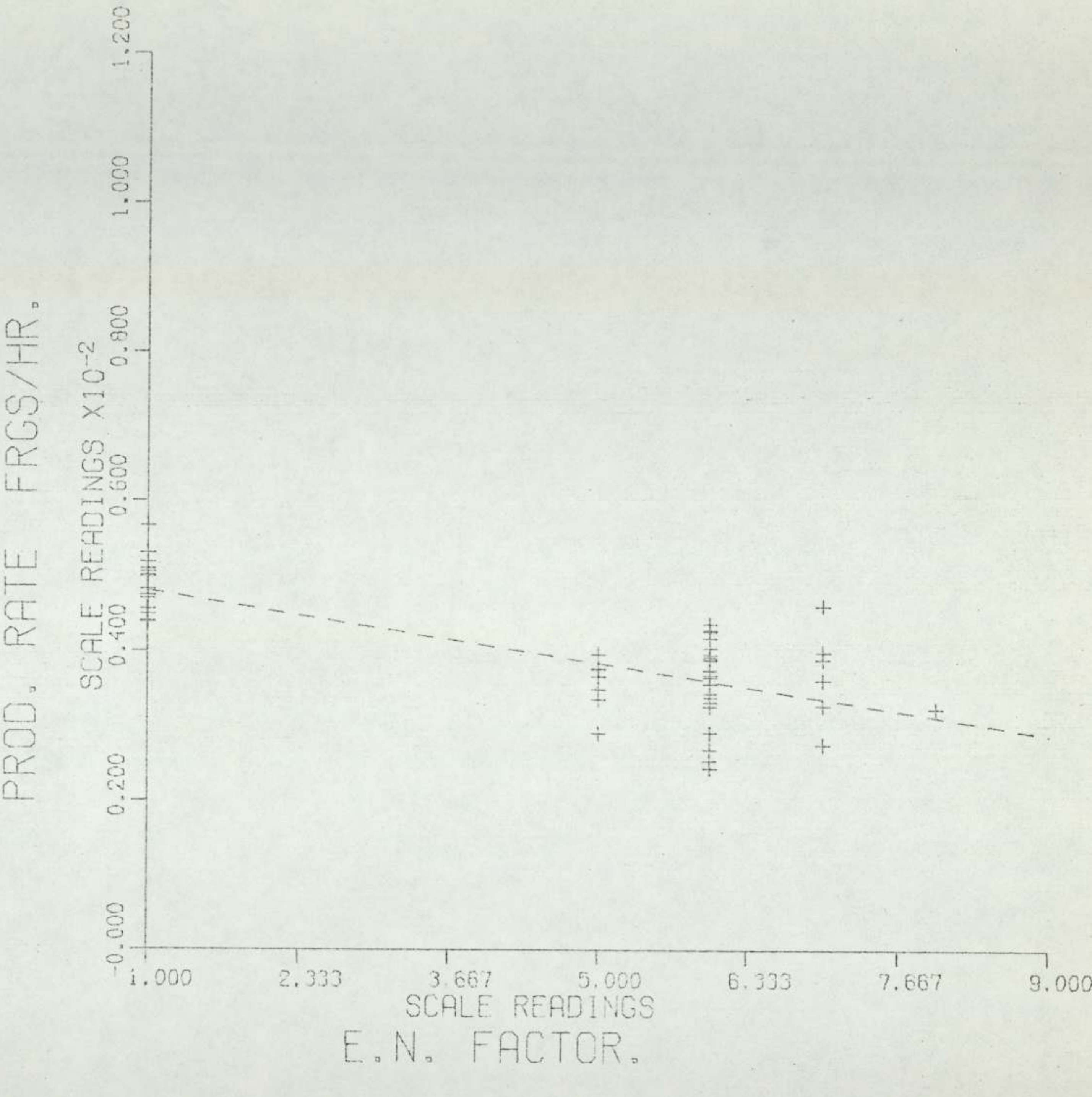


Figure 19f.

RATE V E.N. FACT.

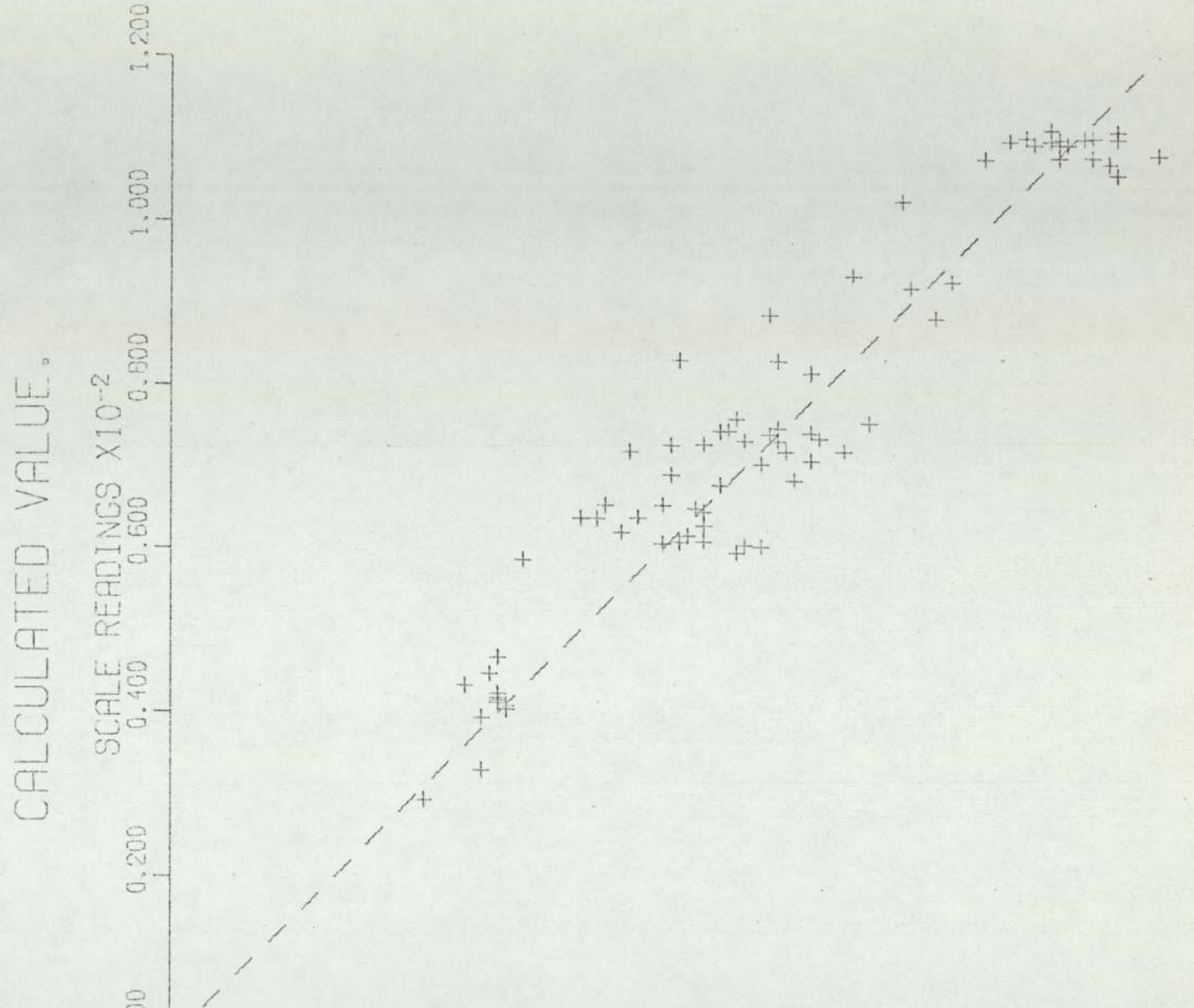


Figure 20a.

OBSERVED V CALCULATED.

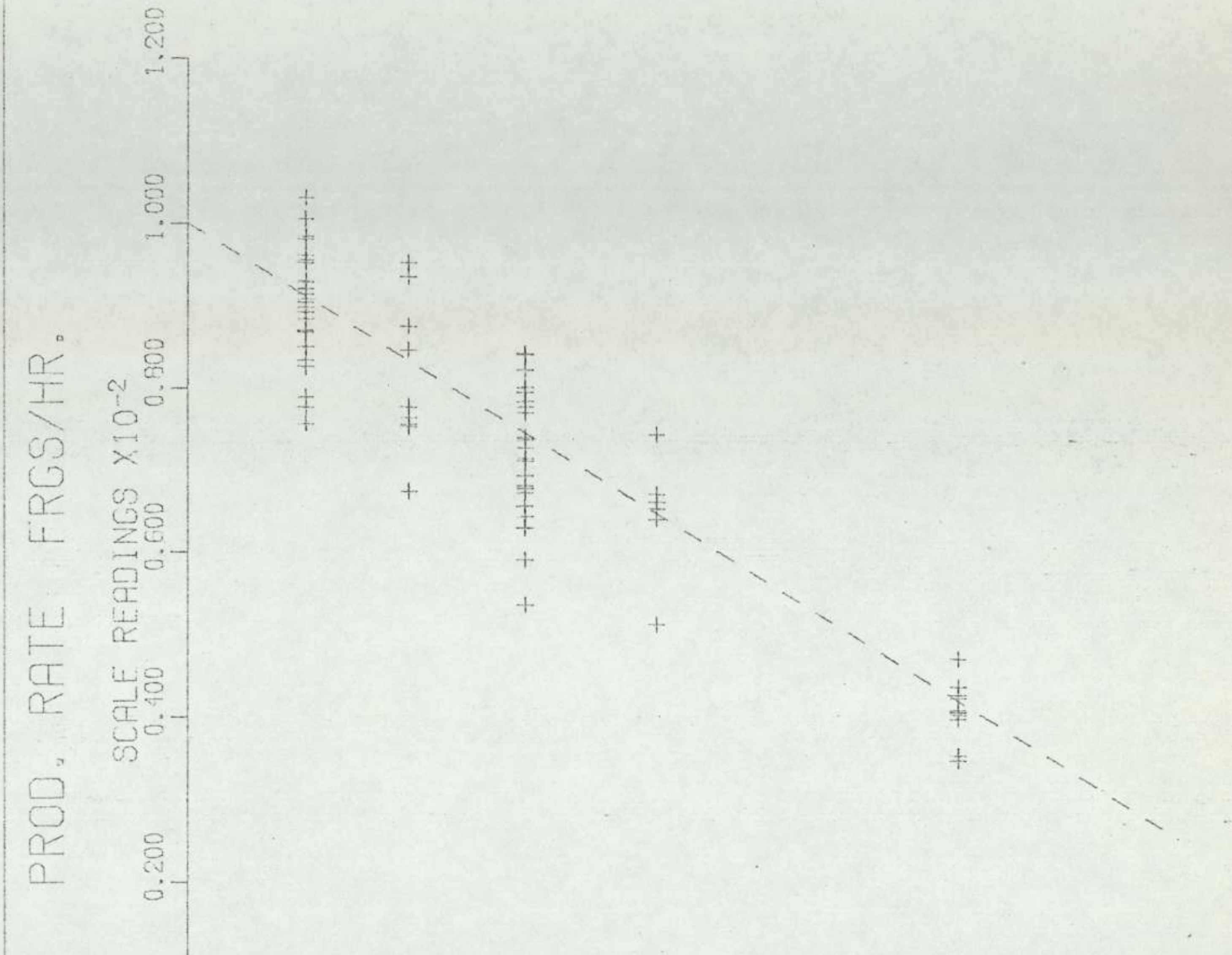


Figure 20b.

RATE V STOCK AREA

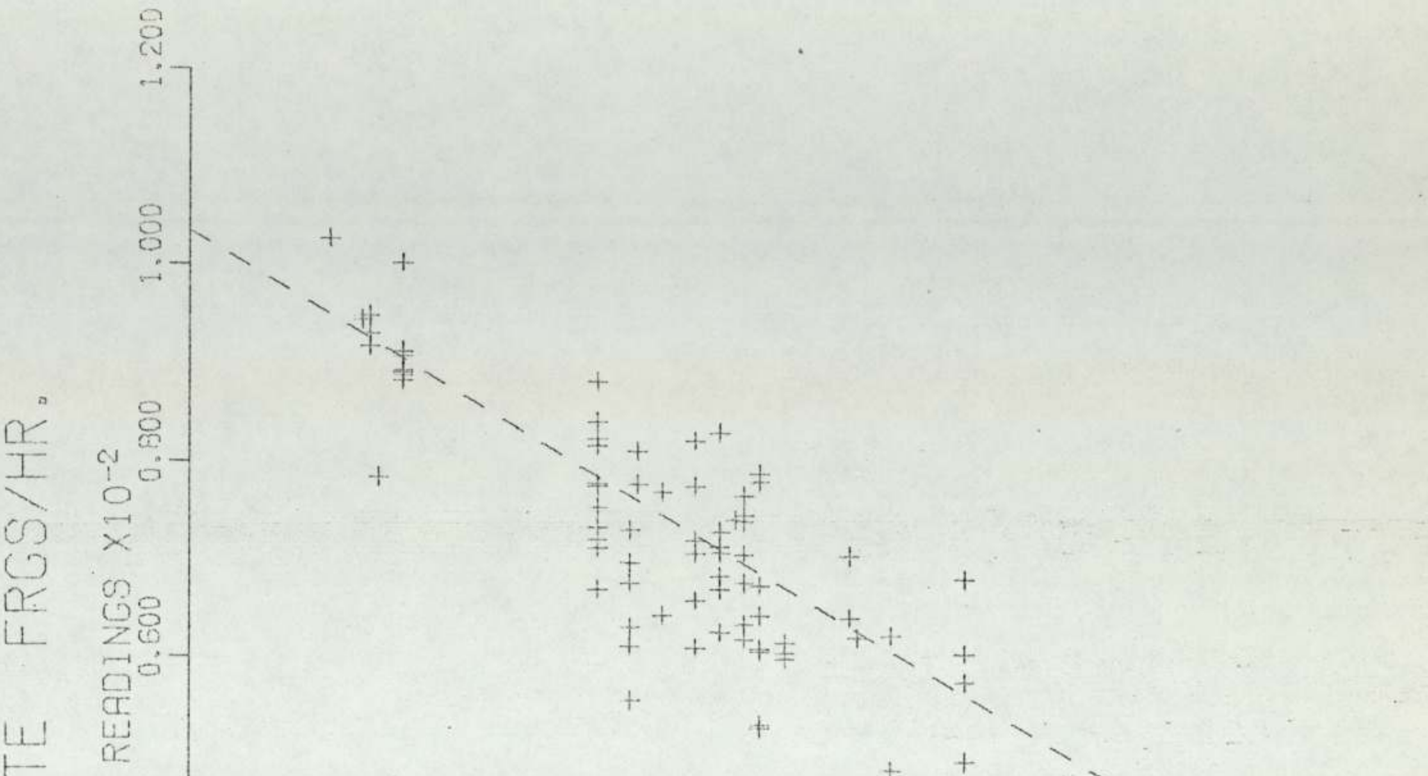


Figure 20c.

RATE V PERIPHERY

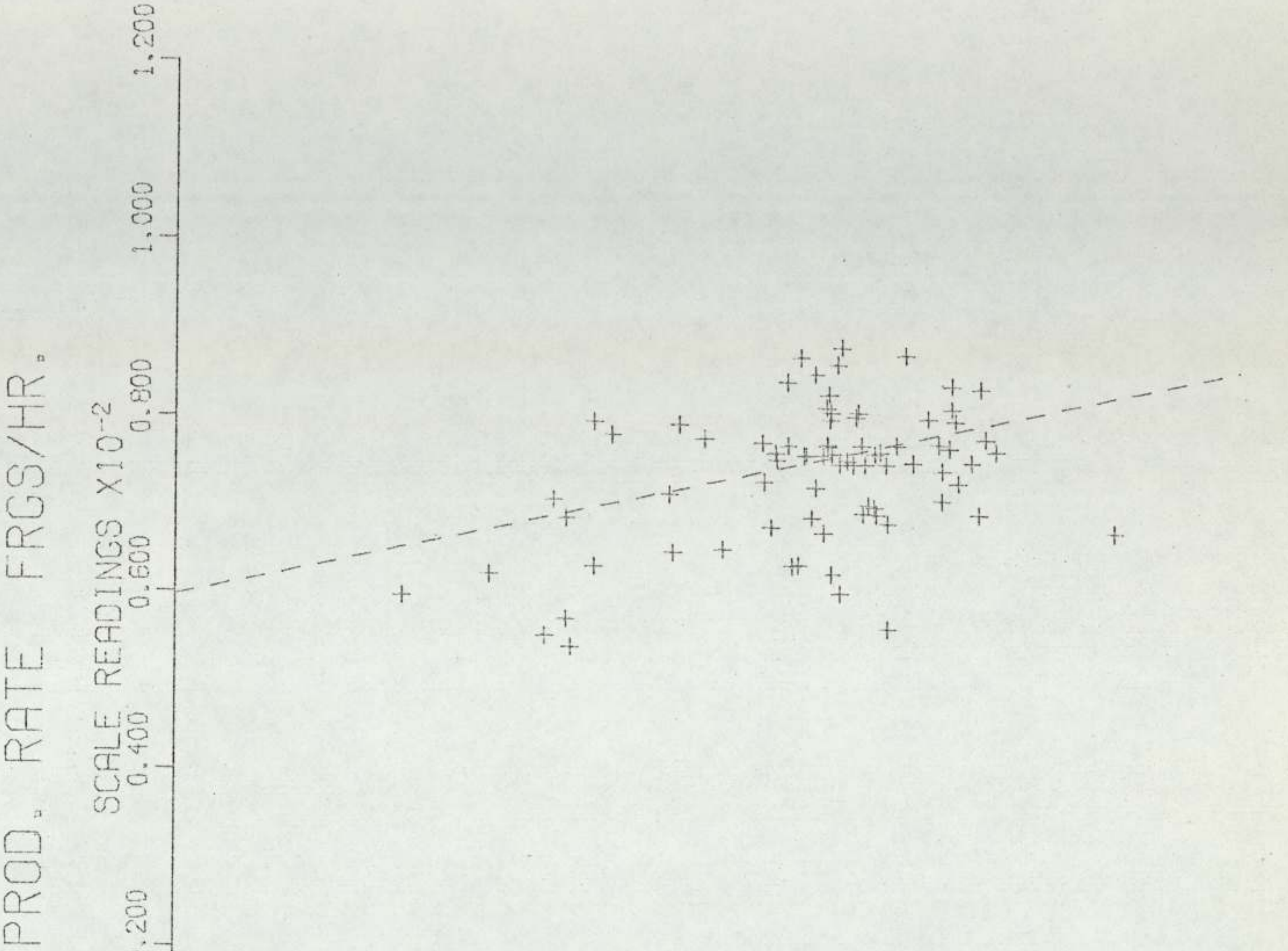


Figure 20d.

RATE V LOG10 QTY

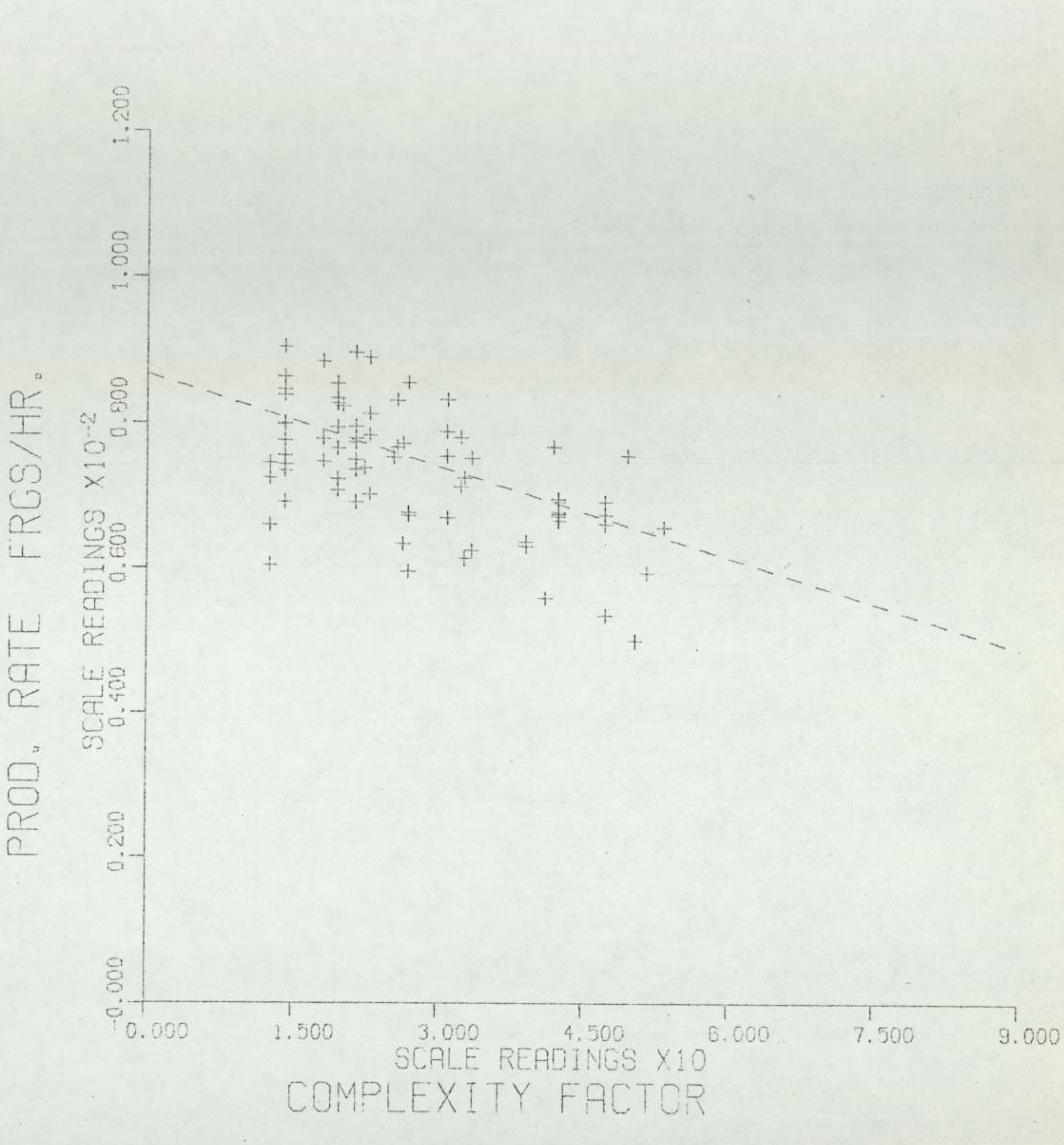


Figure 20e.

RATE V COMPLEXITY

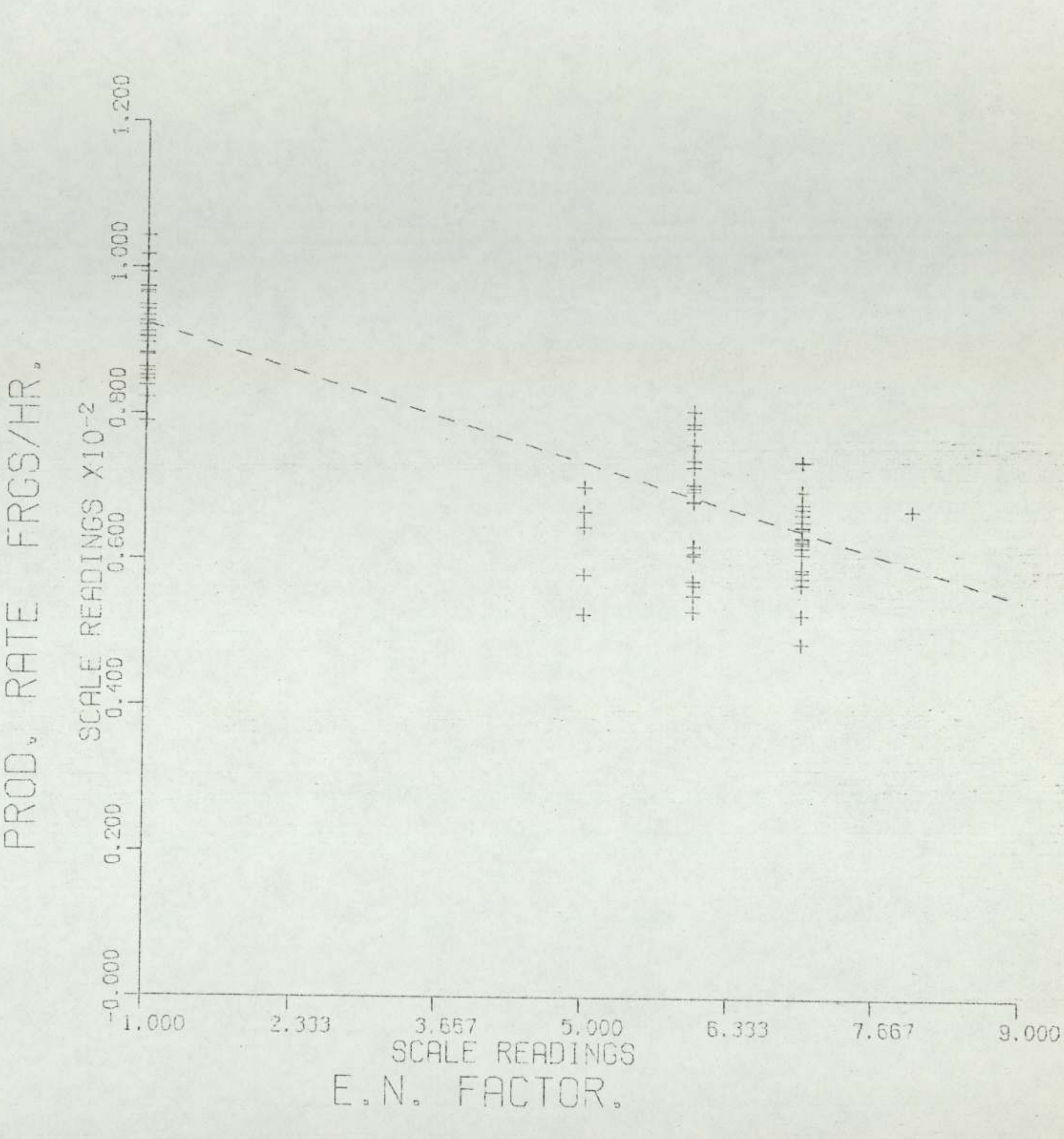


Figure 20f.

RATE V E.N. FACT.

5.2 Direct Benefits of Improved Accuracy

In addition to comparing the accuracies of the two systems (present manual and model-based), table 3 also contains values of mean percentage error for both flash weight and production-rate predictions. Examination of these values shows that, in general, the manual estimator tends to predict flash weight and production rate values that are 22% higher and 7% lower (respectively) than the subsequently achieved values of these production variables.

Let us consider the implications of these 'biases' in the context of sales policies and the benefits likely to result from the use of a more accurate estimating technique.

5.2.1 Selling price - A Hypothesis

When arriving at a quoted selling price via a cost estimation, whatever estimating method is used, there will inevitably occur errors in the prediction of the production variables. The percentage differences between the quoted selling price, based on these predictions, and the 'ideal' selling price (based on achieved values of the variables) should be normally distributed around zero, assuming no bias in these predictions.

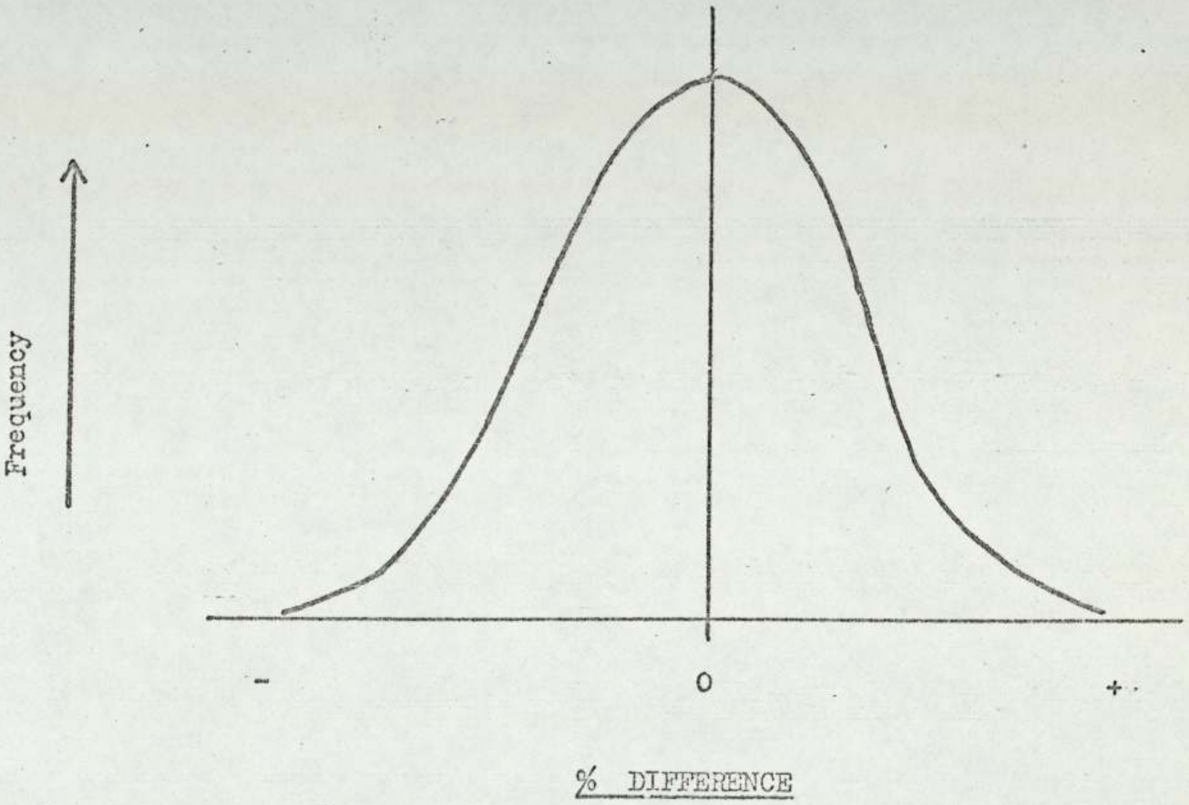


Figure 21

This may be explained alternatively: for any job, the quoted selling price should lie somewhere near the 'ideal' selling price, with a normally distributed deviation. The 'ideal' selling price ($\bar{x}$) is the price that would have been quoted (cost plus contribution) had we been in the idealized situation of knowing, beforehand, the values of the production variables with absolute certainty.

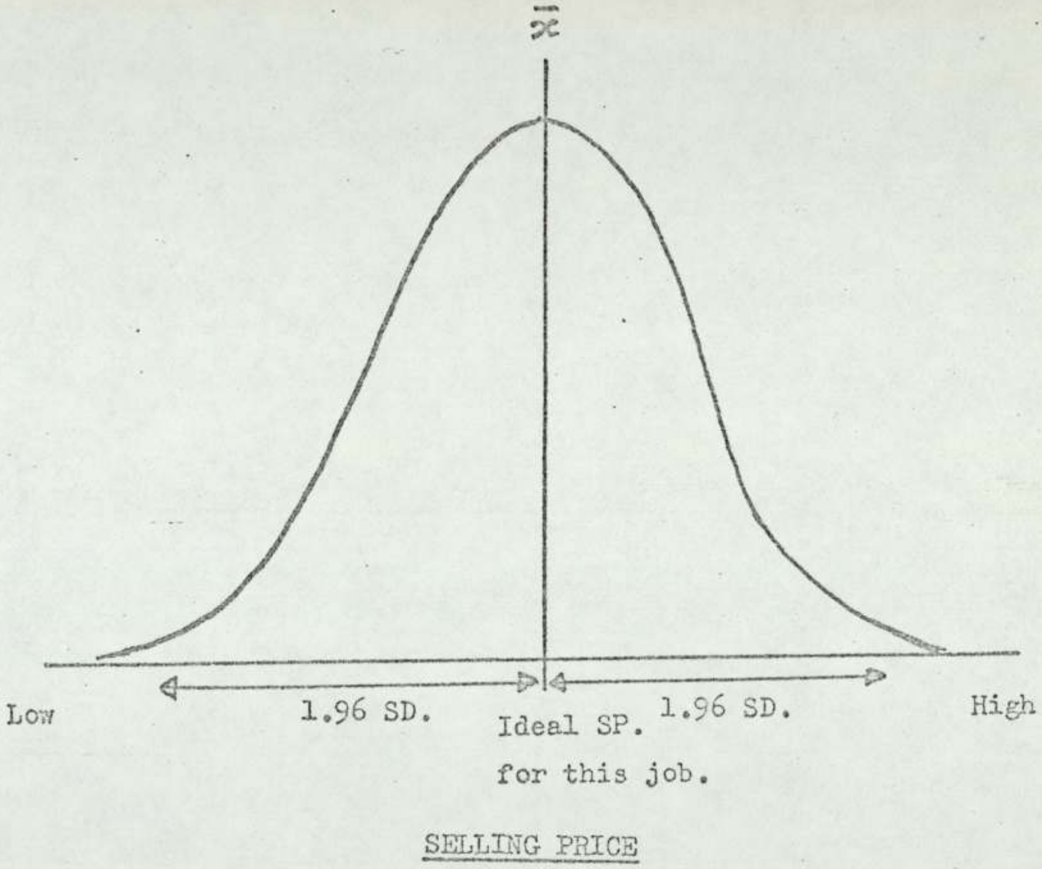

$\bar{x}$
Low
1.96 SD.
Ideal SP.
for this job.
1.96 SD.
High
SELLING PRICE

Figure 22.

Let us superimpose a further line on our diagram, x'

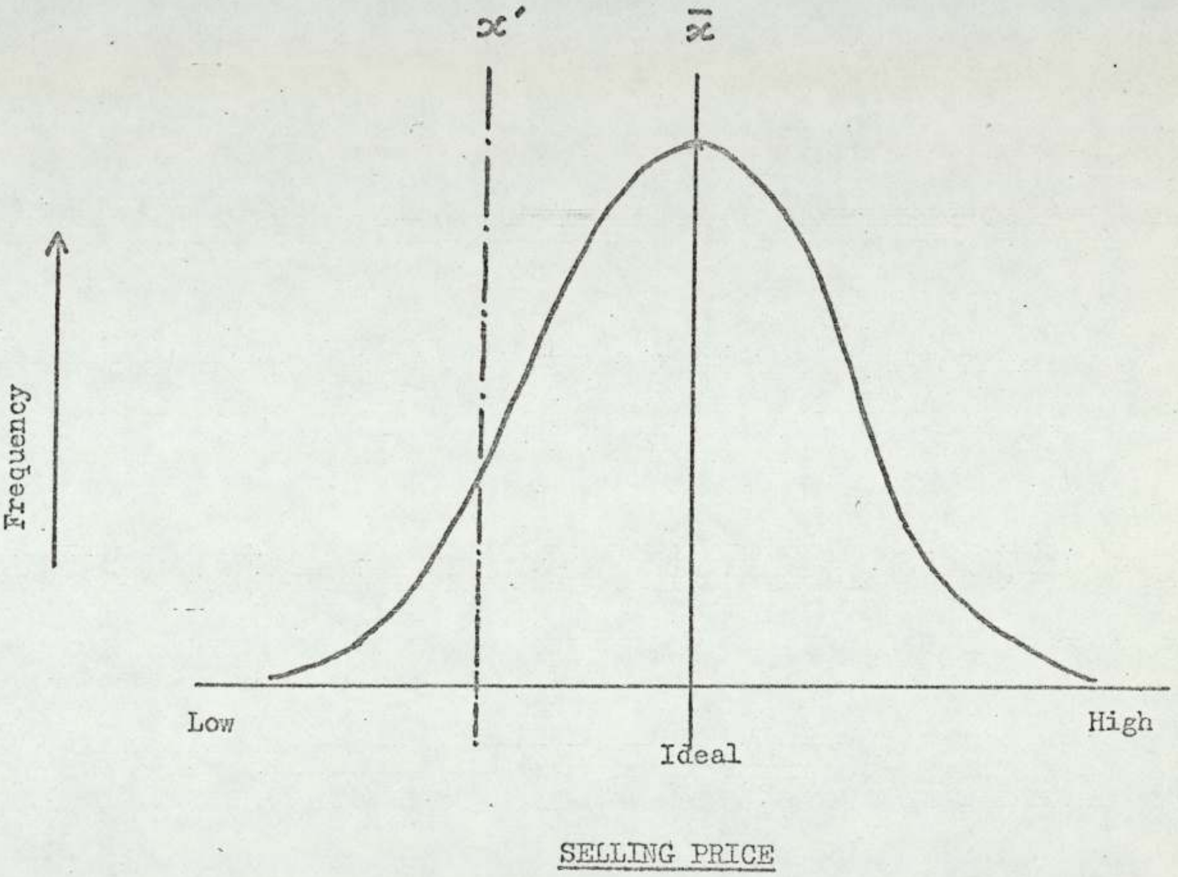


Figure 23.

x' represents a price resulting in a certain contribution for the job. This value is the lowest contribution with which we are satisfied. For prices quoted below this level (resulting from extreme estimation errors) we would rather not win the order, since the production time could be more fruitfully employed in manufacturing a more realistically priced job. x' can thus be thought of as a threshold value, below which we would desire no more than 5% (1 in 20) of our tendered prices to fall.

It is possible, however, that with our estimating system more than 5% of our quoted prices will fall below this threshold value, if SD. $> (\bar{x} - x')/1.96$. Thus a general upward movement of the price structure is required ($\acute{y}$) in order to reduce the risk of 'unsatisfactory' prices (resulting from extreme estimator errors) to 5%

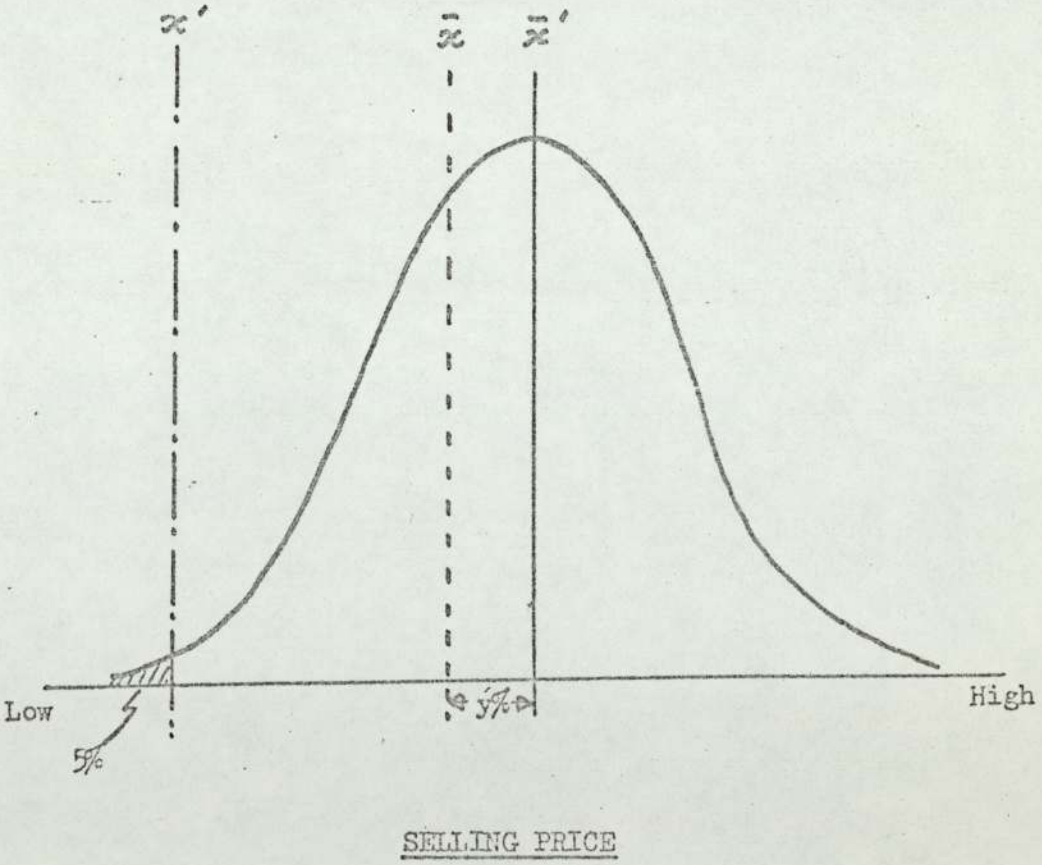


Figure 24

In practice, the threshold price for a job will not have been defined by anyone, nor will management admit to employing any consideration of the concept of a 'threshold' selling price. Nevertheless, the management instruction to bias production parameter forecasts as a safeguard against estimator error (section 4.1.1), and the values of prediction bias observed (table 3), are consistent with there being such a value, intuitive though it may be.

Since the study firm continue to survive, in an extremely competitive market, despite their policy to slightly inflate prices, one can only assume that this procedure is not unique to this specific drop forge.

Let us consider, out of the numerous drop forges, those with similar forging equipment and similar expertise in producing a certain type of forged component, say "n" suppliers. If each of these forges uses a similar method of predicting production variables, so that the relative accuracies of the individual suppliers predictions are the same, then the probability of any one specific forge quoting the lowest selling price, out of all the tenders, is $^1/n$. If we assume that the prospective customer will accept the lowest tender, then each supplier has a $^1/n$ probability of securing the order.

Since the customer is the discriminating party, let us superimpose on our diagram one more item, z.

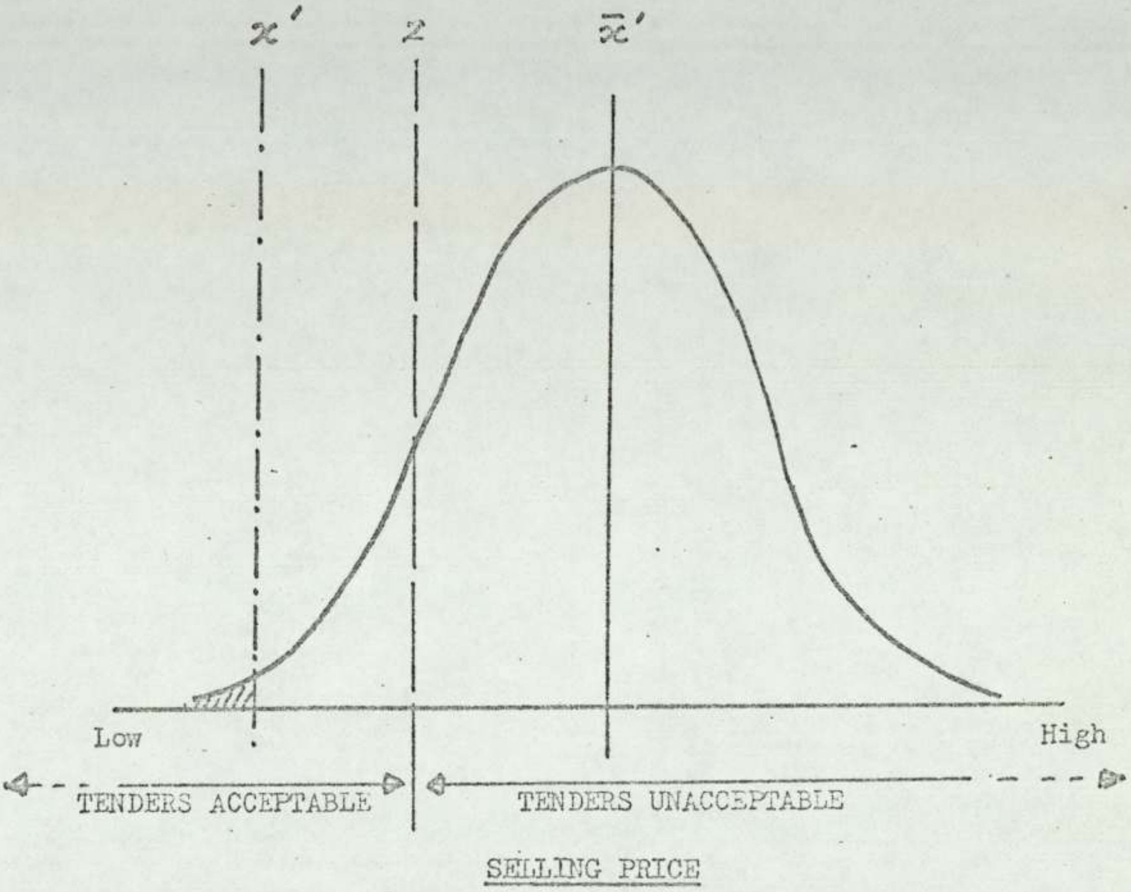


Figure 25.

This represents an (arbitrary) upper limit, below which our tendered selling price must fall if we are to stand any chance of winning the order. A selling price quoted higher than this level will almost certainly be undercut by one of the similar suppliers.

In figure 26 a further curve (B) has been added. This curve is typical of the distribution of quoted selling prices resulting from a more accurate estimating system. In order to obtain the same safeguard against extreme estimation errors (giving rise to selling prices below the threshold value, x'), less inflationary bias is now necessary.

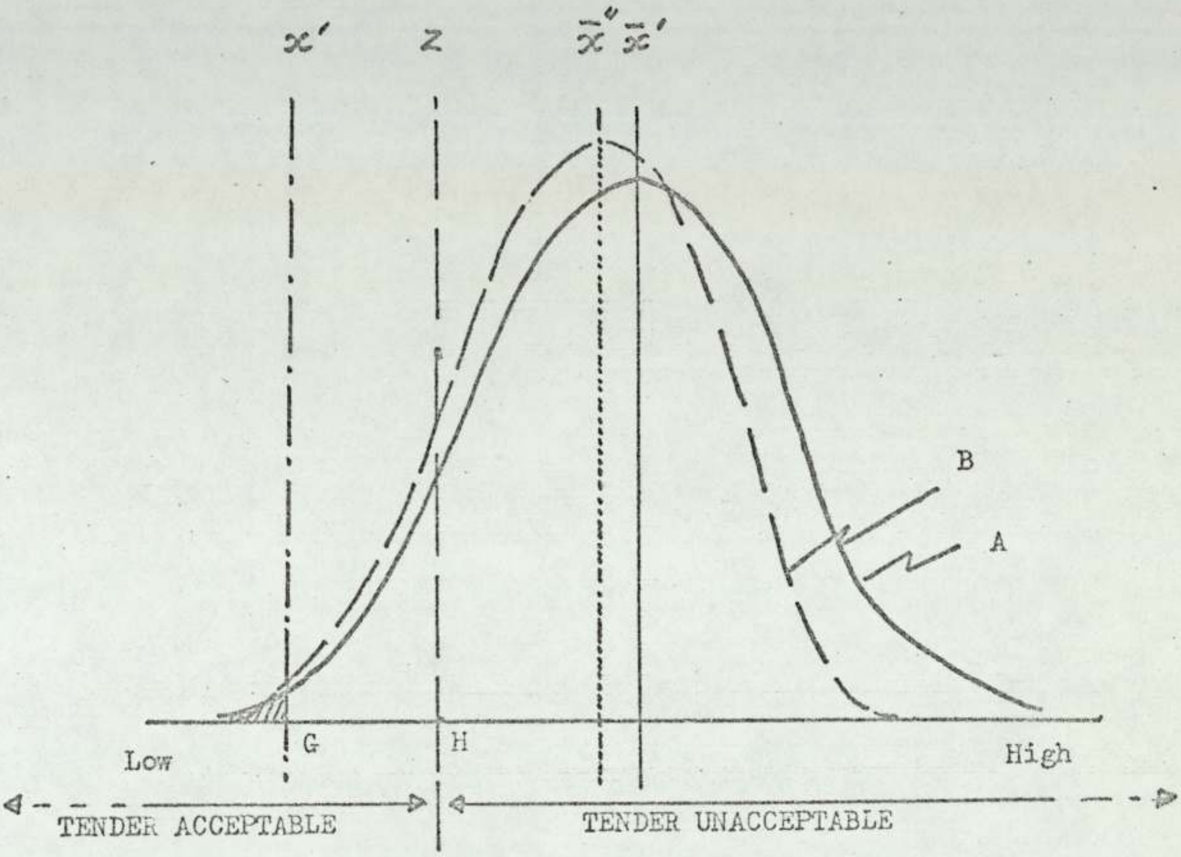


Figure 26.

With a more accurate estimating system (B), employing less protective bias, the overall average selling price will obviously be lower than in the case of the less accurate system, (A). The average selling price per job for orders won, however, lies somewhere within the acceptance range G-H, for both the less accurate system and the more accurate one. The average 'profit' per job for orders won, therefore, is unlikely to be significantly different for either of the two systems. ('Profit', for the want of a better word, refers to the difference between the tendered selling price and the threshold selling price, x'.).

The probability of any one tendered price falling within the acceptance band (represented by the lines x' and z) is proportional to the area under the curve, bounded by these two lines. Since the total areas enclosed by each distribution are equal (unit), then the area occurring between these two lines, x' and z, is clearly greater in the case of the 'more' accurate distribution (B) than it is for the 'less accurate' distribution, (A). In simple terms, this implies that there is an increased probability of any one tendered selling price falling within the acceptance band.

It is logical to anticipate that this increased probability could be translated into an increased market share for the firm involved, since a greater proportion of the tendered prices will fall within the acceptance band, compared to those of their competitors.

There is an additional benefit that the 5% of estimates falling below x' will, on average, not be so far below the threshold value. Considering figure 27, the area in the 'tail' of the two distributions is the same for both, i.e. 5% of the total area.

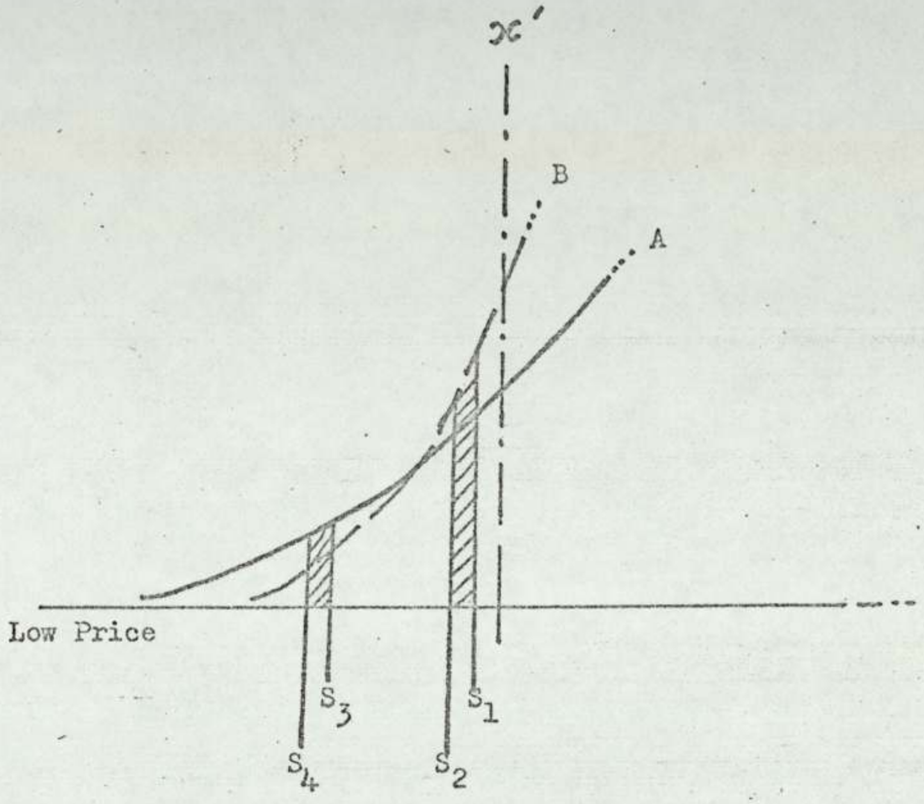


Figure 27.

If the total area of the curve is unity, then the probability of any one value occurring by chance is represented by the height of the curve at that point. From our diagram, it is clear that there is a far greater probability of predictions falling within the range, say, S_1 to S_2 for a relatively accurate forecasting system than there is for a less accurate system. The converse is also true; in the case of a relatively accurate estimating system, there is less probability of a forecast selling price falling within the range, say, S_3 to S_4 than there is with a less accurate system.

So that the above hypothesis might be tested, a simulation experiment was devised. Several authors have discussed simulation technique at length[76, 77]. Briefly, it is a technique in which a situation that would be impossible or uneconomical to reproduce by direct implementation or conventional experimentation, may be imitated and, hence, investigated. It involves, essentially, producing a 'model' of the situation and generating distributions such that any stochastically varying quantity may be 'sampled' and the effect on the overall model observed.

For this specific simulation, it was necessary to produce a model of the complete estimating and pricing system at the study firm. The stochastic variables in this case included the prediction of the production parameters, flash weight and production rate. Six 'suppliers' were incorporated into the simulation, each supplier 'tendering' a selling price for each of 300 'forgings' according to the pricing policy operated by the supplier. (By pricing policy we mean the combination of estimating accuracy and the degree of bias applied to each prediction.) Each forging order is won by the supplier offering the lowest tender. (see footnote.)

FOOTNOTE:

It is realized that lowest tendered selling price alone is not the only criterion by which orders are awarded by a customer to a specific supplier. Reliability, quality of product, in addition to an 'inertia' effect (customers tending to give orders to suppliers with whom they have previously done business in preference to 'unknown' suppliers) all exert some degree of influence on this decision. However, for the purpose of this study, we may ignore these effects, assuming them to be identical for each supplier. The awarding of an order is then dependent only upon selling price.

The performance (i.e. the number of successful tenders etc.) of each of the suppliers is registered and output at the end of the computer simulation.

5.2.2 Some practical aspects of the simulation

There are several programing languages designed specifically to suit simulation studies. One of the most widely used is SIMON. SIMON, however, has a number of limitations, including a rather rigid programming discipline, around which the specific simulation problem must be constructed. Hence, it was decided to write the present simulation programme in the more flexible ALGOL language (Appendix XIV).

The generation of the various frequency distributions was achieved by reading in the standard deviation and mean of the distributions. These two values, together with the normal distribution table, stored internally within the computer programme, were sufficient to enable the programme to generate quite detailed frequency distributions based on twenty or so points. For example:

x	PROBABILITY
180	0.003
182	0.015
184	0.070
186	0.260
188	0.800
190	2.300
192	5.500
194	11.500
196	21.200
198	34.500
200	50.000
202	65.500
204	78.800
206	88.500
208	94.500
210	97.700
212	99.200
214	99.740
216	99.930
218	99.985
220	99.997

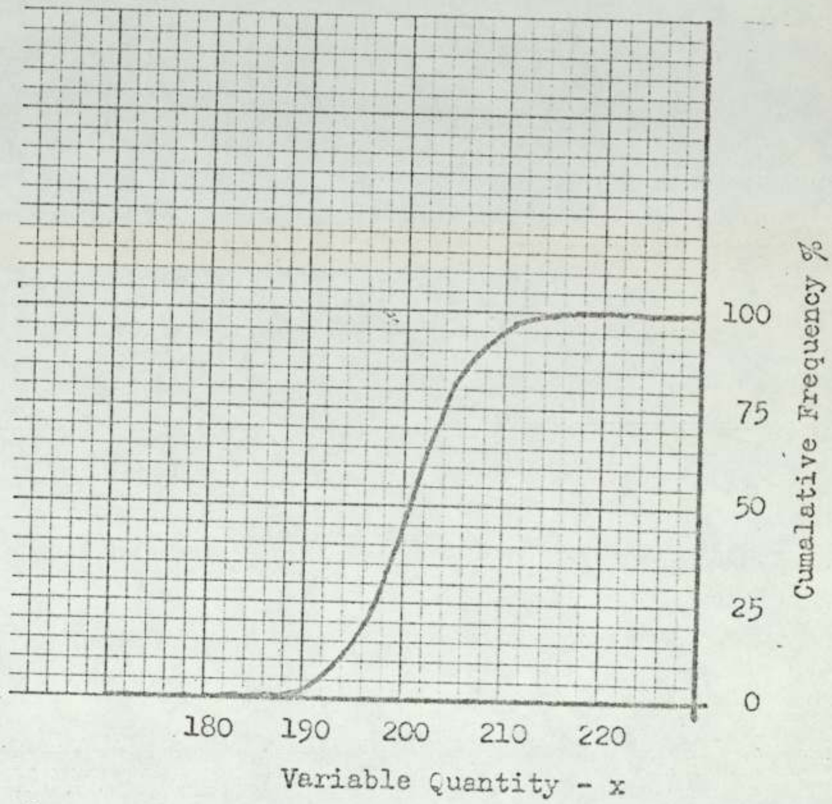


Figure 28

This in itself is a significant improvement over the SIMON system which requires ten pairs of values to be input to the programme, i.e. x values and associated probability values. (Which have to be obtained by inspection or calculation from the source data.)

The distributions were sampled by generating a random number (using a library random number generator routine) and transforming this to a value within the range 0.000 to 100.000. This value is then matched by the computer to the probability values in the respective distribution table, and the 'x' value computed by interpolation between the pairs of probability values bounding this (transformed) random value.

5.2.3 Results of simulation study

The results of the simulation experiment are given in table 4 and in figure 29. (A detailed extract from the computer output appears in appendix XV). The confidence limits shown on the plot were obtained by running a simulation in which all six 'suppliers' were given a common sales policy (i.e. the same estimating accuracies and biases as those currently characteristic of the study forge). In this way, any deviation of market share (percentage of orders captured) from the theoretical $^1/6$ (16.6%) due to random effects, could be isolated.

The simulation run proper involved giving five of the suppliers a common sales policy (as for the 'random' run), whilst the sixth supplier was given a superior policy (greater accuracy amd, hence, less protective bias). The accuracy figure used was, in fact, the accuracy that has been shown possible by the use of the mathematical forecasting models.

Examination of table 4b shows that the adoption of a more accurate estimating system (supplier 2) based on mathematical models, and the associated decrease in protective bias possible with

SUPPLIER	1	2	3	4	5	6
ST.DEV (PR)	21.0	21.0	21.0	21.0	21.0	21.0
PR. BIAS	-7.0	-7.0	-7.0	-7.0	-7.0	-7.0
ST.DEV (FW)	47.0	47.0	47.0	47.0	47.0	47.0
FW BIAS	22.0	22.0	22.0	22.0	22.0	22.0
NUMBER JOBS	49	37	49	54	53	58
PER CENT	16.3	12.3	16.3	18.0	17.7	19.3

Table 4a Simulation Results, "Random" Test

SUPPLIER	1	2	3	4	5	6
ST.DEV (PR)	21.0	16.0	21.0	21.0	21.0	21.0
PR. BIAS	-7.0	0.0	-7.0	-7.0	-7.0	-7.0
ST.DEV (FW)	47.0	35.0	47.0	47.0	47.0	47.0
FW BIAS	22.0	-1.0	22.0	22.0	22.0	22.0
NUMBER JOBS	39	89	35	45	43	49
PER CENT	13.0	29.7	11.7	15.0	14.3	16.3

Table 4b. Simulation Results

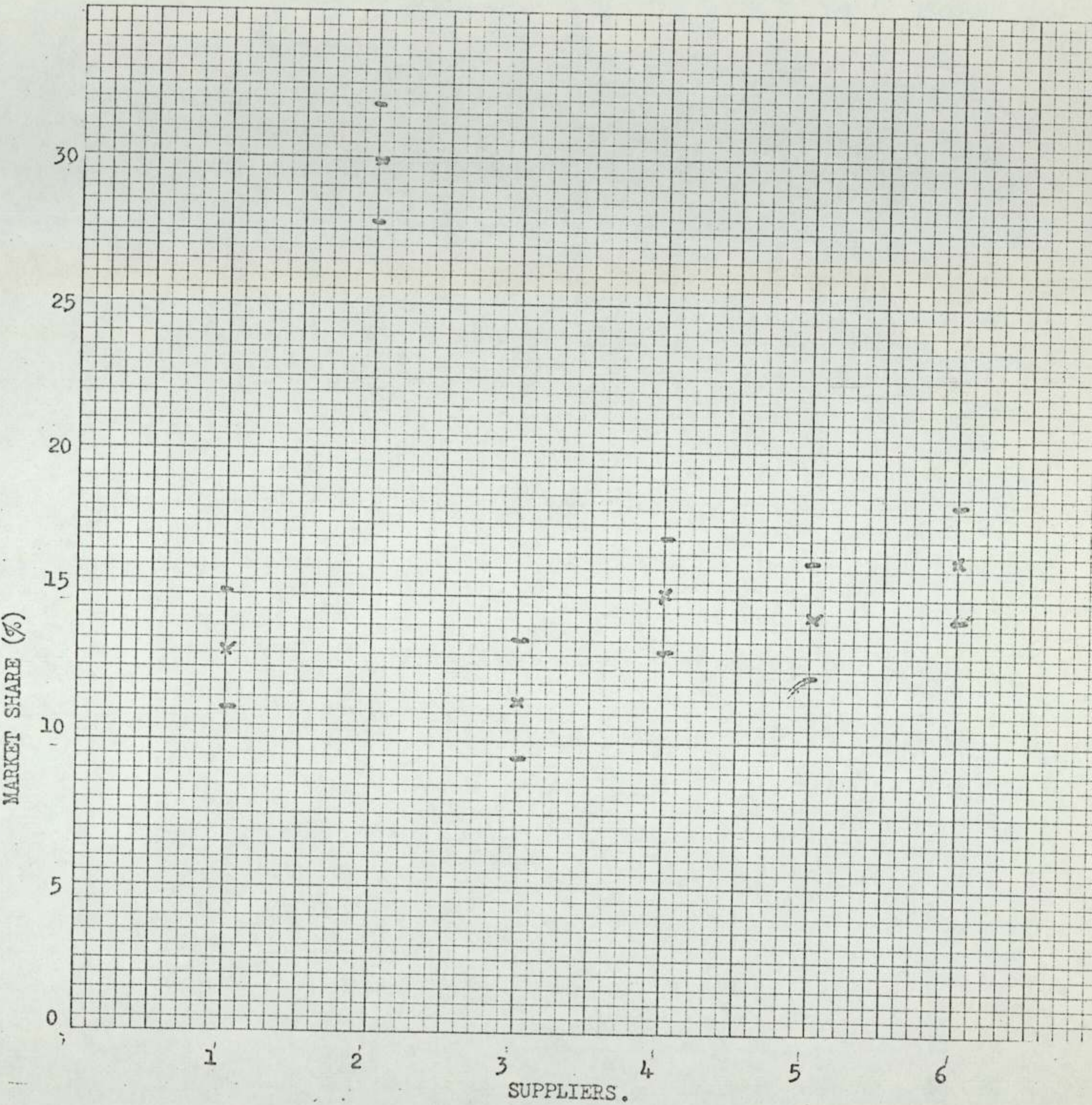


Figure 29.

such a system, might be expected to almost double the number of tenders accepted by prospective customers. This increase in market share, from 16.6% to almost 30%, is statistically significant at the 2.5% level when subjected to the χ squared test.

Increasing the number of tenders accepted by a factor of almost two becomes a very attractive proposition in times of recession or if one has spare capacity readily available. If spare capacity is not currently available, the increase in potential business indicated might well justify an expansion in one's capacity via more hammers etc.

If production capacity is inadequate to take on extra orders, and no increase in capacity is envisaged, then by adopting a slightly greater degree of protective bias than that necessary to produce the usual 1:20 protection, it might be possible to maintain the same rate of order capture as that obtained with a less-accurate estimating systems. However, the average 'profit' per order won will be slightly higher. This can be shown diagramatically:

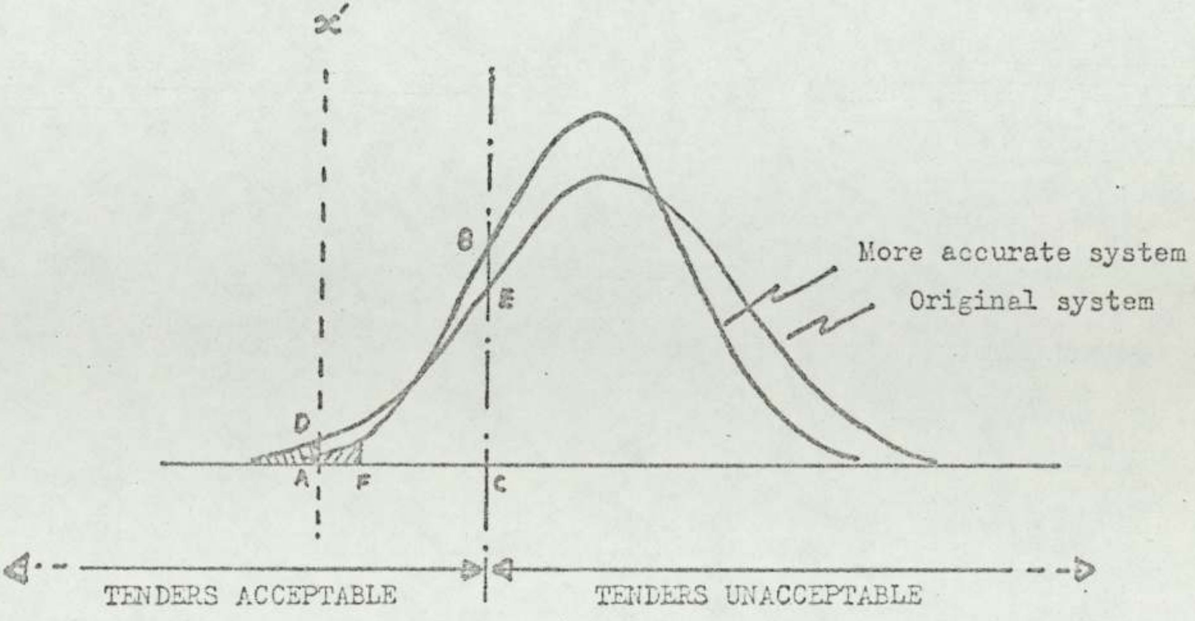


Figure 30.

Where area $\triangle$ ABC = area $\triangle$ DEC. Thus, the probability of tenders falling within the acceptance band is the same for both systems. The average selling price of tenders accepted, however, will lie somewhere within the range A to C, in the case of the original system: but somewhere within the narrower range F to C in the case of the more accurate system.

5.3 Implementation and operating costs of model-based estimating

The models may be integrated into the estimating system in two slightly different ways.

a) Computed manually using a desk-top calculator, prior to a conventional, manual, cost-extension routine.

or, b) Evaluated by a computer as an integral part of the overall estimating/cost-extension routine. The parameters of the forging required by the models being supplied via the punch document carrying the remainder of the cost/production information.

Whichever method is adopted, the values of the various component parameters still have to be extracted or measured from the information/drawing for the forging.

The two systems were compared with the present manual system in terms of human involvement (time) and hence, cost per estimate. This comparison is summarised in table 5.

SYSTEM BASED ON MODELS		CONVENTIONAL SYSTEM BASED ON HUMAN EXPERIENCE ETC.
SIMPLE CALCULATOR	FULLY COMPUTERISED	
Measurement of:		
Stock Area	Stock area	Stock area
Net wt.	Net wt.	Net wt.
Qty.Req.	Qty.Req.	Qty.Req.
Periphery	Periphery	Periphery
Complexity	Complexity	Complexity
Area at P.L.	Area at P.L.	-
-	-	Scan past records for similar job
-	-	or, 'Visualize' production
-	-	Sketch flash outline
Evaluate models	-	-
-	Prepare punch doc.	-
3 - 4 minutes		3 minutes

Table 5.

A number of the forging parameters have to be determined irrespective of the system subsequently used. Projected area at the parting plane is an exception, this value is not necessary for the present, conventional technique. The measurement of this parameter using a planimeter requires two to three minutes, depending upon the intricacy and size of this section.

Considering the integration of the models into a completely computerized cost-extension routine; the marginal increase in computational effort required to compute the relatively simple equations involved, is likely to be insignificantly small, certainly not contributing noticeably to the total computer cost for the overall routine.

The time saved due to the non-requirement of creative thought, examination of production records, etc., (three minutes), almost balances the extra time, and hence cost, involved in extracting the additional parameter from the drawing and solving the necessary arithmetic (three to four minutes).

In the case of the models, we must consider a certain element to cover development costs. At the study forge, development costs consisted of one analyst for one year at a cost of £2,500 p.a. Computing cost contributed only a further £50, making a total of £2,550. If this cost is recovered over ten years it becomes £255 p.a.

In addition to development costs, a re-analysis every, say, twelve months would be desirable, at a further cost of £10 p.a. This re-analysis would serve to modify the models in accordance with any general drift or trends in production methods and/or plant during this period. For example, plant may slow down in terms of striking rate due to clutch wear, slide wear, etc., changes in production methods may reduce the amount of flash formed for any given forging. All these factors can be readily acknowledged by such a re-analysis at periodic intervals and incorporated into slightly modified models. Similarly, management may be alerted to any gradual loss in efficiency.

Manual prediction methods can only subjectively evaluate the rôle of these changing influences, if indeed they are recognised at all.

The total development and maintenance costs might thus amount to little more than £260 p.a. Clearly, there is negligible extra time or cost involved in using a prediction system based on mathematical models compared with one based purely on the skill and experience of an undividual, the estimator.

5.4 Intangible benefits arising from the use of Models

The obvious benefit afforded by the use of models, that of enhanced price structure, has been discussed at length in Section 5.1.2. In addition to this direct benefit, there are several other intangible, but nevertheless very real, advantages to be gained by the use of a more analytical estimating technique, compared to the traditional experienced-based one. These advantages may be summarized:-

1. Reproducibility and consistency of pricing structure.
2. Ability to recognise and adapt to insidiously changing trends in production technique etc.
3. Prestige effect.

1. Reproducibility and Consistency of Pricing Structure

This is an important advantage when one considers that the present manual system can produce two very different predictions of dependent variable, based on almost identical components, the only difference between the two estimates being the calendar time separating them. A technique based on human experience cannot, by its very nature, be truly reproducible since the man follows no set rules in arriving at his predicted values. He is free to (and often does) interpret almost identical information to suggest differing characteristics from one period to another.

This lack of reproducibility and the associated inconsistency of pricing structure, can often be embarrassing for all concerned. This 'embarrassment' may be purely internal, for example, the general manager may question the estimator in an attempt to determine the reason for noticeable differences in production rate predictions for seemingly similar forgings. More important, however, the embarrassment may be externally generated when, for instance, a customer questions why two very similar forgings he purchases from the supplier should have widely differing prices. This obviously may lead to loss of goodwill and, to a certain extent, loss of confidence in the supplier's integrity.

(Brown and Jaques[40] define a reproducible pricing system as "one that presents to the market, a price structure which will be perceived as inherently consistent, that is to say, the relative prices of different articles appear to be fit and proper when compared to one another.")

The use of mathematical models does not require any specialized knowledge or wide experience, the same result would be obtained if the estimator evaluated the model as would be obtained if some other reasonably competent employee performed the necessary computation. Thus, a system based on preditive models is independant of the person using it, and as such is less likely to be disrupted by the absence of the estimator through sickness or his leaving the firm.

Since the models are buffered against the prospect of some person other than the usual estimator having to perform the estimator's role, so they are also buffered against day-to-day changes in the personality and subjective-reasoning ability of the estimator.

No one can shut out his personal or domestic life, even when he has such a demanding job as that of the estimator. The estimator must rely on his experience, i.e. the recognition of certain component characteristics and the recollection of similar components produced in the past. It has also been noted that in some instances the estimator may have to try to visualize the mode of working etc., that he expects the stamper to adopt. If the estimator's concentration is disrupted, even slightly, (by some domestic problem, slight ill-health, etc.), then the technique, which is inherently open to individual interpretation, runs the risk of deviating even farther from the ideal.

2. Ability to recognise and adapt to changes

One intangible benefit of models has already been mentioned in the preceding section, 5.2. That is, the ability to recognise and adapt to changes in production or plant characteristics. These changing trends tend to be insidious by nature, and as such, are unlikely to be recognised by the estimator (who, in any case, could only make a subjective appraisal of such trends).

A limited, periodic re-analysis, as suggested earlier, is capable of identifying such changes and of modifying the predictive models accordingly.

3. Prestige Effect

The use of (apparently) sophisticated techniques in arriving at manufacturing costs and, ultimately, selling price, in preference to the rather vague method based on human experience, could prove a considerable asset to a forge in improving its status in the eyes of prospective customers.

The value of this type of industrial status symbol has not gone unnoticed at the study forge. Certain of their file-keeping and invoicing systems are exhibited with a flourish to visiting prospective customers. The addition of a technically sound estimating technique,based on mathematical models, could prove of great benefit in improving the firm's status and prestige. (Although, one hopes this would not be the chief justification for employing such a technique).

The above intangible benefits arising from the use of models are, obviously, impossible to quantify in terms of hard cash. No one can put a value on the reduced risk of losing customer goodwill due to irrational selling prices for similar items. Nor can a value be ascribed to the benefit in terms of increased confidence generated amongst the staff by the use of a more firmly based prediction technique. Nevertheless, these benefits must not be underestimated since, indirectly, they represent a contribution to the efficiency and profitability of the firm as a whole.

5.5 Subjective arguments offered, opposing the use of mathematical models

The comparison of a prediction technique based on mathematical models with one based on human experience has, so far, been discussed in objective terms, that is, in terms of characteristics that may be readily definable, even if not always quantifiable. It was realized, however, that in an industrial environment, other subjective factors may have to be considered, in addition to the more definable factors usually of interest to the technologist or researcher.

In a traditional industry such as drop forging, there tends to be a certain inertia resisting change. Hence, any change in plant or technique is usually initiated and expedited by upper management personnel, such people having the necessary power and respect to break down this natural resistance. This investigation had no such backing, and so, an obstacle was encountered from those who would ultimately have to use and/or approve these new techniques.

This criticism included:

a) Superficiality of model making approach.

b) No tremendous increase in accuracy possible using models, marginal improvement only.

and, c) Even distribution of errors around zero, unlike errors arising from present system which tends to over, rather than under, estimate.

Some of these points have already been discussed indirectly: particularly points b) and c) which entered the discussions in section 5.2. Further discussion of these subjective arguments here would achieve very little.

5.6 Wider applicability

All the previous discussions here assumed that the models should be assessed in the environment in which they were developed, in other words, the firm at which the investigation was based. The results of such an assessment have shown it to be a viable proposition to predict production rate and flash weight by the use of mathematical models. Let us now consider the possibility of using similar models at other forging companies. The comparison of the models with a more conventional technique based on human experience was based on the premise that the study forge presently employ an estimating technique that is typical of all other drop forges of comparable size. If this is so, then there is no reason why other similar-sized forges could not develop an estimating technique on such models and obtain similar benefits as those envisaged for the study forge.

As we move from smaller to larger sized firms, or, as the size of a given firm grows due to expansion, so the problem of predicting production variables becomes more acute. If we concede that presently one man can exhibit the necessary degree of plant and shop-floor familiarity, knowledge of individual production-unit characteristics, etc., and can mentally weigh and evaluate the interplay of all these factors and more; then clearly, as the firm gets larger, so this mode of working becomes more and more unsatisfactory.

Large forging plants require large estimating staffs in order to cope with the increased demands placed upon the department in terms of greater inflow of inquiries and the increased difficulty of maintaining an intimate knowledge of plant and forge-shop. By increasing the estimating department staff from one to two or more, then we tend to lose the very attribute which, it is claimed, contributes so greatly to the traditional method of production variable prediction - namely, individual human experience. Two or more people, attempting collectively to fill the role of estimator, will inevitably be faced with the problem that they think and recollect experiences as individuals. This introduces the possibility of even greater inconsistence due to the difficulty of communication implicit in any human experience orientated process.

Summarizing, with firms larger than the study forge (turnover £1.5M p.a.), then we may expect the degree of accuracy exhibited by traditional methods of prediction to be no better than the case where the estimating department consists of only one man. Thus, the values of the standard deviation of errors arising from the experience-based technique, given in table 3, would, no doubt, be optimistic if one were to consider a larger forging establishment.

It is unlikely that the models developed during this investigation could be directly applied to other firms, since each firm will be unique with regard to its plant workforce and production methods. It would, however, be unlikely that the significant parameters would be any different, only the coefficients of these parameters. To determine the value of these coefficients for any particular environment would require a very much smaller analysis of records than the one conducted by the present researcher, since the important parameters have already been isolated. It is thought that only one to one and a half man months would be necessary to obtain working models. The computer costs would be negligible, in the order of five to ten pounds.

The models, although requiring a computer to develop, can be evaluated in seconds on a conventional desk-top calculating machine, thus rendering them independent of the presence or otherwise of a computer at the firm.

5.7 'Spin-off'

An unexpected benefit resulting directly from this investigation was that, presented with tables of results, comparing manually estimated - and actual values of production variables, the firm's management realized, for possibly the first time, that significant discrepancies did occur. In view of these discrepancies and, more important, the failure of the existing monitoring system to detect such discrepancies, a feed-back system consisting of an inspector weighing flash losses, recording this actual value and informing the estimating department of the results was initiated. In this way, any significant discrepancies between estimated and actual value are readily evident and their history may be investigated to determine the cause. (Poor estimating, wrong material, malpractice during forging, etc.). Although not intended, this side-effect of the investigation has proved of great benefit in improving managerial control of the inter-relationship between estimated and achieved production performance.

The above comments should not be taken to suggest that no feed-back systems previously existed at the firm, but rather that, although figures did exist, they were not always compared with the estimated values to highlight discrepancies.

This concludes discussion of the investigation into cost-estimating procedures using various computer-aided statistical techniques. The following sections of this thesis concern an application involving continuous rather than sporadic use of a digital computer. That is, the function of production scheduling or planning.

6. PRODUCTION SCHEDULING

In section 3.2 the point was made that production control comprises two related functions (as with cost estimating). These were identified as:-

a) The assigning of work to specific production periods-scheduling.

and, b) The associated data-processing function.

While work scheduling is a topic that has generated interest amongst both academics and industrialists, the data processing function has been dismissed as yielding to the conventional approach of a computer data processing department; and as such, worthy of little further discussion in this thesis. However, in order that we may examine the scheduling problem in true perspective, (particularly with regards to operating costs) it is necessary to firstly consider the production control area as a whole. To this purpose, a pilot investigation was initiated in which the actions of the department were analysed, and the possible rôle of a computerized production scheduling system identified.

6.1 The Pilot Investigation

This pilot investigation consisted of a careful study of each aspect of the day-to-day functioning of the production control department at the forge. Note was made of all tasks incurring the expenditure of clerical effort; in generating, amending and up-dating files, records etc. Sample copies of all data processing documents and records were obtained from the department for subsequent study and analysis. The scheduling function itself was, of course, observed closely, (this is fully described in a later, relevant section 6.2 of this thesis).

The production control department function may be summarized by the diagram in figure 31. In addition to the various functions shown in this diagram, the production control department also adopt the very necessary 'intermediary' role between customer and supplier. The department thus provides enquiring customers with information regarding the status and progress of any particular order.

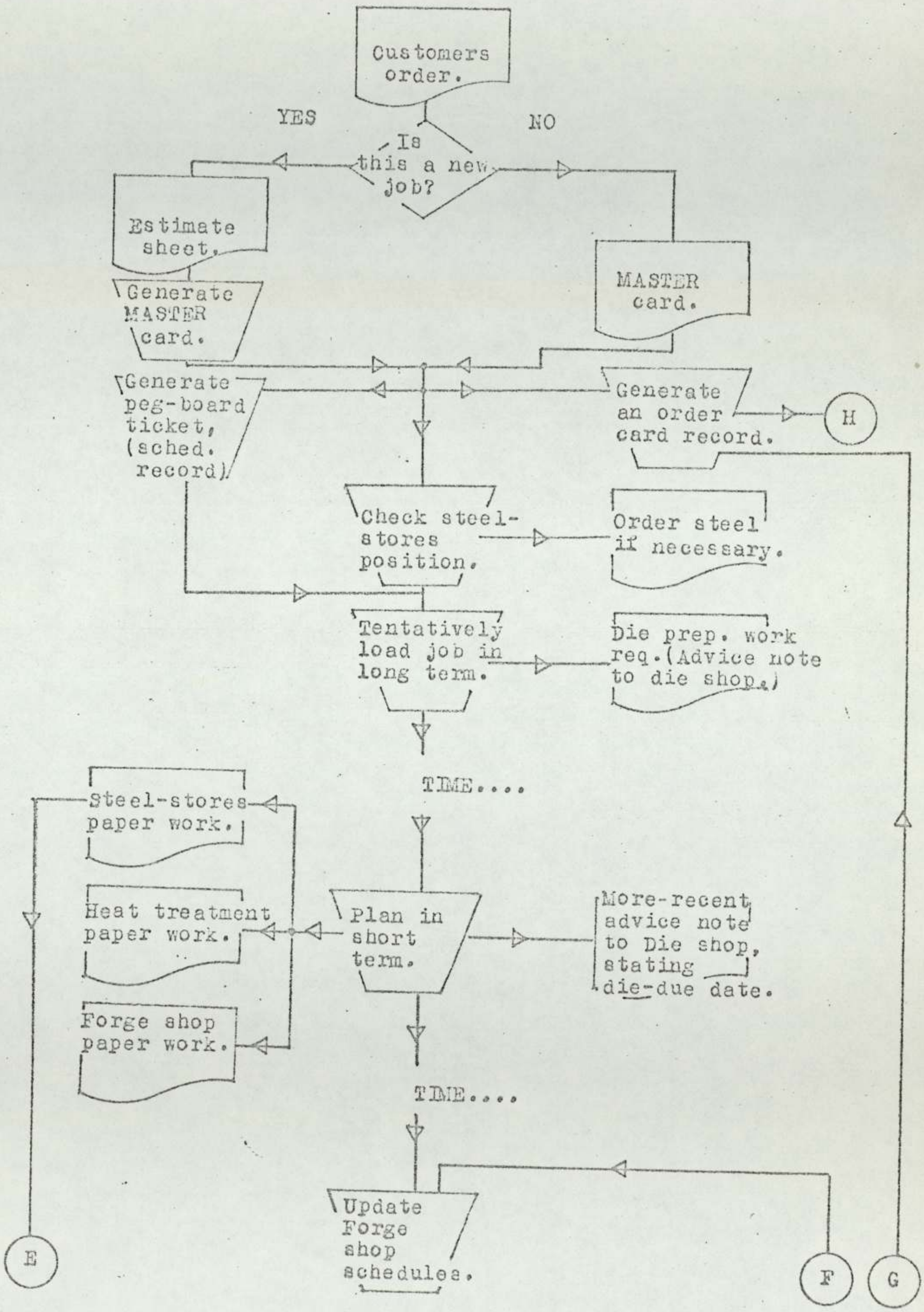
This pilot study served to confirm that the various data processing functions associated with production control were, in fact, amenable to computerization. For reasons outlined in the preceding section, one such totally-integrated system is discussed below, together with an analysis of comparative operating costs and associated benefits.

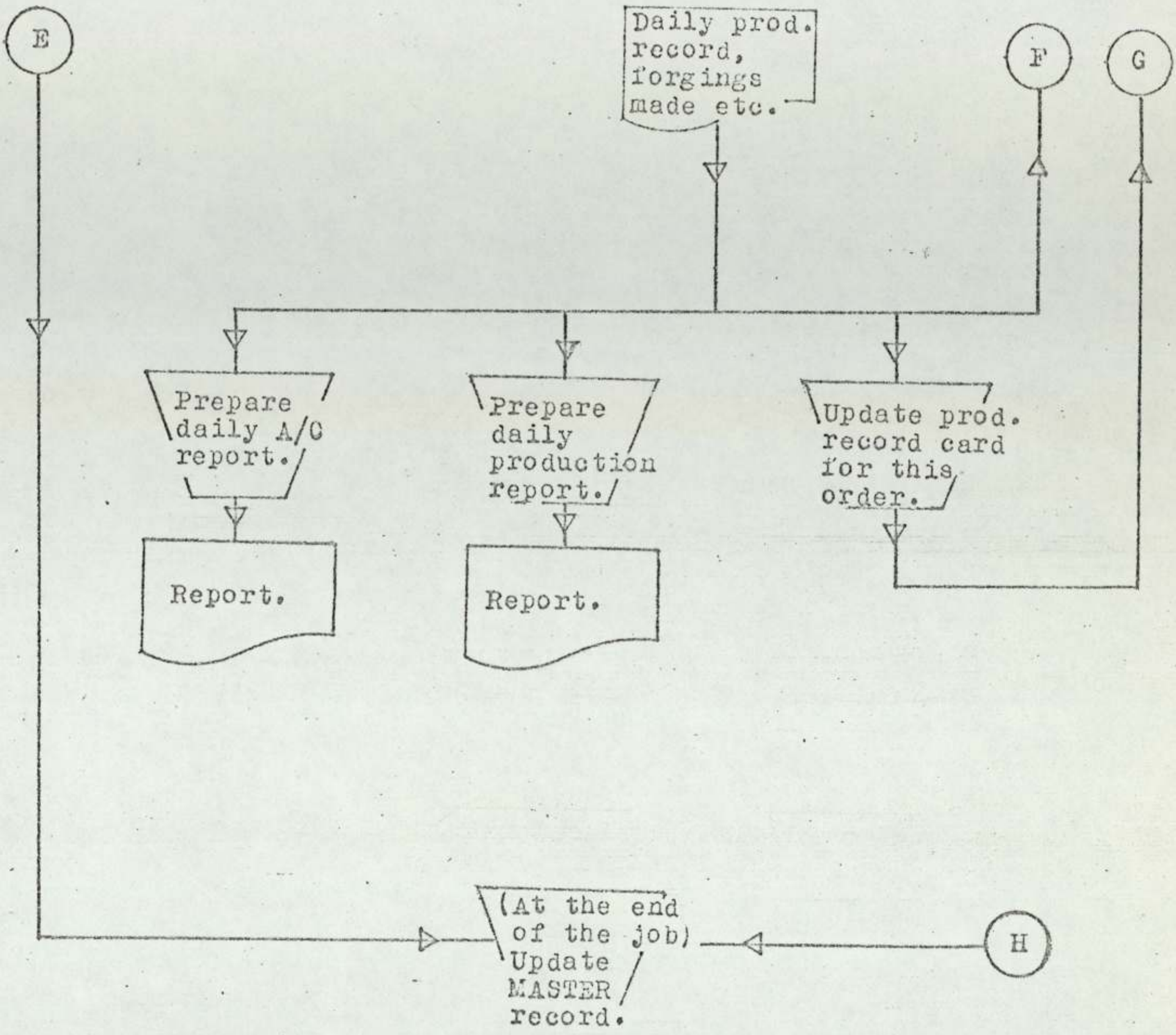
6.1.1 The rôle of computerized production scheduling in an integrated, computerized production management system

Figure 32 is a schematic diagram depicting such a system suitable for the study forge. (A system should, ideally, be 'tailored' to each firm's individual requirements.)

The essence of the system is that information input

Figure 31. Schematic representation of the Production Control Department.




E
Daily prod. record, forgings made etc.
F
G
Prepare daily A/C report.
Prepare daily production report.
Update prod. record card for this order.
Report.
Report.
(At the end of the job) Update MASTER record.
H

once to the computer may be stored and used, as required, to perform several activities, reports etc. In this way, the clerical effort of writing down the same item of information on several individual forms or file cards is greatly reduced. The pilot investigation at the study forge revealed that information regarding daily forge production, for example, was recorded on no less than four individual documents, each time the girl clerk physically recording the values on paper. In addition, most of these tasks involve subsequent manipulation of these values (addition, division, comparison etc.). A computerized control system could automatically manipulate these values to update files, produce monthly W.I.P. reports etc., again reducing the human effort involved.

An integrated system can also be responsible for the generation of paperwork. For example, at the study forge, when a job enters a period covered by the forge schedule for the next ten days, then certain paperwork is generated to aid the subsequent issuing and expediting of the job. An integrated system, coupled to a computerized scheduling system, could quote easily produce this paperwork automatically. In this way, not only would the production control personnel be relieved of this mundane clerical task, but also, there would be less risk of 'overlooking' the generation of these important documents (as can, and does, occur with the present clerical systems).

A computerized system would allow automatic checks to be carried out, comparing values of certain production or cost parameters with other, standard values; or the determination of whether the achieved value falls within certain acceptable limits. If not, then a warning can be printed by the computer, drawing the production controller's attention to this fact, so that he may investigate and take remedial action. For example, estimated values of, say, production rate may be automatically compared with the subsequently achieved values, estimated monthly steel usage figures may be checked against actual usage etc. etc.

A further development of a computerized control system would be the automation of steel stock control and ordering. Orders could be automatically issued to replenish stocks of regularly used types and sizes of steel when levels fall below a certain 're-order' level, greatly reducing the risk of run-outs.

(The following section may not be of interest to all readers, since it describes a proposed computerized data processing scheme for the study forge and is, hence, rather unique to this firm. If this is so, then the reader is advised to proceed to section 6.1.2.).

Brief description of the proposed system

On receipt of an order

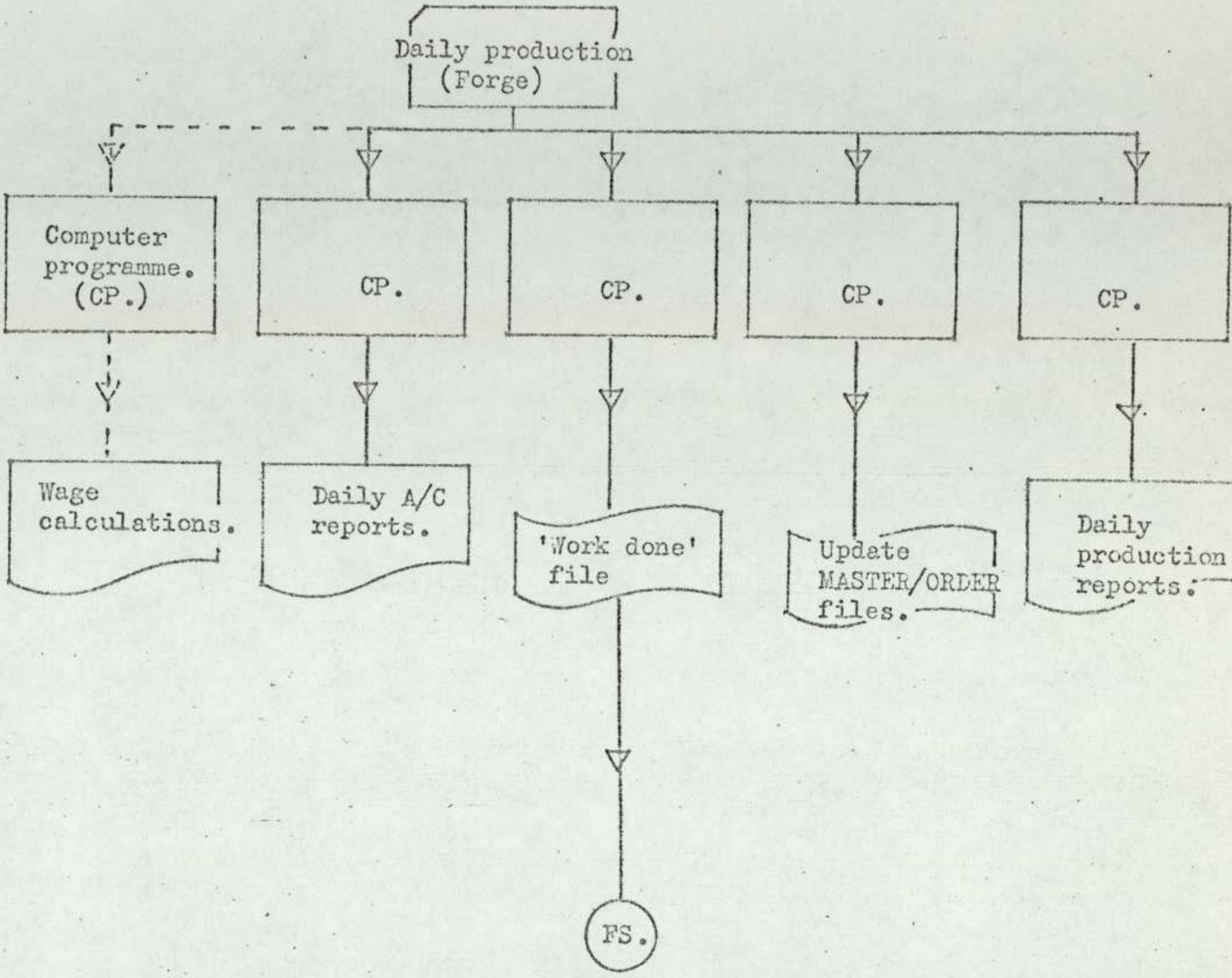
Information would be copied from the original order note to a punch document by the clerk. This document would be subsequently passed to the computer installation at the end of the day. The data would be used to:-

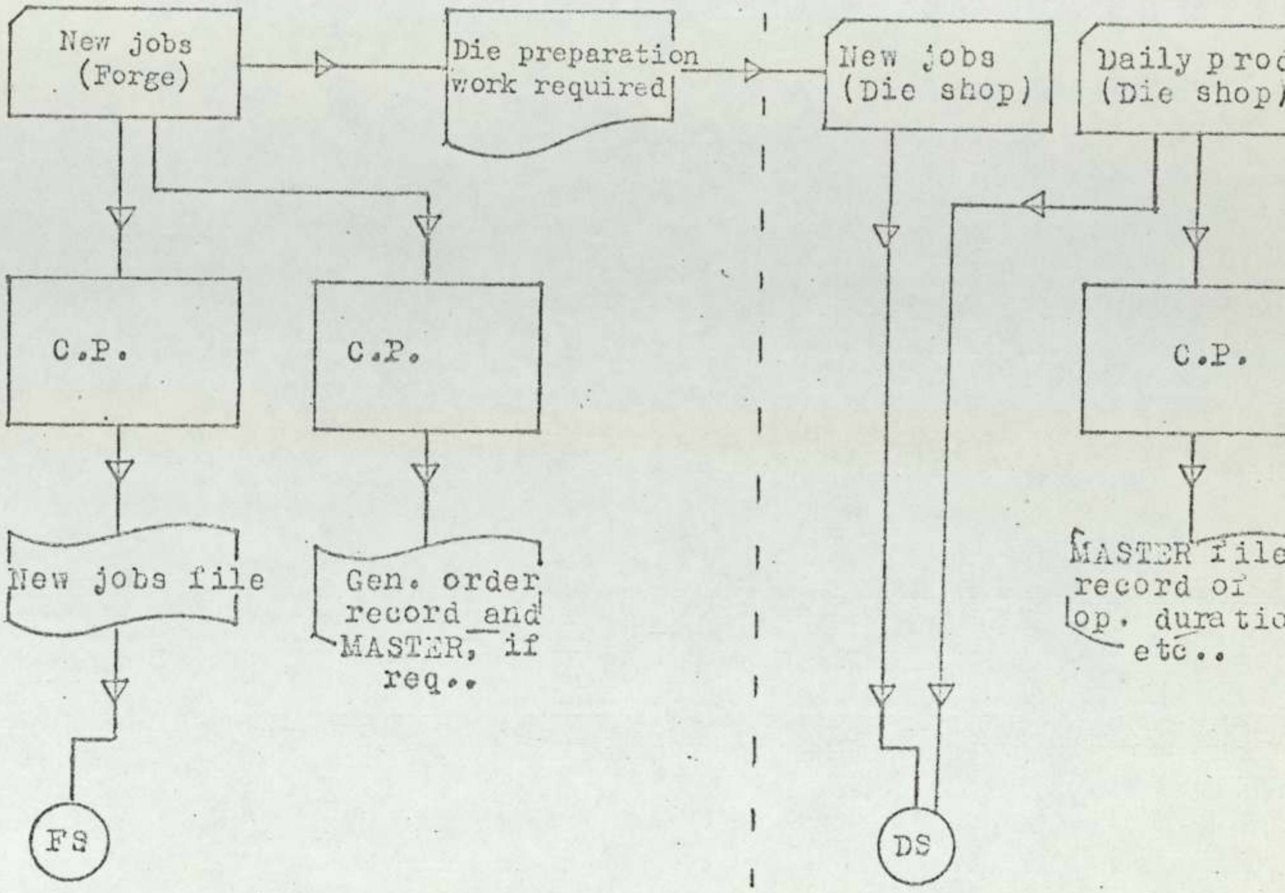
1. Produce an entry on a disc or tape file, 'Order file'. This would form a permanent record of the order details and subsequent daily production of forgings for this order. (The manual system equivalent to this disc file records is shown in figure A4.).
2. Input to the scheduling/updating programme. A programme converts the date regarding new orders into a form suitable for inputing into the scheduling programme. This 'converted' form would be held on a temporary holding file.

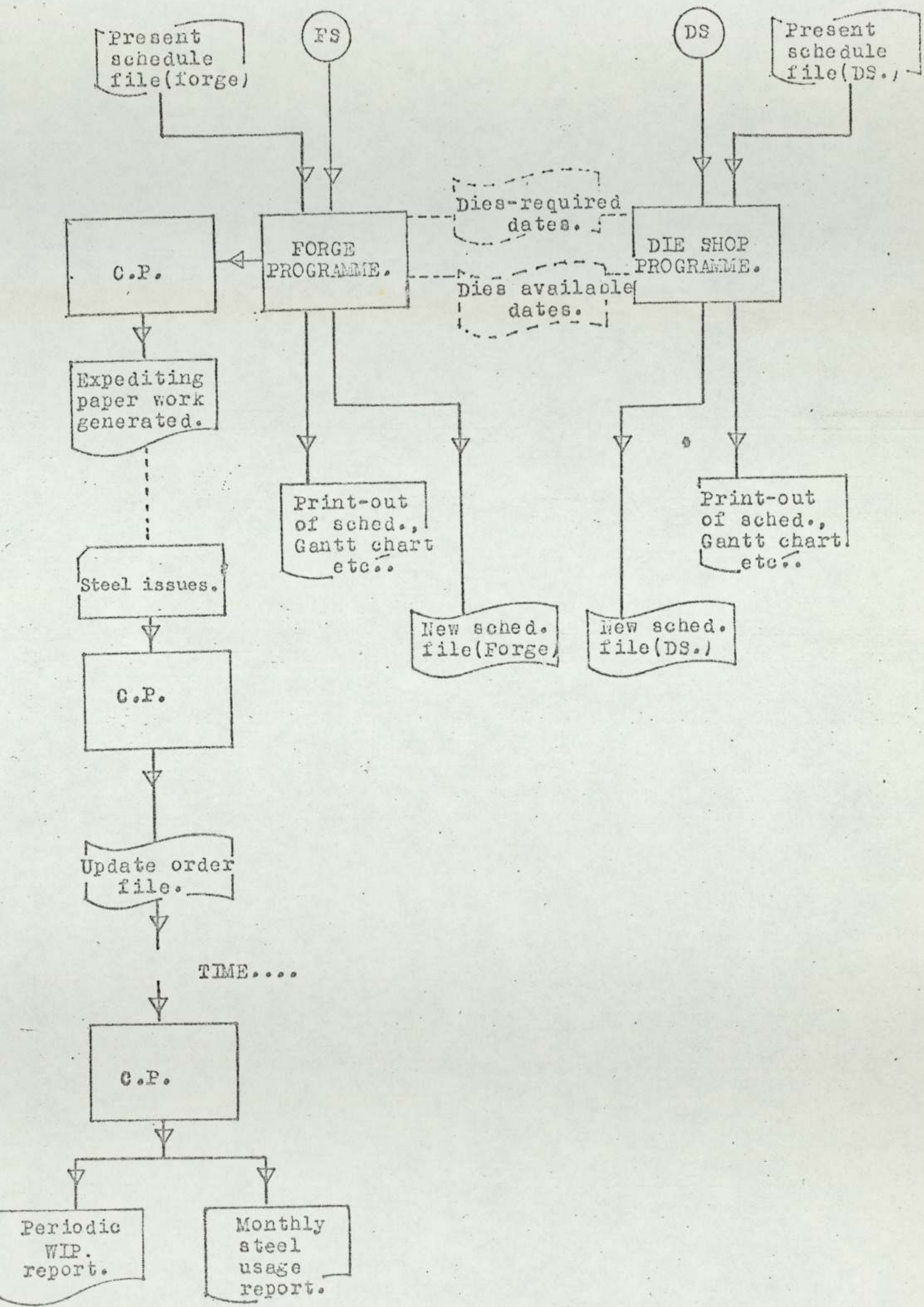
If an order received is the <u>first</u> order for a particular forging, then a further punch document must also be prepared from the original estimate data. This document is used to:

1. Generate an entry on a permanent disc or tape file, 'Master file'. This file forms a permanent record of standards for this job. There is <u>one</u> entry for each job, irrespective of the number of repeat orders subsequently received for that job. Once a job has actually been made in the forge shop, the <u>estimated</u> standard values (production rate, die life etc.) would be replaced by the <u>achieved</u> values.

Figure 32. Schematic representation of a possible computerized production management system.




New jobs (Forge)
Die preparation work required
New jobs (Die shop)
Daily prod
(Die shop
C.P.
C.P.
C.P.
New jobs file
Gen. order record and MASTER, if req..
MASTER file
record of
op. duratio
etc..
FS
DS


Present schedule file(forge)
FS
DS
Present schedule file(DS.)
Dies-required dates.
FORGE PROGRAMME.
DIE SHOP PROGRAMME.
Dies available dates.
C.P.
Expediting paper work generated.
Print-out of sched., Gantt chart etc..
Print-out of sched., Gantt chart etc..
Steel issues.
New sched. file(Forge)
New sched. file(DS.)
C.P.
Update order file.
TIME....
C.P.
Periodic WIP. report.
Monthly steel usage report.

Daily Forge Production

The clerk transfers informationfrom the forge-shop foremans daily 'tickets' (figure A9) to a punch document. This document would be taken to the computer installation at the end of each working day. This data would be used by several programmes:

1(a) To update the relevant entry on 'Order file', thus maintaining a continuous daily record of production on each order.

If an order is completed,

1(b) The same programme terminates this 'Order file' record and generates an entry on 'Master file'. This entry consists of the achieved values of job standards (production rate, etc.). Thus, a summary of each production run would be permanently stored in 'Master file'.

2\. To produce a daily production report containing a summary of the previous day's production, down-time, scrap-made etc. listed in hammer order.

(A manually produced specimen is shown in figure A4.)

3\. To produce a daily accounting report on each job currently in progress. This uses cost and price information stored in the relevant 'Master file' entry.

4\. To input to the updating/scheduling programme.

A convertion programme provides data in a suitable form for the updating/scheduling programme. This would be temporarily stored on disc or tape.

5. To perform wage calculations. Several computer manufacturers and bureau have standard programmes which could be used after trivial modification.

The Generation of Paperwork

The generation of paperwork, indicated when a (forge) job enters a period covered by the next ten days, could also be performed automatically. At the end of each rescheduling run, a check would be made to determine if paperwork should be generated for any specific jobs. If so, then a programme prints out the relevant documents, extracting any necessary information from the disc files, 'Master file' and 'Order file'. The details carried on these documents inform the various departments concerned of:- size and specification of material required for the order, post forging treatments required, hammer unit to be used etc. (Examples of paper-work generated by the present manual system are shown in figures A6, 7, 8).

Steel Stores Control

The girl clerk notes daily the weight of steel issued to each job currently in production. These entries could be made on the steel stores document previously printed as part of the generation of paperwork. Thus, no separate punch document as such is necessary. When a job is complete, any steel returned to the stores is similarly recorded on the document, which is then taken to the computer installation. This information is used:-

1. To calculate the actual gross weight, the number of forgings actually produced is extracted from the file - 'Order file'. This actual gross weight figure is transferred to 'Master file', under the appropriate job entry.
2. Adjust steel stock levels in light of the amounts of each size and type of steel consumed by the various orders. The stock levels are compared to the re-order levels and any warning reports printed accordingly.

At the end of each month are produced:

3. A monthly steel-usage report; detailing the actual and estimated quantities of each size and specification of steel used during the previous month.
4. A monthly W.I.P. report; detailing the value (£) of partially completed orders, in terms of both stocks of finished forgings and dies, and stocks of steel allocated to the partially completed order.

The die shop situation is a little simpler. No real data processing function is performed at present. Although, a means of storing and retrieving details regarding the duration and sequencing of operations on any particular job would seem highly desirable, particularly with a larger, or expanding company. (This would not be too difficult to arrange with a computerized system, as indicated in figure 32). New orders are initiated by a note passed from the production controller to the die shop supervisor, advising him of the need for die preparation work for certain forgings. The supervisor then fills in a punch document for the work required.

Simple interrogation programmes would allow the retrieval of information stored on the various disc or tape files.

6.1.2 Cost of a totally integrated, computerized production management system

The probable day-to-day running costs of operating such a system is indicated below. The time required by each clerical operation, to document or prepare data etc., has been noted and compared to the time, and hence cost, of performing equivalent operations under the present manual system.

A few additional sentences of explanation regarding the costing of clerical effort may be necessary. For the purpose of this feasibility study, each action has been assigned a certain duration (from observation), and hence, a cost. The sum of all such actions required under each of the two systems has been evaluated, and ultimately, a total cost for the manpower element of each system. We are thus costing work actually performed. A work-efficiency of 80% has been assumed[78] to account for the fact that a proportion of each working day is not used for effective work. This portion of each employee's time is consumed by various other activities such as conversation, drinking coffee, thinking about none-work subjects, etc.

The computational costs assume the use of a bureau or time bought on another firm's machine. If a computer of suitable configuration is accessible to the drop forge, and additional capacity is readily available, then on a marginal costing basis, computational costs are reduced dramatically.

COMPUTER DEVELOPMENT COSTS

		£
Analyst/Programmer for two years at £3,500 p.a.	=	7,000
Computer trials	=	1,000
		8,000
Over, say, ten years	=	800 p.a.

COMPUTER RUNNING COSTS

Computer time, 40 mins/week at £40/hr.		1,320 p.a.
Card preparation	=	300 p.a.
Development costs	=	800 p.a.
Clerical involvement	=	125 p.a.
Courier		250 p.a.
Total Cost		2,795 p.a.

CLERICAL/MANPOWER COST (MANUAL SYSTEM)

TOTAL COST	=	1,544 p.a.

6.1.3 Benefits of such a system

Although an integrated computer production control system is unlikely to be significantly cheaper to operate than a conventional manual system (a conclusion also reached by Muir[64]), there are several other benefits associated with such a computerized system. (Some of these have already been mentioned in section 6.1.1.)

There is far less risk of clerical errors being injected during the transfer of data from one source to another. With a computer system, data is copied to a punching document once only. Compare this to the present manual system in which there is often considerable movement of figures from one record to another, update, moved back to original record etc. The verification operation performed after punch cards have been prepared is carried out by the computer installation personnel and almost completely eradicates the introduction of errors at the card punching stage.

Files, records etc., may be updated or modified automatically, according to rigid procedures. It often occurs in manual systems that clerical operations (generation of paperwork, initiation of records etc.) are forgotten, due to human error. The omission of such tasks is not conducive to the smooth running of a production control department, or even of the company as a whole. Any means of reducing the risk is to be welcomed.

It is often the case that useful figures are generated by the present manual system but, because of pressure of work and lack of available time, the production control staff (on their own admission) cannot take full advantage of these important by-products. The example was mentioned in an earlier chapter, in which actual and estimated production rates and material weights <u>should</u> be compared for each job. In this way, a greater degree of control is afforded, highlighting any downward trends or exceptional occurrences. With a computerized system, these values may be checked <u>each time</u>, an 'action-required' report being produced only in the case of exceptions.

A benefit closely associated with the previous paragraph is that of the many more management and production reports that are possible with a computerized system. Such reports <u>could</u> be produced by a manual data-processing system, but the time and effort involved preclude this possibility. Since the information has already been input to the computer to serve various other functions, considerable manipulation and collation of this data may be obtained for marginal increments of computational time.

To obtain the same amount of additional information, reports etc., from a manual system would necessitate the employment of a further girl clerk (since the firm consider that their present staffing arrangements are stretched to breaking point with the amount of management information <u>presently</u> being produced). The annual cost of one girl clerk, say £1,000 p.a., would more than offset any increase in operational costs due to the use of a computer.

It is, however, imperative that management is only given the reports it feels are useful (after being made aware of all the possibilities). If this is not observed, there is the risk of management being 'swamped' by computer print-out with the result that:

a) Management could not possibly have time to read it all,

and, b) Even if it could, it would not be interested in more than 50%.

One important benefit of computerized systems, but one which is not always given the acclaim it deserves, is the improvement in 'customer image' resulting from the installation of sophisticated computer systems. This prestige effect is a very real one, and is no more abstract than the benefit obtained from, say, an advertising campaign. Several firms (not necessarily in the drop forging industry) have taken the decision to 'go computer' based on anticipated benefits, of which improved company image figures prominently. The feeling is that the increased status bestowed by computerization has very real benefits in terms of improved image, and hence marketability, of their company and its products.

There are definite benefits to be obtained from the use of computerized work scheduling techniques. We have already identified scheduling to be a topic worthy of further, detailed investigation, (section 3.2). The following sections of this thesis deal with the development of a scheduling system for both die- and forge-shops, and the benefits likely to arise from the use of such systems.

6.2 An Investigation of a Computerized Production Scheduling Technique

In order that there shall be no ambiguity or misunderstanding, the various scheduling terms used in this thesis are defined in appendix VIII. This nomenclature follows closely that suggested by Gere[45], and should be consulted before proceeding to following sections of this thesis.

6.2.1 A Definition of Scheduling in the context of this Investigation

The term 'scheduling' is perhaps one of the most abused words in the English language. Numerous definitions have been applied to scheduling, each authority tending to produce a definition moulded, to a greater or lesser extent, to suit its own particular situation. Below is given one definition of the term.

Scheduling is the technique whereby a number of jobs, each comprising one or more operations to be performed in specified sequence on specified machines and requiring certain amounts of time, may be planned such that all due-dates will be met, or failing this, costs due to lateness minimised.

6.2.2 Scheduling and Production control in the Drop Forging industry

Job scheduling in a drop-forge involves two, slightly different, problem areas. Works has to be scheduled or planned in the forge shop itself and additionally, dies have to be planned through the die shop. The former problem area, the forge shop, is the simpler of the two cases. Each job receives only one operation during its stay in the forge shop, i.e. forging proper. (The ancillary operations, hot Clipping, straightening, etc. are often by necessity performed while the forging is 'fresh' from the hammer, the whole forging cycle being considered as one operation.)

The second example of scheduling in a drop-forge, planning work through the die shop, is far more complex. In the die shop each job may require several operations (i.e. shaping, milling, bench-sinking etc.) during its manufacturing cycle. Thus, each job does not simply have to be planned so that it appears only once in a particular facility queue, but rather, each <u>operation</u> has to be individually planned on the facility required by that operation. This has been referred to in the previous literature survey section (2.5) as the m x n scheduling problem.

The two problem areas outlined above cannot be considered as unique entities, completely independent of each other. Obviously forge production cannot begin until dies have been made and are available. Thus, there is a complex interrelationship between due date for forging, due date for dies, earliest possible start date for forging, planned start and finish dates for dies, etc. This interrelationship of dates in the two departments is discussed further in section 6.4.3.

The literature review yielded no evidence of any drop forge presently using a computerized scheduling system for planning the die shop, although one successful example of a computerized system for forge shop scheduling at a medium/large drop-forge has been acknowledged[64].

The production control department, in addition to planning work and continuously updating these schedules, must also prepare and maintain various records/files necessary for the ordering of steel; accountancy information, etc. It has been indicated (6.1) that such file keeping routines are readily amenable to computerization, record storage and retrieval being one application in which computers excel. This application, however, is outside the terms of reference of the present investigation.

6.2.3 The Present Scheduling method employed at the Study Firm

The idealized situation in which every customer's required due dates are satisfied exactly is almost impossible to achieve unless considerable overtime is worked or excessive shop capacity is available. (This is due perhaps to inefficient marketing.) The best practical solution that can be achieved is some degree of compromise in which overall customer dissatisfaction is reduced to a minimum.

Presently, this 'compromise' or 'optimum' solution is obtained (hopefully) by what might be termed a 'jigsaw' approach. Essentially, this involves the interchange of the positions of various jobs along some time scale so that the new arrangement is an improvement over the original arrangement. The choice of which jobs to attempt to interchange and the new positions into which to move them, is a matter of experience on the part of the production controller. With this approach, priority rules are not explicit. However, one feels that it must involve some intuitive sense of job slack.

A convenient method of displaying such schedules, and one which is amenable to the frequent positional interchange required by this approach, is that of using tickets to represent each job. These tickets are hung on a peg board, the horizontal axis of which represents calendar time. When applying this jigsaw approach to die-shop scheduling, even greater care is required if the logical sequence of operation start and finish times for any job is not to be destroyed.

The production controller reschedules this complete forward work-load every three or four weeks, depending upon the time at his disposal. The immediate plan (i.e. of work due to begin production within the next two week period) is rescheduled weekly and updated daily in view of jobs completed, unexpected delays, etc. Jobs requesting delivery dates more than six weeks in advance are not planned in detail for any specific start and finish date, but are assigned an approximate month of manufacture only. The reason for this is that beyond six weeks or so, detailed plans are likely to be rendered obsolete by unpredictable delays, arrival of more urgent jobs etc. Additionally, the rescheduling effort involved means that manual scheduling more than six weeks forward load is not practical. (It should be recorded that the production controller has intimated his desire for a forward plan farther forward than six weeks, if this were feasible.)

On planning a job for a specific production period, the controller informs the die shop superintendent of the dates on which the appropriate dies are required. This date is then the due-date for the dies. However, in order that the controller may plan the job in the forge, he must make some assumption or estimation of when the dies will be available. This estimation often takes the form of a straight two to six week lag, depending upon the degree of preparation work required on the dies. It rarely includes any detailed knowledge of the die-shop work load or available capacity.

There is thus an interactive situation operating. An integrated computer scheduling system, capable of planning both the forge and die shops, could adopt a more systematic, analytical rôle; the various interrelated dates being balanced and related so as to obtain optimum schedules in both production shops.

6.2.4 Implications of poor scheduling performance

The implications of not meeting a customer's due-date must be considered. In some industries, particularly the building and aircraft industries, these are only too obvious, often in the form of a penalty clause written into the original contractual agreement. The drop forge, however, faces a more subtle 'penalty clause'. It is very rare for a customer to insist on a formal clause in the contract to buy. However, one very real danger of not meeting agreed due-dates is the risk of losing customer goodwill. This loss of goodwill may manifest itself ultimately in the loss of future orders from both this customer and other customers, who have subsequently heard of the firm's (damaged) reputation for unsatisfactory delivery promises. Gere[45] has indicated that poor scheduling performance may be accompanied by other undesirable consequences:-

1. Direct dealing with customers - paperwork, telephone calls, staff involvement in discussions etc.

and, 2. Expediting - attempts to hurry work along; overtime working, extra supervision, inefficient use of men or machines.

The present manual scheduling system employed at the study firm is subject to individual interpretation, since there is no formal approach to the jigsaw philosophy. Such a manual system is open to external stimulii; telephone calls from complaining customers, personal directives from management regarding specific jobs, etc. This sensitivity to external forces is not necessarily a disadvantage of the manual system, and may even be a necessity for an efficient scheduling system if it is to be flexible and responsive to changing needs. It is considered, however, that the degree of sensitivity arising from manual scheduling methods, particularly with respect to telephoned complaints, is undesirable.

The changes to a schedule resulting from a telephoned complaint may bring a short term benefit in improving the status of a specific job, but this alteration may have repercussions which adversely affect other jobs in that facility queue, to the detriment of the overall scheduling goal.

This oversensitivity to external influences was a contributing factor for the adoption of a computerized forge scheduling system to replace the original manual technique at drop-forge mentioned earlier[64].

6.3 The Development of a Computerized scheduling system

In order to formulate an alternative, computerized scheduling system, it was necessary to spend considerable time with the controller to observe his mode of working and his scheduling philosophy.

Directly questioning about method used, decisions taken, etc., proved fruitless. The man, although wanting to be informative, could offer no set method of working. Experience again was given a fair proportion of the credit for his scheduling ability.

The degree of flexibility required by a system to cope with the dynamic situation characteristic of a modern Drop Forge made it clear that the rather rigid approach afforded by most 'package' scheduling systems was likely to prove unsuitable. For this reason, and after consideration of the recommendations suggested by various authors in the literature, it was decided to devise a 'home-made' system. It was intended that the programmes should be written in such a way that they might be used by similar drop-forges with the minimum of modification. Scheduling systems may be classified thus:-

1. Systems depending upon a hierarchical structure of priority rules for resolving job/time conflicts.
2. Systems depending upon heuristics or 'rules of thumb'. (Examples are given in appendix VIII.)

The literature section of this thesis (2.5) documented various workers and the priority rules and heuristics used by them with varying degrees of success in solving the job-shop scheduling problem. Gere has been noted as making a useful contribution to this literature. Gere concludes that systems incorporating both priority rules <u>and</u> heuristics are far superior to either priority rules or heuristics used alone.

The present author had already decided that a priority rule system would be unsuitable for resolving job conflict at any moment in time. This is due to their inability to anticipate the effect of any decision made <u>now</u>, regarding the choice of next job, on <u>other</u> jobs waiting for production time on this machine. (Priority rules answer the question; "what job should I load next out of all the possibilities?" They offer no answer to the question; "If I load job alpha next, what effect will this have on <u>other</u> jobs waiting in the queue?"). It was thus decided to develop a forge scheduling system that was a 'hybrid' incorporating both priority rules and heuristic scheduling rules.

6.3.1 Resolution of Conflict

Let us consider the question of priority rules and scheduling heuristics, suitable for a computerized scheduling system for use in a drop forging environment.

6.3.1.1 Priority Rules

Priority rules may be of two types; static and dynamic. These are self explanatory but basically the static rules give the same priority rating to a job when it is six weeks early as they would if the job were running six weeks late. An example of such a rule would be, 'Job entry date'. (The date of which the job was received as an order from the customer.) Dynamic priority rules , on the other hand, have the ability to increase the effective rating of a job as that job becomes increasingly critical (late), for example, 'job slack'.

It is obvious that dynamic rules offer many advantages over static ones. However, it was considered that a static, management set, priority factor should be included in the scheduling logic. The reasoning behind this is that, presently, the satisfaction of certain customers is considered more important than meeting the requirements of other customers. This is often a reflection of the size of the order-book for respective customers, but may occasionally be of a more subtle nature. For example, the need to encourage a new customer to gain his confidence, or the need to satisfy an old established customer who has, for one reason or another, been disillusioned with the firm's image in recent times.

6.3.1.2 Scheduling Heuristics

The ideal situation is to be able to enumerate every possible solution to the m x n scheduling problem, evaluate the nearness with which each solution meets the ultimate scheduling goal, and to choose the best possible schedule on this basis. However, the monumental computational effort of complete enumeration renders all but the most unrealistically small problem impossible. If, for the purpose of argument, we wish to schedule ten jobs on only one machine, then there are almost 4×10^6 possible arrangements of just these ten jobs (that is, ten factorial, 10!).

Clearly such an approach is ridiculous. If, however, we take a small subset of all the possible jobs, say for example three; then it is computationally feasible to enumerate all the possible arrangements of these three jobs, and choose the most suitable. (There are 3!, or 6, possible arrangements.)

6.3.1.3 Objective Functions

When scheduling jobs, whether manually or by computer, there has to be some ultimate goal or overriding scheduling philosophy. This may take the form of an unquantified, 'to avoid customer complaint', or it may be a more rigorous objective such as, 'Minimize Work in progress (W.I.P)'. Whatever the objective function, any scheduling decisions taken by the system should be such that the objective function is maximised (or minimised, as the case may be).

An often quoted, and not unreasonable, goal is that of minimizing customer dissatisfaction. What is really required is that the system should avoid antagonising customers, such that there is a risk that the company may lose income from their not placing future orders. Smith[59] has assumed this risk to be directly proportional to the degree of lateness of the job, although an equally acceptable assumption might be that the risk increses as the squared term (for example) of the lateness.

Minimized lateness, or mean lateness, was taken to be the objective function for this scheduling study. This is consistent with the desires of the study forge, and other similar forges, in wishing to mimimize customer dissatisfaction arising from 'poor delivery' performance.

6.3.2 Scheduling Logic of a computerized system

In figures 33 and 34 are partial flow diagrams for the scheduling-decision segments of the computerized system.

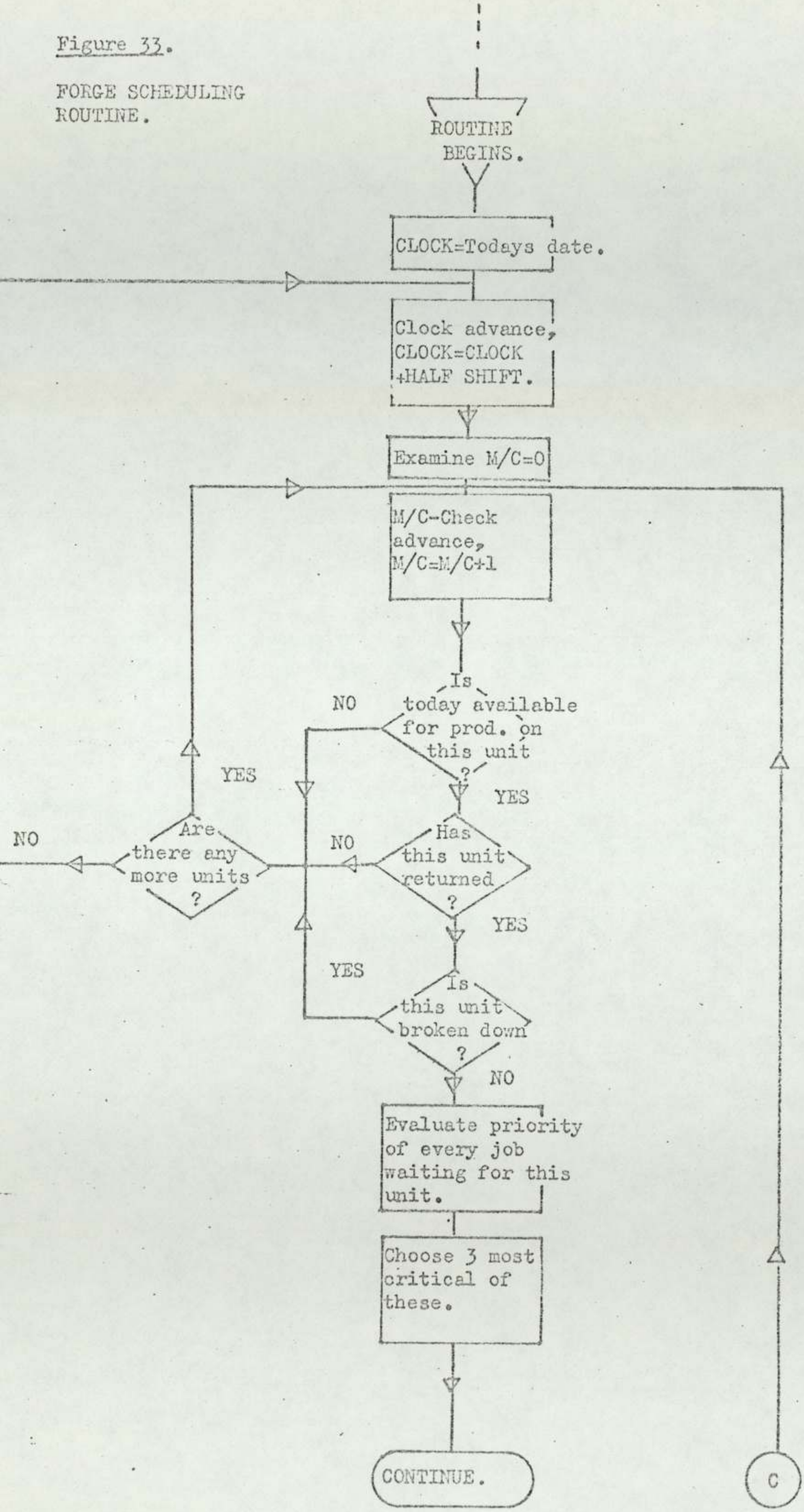
Present machine loading commitments, jobs awaiting scheduling, etc., are stored internally in the computer in three-dimensional arrays. This allows the scheduling routine ready-access to the information it requires for subsequent operation.

The first facility (production unit - hammer, machine) is examined and checked to determine its availability at the present time. If the facility is available, then the scheduling programme proceeds to evaluate a priority rating for each job/operation waiting for production time on this unit. If the facility is not available at the current time, then either the next facility is examined or, if all facilities have been checked, the clock time is advanced one half-shift.

In evaluating priority ratings, the programme uses a mixture of dynamic and static rules as indicated earlier. The dynamic rule used is the relatively simple rule, job slack. Job slack is the amount of time from now until the due date, less the time required for production. It is a measure of 'float'. This job slack value may be negative, indicating that the job will inevitably be completed late, even if loaded immediately. The static part of the rating is in the form of a value; 1, 2 or 3. The value '1' represents the highest priority rating, associated with a large, influential customer, while a static rating of '3' is indicative of a smaller, or casual-type customer. The compound priority rating is so devised that there is an equal debit in producing a 1-type job five days late, as there is in producing a 2-type job ten days late, and so on. These static ratings were determined with the aid of the production controller, but may be adjusted to suit individual needs. The values need not be greater than one, nor need they be integer values.

Figure 33.

FORGE SCHEDULING ROUTINE.



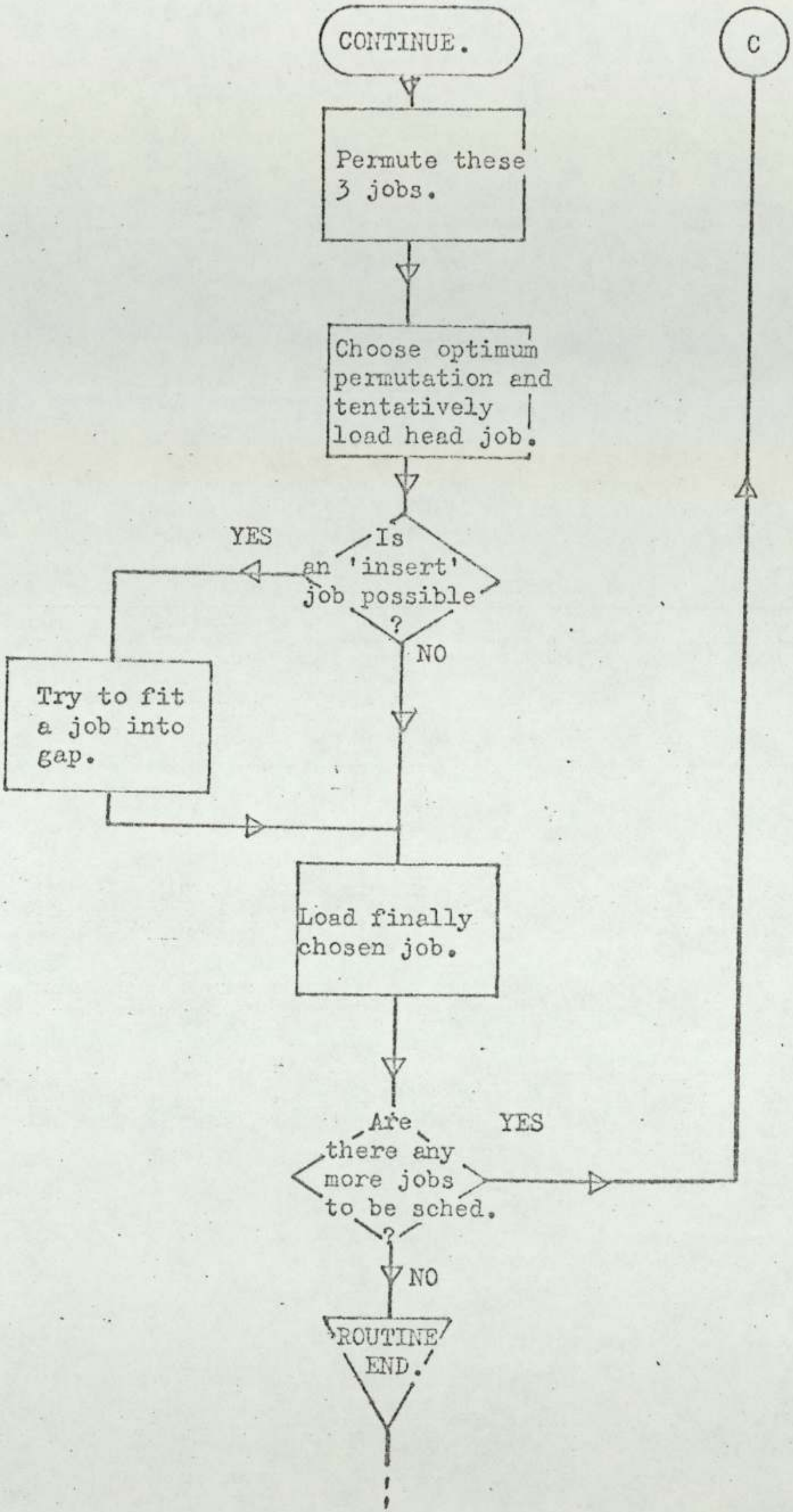
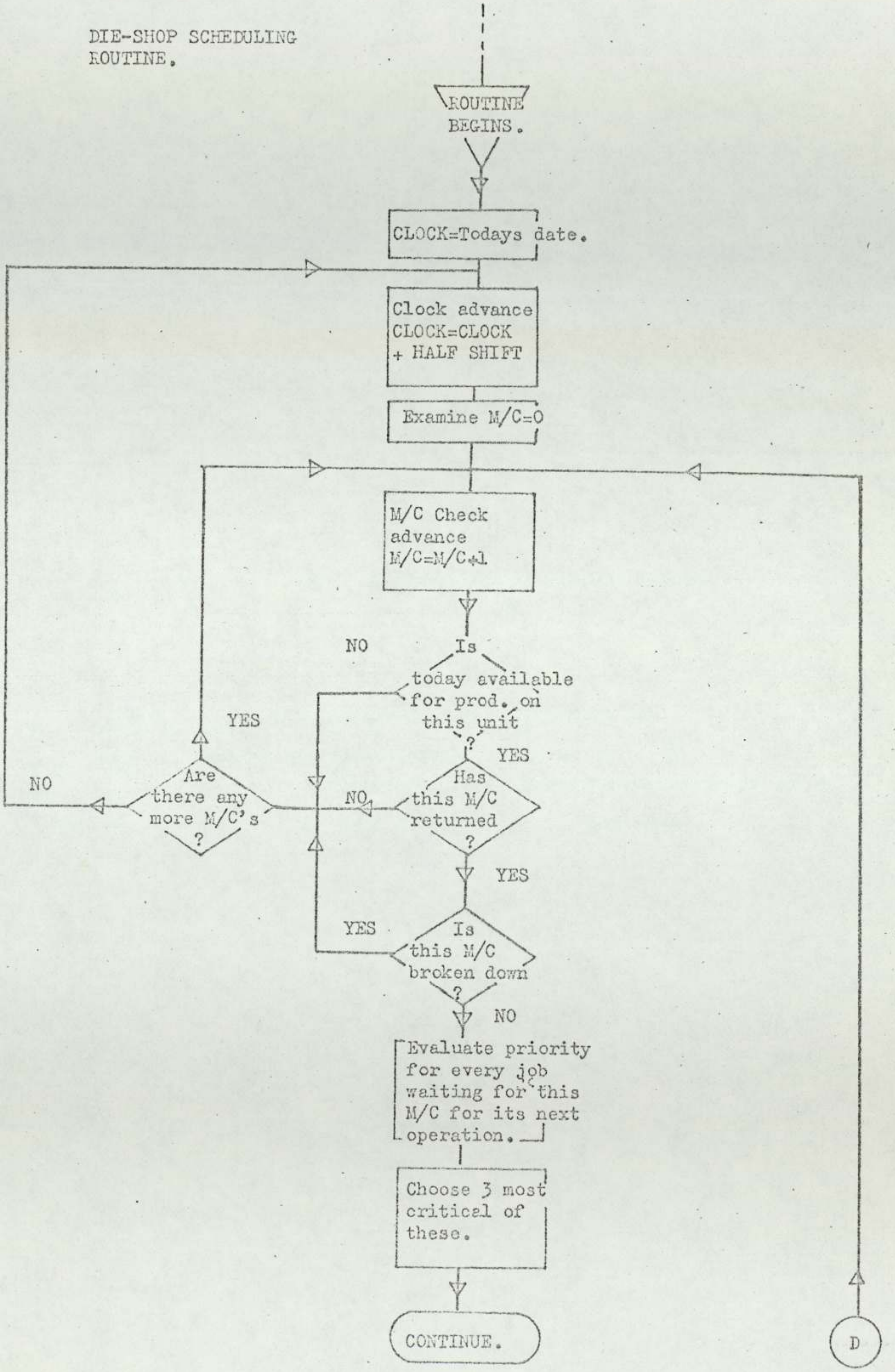
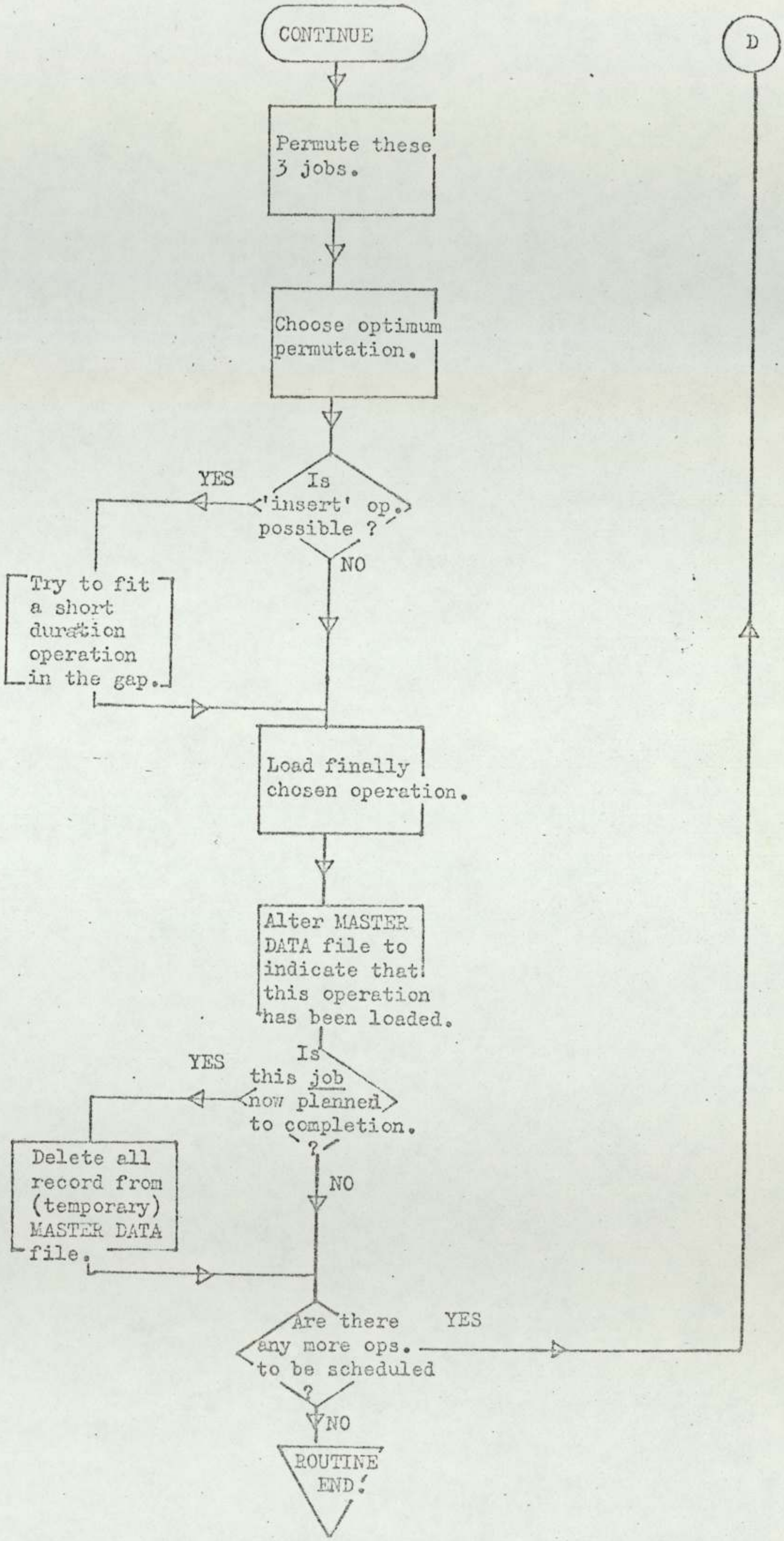

CONTINUE.
C
Permute these 3 jobs.
Choose optimum permutation and tentatively load head job.
Is an 'insert' job possible ?
YES
NO
Try to fit a job into gap.
Load finally chosen job.
Are there any more jobs to be sched. ?
YES
NO
ROUTINE END.

Figure 34.

DIE-SHOP SCHEDULING ROUTINE.




CONTINUE
D
Permute these 3 jobs.
Choose optimum permutation.
Is 'insert' op. possible ?
YES
NO
Try to fit a short duration operation in the gap.
Load finally chosen operation.
Alter MASTER DATA file to indicate that this operation has been loaded.
Is this job now planned to completion. ?
YES
NO
Delete all record from (temporary) MASTER DATA file.
Are there any more ops. to be scheduled ?
YES
NO
ROUTINE END!

Job Slack = (Due date - Current date) - (Production duration)
(J.S.)

Compound rating = J.S. x Static factor

(if J.S. $>$ zero)

Compound rating = J.S. $\div$ Static factor

(if J.S. $<$ zero)

(-00 $\equiv$ Most critical, most urgent job,

+00 $\equiv$ Least critical, least urgent job.)

The programme chooses the three jobs having the most critical (most negative, least positive) compound rating, and permutes them in their six different arrangements:-

A B C
A C B
B A C
B C A
C A B
C B A

The permutation resulting in the minimum value of objective function, mean tardiness, is selected and the job/operation at the head of this permutation is chosen as the one to be tentatively loaded next on the facility under consideration.

The logic behind loading the job at the <u>head</u> of the chosen permutation, rather than electing to load <u>all three</u> jobs in the chosen order may be easily demonstrated. In an heuristic loading all three jobs, a job currently (say) fourth in the priority 'league' would not be considered, since the heuristic only selects the three most critical jobs and permutes these. However, it may be that by loading this (fourth) job in (say) second place a more optimum overall schedule would result. An heuristic loading all three jobs cannot foresee this possibility.

An heuristic which loads only the head job of the chosen permutation does not suffer from this 'short-sightedness'. After loading the head job, the next cycle of the heuristic will again select the three most critical jobs, including of course, the job previously fourth, now third, in the priority 'league'. Thus, this job will find its way to the head of the selected subset (if such an arrangement results in the optimum value of objective function for the subset) and will be loaded on the machine accordingly.

Before loading the job/operation chosen by the previous routine , a further heuristic is employed, termed (for the want of a better expression) the 'insert' heuristic. The function of the insert heuristic is to check the possibility of fitting the production of another, short duration, job into any time lag that may be present before the chosen job is scheduled to start. Such a time gap may arise if there is some delay to the start date of the chosen job due to, for example, non-availability of steel orders at the current time. If an 'insert' job is possible, without delaying the planned start date of the originally chosen job, then this insert job is loaded onto the respective facility. The insert job is not loaded if to do so would delay the start of the originally chosen job, even if the original job has positive slack, i.e. could be delayed without becoming late. The reason for this is that we are not concerned only with the originally chosen job, but also all other jobs in the queue. To delay the start of the originally chosen job (itself perhaps not critical, positive slack), in favour of an insert job, might well delay the start of some following, critical job, to the detriment of the overall schedule.

When a job is loaded onto a facility, the programme logic loops back to the beginning of the scheduling segment, considers the next facility (production unit) and continues as before until all jobs/operations have been assigned positions in the respective facility queues.

6.3.2.1 The permutation Heuristic - Experimental Development

In the previous section, the heuristic involving the permutation of the 'n' most critical jobs was discussed. During the development of this heuristic device, it was necessary to decide what value 'n' should assume.

The choice of too low a value for 'n' would probably result in an insensitive heuristic, without the necessary ability to anticipate the future development of machine schedules. The choice of too large a value, on the other hand, would be similarly unsatisfactory due to the rapid increase in computation time associated with high values of 'n' and with the n! possible arrangements involved.

i.e.

n	Number of possible arrangements of 'n' jobs.
1	1
2	2
3	6
4	24
5	120
6	720
.	.
.	.
.	.
.	.
N	N!

The table shown above clearly demonstrates the rapid rise in number of possible arrangements with increasing values of 'n'.

A starting value of three was chosen, since the number of possible arrangements involved seemed intuitively reasonable at six. A schedule was produced using a permutation heuristic with n = 3. Using the same raw data (i.e. same file of jobs to be scheduled), machine loading plans were produced by computer runs using:-

a) the heuristic with n = 2.

b) the heuristic with n = 4.

The computational times and values of objective function, mean tardiness, resulting from these three computer runs are detailed below.

n	Computational time (seconds)	Mean Tardiness (days)
2	175	1.22
3	182	1.00
4	228	1.00

Graphically:-

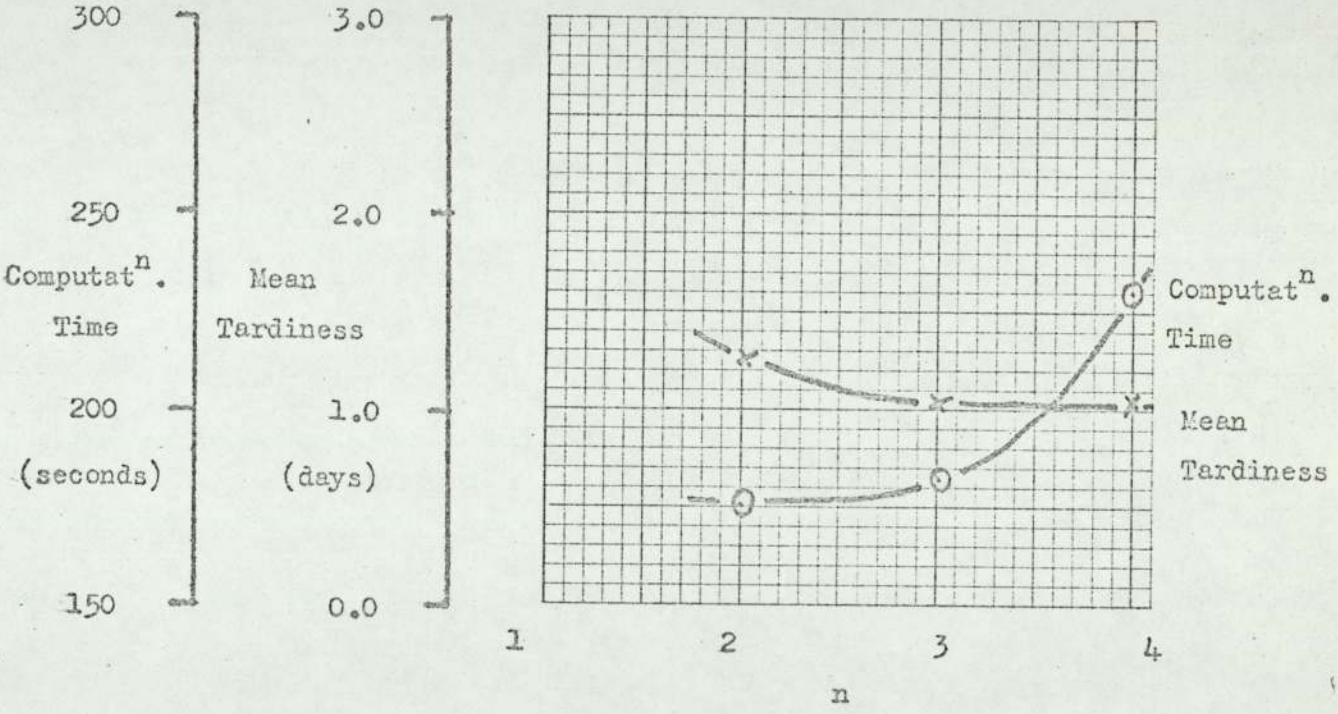


Figure 35.

From these results it is clear that a value of n = 3 appears to be most suitable. A larger value increases computational effort with no improvement in objective value; a lower value reduces the computational effort very little but with an associated increase in the value of objective function.

6.3.2.2 Size/Computational-time relationship

For a computerized scheduling system such as the one currently proposed, it is important to know the relationship existing between the number of jobs requiring scheduling and the computation time (and hence cost) involved. This relationship has a direct bearing on the size of scheduling problem that may be tackled by this approach, influencing the applicability of the system to other, perhaps larger, forging installations.

So that this relationship might be determined, the forge-shop scheduling programme was run on several occasions, each run having a different number of new jobs included. All other conditions, current hammer commitment etc., were held constant throughout the various trials. The mean computation time per job, resulting from each trial are tabulated below, table 6, and plotted in figure 36.

Trial Number	Number of Jobs to be scheduled	Meantime per job. (seconds)
1	25	3.25
2	54	3.10
3	74	2.94
4	90	2.90

Table 6.

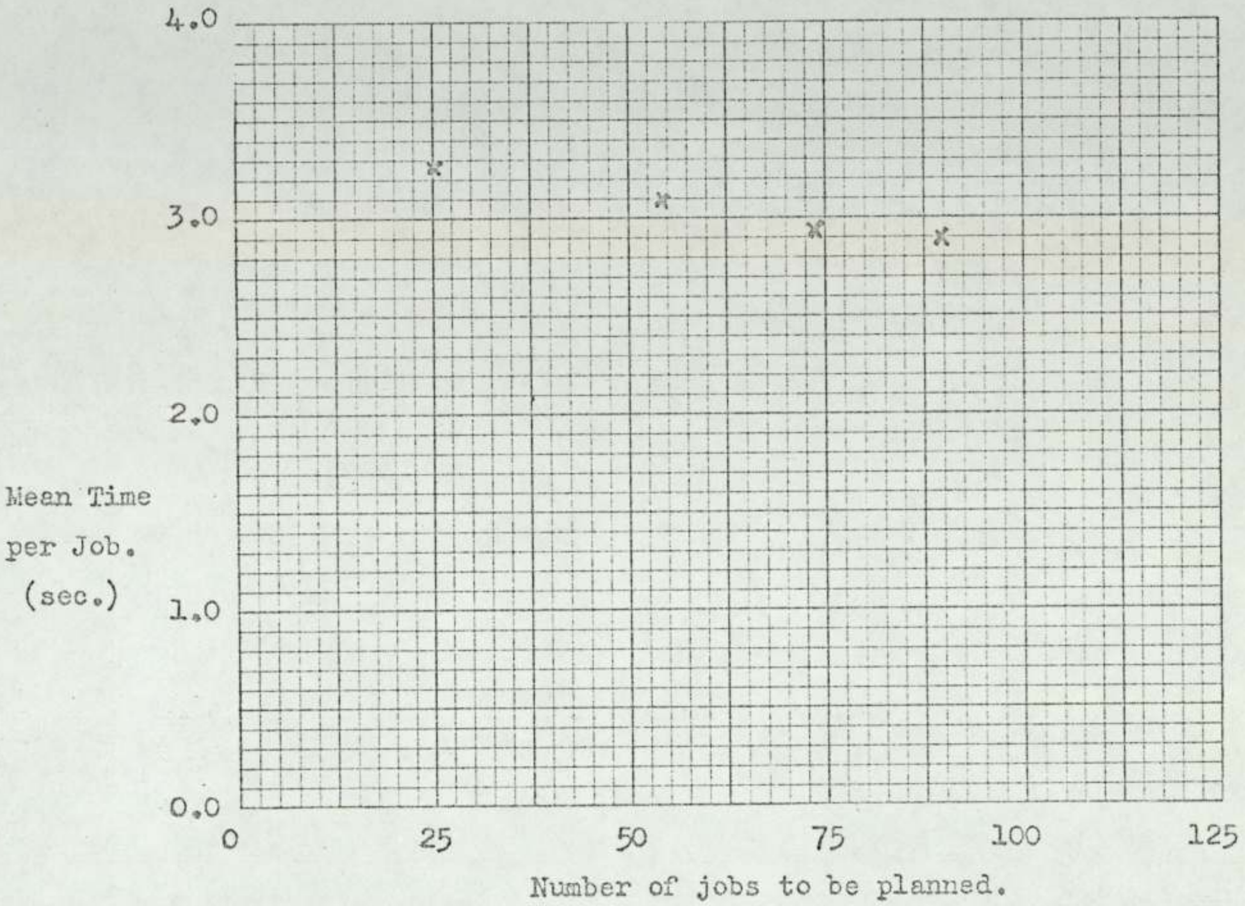


Figure 36

The plot of the four points appears to follow an almost horizontal straight line relationship, indicating that the mean computational time per job is independent of the number of jobs being scheduled. This is encouraging since it suggests that large firms, scheduling considerable numbers of jobs, could use the system: the computational time being proportional to the size of the scheduling problem involved.

6.3.2.3 Die-Shop Scheduling - A special case

The scheduling routine devised for the die-shop differs from that for the forge shop on a number of points. The die shop, we have noted, presents the problem of planning jobs as a series of operations, rather than as discrete entities. This requires a slightly different method for evaluating priority values and a more sophisticated permutation heuristic.

The technique of checking the availability of each machine and advancing clock time is common to both the forge- and die-shop systems. When evaluating priority values for any particular job, the method adopted is to calculate the sum of all remaining operation durations; the job slack value then being expressed as:-

J.S. = (Time remaining until Due Date) - (Sum of remaining operation durations.)

When calculating the sum of all the remaining operation durations, the programme checks to determine any limitation on the start date of each operation. For example, operation $(n + 4)$ of a particular job may require machine 'm'. Machine 'm', however, may be heavily committed until time $(t + 30)$. Thus, the earliest time (for the purposes of calculating job-slack) that operation $(n + 4)$ may commence is $(t + 30)$. This commitment is explained more fully below.

The permutation heuristic used for the die-shop system is fundamentally the same as that for the forge, i.e. three jobs selected on the basis of priority rating are permuted in each of their six different arrangements. The lowest scoring permutation indicates the operation to be loaded next on the machine in question. The diffence arises in that the heuristic plans job 'A' to completion (i.e. <u>all</u> remaining operations, on respective machines), followed by job 'B' planned to completion, followed similarly by job 'C'. The objective score is evaluated on the basis of the 'finish' date resulting from the above approach,

i.e.

$$\left[O_{A_{n}}, O_{A_{n+1}}, O_{A_{n+2}}, \ldots\ldots O_{A_{n+n}} \right], \left[O_{B_{n}}, O_{B_{n+1}}, O_{B_{n+2}}, \ldots\ldots O_{B_{n+n}} \right], \left[O_{C_{n}}, O_{C_{n+1}}, O_{C_{n+2}}, \ldots\ldots O_{C_{n+n}} \right] :$$

(Thus, the act of 'planning' job A to completion, for example, commits some of the capacity of the various machines involved. This has to be taken into account when 'planning' jobs B and similarly, C).

A further sophistication made necessary by the more complex die shop problem is that, throughout the scheduling routine, constant checks have to be incorporated if logical schedules are to be produced. These checking routines ensure that no operation of any job is planned to start on a machine before its <u>preceding</u> operation has been planned to be completed, or that any other factor logically prevents the commencement of this operation. These checks are carried out throughout the programme prior to every scheduling step involving the time-scale.

One other complication is introduced by the die shop situation. This is a computer-programming complication. Due to the volume of data (regarding operation sequencing, operation durations, etc.) that has to be stored for each job, it is not feasible to store all this information in the same array as that holding the machine loading schedules. (As is done in the case of the forge programme.) Instead, the job data required for scheduling is stored in a pair of multi-dimensional arrays, 'MASTER' and 'SUBMAST'.

6.4 Description of the Complete Programme - the 'Executive'

The scheduling programmes were written in ALGOL and developed and tested on the University of Aston's ICL 1905E computer.

The two programmes, forge- and die-shop scheduling, read in data files from an externally stored source (tape, discs or cards) and stores these files internally in various multi-dimensional arrays. This externally-filed data includes: present machine loading, planned maintenance/holiday periods, etc. Various outputs are printed on a line printer, to verify the status and accuracy of the material thus input.

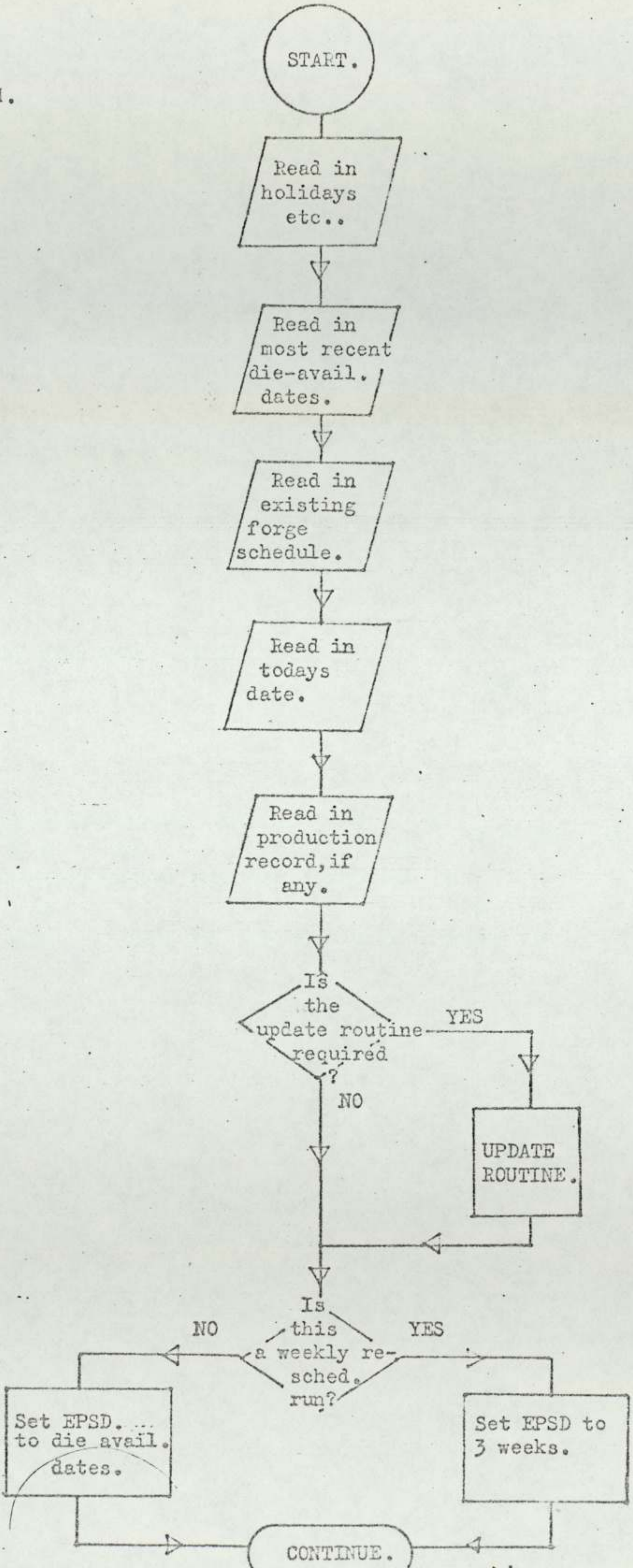
Data peculiar to a particular computer run is input from cards, for example, today's date, new jobs requiring scheduling and previous days production (for updating). It is possible to change any of the externally retained files by reading in new information regarding these files from specially prepared cards.

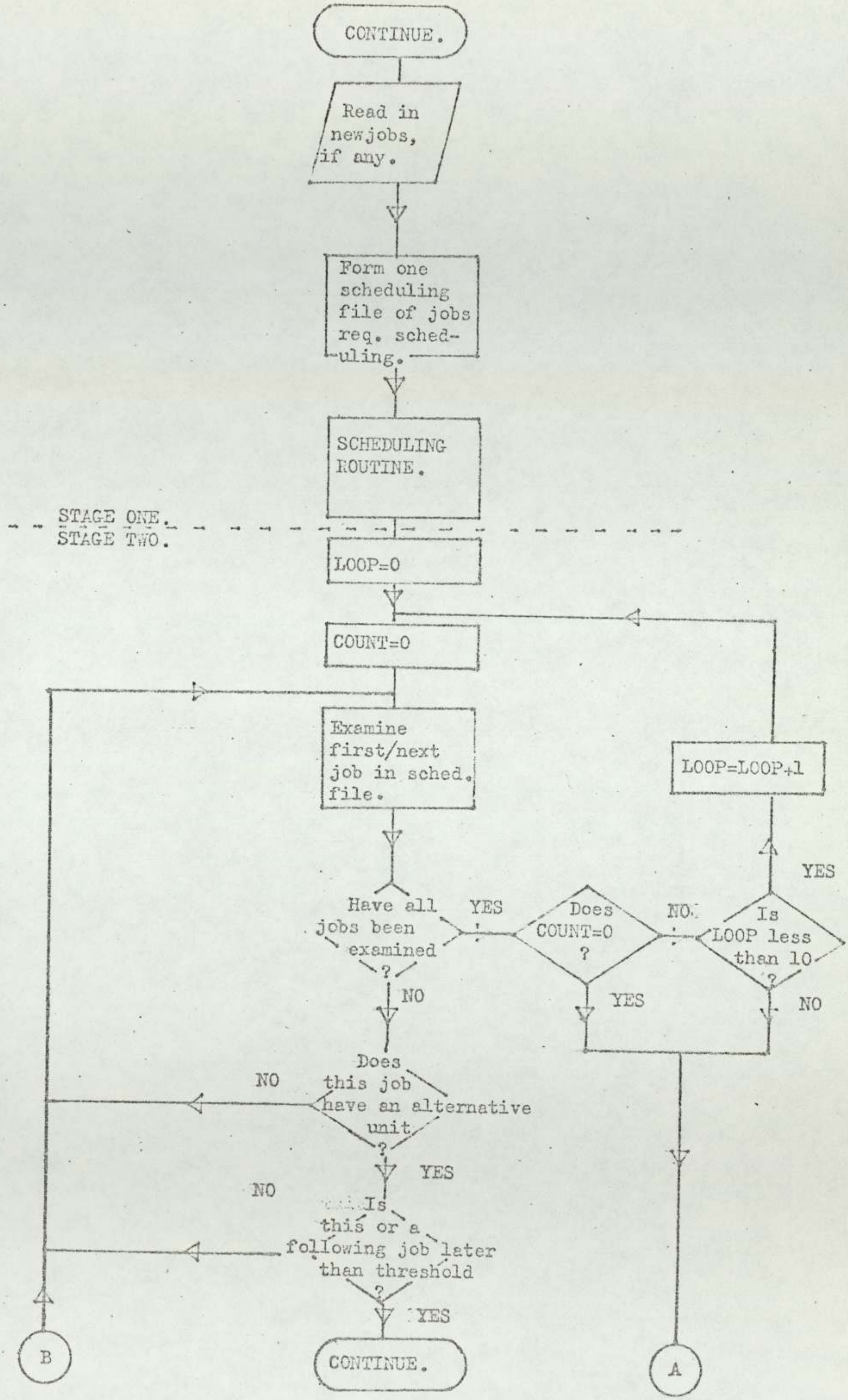
Once the relevant information has been input to the computer, the system begins to function. The previous days production is acknowledged and the present machine loading arrays updated/modified accordingly (section 6.4.1.d). When the updating facility is complete, the new jobs awaiting scheduling join all the jobs in the present machine loading array on which production has not yet commenced to form a new 'pool' of jobs awaiting scheduling. This job list is stored in a two dimensional array. Thus, jobs already in production on a machine are not removed from the head of the respective machine queues. All jobs not yet started, however, are reconsidered in the light of new competition from new orders requiring scheduling.

The scheduling routine has been discussed (section 6.2.2). When all jobs/operations have been assigned positions (production time) in the respective machine queues, the final schedule is written to a recording device e.g. tape, disc or cards. This then forms an external, semi-permanent record of the schedule, ready to be 'read-in' at the beginning of the next computer run. These schedules are also output in various formats on a line printer for use by production and management personnel (section 6.4.2).

Figure 37.

FORGE SYSTEM.




CONTINUE.
Read in newjobs, if any.
Form one scheduling file of jobs req. scheduling.
SCHEDULING ROUTINE.
STAGE ONE.
STAGE TWO.
LOOP=0
COUNT=0
Examine first/next job in sched. file.
Have all jobs been examined ?
YES
Does COUNT=0 ?
NO
Is LOOP less than 10 ?
YES
LOOP=LOOP+1
NO
YES
NO
Does this job have an alternative unit ?
NO
YES
Is this or a following job later than threshold ?
NO
YES
B
CONTINUE.
A

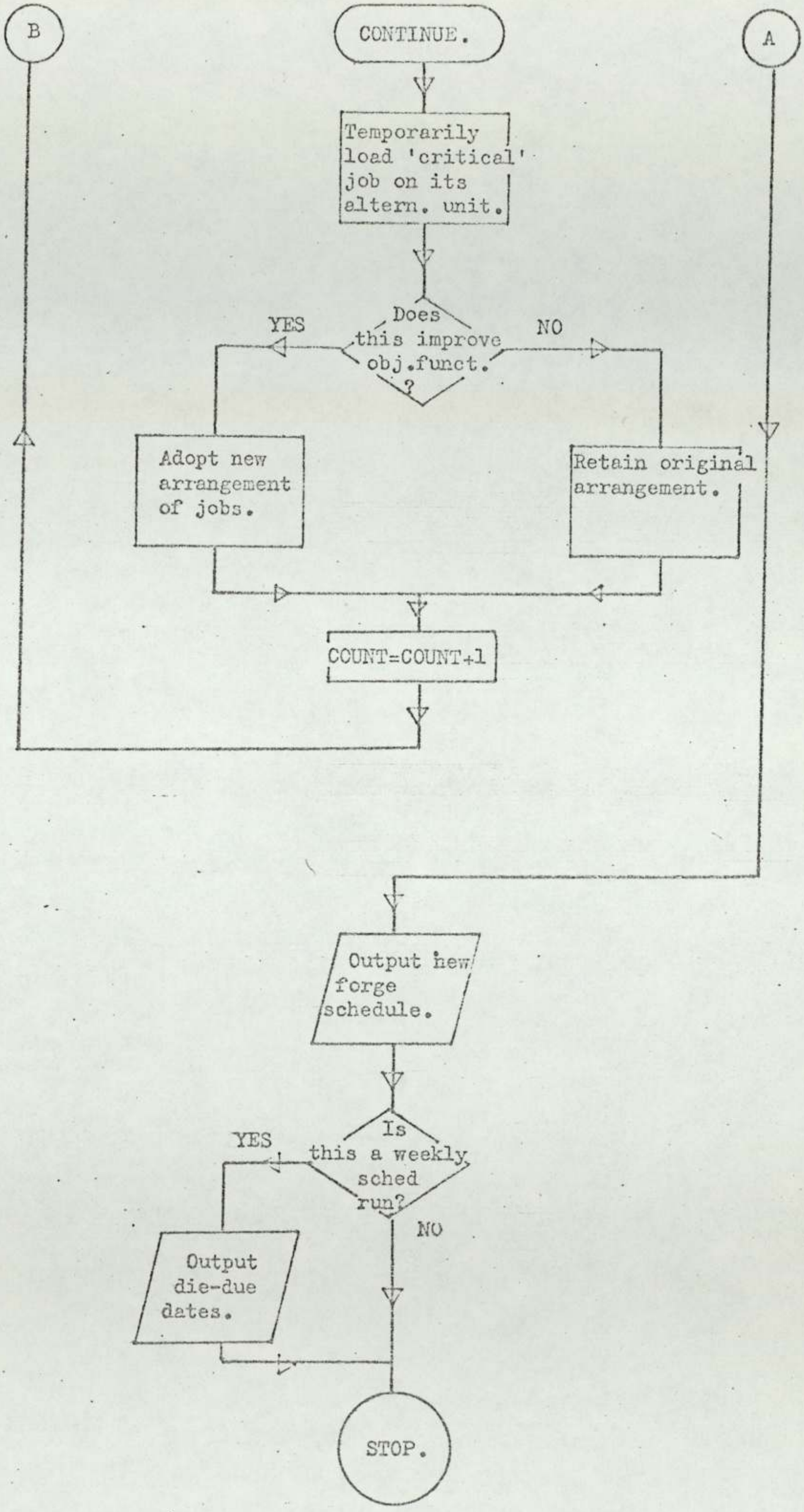
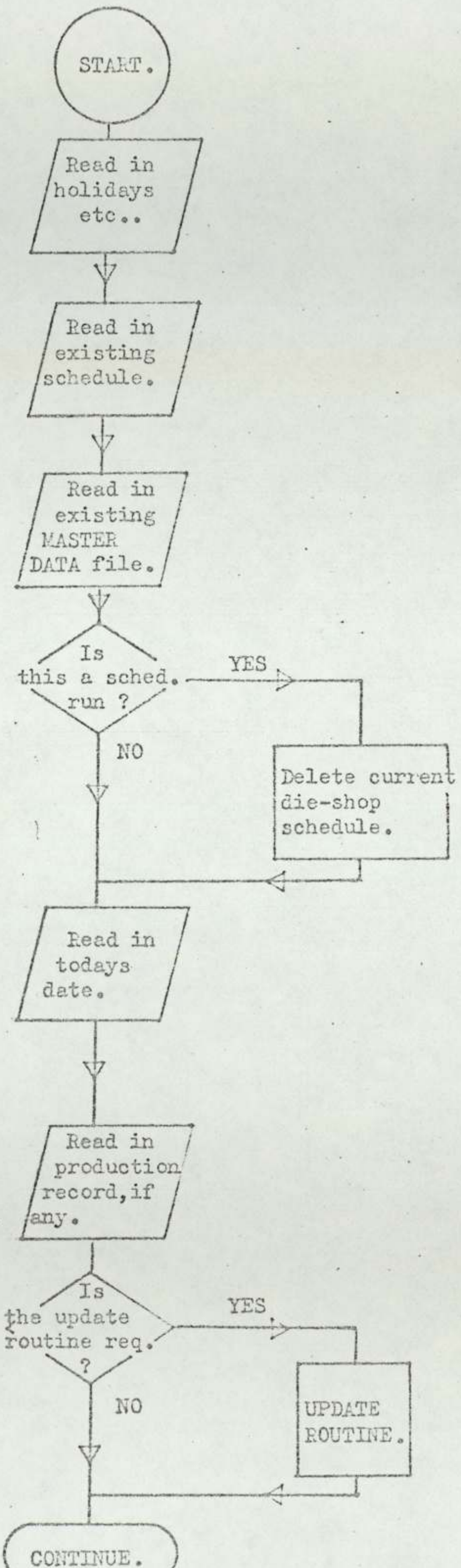
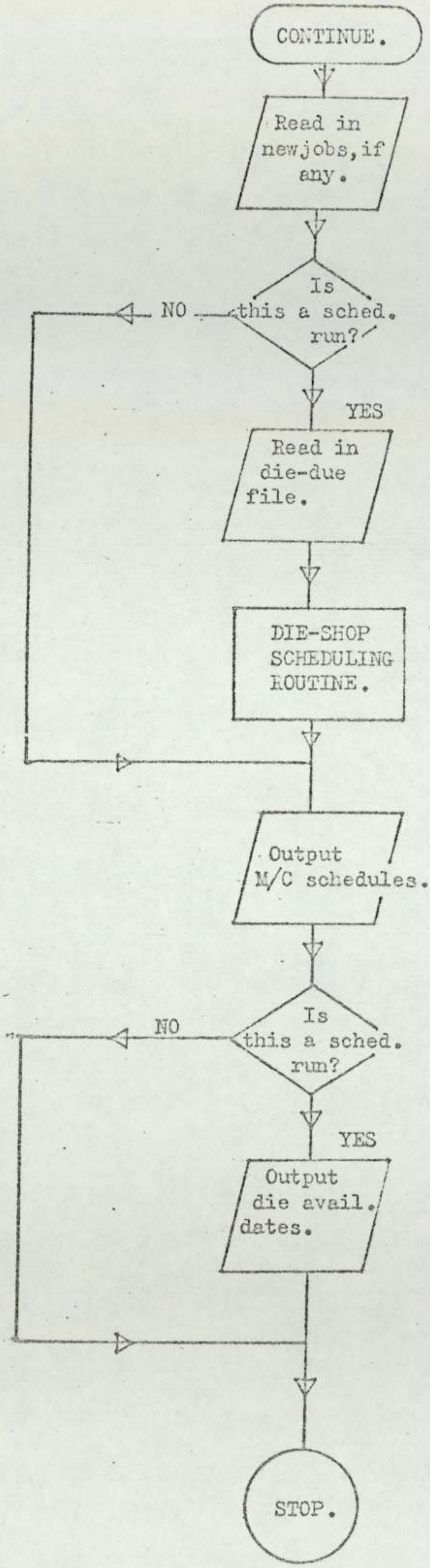

B
CONTINUE.
A
Temporarily load 'critical' job on its altern. unit.
Does this improve obj.funct. ?
YES
NO
Adopt new arrangement of jobs.
Retain original arrangement.
COUNT=COUNT+1
Output new forge schedule.
Is this a weekly sched run?
YES
NO
Output die-due dates.
STOP.

Figure 38.

DIE-SHOP SYSTEM.




CONTINUE.
Read in newjobs, if any.
Is this a sched. run?
NO
YES
Read in die-due file.
DIE-SHOP SCHEDULING ROUTINE.
Output M/C schedules.
Is this a sched. run?
NO
YES
Output die avail. dates.
STOP.

6.4.1 Facilities available

Various facilities are provided with the computerized scheduling system, increasing flexibility and applicability.

a) Multiple Choice of production unit

Both the die shop and forge shop scheduling systems allow the user to specify a number of production units on which any particular job may be manufactured. This reproduces the real-life situation whereby the production control department may assign a job to any one of, say, three equally suitable hammers. Similarly, in the die shop, where a number of machines may be capable of performing a particular operation. The programme in this instance allows the operation to have several durations (production times), to account for machines of differing cutting speeds/efficiencies.

In the case of the forge shop, a special routine has been developed, stage two. In essence, this reviews the hammer loading schedules produced by the system and determines whether any of the jobs can benefit from being made on one of its alternative-choice units, instead of the unit on which step one originally planned it.

b) Single-Double shift working

The scheduling system is capable of dealing with hammers on both single, and double shift working. Hammers in double shift mode are planned in clock-time movements of one quarter day, i.e.

one half of a shift (four 'half' shifts per day). Hammers in single shift mode are planned in increments of one half day (one half of a single shift).

The user need take no special action to accommodate double shift working, other than to advice the computer of any units changing from single to double shift working or vice-versa.

c) Planned maintenance, Holiday periods etc.

This facility has been mentioned briefly previously. Both the die shop and forge shop scheduling programmes offer the user the opportunity of specifying up to three periods for each production unit, during which time that unit will not be available to produce work. These non productive periods may be the result of; planned maintenance, holidays, pre-allocation of production capacity for 'specials', etc. These periods are identified by start and finish dates, and may be changed by inputting previously prepared cards carrying new period-start/finish dates in conventional D/M/Y format. At every stage in the scheduling programmes, the various dates stored, scheduled start/finish dates etc., are compared with these none-availability periods and the scheduled dates modified accordingly to retain overall chronological sense.

d) Daily updating routine

In a typical drop forge, forgings are being produced and dies are being prepared daily. This is likely to render any schedule, however produced, inaccurate unless account is taken of this dynamic situation and the schedules are modified accordingly. For this reason, a means of daily updating the stored machine schedules had to be devised and incorporated in the scheduling system.

The previous day's production is input on cards. Three items per job are required for the forge shop record and two items per job (operation) for the die shop version. Forgings produced, or operations commenced, are deducted from the balance remaining for the respective job, completed jobs being deleted from the respective hammer/machine queue. Checking routines are included in this facility to guard against, for example, an operation on a die being reported started <u>before</u> the previous operation on that job has been started. Daily 'work produced' inputs may also indicate jobs to be deleted (cancelled orders etc.) and machine failures. In the latter case, the report must be accompanied by a manual estimate of when the broken machine will again be available for production, this job queue being adjusted accordingly.

The updating facility ensures that the machine loading schedules for both the die shop and forge shop are maintained daily in an up to date form; subsequent rescheduling runs, thus, always computing <u>new</u> schedules on the basis of accurate, up to date information.

e) Urgent jobs - Element of manual intervention

In certain instances, it may be desirable to rush an urgent job through the factory. This might arise if a very influential customer makes some request which, the senior management feel, must be respected in the interest of the profitability of the forge, present or future. The possibility of introducing disruption to other jobs by such an action has already been indicated. However, in order to produce a system in which management and/or users could have confidence, it was decided to incorporate a facility enabling the processing of 'urgent' jobs.

In order to ensure that 'urgent' jobs are processed in preference to all other jobs, either in the forge- or die-shop, it is only necessary to give the job in question a static priority rating of, say, 0.1. In this way, the job will inevitably be scheduled to start as soon as the required production unit(s) is first available.

6.4.2 Line-printer Outputs

The outputs from the scheduling programmes are displayed in a number of printed formats (appendix X). In the case of the die shop programme, the machine loading schedules are output:-

i) By Machine sequence.
ii) By Job sequence.
iii) As a Gantt chart.

The forge programme, obviously, does not output the schedules by job sequence, ii, (since each job only comprises one operation). The programme segment to produce the Gantt - or bar-chart representation, is listed in appendix XI. (It is possible that such a programme could find use in a number of research fields.

Two versions are given, one using a line printer and one using a CALCOMP x - y plotter).

In addition to listing the whole schedule, a subroutine has been developed that lists only the jobs that are likely to be produced late with respect to their required due dates. In this way, the attention of the production controller is drawn to the jobs likely to require particular supervision, expediting or overtime.

The programme produces listings of several files, for example:- planned maintenance/holiday periods, new jobs requiring scheduling, master data for dies, etc. These outputs are intended only as a means of visually checking the validity of the information, and not as output required for the day-to-day running of the department. These outputs may be suppressed if desired.

One other output is also produced. This is a report analysing the performance of the planned schedule in terms of percentage of jobs planned to finish 'x' days late, machine utilization, etc. The former values are also displayed in the form of a histogram distribution.

6.4.3 Interface between Die-shop and Forge-shop systems

It has been indicated that there must be some degree of interrelationship between schedules produced by the die shop programme and those produced by the forge shop programme.

The forge programme produces an initial forge schedule on the premise of there being an arbitrary delay before the dies are available for any particular job, say three weeks. The resulting die due-dates (the forge planned start dates) are recorded in a holding file on a semi-permanent medium, for example, disc. The die shop scheduling programme, when initiated, reads this disc file and schedules the various jobs/operations in the die shop with the aim of meeting these due dates. The die-shop computer run, in turn, produces a file of <u>die availability</u> dates resulting from this scheduling run. These dates are recorded on disc and subsequently read by the second-cycle run of the forge programme.

This second-cycle run of the forge programme uses these die availability dates and substitutes them for the original three-weeks value. The forge schedule produced by this second scheduling run is, thus, <u>consistent</u> with the die shop schedule previously produced.

The intermediate step, between the die shop scheduling run and the second-cycle run of the forge programme, allows for the intervention of the production controller and/or die shop supervisor. The die-availability dates may be examined and, if they consider any die preparation job would be better sub-contracted as 'out-work', then they may authorize the deletion of this die-job and reschedule the die shop (via a further computer run)accordingly.

This interface between the forge and die shop systems is referred to in the following section, in which the practical implementation and usage of the system are discussed.

7. DISCUSSION OF COMPUTERIZED SCHEDULING SYSTEM

7.1 Comparison of Manual and Computerized Scheduling Systems

In order to compare the relative effectiveness of the two scheduling systems in resolving scheduling conflicts, the computerized system was used to produce a production schedule, starting with the same, real data as that currently available to the human scheduler. In this way, the schedules produced by the computer, and those produced by the production controller were directly comparable; both systems attempted to solve the same problem, limited by the same constraints. The values of the objective function - mean tardiness - were compared for the schedules produced by the two methods.

7.1.1 Scheduling Performance

The results of the test are given in table 7. Figures 39 and 40 show the cumulative percentage of jobs greater than 'n' days late.

Table 7

	FORGE SHOP		DIE SHOP	
	MANUAL	COMP	MANUAL	COMP
MEAN LATENESS (DAYS)	3.7	2.6	6.0	4.0

The reduction in value of objective function for both the die- and forge-shops is of the order of 30%, when compared to the value resulting from manual scheduling.

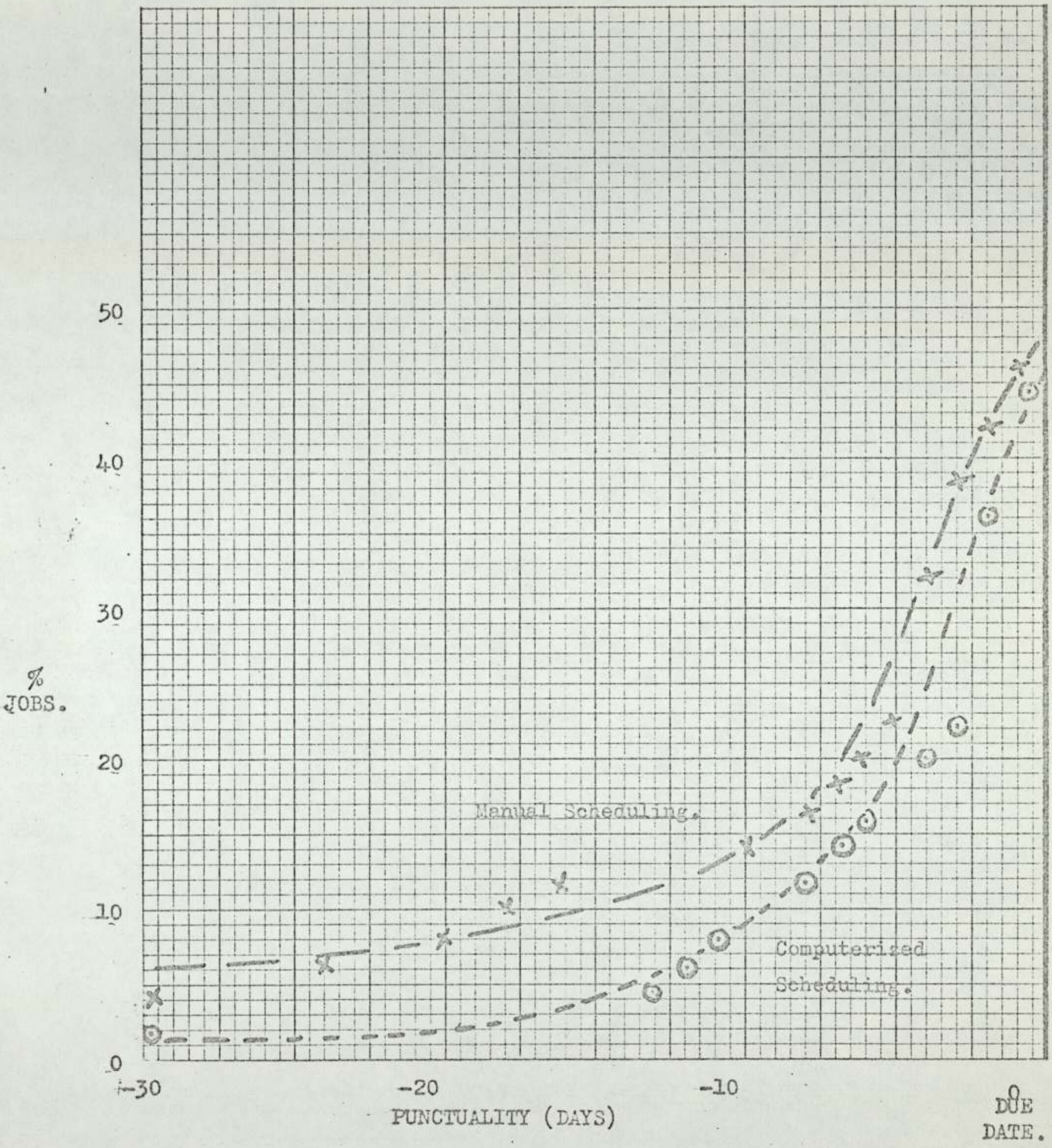


Figure 39. Forge-Shop Schedule.

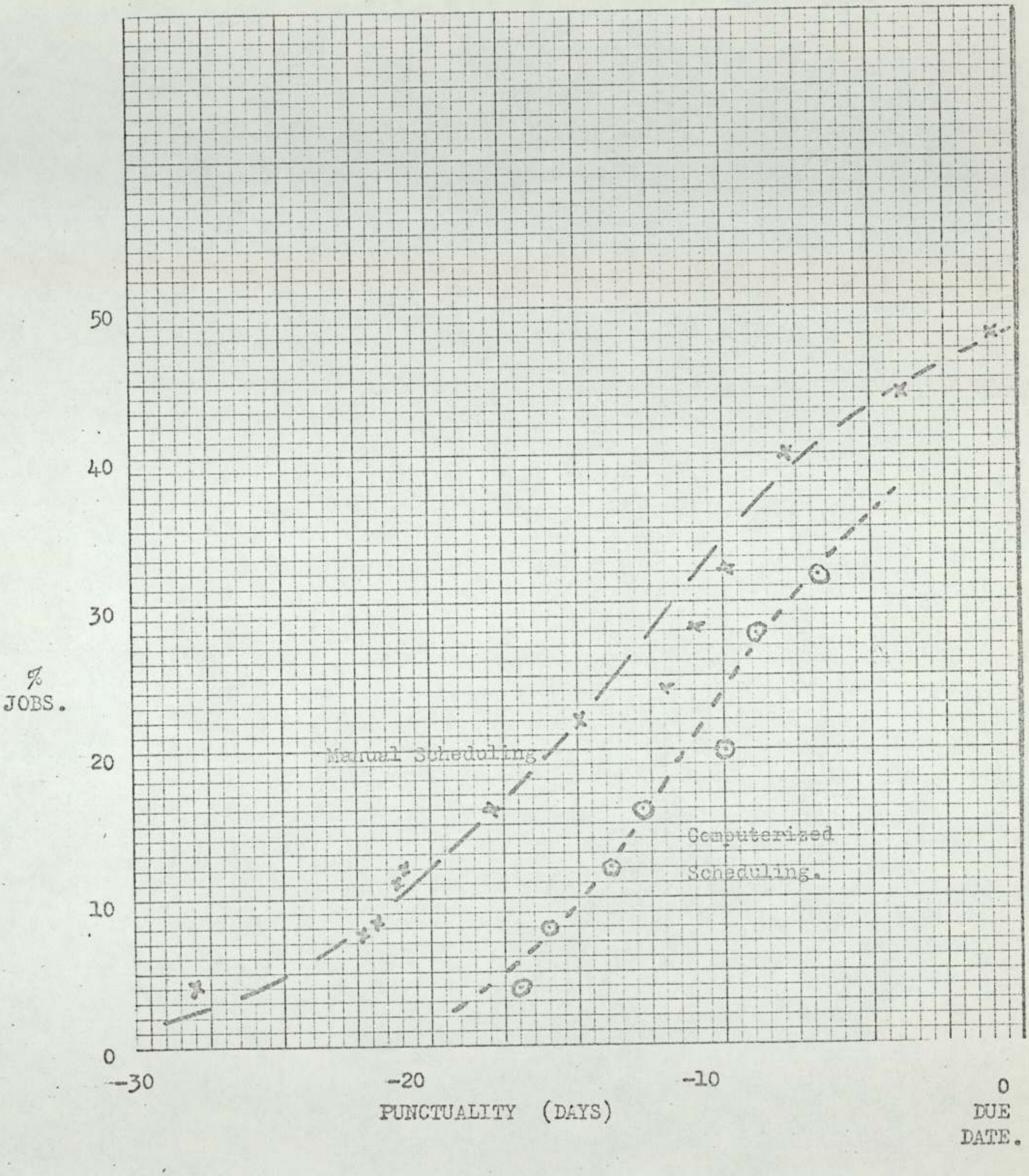


Figure 40. Die-Shop Schedule.

7.1.2 Envisaged benefits through improved customer satisfaction

The financial benefits in terms of hard cash resulting from a reduction in job lateness are difficult, if not impossible, to assess. Such a reduction would doubtless improve the firms marketing position. Enhancing sales prospects for tenders when compared to those of other companies offering similar selling prices but unable to offer such an attractive and reliable delivery performance. Muir, in his recent paper, has a similar difficulty in assessing the cash benefits resulting from computerized production scheduling. However, he is able to quote an improvement in vendor rating (see footnote) from 50% to 95% during the period that his system has been in use. Varley and Daniels[79] (Foundry Industry) add weight to the argument by suggesting that improved performance gives rise to increased customer confidence in the reliability and service offered.

FOOTNOTE: A vendor rating is a value assigned to each supplier by some of the larger customers of forgings, usually the automobile manufacturers. This rating value is a measure of the number of orders actually delivered on time in any given period, expressed as a percentage of those promised for the same period.

It might further be anticipated that an improved scheduling system could result in some decrease in W.I.P. and an improvement in machine utilization, particularly in the multi-operation-job situation characteristic of a die-shop. (An increase from 75% to 90% has been indicated by test data.) An improvement in machine utilization gives rise to increase throughput and the need for less overtime working or subcontracted work.

The conclusion might be drawn that, while a computerized scheduling system will almost certainly improve the market position of a company, the magnitude of this improvement in terms of increased annual turnover is impossible to measure. This is a value that will only be available after several months of successful implementation. During this time, the customers themselves will answer this question by way of their trading policy with the forge.

7.2 Implementation and operating cost of 'Stand Alone' scheduling system

The question of the best method to adopt for implementing a computerized scheduling system is not an easy one to answer.

The proposed scheduling system provides a means of planning the work load in both die shops and forge shops with a degree of objectivity impossible by any manual technique. This is only part of the story, however. An industrial production control department is responsible for several other functions in addition to that of job scheduling. These functions have been discussed in section 6.1, and include the initiation and maintenance of production records and files, generation of paper work etc. These functions may be described as mundane, clerical functions, disassociated from the subtleties of scheduling philosophy. They are, however, an unavoidable necessity for the efficient functioning of a production control department.

The ideal solution would be a totally integrated system, capable of the critical function of scheduling and all the data processing functions associated with scheduling and production control. The development and programming effort involved in such a task renders this an unobtainable ideal for a post-graduate research project. (The reader is reminded of the effort expended by the firm discussed by Muir[64] and by Knight[66] in somewhat similar tasks.) It has also been pointed out that such an integrated system would inevitably be unique to the firm at which it was developed and of little use to the industry as a whole. The net result is that the developed computerized scheduling system (which need not be restricted to the study forge) has to be evaluated, in terms of operating costs, in the unreal situation of its being a 'stand alone' system. This tends to prejudice the case in favour of the status quo, that is, the retention of the present manual scheduling system. For example, one item of information may have to be recorded for a computer scheduling system in a more detailed fashion than would be required for a manual system. However, in a totally integrated computer system, this item of information may be input to the computer once only but may be used by several programmes in performing different functions: generation of management reports, W.I.P. reports, updating machine schedules, etc. In a manual system, this same item of information would have to be recorded each time for each of the various functions. Thus, with an integrated computer system there would be a reduction in the overall clerical effort but the same reduction would not be apparent when considering the scheduling system on a 'stand-alone' basis.

The scheduling programmes were written in ALGOL and developed on an ICL 1905 E computer. The programmes are both quite demanding in respect of the central process or core store required, approximately 40 K words. (This reflects the need for several multidimensional arrays for storing files of job characteristics, machine queues etc.).

The language used, ALGOL, should pose no problem since most computer installations offer the facility for compiling ALGOL programmes. In fact, the programmes could be 'translated' to some other suitable language, say FORTRAN, within one or two months if the services of a professional programmer were obtained. The amount of core store required, however, restricts the running of these programmes to fairly large machines. Many drop forging firms belong to large groups, who often have a fairly large computer installation, serving the commercial needs of their subsidiary companies. The study firm, however, is controlled by a relatively small holding company with a modest computer installation, an IBM systems 3.

This is essentially a commercial machine with limited core store. For this, and other firms having no computer facilities, a bureau would appear to be the answer.

Bureau and computer installations remote from the firms 'site' give rise to problems of data transmission. The input data has to be communicated to the computer centre and output communicated in the opposite direction. This transmission may be in the form of a motor car collection service with overnight processing, or the more flexible computer terminal system may be used, coupled to G.P.O. communications channels. A courier service has obvious draw backs; possibility of hold-ups or delays (traffic/weather), problem of confidentiality, etc., but is perhaps the cheapest form of data transmission. A terminal, on the other hand, is available for immediate interrogation of files etc., and usually has an excellent response time (compared to a courier service). The charges, however, are not cheap, typically £40 - 50 per month including a MODEM, but excluding the charge of calls at the usual G.P.O. rates.

7.2.1 Method of Implementing a 'Stand-Alone' computerized scheduling system

A suitable method of implementing the computerized scheduling system is shown diagramatically in figure 41. The following discussion assumes a courier service for data transmissions, although the mode of implementation is basically the same irrespective of the method of data transmission adopted.

Daily Forge Production

The foremans 'tickets' containing daily production data currently arrive in the production control department on the morning of the day following production. In order that computer runs may be processed overnight, it is anticipated that these tickets will have to be available by 16.00 hours on the day of production. The information would thus be correct up to 15.30 hours or so.

Some of the information carried on these tickets would have to be copied to a punch document by the clerk (figure A11). Each ticket represents the daily production by one hammer.

New or repeat orders

If any new or repeat orders arrive in the department, resulting in jobs awaiting allocation to a production unit (i.e. scheduling), then:

1. Details of these jobs are also entered onto a punch document, as and when they arise. (figure A22).
2. Paperwork is issued to the die shop, advising the foreman of the need for dies to be prepared for this job. If no die preparation work is involved, then no die shop advice note is necessary.

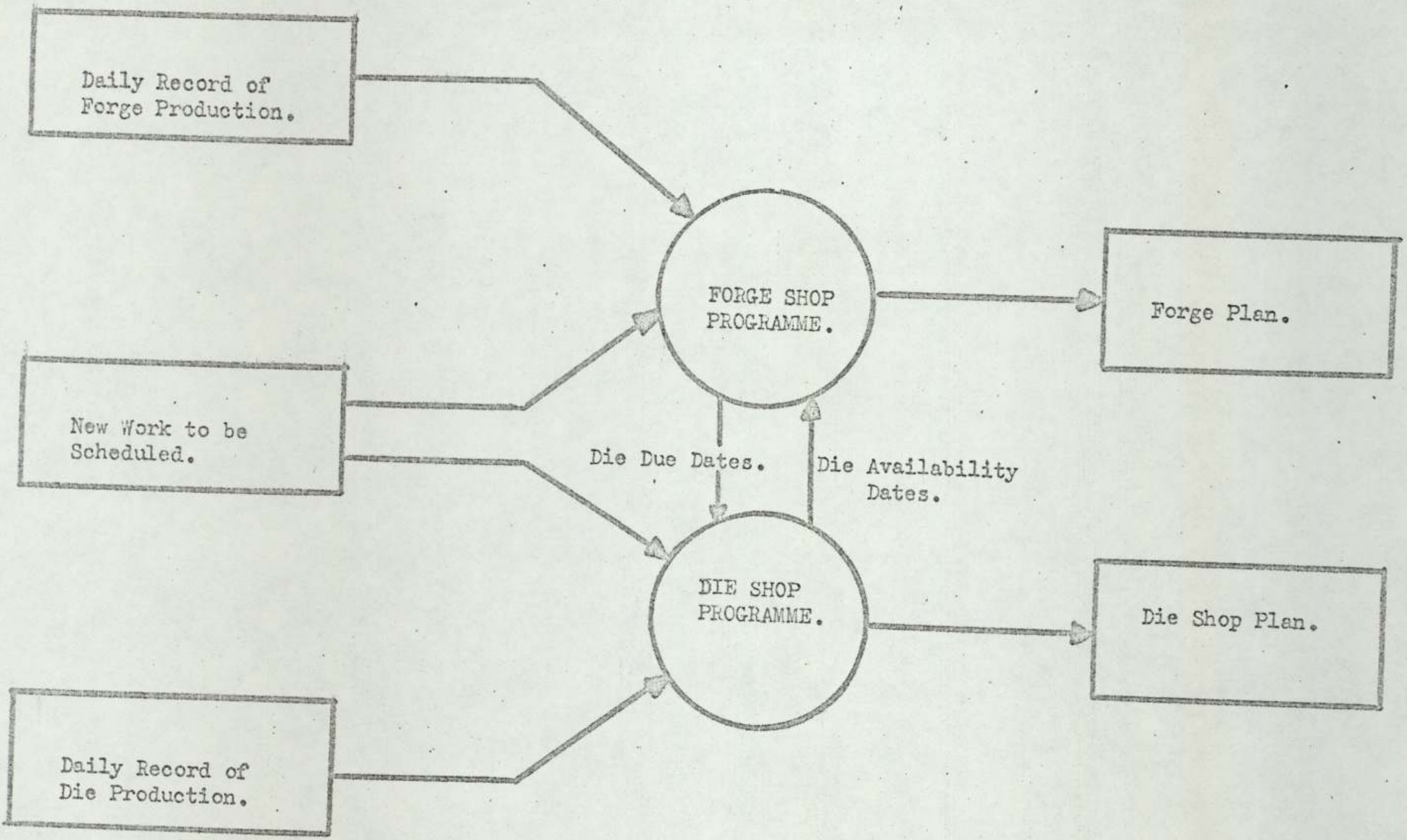

Daily Record of Forge Production.
New Work to be Scheduled.
Daily Record of Die Production.
FORGE SHOP PROGRAMME.
DIE SHOP PROGRAMME.
Die Due Dates.
Die Availability Dates.
Forge Plan.
Die Shop Plan.

Figure 41.

Towards the end of each working day

The production controller fills in a small punch document indicating todays date and the type of computer run required (figure A13).

It is envisaged that all (forge) punch documents would be collected by the courier at some time later than 17.00 hours for transmission to the computer installation. The line-printer output resulting from the overnight computer run could thus be back on the firms premises ready for the beginning of the following working day. (Overnight computer runs have the incidental advantage that bureau charges are often lower during the night than day-time rates.)

The above procedure ensures that schedules and scheduling information are updated to take account of daily forge shop performance and constant inflow of new or amended orders. Similarly, die-shop schedules must also be daily updated:

Daily die-shop production

Each die set, as it progresses through the various stages of die preparation, is presently accompanied by a card (figure A10). This card carries information regarding each operation. As each operation is completed, the card is signed by the machinist and the actual time taken to perform the operation noted.

With a computerized scheduling system:

1. These cards would have to be examined at 16.00 hours by the die shop foreman and information transferred from them to a punch document by him. (figure A14)
2. A small punch document would also have to be completed, detailing todays date and type of computer run required. (figure A13).

It is intended that the completed punch documents be collected by the courier, together with those for the forge shop ready for an overnight computer run.

New die-preparation jobs

These may be entered onto the respective punch document (figure A15) as and when they arise. The die-shop foreman can similarly enter any die preparation work not associated with a specific order. This might be necessary when dies for special projects are required, for example, or when preparing dies for other forges (subcontracting).

New die jobs may be input to the computer daily but, unlike the forge shop programme, new jobs are not allocated production time (scheduled) until one specific day each week (usually, Friday). Daily rescheduling of the die shop would be very demanding in terms of computer time and cost, due to the very much more complex nature of the die-shop scheduling programme.

The weekly Die-Shop reschedule - Interaction between forge- and die-shops

Each Friday, the forge shop 'flag' document containing todays date (figure A13) is completed so that the need for a die shop rescheduling run is indicated (as opposed to the daily 'update' type of run). Similarly, the die-shop 'flag' document is completed to show that a die-shop rescheduling run is required.

The line-printer output from the first cycle of the forge shop computer run, processed Friday night, is suppressed, the chief product of this run being a disc file containing 'die-required' dates (depending upon the forge shop schedule). The die shop programme is then processed, the dates held on the disc file, just produced, are read and used as targets or due-dates for the various die-preparation jobs. It is intended that the line-printer output from this computer run be despatched by courier to the drop forge, ready for examination by the production controller and die-shop supervisor early Monday morning, or preferably, Saturday morning. If examination of the exception report of 'dies likely to be late' yields jobs which the two men in consultation feel should best be subcontracted for some reason (say, excessive planned lateness), then a punch document is filled in accordingly. In any case, the flag documents are filled in and collected by the courier at around 09.00 hours. On reaching the computer centre, these few documents are punched up ready for the final stage of the rescheduling routine.

If it is thought desirable to sub-contract some particular die preparation job or jobs, then the die-shop programme must be re-run, followed immediately by the second cycle of the forge-shop programme. If no action was needed as a result of the examination of the original die-shop print out, then only the second cycle of the forge shop programme is necessary (there being no need to re-run the die-shop programme).

The die-shop run, in addition to the usual line-printer output, also produces a disc file containing 'die availability dates'. This disc file is read by the second-cycle run of the forge-shop programme, which uses these dates as earliest possible start dates for each respective forge-shop job. (The user need not concern himself with the existence of either the 'dies-requested' or 'die availability dates' disc files).

The line-printer output from the second-cycle of the forge-shop programme, together with the modified die-shop line-printer output, should be available at the firm by 12.00 noon, assuming a fairly efficient courier service. The organisation of the weekly rescheduling routine is more easily understood with the aid of the logic chart in figure 41.

The 'stand-alone' system was costed out adopting the same approach as that used for costing the totally-integrated system; that is, each clerical task was assigned a duration, and hence, a cost. The 'development costs' refer to the costs that would have been incurred had a systems analyst/programmer been employed by the firm for the duration shown. Since the services of a student were obtained by the study firm (myself), at very little cost to themselves, for the special case of the study firm, these development costs are pessimistic in the extreme. For other firms, however, these development costs must be considered although, again, they are likely to be pessimistic, since a very large proportion of the systems work has already been done and will be applicable to many drop forging establishments.

COMPUTER DEVELOPMENT COSTS

		£
Analyst/Programmer for one year at £3,500 p.a.	=	3,500
Computer time, test runs etc.	=	500
		4,000
over, say, ten years	=	400 p.a.

COMPUTER RUNNING COSTS

Computer time, 20 runs/week at £40/hr.	=	660 p.a.
Card preparation	=	200 p.a.
Development costs	=	400 p.a.
Clerical Involvement	=	68 p.a.
Courier		250 p.a.
TOTAL COST		1,578 p.a.

CLERICAL/MANUAL COST (MANUAL SYSTEM, PRESENT) = £ 575 p.a.

From these figures it can be seen that a computerized scheduling system, implemented in isolation divorced from computerized data processing routines, would probably incur additional annual operating costs of £1,000 when compared to a conventional manual scheduling system.

7.3 Intangible Benefits of Computerized Production Scheduling

Various intangible benefits resulting from the use of a totally integrated production scheduling/production data processing system have been indicated earlier, in section 6.1.3. Several of these benefits also apply to a 'stand alone' scheduling system. In addition, with a computerized scheduling system, there is a regular, daily updating of the machine loading queries. Unavoidable delays are acknowledged and the queues modified accordingly, not, as sometimes occurs with manual systems, when the production controller "finds time". Thus, the scheduling information available is always right up to date, enabling management to make better informed, more confident, decisions when using this data.

With the proposed computerized scheduling system, it should be evident that there is a considerable degree of interaction and inter-dependence of the forge- and die-shop scheduling. With such a computerized system, any changes, breakdowns or other unforeseen circumstances in the forge shop are automatically acknowledged by the die-shop system and the die-shop schedule adjusted accordingly. Similarly, vice-versa. This represents a significant improvement over the present manual system, in which the communication between the die shop and production controller is somewhat ill-defined, with the result that dies may have to be "rushed through" at the last moment if the order is not to be delayed. The production controller admits that the die shop is too complex for him to consider in detail. He must rely on casual observation and the occasional visit from the die-shop supervisor for his knowledge of the current die-shop position. This problem would not arise with the proposed system.

7.4 Wider Implications - Applicability to other Forges

For forging establishments similar in size to the study firm, it is anticipated that both comparative costs and benefits-obtainable will be very similar to those envisaged for the study firm. The study firm may be assumed to be a typical drop forge of its size.

The point was made earlier that the drop forging industry includes a diversity of firms; ranging from companies specializing in long running, repeat orders; to those chiefly involved in several short-run jobs, characteristic of a jobbing environment. (It is interesting to note Muir[80], "We make our money by changing dies.") The study firm falls someway between these two extremes, making both short-run jobs for certain customers, and also long-run jobs for others.

The 'mix' of short- and long-run jobs will have some influence on the benefits likely to be obtained from the adoption of a computerized scheduling system. Scheduling is a more acute problem for jobbing forges than it is for their long-run counterparts, where both the number of jobs to be planned and the frequency of rescheduling are relatively low. It is in a jobbing environment that most benefits are likely to be obtained. Conversely, an exceptionally high incidence of lost time through breakdowns etc. (perhaps due to rather old equipment), will drastically reduce any benefits from computerized production scheduling. A typical value for lost time is of the order of 15%.

In evaluating the suitability of the scheduling system for other, differently sized, establishments we must consider how the operating costs of a computerized system are likely to increase with problem size; compared with how the operating costs of a manual system are likely to be influenced by size.

As the problem size increases, it is almost inevitable that additional clerical staff have to be employed to cope with the additional data processing necessary under the present manual systems. Already the production control personnel at the study forge have expressed the need for an additional (male) production control assistant, since they consider that the department is presently working to the limit of its resources. Cost of data processing by conventional (clerical) methods depends very much on the volume of work processed. Once a computerized system is installed and functioning correctly, the dependence of cost on volume of work diminishes considerably.

Thus, as the volume of work increases, so computerized systems become increasingly less costly to operate than their manual (clerical) equivalents.

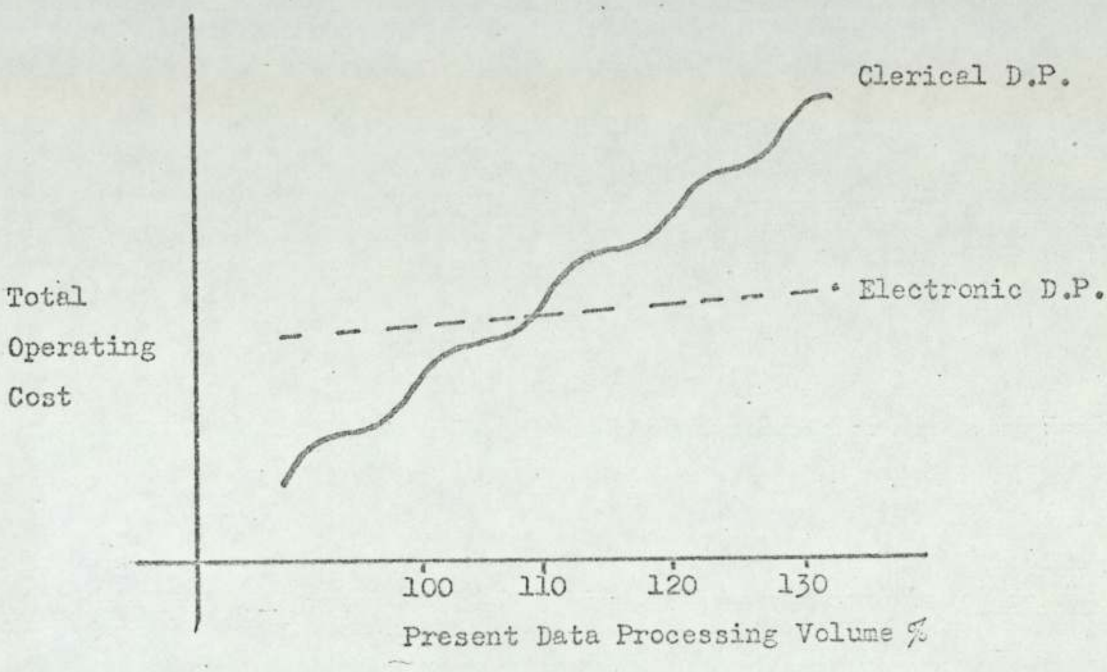


Figure 42 Relative costs of data processing (After Diebold[22]).

It should also be stated that, although so far we have considered the drop forging industry, the scheduling system could be used, with little modification, in a number of industries where the aim is to plan work through a series of production facilities.

8. CONCLUSIONS AND RECOMMENDATIONS

1. A cost estimating system based on forecasting models has been shown to be a practical proposition. The adoption of such a model-based system can be expected to provide increased accuracy in predicting values of flash weight and production rate for any forging.

2. The increased accuracy resulting from mathematical forecasting models has been shown by simulation to exert some influence on the marketability of the firm's forgings. An increase in market share by a factor of two has been indicated by the simulation experiments.

3. Multiple regression analysis by computer, as a technique for problem investigation and formulation of models, has proved to be a very powerful tool. It is considered worthy of further research effort in providing other opportunities for its use in a Drop Forging environment.

4. Discriminant analysis has been found not to be a very satisfactory technique for providing a solution to the hammer selection problem. A possible method of improving hammer selection has been indicated. It is recommended that further research work, perhaps at M.Sc. project level, be conducted on this important topic.

5. It has been shown that a computerized scheduling system,

suitable for planning work through both die- and forge-shops, is a practical reality. It has further been shown that the computerized system is not restricted to the study firm, but may find wider applicability throughout the industry. The heart of this system is a heuristic which anticipates the development of the machine loading queues.

6. The reduction in planned lateness accruing from the use of a computerized scheduling system, typically 30%, will doubtless result in an enhanced reputation for the firm, coupled with an increase in the amount of business placed by satisfied customers. Attempts to predict the magnitude of this increase can only be speculative, the answer being supplied in the long term, by customers trading policies with the forge, after several months of successful implementation of the system.

7. A pilot investigation, surveying the possibility of a totally integrated management reporting/control system (of which computerized scheduling is a fundamental part) has revealed that such an integrated computerized system is possible at the study firm. An integrated system can be expected to result in the availability of considerable additional information, currently not possible with manual systems. The annual operating costs of the computerized system are likely to be initially higher than those of the manual system. This cost differential, however, would reverse if the company becomes larger, and at the same time, more complex.

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