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# A Computer Simulation Study of Work Flow in a Manufacturing System

By

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## Synopsis

Batch production represents one of the most complex forms of manufacture and poor performance can often be traced to the lack of integration between the various aspects of the system. Solutions optimised with respect to the immediate set of objectives are frequently found to conflict with one another, thus affecting the effectiveness of the system as a whole. Group Technology has been widely advocated as a superior manufacturing method for improved work organisation. Despite the voluminous publications on the subject, not many consistent guidelines applicable to the general production situation have emerged by consensus. Experience of industrial applications relates to a relatively few selected case histories which were already pre-destined in favour of particular forms of GT solution, and atypical of the application of the more general principles to amorphous product mixes. A review of current philosophy and experience is presented, from which the areas of doubt in cause-and-effect and preferred policy and strategy are examined.

To investigate 'experimentally' the intricate issues and interactions, computer simulation of the influence of a range of production factors on the various system effectiveness measures has been carried out. These factors include the priority despatching rules, process-time distributions, batch sizes and frequencies, work-in-progress levels, and job inter-operation transit times. Further experiments have been conducted on the effects of a number of aspects pertaining more specifically to cellular manufacture such as the significance of cell size, number of tool set-up configurations, and manning levels and types. Grouping methods proposed for the design of cells have been examined and their influence on cell characteristics and size assessed. Also, an analysis has been made of the social implications of Group Technology. On a "micro" level some effort has been directed at determining the causes for the prevailing employment of sub-optimal cutting conditions, and the advantage that could be derived by exploiting the flexibility in the choice of machining data based on different criteria to meet with a changing work demand.

Among the conclusions reached is that manufacturing in smaller batches yields a better productive performance than larger ones, due to the property of being more readily distributed. In addition, by incorporating

a tool-setting minimisation factor into the priority rule the disadvantage of proportionally higher setting times for such smaller batch sizes is overcome. Priority rules have been found to exert a significant influence on the system performance. The most proficient rule is a hierarchical procedure incorporating the shortest imminent process time, least job slack, and tool setting minimisation elements.

Preoccupation with high machine utilisation usually leads to the use of an undesirably high work-in-progress. Experimental results indicate that by reducing the job queue length from 4-5 to 2-3 a substantial improvement in the system-throughput performance is obtained at the cost of a small decrease in utilisation. For cellular manufacture larger cells have been found to exhibit a superior work flow characteristic. The argument that keeping cells small (and hence achieving ostensibly a considerable saving in setting time) appears unfounded, as the throughput performance does not show much advantage beyond a very small number of tool set-up configurations, too small in fact to be commonly encountered in practice. Also, irrespective of cell-size effects per se, prolonged periods of matching the tool set-up type on subsequent loaded jobs is to be discouraged as the small improvement in work flow cannot justify the large deterioration in the reliability of meeting due dates. On re-examination, cellular manufacture has been found to be potentially favourable for greater job satisfaction and enrichment. But despite this, surveys of existing cellular systems tend to indicate that the social aspect has been largely neglected to the extent that those employed in them may actually suffer a lowering of conditions of working.

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# Chapter 1

## 1. Introduction

Job shop modelling was conceived in the 1950's, but earlier efforts were concentrated mainly on the study of scheduling rules. A further development that has so far been largely unexplored is the application of computer simulation for appraising the effects of various production aspects on work flow and the system performance. This area constitutes the subject of the present study.

Decisions made in production are often insular in nature, and hence, the solutions tend to be "local-optimum" rather than "overall-optimum". One example is the determination of batch sizes using the economic batch quantity theory. Batch quantities are derived on the basis of parameters pertaining to each batch and little consideration is given to the influence on the general work flow. The effect of batch sizes together with priority despatching rules, process time distributions, due date assignment and the work in progress level on the system performance will be investigated.

Despite the multitude of benefits that has been claimed for Group Technology, the number of firms which have actually implemented cellular manufacture is small. In view of the dimension of the innovation and the extent of re-organisation required it is not unexpected that many companies do not readily identify themselves with the situations of previous successful applications but maintain that more tangible evidence is needed to assess the suitability of their particular case. In this respect computer modelling can make a very valuable contribution.

The present work examines three facets of Group Technology. First, the cellular grouping methods advocated by various exponents are collated. Secondly, experiments are conducted to investigate the effects of cell size, number of part families within cells, manning arrangements, and the job inter-operation times on system performance. Thirdly, an analysis is made of the social implications of Group Technology.

One of the principal functions of production management is to achieve a balance between the manufacturing resources and the work demand so that a satisfactory job throughput is obtained. Whenever an increase in the production capacity is contemplated it is usually considered on a "macro-level", that is, through the purchase of additional facilities or adoption of a more advanced technological process. The alternative "micro-level" approach which consists of the employment of optimum cutting conditions remains largely ignored despite extensive theoretical research. The reasons for this theory-practice gap will be investigated.

# Chapter 2 : A Review of Job Shop Scheduling Studies


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## 2. Introduction

Over the last two decades a considerable amount of research has been directed at the job shop scheduling problem. This work falls mainly into one of two categories; the analytical approach and simulation studies. The earlier analytical efforts were focussed on the integer linear programming and complete enumeration methods. Bowman (1959), Wagner (1959) and Manne (1960) independently developed the job shop scheduling problem as an integer linear programming problem. However, because of the tremendous computational requirements for the solution of even small-sized problems (such as 3 jobs x 4 machines) little headway was made. In an attempt to simplify the problem to suit the capacity of the methodology studies were limited to flowshops. This differs from the general job shop in two respects. First, the work flow is unidirectional and the jobs visit the machines in the same order. Secondly, the processing order of the jobs on each machine is unaltered i.e. no passing is allowed. Effectively the previous $(n!)^m$ possible sequences for the n job x m machine problem are now reduced to a total of n! permutations. Despite this, in a study by Story and Wagner (1963) of six sets of the 9 jobs x 3 machines flowshop problem only in one case was a solution obtained when a run-out limit of 1000 iterations was assigned. In a yet further step towards a solution Giglio and Wagner (1964) employed an approximate method in which the integer constraints were ignored. Although the rounded linear programming solutions proved to be more successful they did not provide consistently good quality schedules and the computational demand still restricted their application to the smaller-sized problems.

An algorithm for the complete enumeration of all active feasible schedules was devised by Giffler and Thompson (1960). The computational experiences showed that for small-sized job shop problems it was practical to generate the complete set of all active schedules and to identify the optimal schedule directly from this set. But as the problem size was increased (to say, a 6 job x 6 machine) the number of feasible active schedules became a formidable statistic. It was then decided to explore the possibility of applying a Monte

Carlo sampling procedure on the population of active schedules to derive an optimal or near-optimal answer (Giffler et al. 1963). From this evaluation they concluded that the sampling strategy provided results similar to when the Shortest Imminent Process Time loading rule (SPT) was used. An alternative complete enumeration algorithm based on the properties of linear graphs was devised by Heller (1960). As with Giffler and Thompson's Gantt Diagram-based approach a Monte Carlo sampling facility was later also introduced to overcome the problem of the vast number of active schedules (Heller and Logemann 1962).

At this stage an impasse appeared to have been reached as both the integer linear programming and complete enumeration strategies were incapable of optimal solution except of trivially small problems. A revival and indeed a massive injection of momentum was given by Ignall and Schrage's (1965) and Lomnicki's (1965) adaptation of the branch-and-bound technique to the flow shop problem. The basic concept of this approach entails the partitioning of the set of all permutation schedules into necessarily smaller subsets and a lower bound is then applied to curtail enumeration of the partial sequences and identify a subset containing an optimal solution. To ensure optimality a backtracking process may be used. The computational efficiency of a branch-and-bound algorithm is judged on the effectiveness of the bounding procedure in reducing the number of nodes explored and producing lower bounds as high as possible so that those values would be close to the objective minimum schedule time. Investigation of a number of bounding procedures have been carried out by Ashour and Quraishi (1969) and Baker (1975).

Another method that has created a great deal of interest has been variously named as Elimination (Szwarc 1971, Baker 1975), Switch and Check (Ashour 1970) and Combinational (Gupta 1971). Here, an elimination strategy is employed to construct a dominant subset among the permutation schedules. It is then only sufficient to enumerate the schedules in this subset. A discussion and assessment of various elimination algorithms can be found in Szwarc (1971).

In a comparative study Ashour (1970) established the supremacy of the

branch-and-bound approach over the elimination method - in terms of the computational requirements. While the computation time escalates rapidly with both methods because of the combinatorial nature of the problem the factor of increase, as the number of jobs is raised from n to n+1, is 2.5 and 6 for the branch-and-bound and elimination methods respectively. A later investigation by Baker (1975) came up with similar findings. He further suggested a composite algorithm as a synthesis of the two approaches such that the branch-and-bound procedure is applied to the dominant set. In tests subsequently conducted an improvement in performance was recorded.

Although increasingly powerful algorithms have been evolved for the optimal solution of the flow shop problem they are still very much limited to the smaller and moderate-sized problems. For the larger and more practical cases the answer is sought in the sub-optimal or approximate methods. Among these are the branch-and-bound without backtracking, modified decomposition (Ashour 1969) and the algorithms proposed by Palmer (1965) and Campbell et al. (1970). The criteria on which the proficiency of these algorithms are based will be the quality of the solution and the computational.efficiency. Ashour's (1970) survey indicated that with the first two methods the average range of solution is 0.92 to 1.00 of the optimal. The rounded linear programming technique which was also compared was found to be less promising. Campbell et al. (1970) revealed figures of 1.38% and 4.58% respectively for the average error of their's and Palmer's algorithms. From the point of view of computational effectiveness Ashour found the branch-and-bound to be superior to the modified decomposition approach and Campbell et al. judged Palmer's to be ahead of theirs.

While the great preoccupation is undoubtedly with the flow shop problem some endeavours have also been addressed to the job shop problem. The approach that appears to offer the most potential is the branch-and-bound, just as for its sister problem. The first attempt by Brooks and White (1965) made little impact due to the prohibitive computational effort even for moderate-size problems (such as the 6 x 4). Later versions by Charlton and Death (1970) and Ashour and Hiremath (1973)

allowed some extension. But the prospect of applying analytical solutions to pragmatic job shop situations appears remote at this point in time even with sub-optimal methods.

## 2.1. Simulation Studies

In digital simulation studies the job shop is programmed as a network of waiting lines, with the jobs commuting from queue to queue until they are eventually completed and leave the system. Depending on the purpose of the investigation varying numbers of features of the real system are incorporated within the model together with the rules that dictate their collective behaviour. The simulated elements are allowed to interact with the passage of time thus presenting a dynamic pattern reflective of the actual environment it is intended to portray.

With the advent of high speed computers in the 1950's simulation techniques as an alternative to the theoretical methods were explored by several workers, prominent among which were Jackson and Nelson (1957), Rowe (1960) and Baker and Dzielinski (1960). It was soon clear that this approach harbours tremendous potential as it provides a great deal of experimental flexibility and is capable of application to large-sized job shop problems. Another advantage is its possible extension for use as a production planning tool. An illustration of such a case is that of the implementation at the El-Segundo Division of Hughes Aircraft Company (Le Grande 1963, Bulkin et al. 1966).

### 2.1.1 Priority Despatching Rules

The central feature of a simulation model is the choice of the queue discipline. The schedule that is ultimately obtained, and its merit judged on various criteria, is primarily determined by the manner in which jobs are selected from queues and despatched through the shop. The bulk of work on computer simulation of the job shop has been devoted to the examination of this singularly significant factor. Although the studies have thrown up certain salient findings this topic will be the subject of continuing research as overall concensus

remains unattainable largely due to differing and often conflicting objectives compounded by the empirical nature of the approach and the underlying stochastic properties.

Characteristic of most production problems, the analysis is either unit-based or cost-based. While this point alone provides fertile ground for debate we will not indulge further than to indicate the reasons for the adoption of each line of action. Cost-based investigations hold immense credibility as they are expected to derive a better and more rounded solution on account of having taken into the formulation the relevant cost parameters. This paradoxically causes its own failing as it also brings forth increased dimensions of inconsistency and uncertainty. In this instance the task of cost attribution, which is generally acknowledged to be difficult and at times arbitrary, is aggravated by the need to enumerate, among other intangibles, the cost of lateness of jobs when cost penalty is used as a measurement of effectiveness. Another peculiarity with regard to the cost-based approach is that depending on the assignment of the relative cost values and the inherent sensitivity one would arrive at a range of answers and consequently possibly also varying conclusions. In the light of this, it is not surprising that the majority of studies tend to be unit-based.

#### 2.1.1.1 Unit-based Rules

The two main measures on which the performance of the rules are assessed are firstly their effectiveness in getting jobs to meet their due dates and secondly their ability at reducing congestion and queueing time. Although the notion of deadline is in no altercation, there is a certain degree of ambiguity on the recording of job lateness. These have been variously designated as mean lateness (Le Grande 1963, Conway et al. 1967, Ashour and Vaswani 1972), mean tardiness* Rochette and Sadowski 1975), sum of tardiness (Gere 1966, Hollier 1968) and number of jobs tardy (Conway et al. 1967, Aggarwal et al. 1973). Some investigators have also proposed penalty functions to tax jobs

* positive lateness.

with increasing tardiness e.g. linear (Gere 1966), quadratic (McNaughton 1959) and exponential (Montagnon 1972). This inevitably places great limitations on the possible direct comparison of the results of the simulation studies. Attempts to rank these criteria would be presumptious as undoubtedly each would prove outstanding in particular situations. For the sole reason that they have been favoured by more workers the performance indices of mean lateness, standard deviation of lateness, number of jobs tardy and throughput times have been chosen to examine the findings of the merits of five simple sequencing rules; FCFS, DDATE, SLACK, SPT and S/OPN (for explanation of notations see Appendix 2.1). The FCFS principle is useful as a standard as well as being basically a practical and popular rule due to its inherent aura of fairness. The DDATE rule is the simplest way to observe the deadline requirement and has also practical applications. A modified version is the SLACK rule where the remaining process time is also taken into account. A further refinement is the S/OPN concept where the slack time is spread over the remaining number of operations left. The results obtained in several studies are given in Table 2.1.

Before embarking on a scrutiny of Table 2.1 it is necessary to delve into the background of the work of Ashour and Vaswani (1972). In their paper it was stated that with the exception of

(i) using a smaller sample of jobs and
(ii) truncating the maximum number of operations per job to 12 instead of 39

the experimental conditions employed by Conway et al. (1967) were closely replicated. What they failed to recognise is that the latter innovation has far-reaching consequences and contributes largely to the reason why their results are often out-of-line with the rest of the researchers. The effect becomes clear by consulting the values of the average jobs in the queues.

Average Jobs in the Queues (Shop)

| | FCFS | DDATE | SLACK | SPT | S/OPN | M/cs |
|---|---|---|---|---|---|---|
| Conway et al. | 58.87 | 23.25 | 51.25 | 49.45 | 51.65 | 9 |
| Ashour & Vaswani | 11.30 | 10.35 | 10.06 | 9.90 | 10.46 | 9 |

Considering that there are 9 machines in the shop model the small number of jobs in a queue at any time (ranging from means of 1.10 to 1.26) deem the role of the priority rules to be diminutive. In a similar context the accentuating influence of heavier workloads on the relative performance of the rules have been observed by Eilon and Cotterill (1968) and Rochette and Sadowski (1976).

As we scan through Table 2.1*, it is immediately clear that even when Ashour and Vaswani's figures are ignored unanimity on the performance ratings of the sequencing rules is seldom realised. This is not unexpected in view of the lack of co-ordination in the specification of model parameters which frequently differs radically from one experimenter to another. Under some circumstances certain sets of conditions may have been used which prove to be more favourable for particular rules. Nevertheless, these exceptions do little to cloud the manifestation of a number of major conclusions :

(1) The SPT rule is distinctively better for mean lateness, mean throughput times and number of parts tardy,

(2) The SPT rule causes a much larger lateness variance,

(3) The S/OPN rule is superior at achieving a low lateness variance.

The Shortest Process Time Procedure

The optimality of the SPT procedure in minimising the mean throughput time for the n/1 (n jobs, 1 machine) problem has been formally verified by Smith (1956). It is interesting to note that this truism is extended to the general job shop and that this property alone, with

* see page 29

the complete ignorance of any due date information, is instrumental in getting most jobs to be finished early. Although this characteristic has intrigued many workers and earned the label of being "easily the most important concept in the entire subject of sequencing"(Conway et al. 1967) the enthusiasm is not shared by practitioners, as can be seen from the reports of recent implementations of scheduling systems (Putnam et al. 1971, Berry and Rao 1975). In addition to the high variance in job lateness what simulators fail to reveal is that when interpreted in actual terms the SPT rule means that small components requiring few operations and little process times (Hollier 1964) are taken quickly through the shop while larger and more expensive parts with high work contents have a more prolonged passage. This culminates in a situation where the smaller parts, finished well ahead of their deadline, incur continuing inventory costs while the backlog of larger components escalate work-in-progress costs as well as suffer progressive lateness penalty costs as they are perpetually passed over.

Nevertheless in the practical sense the SPT rule is still completely viable as the vastly superior throughput performance could be equated to a higher capital turnover. A sensible remedy is to modify the rule so that some account of due date is incorporated. One strategy investigated by Conway et al. (1967) involved the formation of a composite rule with the S/OPN rule which from Table 2.1 is known to excel in lowering the lateness variance. The effectiveness of the composite rule in the form of a linear combination with different relative weights is given in Table 2.2. From these results, Conway et al. concluded that equal weighting (0.5 S/OPN + 0.5 SPT) produced the best overall performance. It is also worth recording that the SPT rule is clearly the more sensitive of the two to the influence of the other rule. In the case of the 0.25 S/OPN + 0.75 SPT weighting a greatly improved lateness variance is obtained at the expense of a steep rise in the mean throughput figure and equally worsen mean job lateness.

Table 2.2

| Rule | Mean Throughput Time | Mean Lateness | Std.Dev. of Lateness | No.of parts tardy |
|---|---|---|---|---|
| S/OPN | 66.1 | -12.8 | 15.0 | 323 |
| 0.7 S/OPN + 0.3 SPT | 67.7 | -17.3 | 19.2 | 158 |
| 0.5 S/OPN + 0.5 SPT | 57.6 | -21.3 | 22.8 | 132 |
| 0.25 S/OPN + 0.75 SPT | 52.2 | -26.7 | 26.4 | 172 |
| SPT | 34.0 | -44.9 | 53.6 | 437 |

Alternatively, hierarchic procedures can be used to improve the lateness variance of the SPT rule (Conway et al. 1967, Eilon and Cotterill 1968). Among other conceivable variations the three types examined were :-

(1) Jobs in a queue longer than a prescribed period, W, are processed on a FCFS basis. Otherwise the SPT rule is applied.

(2) Calculate the float of each job viz :

$$\text{Float } F_i = d_i - t - \sum_{j=J}^{g_i} P_{i,j} - U$$

where $d_i$ = due date of job i
$t$ = current time (at selection)
$g_i$ = total no. of ops. of job i
$J$ = imminent operation of job i
$P_{i,j}$ = processing time for the jth op. of job i
$U$ = a control parameter for delay (queue) allowance.

Two queues of jobs are formed; one for jobs with $F \leqslant 0$, the other $F \geqslant 0$. The $F \leqslant 0$ queue has priority and the SPT principle is applied in each case. This rule has been designated as the SI* rule.

(3) As for (2) except that for the $F \leqslant 0$ queue, the job with the lowest F value is selected.

Method (1) is a simple safeguard that no job is allowed to stagnate too long in any queue. As the value of W is increased (from zero) the trend shifts from the FCFS principle until at $W = \infty$ it is equivalent to the SPT rule. Conway et al. found that the SPT rule is sensitive to the truncation. Even for W = 32 (which is roughly 12 times the average waiting time of jobs with the pure SPT rule) a loss of 41% of the SPT's advantage over the FCFS rule is incurred. In methods (2) and (3) the jobs in the queue are assessed on their lateness with respect to their present due date instead of the period they have been in the queue. Hence the SPT principle is allowed to operate as long as jobs are not running late. For method (2) attempt is made to extend the SPT concept even to jobs that are recognised to be behind schedule.

Although Eilon and Cotterill have studied all three methods no definite conclusions could be derived due to deficiencies in their experimental design. The unusually small lateness variance for the SPT rule was explained to have arisen from the non-recording of long jobs still trapped within the system at the end of the simulation run. One would suggest that a more major contributory cause stems from the employment of the rather low load ratios. This is confirmed in the low mean delay factors (ratio of throughput time to processing time) that resulted. Method (2) was again later examined by Eilon and Chowdhury (1976) in the context of due date allocations. In this work they found that the lateness variance of the SPT rule can be reduced to the level of the FCFS principle at the expense of a fairly big drop in the mean lateness performance.

Look Ahead Procedure

A different line of approach is to find a concept that possesses the quality of the SPT rule in shortening the job lead times and yet does not aggravate the pace of the larger parts. One way of achieving this is to select jobs so that when they are finished they will join a queue which has little congestion. As the queue status which is determined at loading may have changed during the time that a job is being processed Conway et al. (1967) devised a modification where the

work accreditted to a queue is also considered. Their experiments showed that the modified version is more effective and that though both were clearly better than the FCFS rule in the mean number of jobs in a queue they do not approach the figure for the SPT rule. Such is not the case in the findings of Hollier (1968) which are given in Table 2.3. Here the WINQ rule is seen to be better than the SPT rule in all 4 measures of effectiveness. The great improvement in the remaining work content arises from the non-discrimination of jobs with long processing times. Another observation that can be made is that since the WINQ also disregards any due date information it does not fare very well in minimising the sum of job tardiness.

Table 2.3

| | SPT | WINQ | FCFS |
|---|---|---|---|
| Remaining work content (mean) | 28.15 | 18.67 | 30.85 |
| Sum of job tardiness | 46.30 | 23.00 | 18.70 |
| Mean throughput time | 7.54 | 7.34 | 9.69 |
| Mean queue time | 1.16 | 1.11 | 1.69 |

Gere (1966) tested the effectiveness of the WINQ procedure as a hierarchical combination with a number of job slack rules and concluded that in general some improvement in the sum of job tardiness is obtained. The same favourable outcome was not found in Eilon and Cotterill's work where the hierarchic association was with the SPT rule. In all measures used (mean throughput, job waiting time, delay factor, mean and standard deviation of lateness) the pure SPT rule emerged better, though in many instances the difference is not great. It is quite possible that this result might not be reliable for the reasons already given above. Conway et al. also examined a composite rule between the SPT and WINQ, viz 0.97 SPT + 0.03 WINQ. They recorded a slight advantage of the composite rule over the SPT procedure.

Minimised Setting Time Procedure

A common scheduling practice in job shops is to attempt to expedite work through the creation of extra capacity by sequencing jobs such that the set-up changeover times are minimised. The merits of this

procedure have been studied by Hollier (1968) and Wilbrecht and Prescott (1969). Two important considerations need to be borne in mind when examining the results from such investigations, especially when comparing the relative proficiencies of various despatching rules. These are :-

(1) the number of set-up configurations used and

(2) the ratio of the set and run times.

In Hollier's study five different types of parts were specified but the set/run time ratio was not given. The two versions of set-up minimisation procedures employed were :-

(1) jobs requiring no setting up have priority. Ties are broken by job numbers issued at shop entry i.e. equivalent to FASFS

(2) DDATE rule with jobs requiring no setting up (SET) as tie-breaker. Further tie-breaker is by FASFS.

Table 2.4 compares the performance of these two procedures against the DDATE and FCFS rules.

Table 2.4

| | SET | DDATE/SET | DDATE | FCFS |
|---|---|---|---|---|
| Remaining work content (mean) | 18.39 | 27.95 | 30.90 | 30.85 |
| Sum of tardiness | 25.20 | 26.80 | 29.70 | 18.70 |
| Mean throughput time | 6.48 | 7.94 | 8.60 | 9.69 |
| Mean queue time | 0.93 | 1.28 | 1.43 | 1.69 |

It is difficult to comment on the results as the savings on setting times are not given. Nevertheless it is interesting to note that although only used as a tie-breaker in the DDATE/SET rule the set-up minimisation concept was able to impart a noticeable improvement on the DDATE rule.

Wilbrecht and Prescott assigned parts with numbers 1,2,3 or 4. The

job in the queue that had a number with the smallest difference to the job just completed was selected. The difference between the two numbers constituted the setting time. There was no mention of the nature of the tie-breaker in the event that two or more jobs may have the same number difference to the processed job.

As sufficient details of the experimental data have been provided it would be interesting to look at the influence of the choice of simulation parameters in this particular study. For reference, some of the results are given in Table 2.5.

Table 2.5

| | RANDOM | DDATE | SPT | SET |
|---|---|---|---|---|
| No. of jobs late (per week) | 54.30 | 63.10 | 25.70 | 48.10 |
| Mean lateness | -47.90 | -45.90 | -16.20 | -26.20 |
| Mean queue time | 61.00 | 64.40 | 34.90 | 44.20 |
| No. of ops. completed (per week) | 91.30 | 88.10 | 91.70 | 102.90 |

First we note that the setting time may be 0, 1, 2 or 3 time units. Therefore, the average setting time is 1.5 time units. With a mean run time of 6.8125 time units the set/run ratio is approximately 22% and the average processing time is 8.3125 units. Table 2.5 shows that the mean queue time for a job was found to be 44.2 time units for the SET rule. Dividing this figure by the process time we estimate that on average there would be 5-7 jobs in a queue at any time. Since there are only 4 types of parts the probability that no setting up is required is fairly good. Hence a very favourable environment was created for the SET procedure. The appreciable time that is saved on setting and given over to running of jobs is reflected in the superior number of operations completed statistic. It is quite remarkable that notwithstanding this it is still unable to rival the SPT rule in the mean queue time and number of late jobs. In their conclusion, Wilbrecht and Prescott found the SET procedure to provide the best all round performance ahead of the SPT rule.

## A Composite Rule

In the above sections we have seen that the SPT, Look Ahead and Set-up Minimisation Procedures are all proficient at reducing job throughput times but as no account is taken of any due date information they often result in unacceptably high job lateness variances. It follows that if a composite rule could be devised to amalgamate some or all of these measures with a due date orientated function a potentially powerful scheduling concept may be evolved. Such was the aim of Conway, Maxwell and Oldziey (1966). The proposed rule is defined as :-

$$Z_{i,j(t)} = o_{i,j} - p_{i,j} + b.[\Sigma p_{i,j}]^r \cdot p_{i,j} + h.W_{nq}$$

where $o_{i,j}$ = operation due date of the jth operation of job i

$W_{nq}$ = ratio of the sum of process times in the next queue this job will visit to the sum of process times of all queues.

b,r,h = constants assigned for a particular run.

The first term $o_{i,j} - p_{i,j}$ is the operation-slack and incorporates the due date information. The second term $b.[\Sigma p_{i,j}]^r \cdot p_{i,j}$ intensifies the SPT effect in a congested condition. The Look Ahead procedure is included as the third term. No consideration is made for the set-up minimisation.

Some of the results of the studies are shown in Table 2.6.

Table 2.6

| | Mean Tardiness | Fraction Tardy | Mean Lateness | Std.dev. Lateness | Mean Throughput Time |
|---|---|---|---|---|---|
| SPT | 12.10 | 0.108 | -49.00 | 106.00 | 107.80 |
| S/OPN | 24.00 | 0.543 | 11.80 | 62.20 | 168.60 |
| (C1) b=r=h=0 (operational slack) | 21.90 | 0.422 | - 1.20 | 60.50 | 155.60 |
| (C2) b=15,r=0,h=0 | 6.52 | 0.152 | -38.70 | 58.70 | 118.00 |
| (C3) b=0.3,r=1,h=0 | 6.11 | 0.118 | -37.30 | 56.30 | 119.50 |
| (C4) b=0.3,r=1,h=160 | 5.43 | 0.120 | -39.40 | 56.30 | 117.40 |

Before proceeding to discuss the composite rule it is relevant to make an observation regarding the operation-slack rule. This rule is similar to the OPNDD principle except that :-

(1) the queueing allowance among operations is allocated in proportion to the process times rather than equally and

(2) the imminent process time of the job is also considered.

Comparing the operation-slack and the S/OPN rules, the former shows an all-round improvement. The most dramatic benefit is derived as we move from the operation-slack rule to C2, which is a linear composite between the operation-slack and SPT. Further gain in the tardiness performance is obtained if the SPT influence is accentuated with increasing congestion (C3). Finally as the Look Ahead procedure is introduced, in C4, all criteria of effectiveness responded favourably. From a practical viewpoint C3 and C4 involve a great deal more control effort and could not be successfully implemented unless there is on-line computer monitoring. Whether these extra cost and labour resources required could be justified by the marginal returns that can be derived is debatable.

### 2.1.1.2 Cost-based Rules

As mentioned in section 2.1.1.1 most researchers have detracted from a cost-based analysis of the scheduling problem due to the considerable difficulties that are associated with it. Nevertheless, in the final judgement, one must still reconcile the answers obtained from the alternative unit-based approach to the realities of a cost situation. A number of cursory attempts to include various cost aspects reflects some appreciation of this point.

The three principal cost measures that are most influenced by scheduling decisions are the inventory, lateness and utilisation costs. The inventory cost is usually reckoned on the amount of work-in-progress in the shop. For a more accurate assessment of comparative scheduling procedures the cash flow returns that can be derived from capital released from a reduced work-in-progress should also be considered.

Other benefits possible with an accelerated stock turnover cannot be so easily quantified. Attempts at defining a job lateness cost function is decidedly more complex as among other factors it is dependent on the manufacturing structure and the organic aspects of the firm-customer relationship. Several forms of the penalty function that have been proposed are, linear (Gere 1966), quadratic (McNaughton 1959) and exponential (Montagnon 1972). Eskew and Parker (1975) agreed with Lawler and Moore's (1969) contention that the function should be monotonically non-decreasing with time but suggested that it should be bounded. To achieve a minimal job lateness variance Eilon and Cotterill (1968) and Eilon and Chowdhury (1976) propounded a cost function viz:

Cost, $C = \alpha L + E$ where $L$ = total job tardiness,
$E$ = total job earliness
and $\alpha$ = a constant.

The computation of the facilities utilisation cost should present little problem since well-established costing methods can be applied. Furthermore, from previous simulation studies, it has been found that with the exception of the set-up minimisation procedure the machine utilisation figures for various priority rules do not differ significantly.

Rowe (1960) was probably the first to include some cost analysis in his work. In his aim to minimise the work-in-progress inventory he assigned flow allowances to jobs in an inverse proportion to their values. These flow allowances were progressively lowered as the values of jobs increased during processing. The net effect is equivalent to a built-in mechanism which expedites jobs as they near completion. An illustration of this phenomenon is given in Table 2.7. For the sequential rule (which is similar to the SLACK rule) a comparison was made between the results (i) when a fixed flow allowance is allocated for each operation and (ii) when a variable flow analysis outlined above is used. It is quite evident the variable flow analysis has led to better performances in both the lateness and inventory criteria.

Table 2.7

| | Fixed Flow Allowance | Variable Flow Allowance |
|---|---|---|
| Capacity utilised | 88.40 | 89.70 |
| Wait time-high value jobs (10%) | 0.58 | 0.12 |
| Wait time-medium value jobs (23%) | 0.55 | 0.22 |
| Wait time-low value jobs (67%) | 0.56 | 1.04 |
| Mean wait time | 0.56 | 0.74 |
| Carrying cost | 457.00 | 389.00 |
| Percentage of jobs tardy | 31.30 | 0.00 |
| Mean lateness | 0.16 | -2.68 |

Previously the unit-based method has shown that the SPT procedure is proficient at minimising job throughput times. But it is known that this has been achieved at the expense of a backlog of parts requiring relatively longer process times, which incidentally are probably also the larger and more expensive items. This conjecture has been proved to be true by Le Grande. The figures for the work-in-progress inventory costs for four scheduling rules are listed in Table 2.8.

Table 2.8

| | FCFS | DDATE | S/OPN | SPT |
|---|---|---|---|---|
| WIP inventory costs | 117836 | 98502 | 102800 | 128909 |

Investigations by Colley (1968) have revealed that with job values as the sole queue selection criterion the average level of inventory investment was just 40% of that of the SLACK rule. In practice this approach is not feasible because of the unacceptability of the delivery performance. The author suggested a compromise in which job values are employed as a tie-breaker for the S/OPN procedure.

The cost-based rule investigated by Aggarwal et al. (1973) consisted of a composite of the inventory, tardiness, setting and processing costs. The influence of each of the constituent elements was :

(i) the inventory cost : $C_1 V_i (d_{ij}-t)$ where $C_1$ = daily inventory cost per dollar of inventory; $V_i$ = value of job i; $d_{ij}$ = due date of operation j of job i and t = current time. Priority was given to high value jobs and jobs with protracted operation due dates.

(ii) the tardiness cost : $\propto C_2 V_i (t-d_{ij})^2$ where $C_2$ = daily tardiness cost per job value; $\propto$ =0 and 1 respectively for early and tardy jobs. Priority increased linearly with job values and quadratically with tardiness.

(iii) the setting cost : $C_3 K_3 s_{ij}^{-1}$ where $C_3$ = setting rate (cost); $K_3$ = mean setting time per operation j of job i. Priority was accorded to jobs with short setting times.

(iv) the processing cost : $C_4 K_4 p_{ij}^{-1}$ where $C_4$ = processing rate (cost); $K_4$ = mean processing time per operation and $p_{ij}$ = processing time of operation j of job i. Priority was assigned to jobs requiring little processing times.

The effectiveness of the cost-based rule was compared with the S/OPN, SPT and SET rules on five performance criteria. Table 2.9 represents the rankings extracted from the graphical results given in the paper.

Table 2.9

| | S/OPN | SET | SPT | COST |
|---|---|---|---|---|
| Cost per job | 4 | 3 | 2* | 1* |
| No. of jobs completed tardy | 1 | 3 | 2 | 4 |
| No. of tardy jobs in queues | 1 | 3 | 2 | 4 |
| No. of jobs in queues | 4 | 3 | 1 | 2 |

* rankings interchanged with a higher load factor.

The ranking of the facility utilisation figures is not included in the table as they have been found to have no significant difference. This is in agreement with the conclusions of other simulation studies. It is interesting to record the effectiveness of the SPT rule in the realisation of a low Cost Per Job. The results given in Table 2.9 are those for a load factor of 0.849. In the case of a high load factor of 0.958 the SPT rule is even better than the COST rule. This is contrary to what one would expect in view of the high inventory and lateness costs that are usually associated with the SPT discipline. The explanation for this is not difficult. With regard to the lateness cost the authors have stated that they were not punitive and constituted only one percent (1%) of the total cost. An equally unrepresentative situation existed for the inventory cost. A correlation was not designed between the length of processing time and the value of a job. Hence a job that is likely to be trapped in the system with the SPT procedure because of the long processing time required, may have a relatively low or high value.

It is also relevant to make an important comment concerning the COST rule. Referring to the computation of the inventory cost we notice that priority is given to jobs with a protracted operation due date since these jobs incur high inventory costs. This is surely fallacious as the implication is to practise a "reverse slack" where jobs with high slacks are expedited at the expense of those with lower ones. This would certainly have contributed as a major reason for the poor lateness performance of the cost-based rule.

### 2.1.2 Assignment of Due Dates

Whereas the choice of a despatching rule is very much an internal decision the same does not always apply in the stipulation of job due dates. It would be instructive to assess the effects of domestically- and externally-established deadlines and furthermore to determine the most effective formulation of the former.

In the RAND study reported by Conway et al. (1967) four due date assignment methods were investigated :-

(a) the flow allowance is in proportion to the total process time,

(b) the flow allowance is in proportion to the number of operations,

(c) the flow allowance is in a constant for all jobs, and

(d) the flow allowance is assigned randomly.

(a) - (c) could be roughly categorised as internally-fixed due dates while (d) represents those subjected to external influences. It is not surprising that the results showed (a) and (b), which take the job characteristics into account, to perform markedly better than (c) and (d). In turn (a) proved to be slightly better than (b) and (c) a little ahead of (d). The criteria for comparison were the mean throughput times,mean and standard deviation of lateness and number of jobs tardy.

Ashour and Vaswani (1972) attempted to examine the merits of a flow allowance that is proportional to the product of the total process time and number of operations. Unfortunately, it is not possible to attach much significance to their conclusions because of certain deficiencies in their experimental design.

More complex forms of the due date formulation were investigated by Eilon and Chowdhury (1976). The four procedures compared were :-

(a) $$d_i = r_i + f \times \sum_{j=1}^{g_i} P_{i,j}$$

where $d_i$ = due date for job i
$r_i$ = time of arrival of job i at the shop
$g_i$ = number of operations of job i
$P_{i,j}$ = process time of operation j of job i
$f$ = a constant

(b) $$d_i = r_i + f \times \left( \sum_{j=1}^{g_i} P_{i,j} \right)^k$$

where k is a constant

(c) $$d_i = r_i + f \times \sum_{j=1}^{g_i} P_{i,j} + f_2 W$$

where W = mean job wait time (determined by simulation experiments)

and $f_1$, $f_2$ are constants.

(d) $$d_i = r_i + f_1 \times \sum_{j=1}^{g_i} P_{i,j} + f_3 Q$$

where Q = number of jobs in progress waiting to be processed on those machines which lie in the route of a given job

and $f_3$ is a constant.

In addition to studying the proficiency of each of the due date allocation methods Eilon and Chowdhury also observed the effects of the tightness of due dates. It was shown that for method (a) the lateness variance is not sensitive to changes in the f values for the FCFS and SPT rules. But for the hierarchic SI* rule (defined earlier) the lateness variance curve takes the shape of a steep-sided trough. This makes the employment of the correct f value critical. With k = 1.0 method (b) degenerates into method (a). As the value of k is increased (to say, 1.4) the lateness variance rises sharply with the f value. This method is hence infeasible as it causes a great dispersion of the job lateness. The paper did not reveal any benefit of method (c) over method (a). This is to some extent predictable as W only considered the average job wait time and not the wait times of individual jobs. Although the conclusion was made that method (d) was the best of the four methods no direct comparison with method (a) was presented. In view of the attention that is paid to the likely delay situation of specific jobs it is undoubted that improvements would arise. But this benefit must be justified against the greatly increased planning effort required. One should also note that depending on the stability of the system the actual job passage might drift from what has been forecast, especially for the later operations.

## 2.2 Concluding Remarks

The preoccupation with the derivation of an optimal priority rule has led investigators to probe into most factors that could conceivably contribute some advantage and this has resulted in some cases in the proposal of highly elaborate formulae. Whilst the findings from a number of these studies are academically interesting, there is ultimately a need to come to terms with the feasibility for implementation of a despatching discipline in a production situation. Cost-based rules, though intuitively preferred, carry considerable difficulties. In addition to the problem of quantifying the various cost factors, the need to continually re-adjust the job priorities as values are altered with each completed operation restricts its application to the more sophisticated computerised production control systems.

For the unit-based approach the 3 desirable characteristics are :

i) a high utilisation of the resources
ii) a low mean job throughput time and
iii) a high reliability in meeting due dates.

With the exception of scheduling rules minimising tool re-setting the difference in machine utilisation is not appreciable. Simple rules have been shown to be inadequate in simultaneously fulfilling conditions (ii) and (iii). For example, the SPT discipline excels in the mean job throughput time performance but tends to finish small jobs ahead of their required due dates and large jobs well behind. The S/OPN and SLACK rules, on the other hand, are proficient in condition (iii) but not condition (ii). The best results are obtained by merging the SPT procedure with a slack-orientated rule either as a composite or hierarchy. A hierarchic arrangement is preferred because of the lesser computational effort as well as being easier to implement on the shop floor. A third aspect that should be considered for incorporation in the hierarchic rule is the minimisation of tool re-setting. This element would not only create extra capacity but when used judiciously it is conceivable that conditions (ii) and (iii) may be even improved. This point will be investigated in Chapter 5.

Table 2.1

| Mean Job Lateness* | FCFS | DDATE | SLACK | SPT | S/OPN |
|---|---|---|---|---|---|
| LeGrande (1963) | - 3.56(4)# | - 4.20(2) | N/U | - 6.56(1) | - 4.16(3) |
| Conway et al.(1967) | - 4.49(5) | -15.53(2) | -13.13(3) | -44.90(1) | -12.79(4) |
| Eilon & Cotterill (1968) | (3) | (2) | N/U | (1) | N/U |
| Wilbrecht & Prescott(1969) | N/U | -45.90(1) | N/U | -20.20(2) | N/U |
| Ashour & Vaswani (1972) | -36.34(2) | -35.34(4) | -35.38(3) | -37.30(1) | -34.79(5) |
| Holloway & Nelson(1973) | N/U | N/U | 7.30(2) | 0.20(1) | N/U |
| Weeks & Fryer(1976) | N/U | N/U | N/U | (1) | (2) |
| **Std. Dev. of Lateness** | | | | | |
| LeGrande | 10.00(4) | 8.20(2) | N/U | 9.90(3) | 2.00(1) |
| Conway et al. | 41.10(4) | 20.80(2) | 20.80(2) | 53.60(5) | 15.00(1) |
| Eilon & Cotterill | (3) | (1) | N/U | (2) | N/U |
| Wilbrecht & Prescott | N/U | 5.81(1) | N/U | 7.03(2) | N/U |
| Ashour & Vaswani | 25.82(5) | 25.41(4) | 23.12(1) | 25.22(3) | 24.48(2) |
| Holloway & Welson | N/U | N/U | 50.00(1) | 152.00(2) | N/U |
| Weeks & Pryer | N/U | N/U | N/U | (2) | (1) |
| **Mean Throughput Time** | | | | | |
| Conway et al. | 74.43(5) | 63.72(2) | 65.79(3) | 34.02(1) | 66.13(4) |
| Eilon & Cotterill | (3) | (2) | N/U | (1) | N/U |
| Ashour & Vaswani | 9.26(5) | 8.01(1) | 8.12(2) | 8.39(3) | 8.51(4) |
| Rochette & Sadowski(1976) | 38.30(5) | 34.10(2) | 38.20(4) | 24.70(1) | 37.00(3) |
| Holloway & Nelson | N/U | N/U | 52.60(2) | 45.50(1) | N/U |
| Weeks & Fryer | N/U | N/U | N/U | (1) | (2) |
| **No. of Jobs Tardy** | | | | | |
| LeGrande ** | 37.80(4) | 33.00(3) | N/U | 24.50(2) | 20.40(1) |
| Conway et al. | 3898 (5) | 1544 (3) | 1916 (4) | 437 (2) | 323(1) |
| Wilbrecht & Prescott | N/U | 63.10(2) | N/U | 26.20(1) | N/U |
| Ashour & Vaswani | 7.00(4) | 0 (1) | 0 (1) | 0 (1) | 10.00(5) |
| Aggarwal et al.(1973) | N/U | N/U | N/U | (2) | (1) |
| Week & Fryer** | N/U | N/U | N/U | (1) | (2) |

* Negative values denote that jobs are early

\# Figures in brackets denote rankings

** Percentage of jobs late

N/U Not used

## Chapter 3 : Human Aspects of Group Technology


| | |
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## 3 Introduction

There is little dispute that group technology was conceived on purely technological and economic grounds, and beyond the question of pay, human factors have been largely ignored. Recently the social aspect has gained prominence mainly due to the overflow of influence from the innovation of work groups and job enrichment schemes that are being evolved in the mass production sector. Although even today many still hold the view that the batch industries do not face the same pressing social problems as their mass production counterparts there is increasing evidence to show that the skilled worker is getting continually disillusioned as his role is slowly reduced to no more than that of a machine minder (Lane 1969). The most startling revelation is contained in a report by Eastwood (quoted in Anon 1976) where it was claimed that approximately 60% of the baggage handlers at Manchester Airport are skilled men. The main reason for the change of designation was stated to be greater job security. This must be ironical when industries are said to be handicapped by a shortage of skilled workers. Indications that management is starting to realise the mounting discontent of their labour force can be deduced from the findings of Bennett and Macconnell (1973). In response to the managerial objectives most sought after in the wish to apply group technology, job enrichment was placed well ahead of systems improvement, stock control and stock reduction. A publication prepared by the tripartite steering group on job satisfaction, which represents the Government, the TUC and the CBI, pointed out that "there is a growing realisation that such arrangements (GT) incorporate a number of features of good job design and can increase the satisfaction of employees" (Anon 1975).

With the adoption of group technology a considerable amount of rearrangement is introduced into the social pattern of the work force. Whilst the outcome has been generally shown to be positive there are a number of major obstacles that merit serious attention. GT is sometimes confused with group working with the consequence that it is automatically assumed that the improvement in job satisfaction is

inevitable and immense. This is not necessarily so for unlike group working, GT is not a job alienation instigated development where a much enriched method of working is substituted for a previously tedious and non-motivative one (Phythian 1974 , Lindholm 1975). Instead the situation is more a matter of trading-off of certain valued features of the conventionally-laid out system with some good points of group manufacture.

For an appreciation of the social implications of GT it would be helpful to structure the investigation on the basis of the work of Herzberg (1968). His theory suggests that the factors involved in producing job satisfaction and motivation are separate and distinct from those that lead to job dissatisfaction. The motivator factors are intrinsic to the job and are given as :-

(a) achievement
(b) recognition for the achievement
(c) the work itself
(d) responsibility and
(e) advancement or growth.

The hygience factors on the other hand, are extrinsic to the job and would include company policy and administration, supervision, interpersonal relationships, working conditions, salary, status and security. Although these findings have been conceptualised from and mainly applied to administrative, clerical, supervisory and technical positions (Herzberg et al. 1959, Paul and Robertson 1970) they have nevertheless much relevance to the blue collar situation.

## 3.1 Achievement and Recognition

On the shop floor the task procedures are usually well defined and technologically restrictive. There is, therefore, little scope in the way of innovative or creative achievement. Any form of achievement will then have to be related to the task itself such as the quality and/or quantity of the work produced. With the payment system often on the basis of individual bonus scheme there is little

incentive for the worker to consistently provide a high level of output as he is conscious of the possibility that the piece-rate may as a consequence be re-adjusted. In a conventionally-arranged machine shop the operator at each functional group performs certain operations on the workpiece before sending it on to other sections for further processing. This transfer of responsibility gives a poor job and goal identification with the result that the quality of the work suffers. Such is not the case in the cell system. Despite the unlikelihood that all the operations required on a job will be finished by a single operator the work is nevertheless completed within the confines of the cell ( that is, with the exception of prescribed extra-cellular processes). The cellular group can then collectively associate themselves with the job entity and a common goal. With the clearer demarcation of responsibilities there is also a greater ease at the attribution and recognition of achievements. Companies which have adopted GT have been almost unanimous in endorsing this positive aspect.

## 3.2 Work Characteristics

On the basis of a review of existing literature Turner and Lawrence (1965) devised a conceptual framework of six requisite task attributes deduced to be positively related to worker satisfaction and attendance. These are variety, autonomy, required interaction, optional interaction, knowledge and skill required, and responsibility. In studies subsequently carried out it was found that people from varying subcultures (town and city) responded differently, in particular to task complexity. To avoid the subcultural influence Hackman and Lawler (1971) proposed the following six job dimensions :

(a) variety
(b) autonomy
(c) task identity
(d) feedback
(e) dealing with others and
(f) friendship opportunities.

The first four are labelled as core dimensions and the last two as interpersonal dimensions.

### 3.2.1 Variety

The group technology principle dictates a reduction in the variety of component sizes and shapes within each cell. While from the setting-up point of view there should be ideally one family of parts per cell; this would present tremendous difficulties in ensuring an effective level of loading. As such cells designed with sufficient foresight and consideration to an eventual stable load balance would provide a larger variety of part features. GT cells are also characteristic in having more machines than men. This in-built operator flexibility in handling more than one type of machine goes towards recompensing the lower work variety. Unfortunately this aspect of cell practice brings forth problems from all quarters (Fazakerley 1974). The firm is concerned that the skilled worker who is paid for his skill should be employed in activities that maximise his abilities. When operators are deployed on machines for which they are not specialised one may have to reckon with a lower efficiency. The third difficulty arises from the early specialisation of the apprentice programme which means that an extensive re-training scheme is necessary for GT implementation. For the employee there is the inherent resistance to change and apprehension of any adverse effects that performing relatively unfamiliar jobs may have on his pay packet. The skilled operator is also nervous about possible dilution of his status. The trade union, generally, is in favour of imposing restrictions on flexibility to preserve the status of the skilled men and maintain job security for all its members. A frequent compromise to this situation is to assign the skilled workers to the principal machines with some flexibility in attending to other tasks while the semi-skilled operators are expected to have greater mobility. In a far more drastic measure operators are transferred between compatible machines in different cells (Barker 1970, Connolly et al. 1970). This action is discouraged by social scientists. A good indication of prevailing cell practices is given in the survey findings of Pullen (1976). He found that :-

16% of the cells had every operator capable of doing all jobs

35% had operators able and willing to do at least two of the jobs in the cell;
27% had some operators with exclusive rights or ability to operate particular machines but otherwise willing to operate other machines;
16% had some operators who did not move for one reason or another and
6% had no operators moving at all.
There is clearly varying success in the achievement of intra-cellular operator flexibility.

### 3.2.2 Autonomy

For an assessment of this factor a set of criteria has been developed (Gulowsen 1972). The degree of autonomy is dependent upon the group being able to :-

(a) influence the formulation of its goals with respect to the quality and quantity of work produced
(b) decide where and when to work and which other activities it wishes to engage
(c) make the necessary decisions in connection with the choice of the production method
(d) make its own internal distribution of tasks
(e) decide on its own membership
(f) make its own decisions with respect to matters of leadership and
(g) decide how the work operations shall be performed.

Needless to say that it would be far fetched to assume that there are many situations where all these attributes could be attained. But in comparing GT and the functional layout there is little doubt that the former would be more conducive to the establishment of some of the above features because of the unified goal of the work group. Technological constraints in the machine shop places great limitations in the allowance of autonomy, especially with respect to (b), (c) and (g). More often the blame lies squarely with the management. Pullen reported that in 67% of the cells the operators were instructed if and when to move within a cell rather than being allowed to organise themselves. He went on to say that there is evidently a lack of

understanding, or a rejection, of the full cell concept of autonomous work groups in many factories. Statistics collected showed that management could interfere with the group arrangement directly in 25% of the cells and indirectly in the rest. 7% of the groups had influence over the the selection of new group members and 71% had a cell leader, but none were elected by the group members. Autonomous responsibility for maintaining cell discipline were enjoyed by only 17% of the cells. No cell had discretion of working hours as all operators were required to clock in and out. More encouraging trends were in the areas of inspection and work progressing which revealed figures of 75% and 89% respectively.

### 3.2.3 Task Identity

Jobs high on task identity are characterised by :-

(a) a very clear cycle of perceived closure - the job provides a distinct sense of the beginning and ending of a transformation process

(b) high visibility of the transformation to the worker

(c) high visibility of the transformation in the finished product and

(d) a transformation of considerable magnitude.

With the exception of property (b) which already exists in any non-process type of production system, the features are just those that GT is committed to; albeit for the reason of a simplified work flow rather than from the point of worker satisfaction and accomplishment. Despite the need for some components to go outside the cell the operators can closely identify themselves with the integrity of the work task. This is enhanced by the delegation of responsibility to the group for the inspection of the finished items. Although in many instances (74% of the cell groups) work "foreign" to the cell is introduced this constitutes a minor portion of the work load and is not likely to upset the sense of work identify. In contrast, operators in a functional system have little opportunity for job identification as the tasks are often fragmented. This is sometimes aggravated by the

lack of control over the quality of previous operations on the work.

### 3.2.4 Feedback

The measure of improvement in feedback within a production cell is quite considerable, according to Craven (1975). Since each operator is aware that the subsequent operation will be performed in close proximity to him and within a short space of time there is an instilled effort on his part to ensure a high quality in his work. A failure to do this will result in an immediate and critical response from his neighbour. While appreciating the benefits, one should also recognise the possible repercussions from the grouping together of workers with varying but interdependent skills, as this may develop into a situation of conflicts. One way of preventing this outcome is to attempt to unify the goals of the cell members. The implementation of a group payment system is a positive step in this direction. To see how far this is practised in existing cells we refer once again to the findings of Pullen. The statistics are :-

8% are on sub-contract;
2% have pooled wages;
4% are paid on a group bonus;
8% receive a salary;
53% are on an individual bonus scheme; and
25% are renumerated in some other way.

Therefore, the position does not look too promising. The difficulty is inherent in the wide range of skills that is expected to prevail in a cell. The solution may well lie with the Swedish approach (Anon 1974) where a weighting factor is formulated for each team member on the basis of his level of skills, contribution to production, and so on.

### 3.2.5 Personal Interaction

The interpersonal relationships can be categorised as either required or optional. The former pertains to the degree to which the job necessitates employees to deal with other people, both within and

external to the company, for the completion of the job; whilst the latter relates to the extent in which the work permits the establishment of informal communication amongst the workers. From their studies Hackman and Lawler concluded that there is no consistent or strong relationship between the interpersonal dimensions and motivation, performance or absenteeism. Emery (1959) also made the comment that "it has been frequently observed that men work better when the relations on the job are friendly, and yet there are some facts to suggest that this is only part of the story - that men will carry out their jobs regardless of personal feelings, if their roles are well enough related to each other." Of an opposite viewpoint, Wild (1974) suggested that group cohesiveness has an important impact in respect to job satisfaction, absenteeism, turnover and productivity.

A central consideration in the investigation of interactive behaviour is the size of the work group. Mainly due to the influence of Rice (1958) and Beek (1964) there is an intense conviction (Williamson 1972, Burbidge 1973, Edwards 1974) that the number of members should be maintained at a low value, preferably below 10. Besides the social aspect the production engineering factor is equally if not more dominant. In the paper by Tetford and Ferris (1976) describing the planning of a GT application it was stated that the initial objective was to design cells containing approximately ten operators each. After a detailed study of the various production and control implications the finalised proposals were for cells with workforces ranging from 22 to 30. Pullen found in his survey a high variance in the number of operators per cell; the smallest is 3 and the largest 36. Some researchers disagree with the great emphasis that is placed on limitation of group size. Fazakerley (1976) gave an instance when absenteeism and turnover actually rose when the cell size was reduced. She explained that within a larger group there is a greater probability of individuals finding congenial co-workers and hence reducing stress. Emery questions the assumption that a satisfactory and efficient work group operates through the psychological identification of the individual with the other persons in the group rather than through the role definition of an individual's task as part of the whole task. In support he reported the surprise expressed (Wilson and Trist 1951, Trist and Murray 1958) when happy

relations were found within large work groups.

A more crucial issue with respect to the work group is its stability. There is little purpose in extolling the benefits of a small cell size if the stability of its membership is continually disrupted. The contradictory position of the creation of a strong in-group feeling and the occasional group detachment produces a highly negative phenomenon. As Craven (1975) observed "the sense of belonging to a particular group virtually imposes boundaries ..... we would think twice about asking an operator to move over to an overloaded cell. It would be no surprise if he objected to such a move even if it were only temporary." Notwithstanding, Pullen's investigation showed that poor cell design causes operator movements in and out of 58% of the cells.

## 3.3 Responsibility

In the quest for job improvement there is a need to differentiate between horizontal and vertical job enlargement. The former is aimed at making the job structurally bigger and more meaningful while the latter serves to provide an enhanced opportunity for the employee's psychological growth and a feeling of personal responsibility for the outcome of his work. Research (Lawler 1969 , Hackman and Lawler 1971) has shown that optimal results are derived in most cases with the simultaneous development of both characteristics. Vertical job enlargement, or job enrichment, poses two problems for management. Firstly, the delegation of proportionally more responsibility to the workforce carried with it high operational risks and secondly, there would be a further reduction of the role of the first line supervisors. On the first count, Paul and Robertson (1970) were able to conclude from their studies there is really little cause for concern. In every case that they encountered the workers have measured up to the accountability of their extended authority. With a large measure of responsibility and control taken off the hands of the supervisors, the requirement for close supervision became superfluous. Although supervision may be redundant, the supervisors need not. On the contrary the supervisor's lot is actually improved as divested of the day-to-day administrative chores he is now able to concentrate

his efforts on higher-order and more meaningful assignments.

In a study of the effects of group production methods on the humanisation of work (Burbridge 1975) it was established that in contrast to the traditional method of working which, with its centralised co-ordination, tends to inhibit the sharing of responsibility, group working facilitates the delegation of decision-making. Views vary as to the extent in which the sphere of responsibility should be increased. Herzberg (1968 II) advocated the inclusion of planning, control and inspection of their work while Lindholm (1975) and Cotgrove et al. (1971) suggested that the workers should also be given the responsibility of collateral and supportive duties such as maintenance, lubrication and minor repairs.

A literature search shows that although numerous case studies have been published on the adoption of GT, comparatively little has been written on the social aspects. Nevertheless indications are that in many instances the inspection function has been included within the cellular groups. The transference of the production planning and control responsibilities has been met with a much more limited success. Also despite a popular conviction that cells should be self-contained, as evident by the widespread provision of tool-banks and the like, there is no report of any application where the group members have been assigned the collateral tasks proposed by Lindholm and Cotgrove and his collaborators.

### 3.4 Advancement or Growth

For the blue-collar worker the probability is high that he will remain a manual wage earner and continue to do a similar level of job for the whole of his working life. Though it may be possible to enrich his job, even appreciably, it would be unrealistic to presume that one can progressively generate more interest and challenge in the contents of his tasks. Faced with this obstacle for individual growth the worker looks to the improvement of his position through the advancement of the group of which he is a member. He accepts that he can only progress with improved earnings, benefits, status and condition of his wage grade or class.

Craven (1975) observed that the cell system provides greater scope for some workers to extend themselves and play a significant part within the group. While it is likely that there will emerge leaders who are chargehands or operators of pacing machines, it is equally possible for other individuals to assume a position of strength because of their natural aptitude as leaders. These workers may not hold key positions in the cell but nevertheless there is now the possibility of satisfactorily engaging themselves in the role of organisation.

The move towards operators performing a multiplicity of tasks and hence the re-training for additional skills may also be seen as a positive step in the provision of some opportunity for advancement. Even in cases where there is little flexibility in the manning procedure a machine operator may gain status. Whereas in the previous functional system he is one of many with the same skill in a department he may now be the only member in the cell possessing his particular type of skill.

## 3.5 The Hygiene Factors

The hygiene factors have been shown to produce little or no improvement in job satisfaction and are powerless by themselves to motivate. However, they form the prerequisites for effective motivation and unless in satisfactory balance would generate losses in morale and efficiency. The trade unions have generally adopted a cautiously enthusiastic posture to the concept of job satisfaction and are mindful that schemes for upgrading job satisfaction through changes in work organisation should not be contemplated as substitutes for improvements in the working environment and terms and conditions of employment (Graham 1976, Whitaker 1972). It would also be relevant to point out that there is evidence that in some cases workers may choose their jobs largely for the extrinsic reasons of pay and security rather than for intrinsic reasons. They seek their satisfactions outside and see work solely as a means of procuring money for the pursuit of these activities (Goldthorpe et al. 1968).

With the introduction of group technology the factors that are likely

to be directly affected are supervision, interpersonal relationships, pay and security.

### 3.5.1 Supervision

There appears to be a reasonable concensus among the case studies published that with cellular manufacture the need for close supervision is obviated. The first-line supervisors are either deployed on other managerial duties or reassigned as working chargehands in a cell. Work carried out by the Institute for Social Research at the University of Michigan (Perrow 1970) asserted that supervisors of high-producing groups seem in the workers' view to behave differently from supervisor of low-producing groups. In many cases the high-producing supervisors was less punitive towards his subordinates; supervised in general ways rather than closely and was more likely to be concerned about his subordinates as human beings, as individuals, rather than as means for turning out a product.

### 3.5.2 Interpersonal Relationships

In Section 3.2.5 we discussed the influence of some cell characteristics on interpersonal relationships. With the unification of goal GT provides great potential for a good working environment within the group. But unfortunately due to either technological reasons or just sheer lack of social consciousness on the part of management these advantages are not always realised. In her investigations Fazakerley (1976) noted that few companies locate their machines with any consideration of how best to develop social integration. In some instances the constraints arise from space availability, cost of moving machinery, and existence of present electrical outlets while on other occasions groups are fragmented by physical obstacles such as gangways, shelves or work stocks.

### 3.5.3 Financial Rewards

The earlier doctrine of economists like Adam Smith of the rational-economic man whose actions are driven purely by the single goal of a maximisation of self-interest has by and large been dismissed as too

simple and inadequate and in its place are suggested various models (Schein 1970) of man with a multiple set of goals. Some evidence in support is given by Whyte (1955), who carried out an investigation into whether money is indeed a prime motivator of productivity in industrial settings. From this study he observed that among production workers the proportion of men who were primarily motivated by money was very low (about 10%). More recent findings are contained in a report of a national survey of British attitudes to money and work by the Opinion Research Centre (Forrester 1977). The statistics showed that :

(1) the respondents were remarkably unambitious in a material sense. Most thought that they should work only as much as they need to live a pleasant life and

(2) working class interviewees were less likely than the middle class to say that they did not want any more money.

Hence, it is clear that in general financial rewards as an incentive will derive progressively diminishing returns, On the other hand, it is very important that the pay should not be "low". In their examination of the reasons for craftsmen leaving engineering the National Economic Development Office (Anon 1977) established that poor pay was one of the major causes of a disturbing number of workers switching to other occupations.

In a wider context it is abundantly evident that pay has become to be associated with status. In the O.R.C. Survey mentioned above it was recorded that whereas most unskilled workers tended to ask for a bit more, over half the skilled workers wanted an extra £15 a week or more - a reflection of the growing concern for differentials.

It is suggested that for management-evolved job enrichment innovations it is necessary to increase the workers' monetary remunerations in accordance with their new responsibilities, as a failure to do so could result in suspicion of management, charges of manipulation and a resistance to future changes (Daniels and McIntoch 1976). While recognising that GT is seldom consciously or directly introduced for

reasons of job enrichment this point is nevertheless relevant in view of wide-ranging changes in organisation and responsibilities. Fortunately with the higher productivity the commensurate increase in pay is possible. In contrast, in the breaking down of the traditional demarcation between different groups of craft workers for the higher labour flexibility it is important to heed the workers' concern for the protection of pay differentials.

### 3.5.4 Job Security

The recurrent economic difficulties, coupled with technological and organisational changes, have brought about a rise in the number of workers being made redundant. This naturally leads to mounting fears about the security of jobs. The GT concept of maximisation of labour utilisation while welcomed in an expanding economy is bound to meet with growing resistance from the shop floor in times of high unemployment. Particularly in regions of large scale unemployment one of the priorities in bargaining is bound to be focussed on guarantees of no redundancy. For a man who has always felt to be at the mercy of his environment, money is no substitute for security, and security lies in a continued need for his services. It appears sensible to him to keep his services marketable by refusing to accept higher pay, even though, paradoxically he is actually increasing the overall cost of his labour by keeping his productivity low.

## 3.6 Personal Characteristics

It is by far too frequent that work attitudes and motivators are regarded in terms of a fixed order of priorities, needs or interests with the implication that all workers are interested in the same things to the same degree in all contexts. Just as jobs differ in their potential for enrichment, so does a gulf prevail among people. Evidence points to one section of workers who take a largely instrumental view of their work and besides ensuring that the financial gain is maximised and their employment secure has little concern for the higher level needs so fervently expounded by Maslow (1954) and Herzberg (1968). Furthermore, it should be stressed that the findings are that in many instances the

instrumental orientation of these workers have led them to seek their present job of low intrinsic satisfaction rather than vice versa (Goldthorpe et al. 1968). A second group of workers show little enthusiasm for the enrichment of their jobs as they are worried about having to take on further responsibilities. They feel their present tasks/already sufficiently demanding and do not share the conjecture / are of outside observers that their work is boring and restricting. Yet other type of workers, counter to popular assumption, actually welcome the safety of not being involved in decision-making and prefer their jobs to be repetitive and simple in order that they may develop a rhythmic tempo in execution of their tasks (Little and Warr 1971).

Notwithstanding, the arguments for the need and urgency of increasing job satisfaction are strong. In particular it is advocated that boring and unfulfilling work is a direct and major cause of wage inflation. Frustrated and demoralised, the workers swell and strengthen the trade unions which in turn put in substantial pay claims to attone for the lack of intrinsic satisfaction in the jobs of their members.

Personal characteristics such as age, sex and intelligence will impose their influence on the extent of receptiveness to changes in the nature of a job. Generally job enrichment has proved to be more successful with the younger, more adaptable staff than with the older personnel who find it more difficult to adjust from the traditional supervised methods. Variations have also been recorded with geographical locations (Lawrence and Turner 1965). Given a similar job situation attitudes and expectations differ depending on whether the employee is urban- or rural-based.

As a final point and in some measure towards putting job enrichment in perspective it is interesting to note that studies conducted by the Institute for Social Research at the University of Michigan showed that there is no evidence to uphold the obvious hypothesis that satisfied workers were more productive than unsatisfied workers (Perrow 1970). No consistent differences emerged between satisfaction in high- and low-producing work groups - in fact in some cases the least satisfied workers turned out to be the highest producers.

## 3.7 Concluding Remarks

Table 3.1 lists the comparative merits of cellular manufacture to the functionally laid-out system in terms of the motivator and hygiene factors. Although Group Technology offers a better environment for job satisfaction this is unfortunately not reflected in many of the existing cells. Poor cell design and the limited success in operators undertaking addition skills result in a high incidence of inter-cell movement of labour, thus disrupting the strength of the group identity that is often advocated in favour of GT. Also, workers are not given the degree of autonomy that is possible with group working. The retention of an individual bonus payment scheme in the majority of cases is liable to produce undesirable consequences in a situation where the task has become more unified and inter-dependent.

Therefore, overall there is little compromise of the economic objectives for a more satisfying and enriched job for the workers. In fact, with GT the social circumstances of the workers are frequently found to be worse than with the conventional method of production.

Table 3.1 : Comparative Merits of Cellular Manufacture to the Functionally Laid-out System

| | | |
|---|---|---|
| (1) | The Motivator Factors | |
| | (a) Achievement and Recognition | + |
| | (b) Work Characteristics | |
| | (i) Variety | +/-* |
| | (ii) Autonomy | + |
| | (iii) Task Identity | + |
| | (iv) Feedback | + |
| | (v) Personal Interaction | + |
| | (c) Responsibility | + |
| | (d) Advancement or Growth | + |
| (2) | The Hygiene Factors | |
| | (a) Supervision | + |
| | (b) Interpersonal Relationships | + |
| | (c) Financial Rewards | + |
| | (d) Job Security | - |

* denotes that there are positive as well as negative aspects.

## Chapter 4 : Description of the Simulation Model


4. Introduction

4.1 The SIMON Simulation Language

4.2 The Job Shop Simulation Model

4.2.1 The Identification of Entities

4.2.2 Identification of Sets

4.2.3 Job Characteristics

4.2.4 Intake of Jobs into the System

4.2.5 Queue Discipline

4.2.6 The Search Procedure

4.2.7 Job Inter-Operation Transit

4.2.8 The Recording of the System Performance

4.3 Running the Simulation Model

## 4. Introduction

The Oxford Dictionary defines "simulate" as "feign; pretend to have or feel; counterfeit." In the technical context it would be more accurate to regard simulation as essentially imitation or role-playing. To elaborate simulation is basically the portrayal of various aspects of the real environment by numbers or symbols which may be more readily manipulated to facilitate their study. This process can be roughly categorised into the three phases of conceptualisation, modelling, and experimentation. In this chapter we shall be dealing with the first two stages while experiments conducted with the model will be discussed in Chapter 5.

The first phase involves the specification of the components (entities) and the interactive mechanisms within the system. Each entity is represented by a set of attributes and the state of the entity at any time is identified by the values that these attributes take. The state of the system as a whole is described by the sum of the entity-states. All changes (events) are associated with the operation of processes (activities) and occur with the start, interruption or completion of processes. An important aspect of an event is that it takes place at a specific point in simulated time and is instantaneous. Advancement in simulated time is obtained by moving from event to event. The behaviour of the system is the collective behaviour of its activities. An activity is a sequence of related events which are separated by specified intervals of simulated time. While active, it changes the state of the model by modifying attributed values of certain entities, by creating, destroying, or regrouping entities, and by starting, terminating, communicating or otherwise interacting with selected activities.

With the concepts of the model established the next step is the design of a working computer programme. The central feature of this task is the control of the sequence in which the interdependent actions forming the model occur. If attempts are made to write a simulation programme using only a general purpose language one soon becomes entangled in the

complexities of the sequencing logic, which is actually of relatively little interest but nevertheless produces surprisingly numerous pitfalls for minor errors. This problem is considerably alleviated by the development of a number of simulation languages (Krasnow and Merikallio 1964) aimed at the simplication of writing simulation programmes and yet providing a variety of powerful capabilities for model building and experimentation. These include the capability to freely structure the components and the interactive behaviour of the model as well as to control the dynamic behaviour through the use of either state- or time-dependent events. Broadly the essential qualities of a simulation language are :-

(1) A mechanism for describing and manipulating the simulation data base
(2) An activity sequencing mechanism. The management of simulation activities is distinctive in that conceptually they operate in parallel. Therefore, the transfer of control from one activity to another is a "sideways" process instead of the usual hierarchic up and down transfer
(3) Facilities for debugging whilst the model is being developed, and
(4) Facilities for the collection of statistical measures of a system's performance.

Some of the discrete simulation languages that are fairly widely used include SIMSCRIPT, GPSS, GASP, CSL and SIMON. A good account of these languages is given by Tocher (1965) and Naylor et al. (1968). The main consideration for the choice of the particular simulation language to adopt is naturally its availability. For our present investigation SIMON has been used for just this reason.

## 4.1 : The SIMON Simulation Language

In common with a number of other simulation languages such as the Control and Simulation Language (CSL), SIMON has been evolved very closely to the principles of Tocher's pioneering General Simulation

Program (GSP). GSP has met with limited usage as it has been written in a symbolic language for the Ferranti Pegusus Computer and the Elliot 503. SIMON introduces the set concept which plays a dominant role in the structuring of the model. This feature has been found to be rather clumsy for simply systems but proves to be very powerful when dealing with more complex situations. SIMON is now available both in ALGOL and FORTRAN IV (Mathewson 1972). The facilities offered by the SIMON Simulation language are :-

(1) A master list for the organisation and execution of the simulation process,

(2) Specification of Entities. To provide for two or more Entities having similar characteristics it is possible to specify a Group of Entities. Members within the group have a common reference number (REFNU) as well as an individual identity (MEMNU). This feature is useful when dealing with several units of machines or operators of the same functional type,

(3) Mechanism for the administration of activities. The procedure entails :-

    (i) maintaining a record of the details of active processes,
    (ii) updating the record when further active processes are included,
    (iii) selecting the next imminent event to occur, and
    (iv) advancing the simulation clock simultaneously to that point in simulated time.

    A routine is also available for interrupting an activity to alter the completion time.

(4) Mechanism for the administration of sets. In discrete event simulation there are often numerous instances of ordered sets (queues). SIMON provides a comprehensive range of facilities for the management of sets. For example, one can :-

    (i) add (delete) a member to (from) the head of a set.

(ii) add (delete) a member to (from) the end of a set.

(iii) delete a specified member from a set.

(iv) rotate a set list (i.e. member at the head is transferred to the end of the set) a specified number of times.

(v) clear all members from a set.

(5) Facility for sampling from prescribed distributions. Routines have been provided for reading in specific distribution patterns which are then sampled by the Monte Carlo technique. Recently a routine has also been included for the sampling of normally distributed variates.

(6) Facility for the collection and outputting of results in a statistical form.

## 4.2 : The Job Shop Simulation Model

Using SIMON as the framework, the construction of the simulation model consists of defining the various elements and interactive processes in a shop in terms of the concepts pertaining to SIMON.

### 4.2.1 Identification of Entities

To assist in the understanding of the need for the introduction of concepts such as Subjects and Dummy Entities, it is necessary to delve into the manner in which the constitution of Activities and the Scheduling of Events are structured within SIMON. For each Activity there are three constituent parts :-

(1) an Entity,

(2) an element to signify the completion time of the Activity, and

(3) a bound object which can be either an Entity or Subject.

Within the simulation infrastructure Activities as such do not exist but instead they are decomposed into a Start Event and a Termination Event. For the Event scheduling procedure each Event is identified by the Entity component. Therefore to be able to include any Event within the scheduling mechanism, it is mandatory to have an Entity

associated with the Event. This is the reason why Dummy Entities have to be employed when projecting Events such as the generation of jobs and the termination of simulation. In SIMON the specification of an Entity takes up four words of the computer core. If, wherever possible, a subject is used instead this not only requires one word but within a 24-bit word one can insert up to three attributes. This procedure is not normally recommended as it inflates the turnaround time of the simulation runs. Unfortunately, it is found to be necessary due to the core restriction imposed at the Cranfield Computer Centre at the time that the simulation model was being developed.

The Entities, Dummy Entities and Subjects identifiable with the job shop environment are as follows :-

Entities - An Entity Group for each machine type.
Dummy Entities - for (i) admission of jobs into the system
(ii) inter-operation transit of parts
(iii) termination of simulation
Subjects - include (i) labour
(ii) jobs

### 4.2.2 Identification of Sets

Whenever there is an accumulation of objects where the number at any time is liable to vary and certain ordering is necessary the Set facility in SIMON can be used to good advantage. In the present job shop model the Sets defined are :-

(i) Unoccupied machines - One Set for each type.
Here there was a choice of either providing a single Set for machines of all types or one Set for each. With the former there would be considerably more sorting involved whenever the Set is accessed. Since only two extra words are required to label a Set it was decided to improve the programme turnaround time and assign a Set for each machine type.

(ii) Jobs in the order book : Jobs on entering the system are placed in the order book in Sets according to their first operations.

(iii) Jobs in queue for the next operation : A Set is assigned for each machine type.

(iv) Unoccupied labour : The model was planned for maximum labour flexibility. This means that each labour type may assume a different designation for the various machine types. There is therefore little purpose in assigning a different Set for each operator type. Instead all unoccupied men are placed in a common Set.

(v) Machines waiting to be set : When a machine is matched up with a job it joins the queue where the service of a setter is awaited. This procedure is introduced to curtail the amount of searching necessary whenever a man becomes free.

(vi) Machines waiting to be run : On completion of setting up a machine joins a prescribed queue to await the service of an operator.

(vii) Utility Sets : Three utility Sets have been provided to cater for various temporal usages

### 4.2.3 Job Characteristics

Job details for the simulation can be either from actual data or generated by the Monte Carlo sampling method. A separate programme has been written for the generation of job particulars. The output is in a format suitable for input into the main simulation programme. For each job the details required are :-

(1) A job number

(2) The batch quantity

(3) The value of the job

(4) The flow allowance (for the computation of the job due date)

(5) The earliest start date

(6) The external priority

(7) The number of operations required. For each operation the particulars needed are :-

(i) the operation type

(ii) the set time

(iii) the run time

(iv) the tool set-up configuration

The Monte Carlo Sampling Technique

Since the phrase "Monte Carlo analysis" was coined by von Neumann and Ulam in the late 1940's, a range of Monte Carlo techniques (Hammersley and Handscomb 1964) have been evolved for application to various problems. For our purpose we are mainly interested in the method for the generation of stochastic variates. Essentially the strategy involves the determination, through observation, of the distribution of each variable in the system and whenever it is needed in the simulation, a random sample is chosen from this distribution. Very often it is possible to represent these distributions by means of probability distributions such as the normal or exponential distribution. A fundamental feature of the sampling technique is a random number generator which gives a uniform random sample between 0 and 1. By scaling this value against the cumulative relative frequency of the distribution the required sample value is obtained. It is frequent in simulation studies to repeat the runs with some variations in the system parameters and to be able to derive a meaningful comparison of the results, it is necessary that the sampled data in all runs should be the same unless otherwise specified. In this context, a pseudo-random number generator is preferred to one where truly random numbers are produced since it provides the facility for repeating the sequence of random numbers. Basically a pseudo-random number generator consists of a formula with which apparently random numbers are computed. For a formula to be acceptable it is required to satisfy certain tests (Naylor et al. 1968).

The Pseudo-random Number Generator

For the present simulation programme it is necessary to devise a suitable pseudo-random number generator as the one incorporated in SIMON produces integer numbers which are larger than can be contained within the 24-bit words of the ICL 1903T. The multiplicative congruential method first proposed by Lehmer in 1951 (Taussky and Todd 1954) has been shown to produce acceptable pseudo-random numbers that pass the set of prescribed tests described in Naylor et al.. Furthermore this method offers relative advantages in terms of computational speed and demand on computer memory capacity. The form of the recursive formula is given by :-

$$x_{n+1} = kx_n \pmod{m} \quad *$$

To ensure that the period between repetition of a sequence of numbers is maximised, certain guidelines have been suggested for the selection of the parametric values (Taussky and Todd).

(i) m - the value of m should be computed from $2^p$ where p should take the largest value compatible with the word size of the computer. In our case p = 16 has been chosen.

(ii) k - can be any odd power of 5. For our purpose k = 125 has been used.

(iii) $x_o$ - any integer satisfying : $x_o = 1 \pmod 5$
Since it is intended that there should be ten random number streams we assigned :-

$x_o = 100\,N + 1$ where N = 1 to 10.

* i.e. $x_{n+1}$ is the remainder when $kx_n$ is divided by m.

GENERATION OF JOBS

The jobs generation programme has been written for interactive working and an indication of the sort of questions encountered in running the programme is shown in Appendix 4.1(a). The flow diagram for the jobs generation procedure is given in Figure 4.1. (page 68)

After specifying the number of machine types there are in the system the simulator is required to select a random number stream (from 1 to 10). This facility for the choice of a random number seed is useful in simulation studies since it is often necessary to establish the statistical acceptability of results by making several runs, each time with a different random number stream.

Except for the set time, run time and flow allowance (for due date computation) the choice of 3 types of distribution forms is given :-

(1) Specified, continuous : The characteristic of the distribution is specified by the simulator and consists of up to 12 pairs of co-ordinates of a cumulative probability distribution. The items must be entered in I3 formats in the order as follows :-

CCCXX1YY1XX2YY2XX3YY3 .....

where CC is a check number to ensure that the correct distribution is read in at the correct point
XXN a value co-ordinate point
YYN a percentage cumulative probability co-ordinate point.

The first number for the percentage cumulative probability must be 0 and the last 100. For an illustration of the sampling technique we refer to Figure 4.2. Suppose the random number generator produces a value Y which lies between YYN and YYN+1. From a linear interpolation we can then obtain the required value, X.

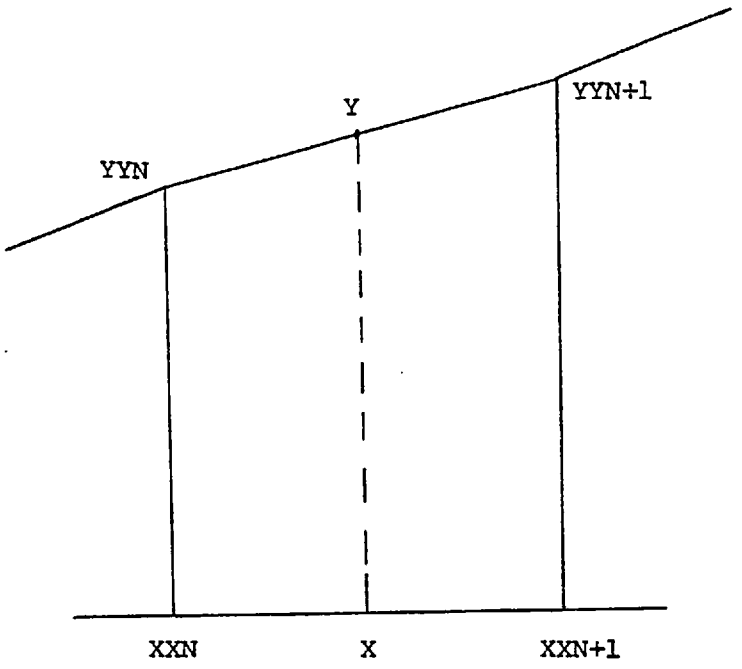



FIGURE 4.2 - MONTE CARLO SAMPLING FROM A SPECIFIED DISTIBUTION

(2) Specified, discrete : The input format is the same as for case (1). The difference arises in that during sampling the value of the X is not obtained by interpolation. Instead X takes the next lower value i.e. X = XXN. This arrangement is required in situations where only values on prescribed co-ordinate points are desirable. One example is in the generation of jobs routing.

(3) Normal : For normal distributions the simulator is required to enter only the values for the mean and standard deviation.

In addition to the above three forms, the set and run times can also be sampled from an exponential distribution. The input data required is only the mean or expected value. For the generation of job flow allowances the following alternatives have been provided :-

(i) FACTOR X NO. OF OPS.
(ii) FACTOR X TOTAL JOB PROCESS TIME and
(iii) JOB PROCESS TIME + FACTOR X NO. OF OPS.

The value for the FACTOR is specified by the simulator.

When conducting a series of simulation experiments it is often only necessary to alter one or two of the input data to generate the next set of jobs. To avoid the irksome task of continually entering the strings of distribution values on the terminal it would be more convenient to store the data on an input file. The file can be easily recalled at the terminal and any modifications required can be edited into the file. A listing from an input file is shown in Appendix 4.1 (b). As indicated in Figure 4.1 the input of data for jobs generation is fairly straightforward. A comment, perhaps, is only required in relation to the external priority. This aspect is to provide facility for distinguishing between jobs that are routine or normal and jobs that have priority and need to be expedited. For the former an external priority of 1 is assigned while a value of 2 denotes an urgent job. Jobs with an external priority of 2 will always be placed in the front of any job queue.

Once all the data has been read into the programme the specified number of jobs will be generated with details sampled from the relevant distributions by the Monte Carlo technique. For each distribution a different random number stream will be applied. The job details are output in a format suitable for input into the main simulation programme. A sample of the programme output is given in Appendix 4.2.

### 4.2.4 Intake of Jobs into the System

Table 4.1 contains a collection of some of the job arrival patterns employed by various investigators. Clearly there is a lack of standardisation despite empirical observations that the time interval between successive jobs approximate very closely to an exponential distribution (Nelson 1959). Apparently there is a greater consensus that it is more accurate to assume that jobs are assigned to the shop at the start of each working period. As a compromise several simulators have chosen to adopt the equivalent situation whereby the number of job arrivals at the beginning of each period is a random variable with a Poisson distribution.

While there is little doubt that the system performance will to a certain

extent be affected by different job arrival patterns it is suggested that the effect is liable to be small compared with other factors such as the load level and average queue count. This is particularly so since it has long been recognised that "a simulation model can produce relative results much more accurately than absolute results." (Conway 1964). Therefore, unless the investigation is specifically intended to examine the nature of queue characteristics the choice of the job arrival mode is unlikely to have a significant influence on the results.

For the present simulation model jobs enter the shop via a two-tier system. At the first stage the jobs are placed on the order book (Figure 4.3). Here they are sorted according to their first operation machine type and queued on the basis of the increasing slack time available. To cater for the various job arrival patterns preferred a large amount of flexibility has been incorporated. Simulators are allowed to vary the number of jobs intake as well as the period between job arrivals. Jobs details present a taxing demand on core space. To be able to accommodate larger-sized problems it is hence necessary to carry more than one attribute in each word. With the present set of attributes six words are required for the job particulars and three further words will be taken up by the details for each job operation.

Jobs are transferred from the order book to the shop on the criterion of a preselected trigger level which could be in terms of the count or workload of jobs in the queue. Different trigger values can be assigned to each of the machine types. Figure 4.4 illustrates the procedure for the intake of jobs into the shop. This routine is called whenever there is a change in the queue situation (such as when a job has been set or completed) or when there is a fresh entry of jobs into the order book. Jobs can only qualify for admission into the shop if their prescribed earliest start date has exceeded the simulation clock time.

### 4.2.5 Queue Discipline

The importance of the queue discipline on the system performance has already been reiterated. Depending on the emphasis placed on various effectiveness measures there is a multitude of proposed methods for the

despatch of jobs. With this in mind it is thought that the best course of action is to construct the computer programme so that alternative forms of queue procedures can be included with the minimum of effort.

At present the queue disciplines made available are :-

(1) FCFS
(2) DDATE
(3) FASFS
(4) SLACK(U)
(5) LWKR
(6) MWKR
(7) FOPNR
(8) MOPNR
(9) SPT
(10) LPT
(11) SLACK(U)/SPT
(12) S(U)/SET/SPT

An explanation of the operative details of these rules can be found in Appendix 2.1. With the exception of rules 11 and 12 these procedures are among the most commonly employed in job shop simulation studies. For priority rule 4 an extra facility has been provided whereby a specified amount (U) of queue allowance can be assigned to each remaining operation. This is an attempt to simulate the S/OPN discipline where both the slack time and the number of outstanding operations have an influence on the priority of a job. The SLACK(U) arrangement possesses the advantage that instead of having to compute the priority rating of every job in a queue each time a job is being selected (as required in the S/OPN procedure), the priority of a job need only be adjusted each time an operation is completed. This factor is vital when assessing the suitability of a despatching rule for implementation in an actual production situation. Hierarchic rules 11 and 12 have been included for an examination of their effectiveness (see Experiment 1(b) in the next Chapter). The flow diagram for job selection is given in Figure 4.5.

### 4.2.6 The Search Procedure

Basically the search procedure involves the matching of a machine, a job, and an operative to create an event. The conditions that trigger the search procedure are :-

(1) The completion of the setting or running of a machine
(2) The intake of jobs into the shop and
(3) The completion of the inter-operation transit of a job.

The flowcharts for the actions subsequent to the completion of the setting and running of a machine are given in Figure 4.6.

The SQMENR and SQMENS sets have been introduced to reduce the amount of search necessary. Whenever a machine/job combination requires the service of an operative for running (such as after the completion of setting up or where the job loaded does not require setting up) the combination is placed on the SQMENR list. Similarly, for a machine group that has free machine(s) as well as job(s) in queue an entry is made on the SQMENS list which denotes that the service of an operative for setting is needed. Here, there is no specific bound between a machine and a job since the machine and job situations are liable to change before an operative becomes available. This arrangement is to allow the chosen queue discipline tc act with the maximum effectiveness.

As illustrated in Figure 4.7(a)-(c) the search routine now entails only the scanning of the SQMENR, SQMENS and the free labour set. Since the model allows for the specification of three labour categories - that is, the operator, the setter and the setter-operator who has the dual function of setting and running machines - it is necessary to formulate the basis on which each type of labour is deployed. For setting a machine a setter should be used unless none is available at the time. In that case, a setter-operator, if free, is employed. Equally, for running a machine, an operator and setter-operator are the first and second choices respectively. Another matter that has to be resolved is the criterion on which the selection of the members within the SQMENR

and SQMENS lists should be made. For this the basis chosen is the queue load at each of the machine types concerned. The machine type with the largest queue load carries the highest priority.

### 4.2.7 Job Inter-operation Transit

On completion of an operation a job is placed on transit to the next operation (unless of course, that was the last operation in which case the job is removed from the system). The inter-operation time is assumed to be normally distributed and a matrix has been provided for specifying the means and standard deviations of the transit time between the various machine groups. Since jobs have been designated as Subjects and not Entities, a Dummy Entity has to be employed for the possible inclusion of the job transit event within the Events-Scheduler. However, only one job on transit can be placed on the Scheduler at any one time in association with the Dummy Entity. As such a transit jobs array has to be used to administer the jobs that are simultaneously on transit (see Figure 4.8). The job that is placed on the Events-Scheduler is always the one with the earliest due transit completion time.

### 4.2.8 The Recording of the System Performance

A print-out of the performance measures that are recorded in the simulation model is given in Figure 4.9. Firstly, for the machines, we compute for each type the proportion of the simulation period

(a) engaged in setting up for a job
(b) engaged in running jobs
(c) idle due to no setting personnel available
(d) idle due to no running (operating) personnel available and
(e) idle due to the depletion of the job queue.

Also, for each machine type we obtain :

(a) the average job queue time (min.)

(b) the maximum job queue time (min.) during the simulation period

(c) the maximum job count in the queue during the simulation period

(d) the existing queue load at the end of the simulation period and

(e) the cumulative load for that machine type in the shop at the end of the simulation period.

Secondly, for the operatives, we record for each labour type the proportion of the simulation period

(a) engaged in setting up machines

(b) engaged in running machines and

(c) idle.

The third piece of information produced is a job route tracing chart which depicts the from-to characteristics of the work flow. Jobs coming from machine type 0 denotes the first operation of the jobs while jobs going on to machine type 0 indicates that the jobs are completed. When actual data is used for the simulation this set of figures provides an aid in assessing the optimality of the present layout of machines with respect to the work flow.

Fourthly, some statistics are given on the jobs performance, viz :

(a) the number of jobs taken into the shop and the number of jobs completed during the simulation period

(b) the number of operations completed during the simulation period

(c) the mean value,standard deviation, maximum value, minimum value,count,and histogram of

  (i) jobs tardy

  (ii) jobs early and

  (iii) the jobs throughput time.

Naturally, with the tremendous improvement in the position of the availability of graphics facilities some thoughts have been directed

at the possibility of introducing some form of visual display of the simulation process. The question of the compatibility between discrete event simulation and interactive graphics has been subjected to a lengthy discussion among a group of recognised experts in the field of simulation (Buxton 1968 pp33). The central problem still remains as to whether it is possible to reconcile the multitude of simulation factors to present a meaningful pictorial interpretation on the screen.

## 4.3 Running the Simulation Model

To illustrate the operation of the simulation model the print-out from a demonstration run is given in Appendix 4.3. The first task consists of the description of the simulated system and for this the parameters required are :-

(1) the number of machine types and the number of units of each type

(2) the number of labour types and the number of units of each type

(3) the labour/machine matching matrix : each of the labour types can be assigned to each of the machine types in one of the following ways :

  (i) they only set the machine(s)
  (ii) they only run the machine(s)
  (iii) they set as well as run the machine(s) and
  (iv) that machine type is not their responsibility.

(4) the queue discipline (see Section 4.2.5)

(5) the job intake into shop trigger level : the simulator first specifies whether jobs are taken into the shop (from the order book) on the basis of the queue count or load. Thereafter he is required to stipulate the value of the level for each machine type

(6) the job inter-operation transit time matrix : to allow for varying distances between machine types a matrix has been provided for the specification of the mean and standard deviation of the transport times between all the work centres. The transit times

are assumed to be normally distributed.

Next, data is also required to be entered pertaining to :-

(1) the job tardiness, earliness and throughput time histogram scales: as shown in Figure 4.9 the histograms consist of 9 co-ordinates point. The simulator is required to specify the value of the first point and the interval between adjacent points.

(2) the period over which the simulation is to be performed : this value is given in terms of the number of days which is equivalent to 480 minutes of simulated time. and

(3) the degree of details of the simulation process : the programme provides the facility for the listing of the events in the simulation. When the listing is intended to produce work schedules for machines and operatives it can be selected so that only events associated with machines and operatives are listed. If on the other hand the listing is required for checking the programme when some modifications are made all events will be printed. Under normal circumstances when the simulation runs are intended for the study of the system performance the simulator responds with a "N" (for No) to this particular question to suppress any listing.

Clearly, the amount of data that is required to be entered is fairly large, especially when dealing with larger-sized problems. To obviate what could be a tedious and time-consuming task it is suggested that the data together with the jobs data should be placed on a file which is called and read in rapidly at the beginning of the simulation system.

With the above data read in, the programme proceeds with the simulation process. On completion of this, the simulator is invited to examine the results for the various system measures. Thereafter the simulator has the option of :

(1) terminating the simulation

(2) resimulating with changes in the machine and/or labour arrangement(s)

(3) resimulate with the same machine and labour arrangements
(4) continue the simulation with new performance records for the next simulation period or
(5) continue the simulation with the same records for the next simulation period.

If the simulator chooses option (4) or (5) he then specifies the number of days of the next simulation period and decides whether he would wish to make changes in :-

(1) the manning arrangement
(2) the queue discipline
(3) the job intake into shop level
(4) the inter-operation job transit time matrix and
(5) the co-ordinate points for the histograms for job tardiness, earliness and throughput time.

When the necessary alterations have been made, the simulation process for the next period is initiated. The simulator is again invited to examine the results and can either then terminate the simulation at that point or continue with the simulation for further periods.

TABLE 4.1

| | JOB ARRIVAL PATTERN | SOURCE |
|---|---|---|
| (1) | Jobs, the number of which is sampled from a Poisson distribution, arrive at the shop at the start of each working period. | Aggarwal et al. (1973) |
| (2a) | As for (1) except that the total for 5 periods (constituting a week) is adjusted to give a constant figure. | Hollier (1968) |
| (2b) | As for (1) except that a cut-off is operated on numbers above a prescribed value. | Rochette and Sadowski (1976) |
| (3) | Jobs arrive singly; the inter-arrival time between consecutive jobs being distributed exponentially. | Nelson (1967)<br>Eilon and Hodgson (1967) |
| (4) | Jobs, the number of which is sampled from a uniform distribution, arrive at the shop at the start of each working period. | Wilbrecht and Prescott (1969) |
| (5) | A fixed number of jobs arrive at the shop at the start of each working period. | Eilon and Chowdhury (1976) |

FIGURE 4.1 : FLOWCHART FOR JOBS GENERATION

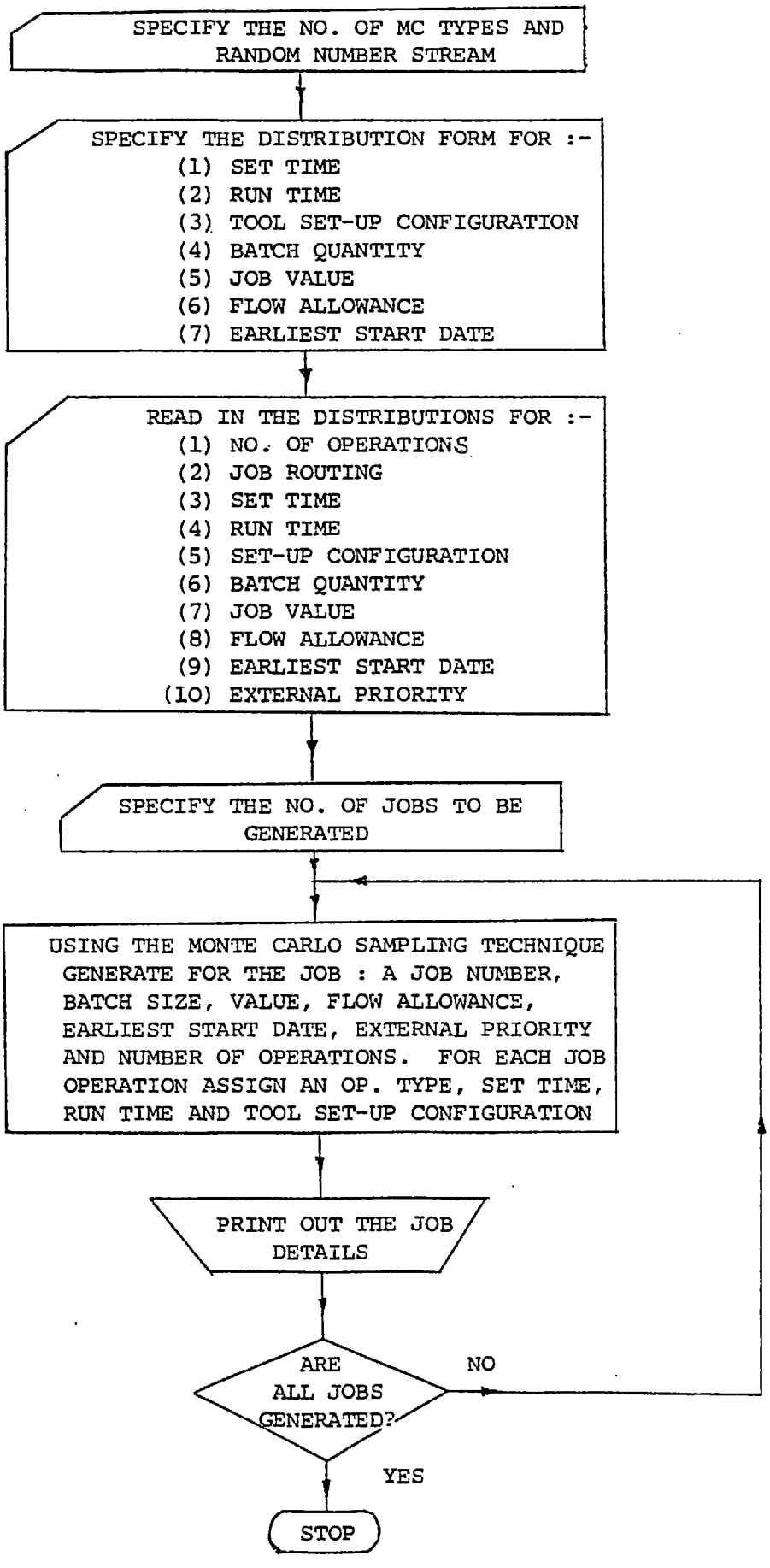


FIGURE 4.3 : JOBS INTAKE INTO THE ORDER BOOK

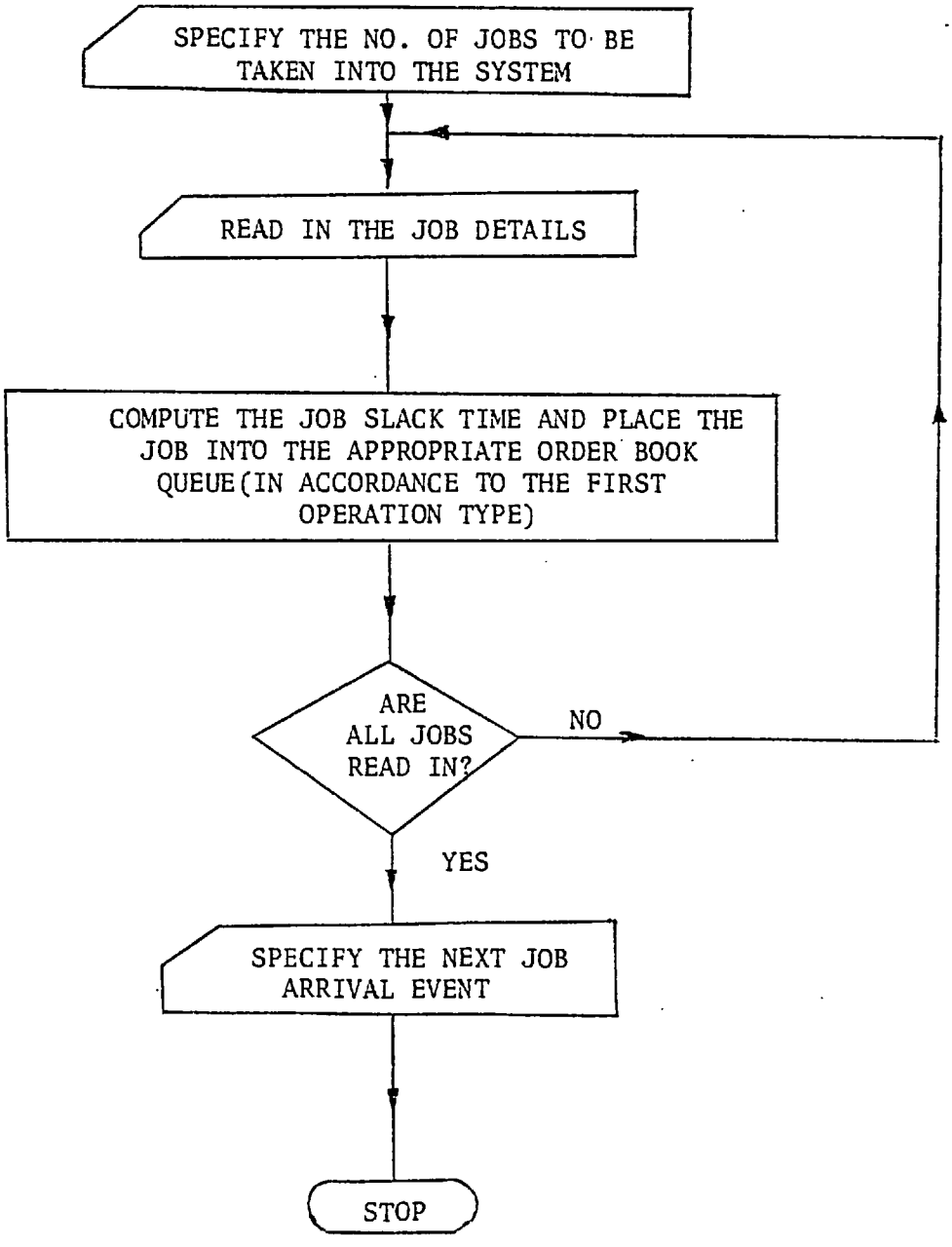
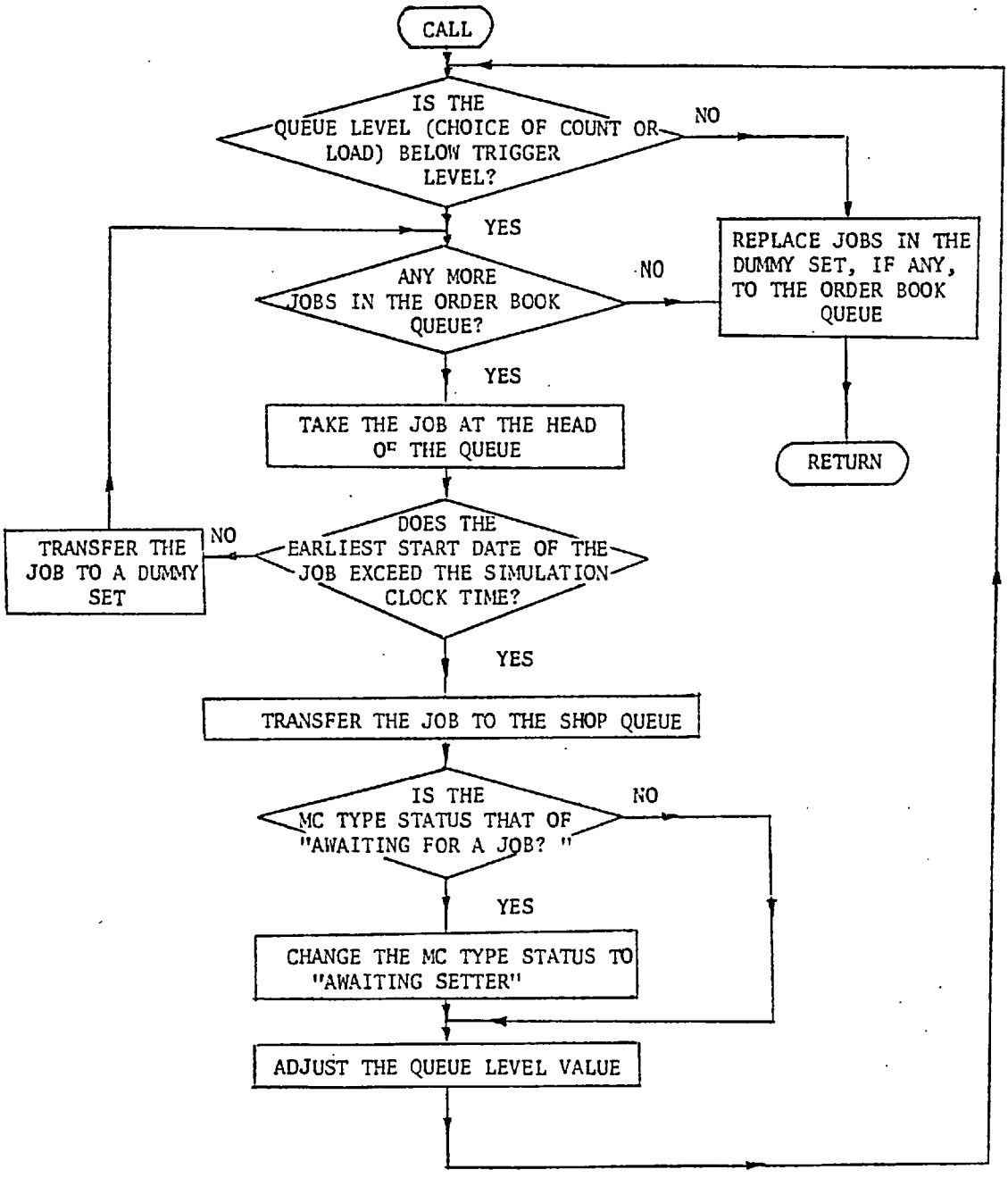


FIGURE 4.4 : JOBS INTAKE INTO THE SHOP



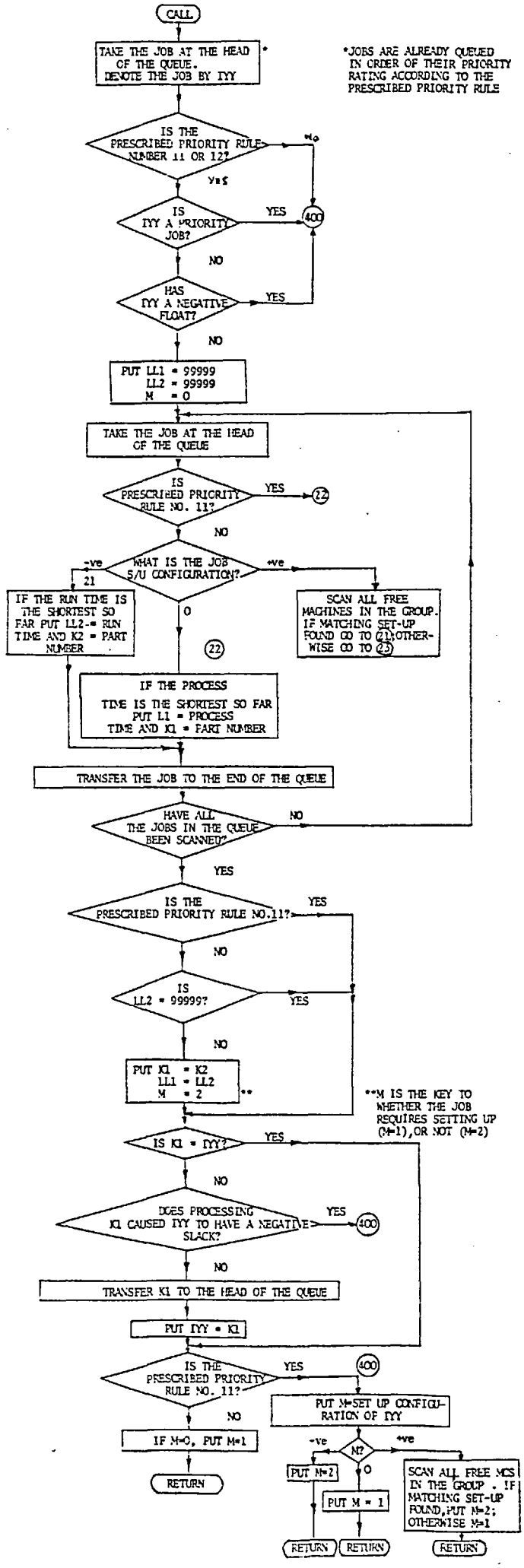
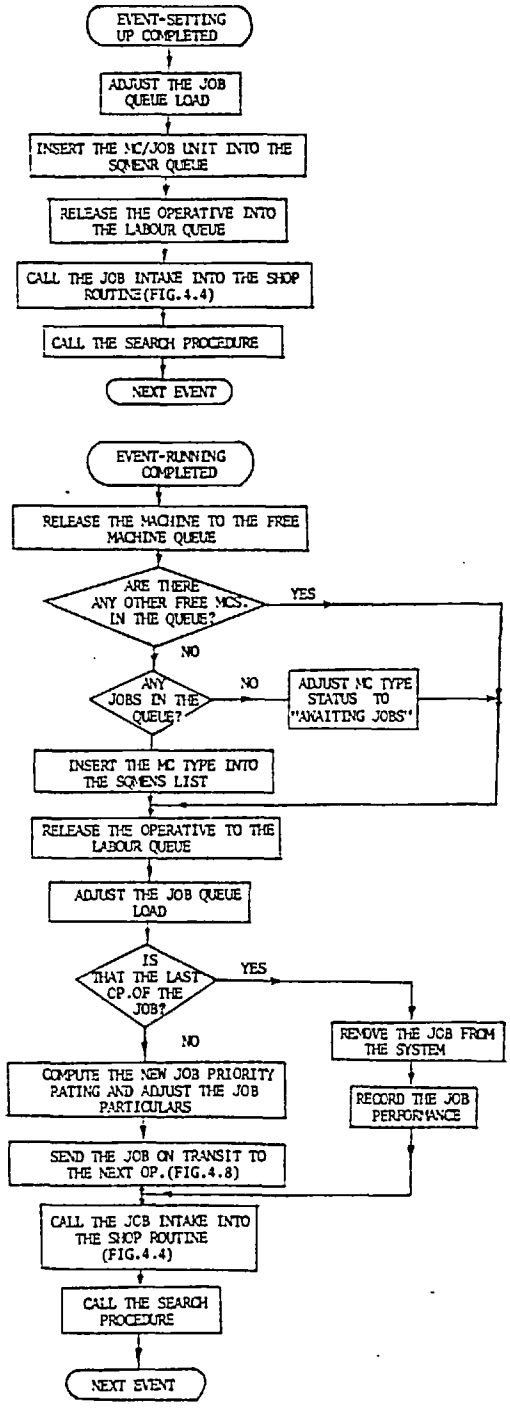



FIGURE 4.5 : FLOWCHART FOR JOB SELECTION FROM QUEUE

FIGURE 4.6 : PROCEDURES SUBSEQUENT TO SETTING AND RUNNING COMPLETED EVENTS



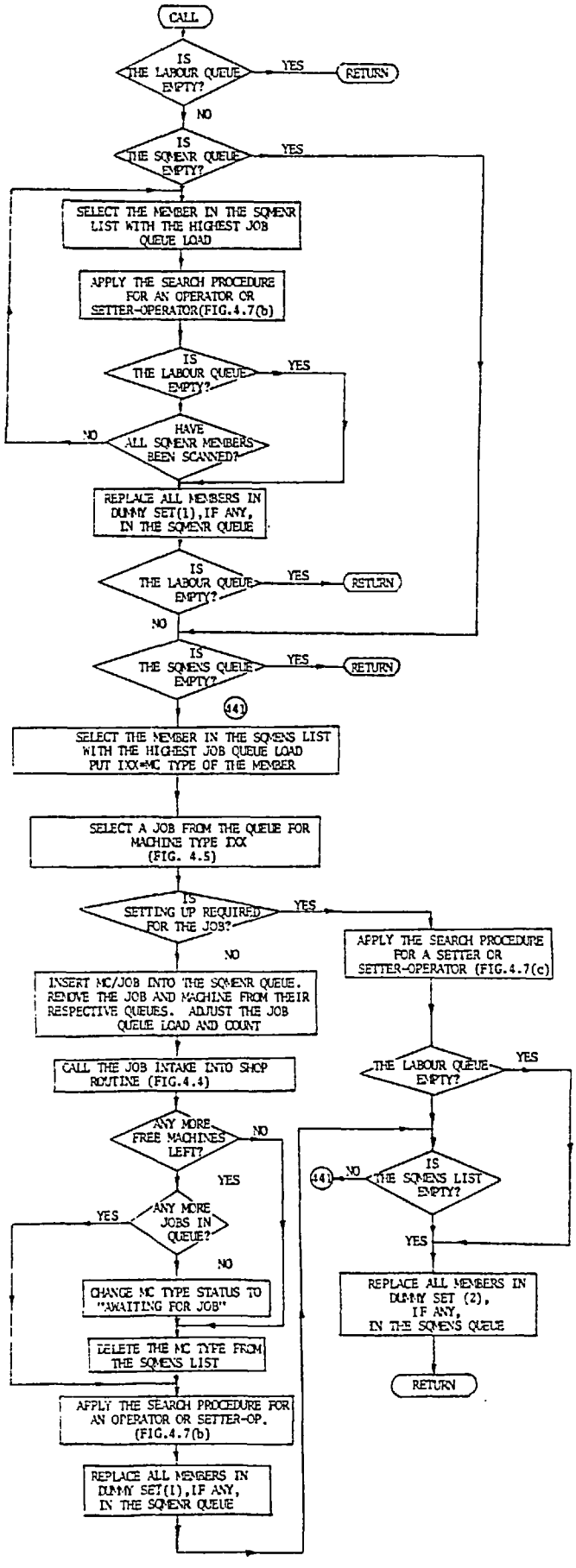



FIGURE 4.7(a) : FLOWCHART FOR THE ACTIVITIES SEARCH PROCEDURE

FIGURE 4.7(b) : FLOWCHART OF SEARCH PROCEDURE FOR AN OPERATOR OR SETTER-OPERATOR

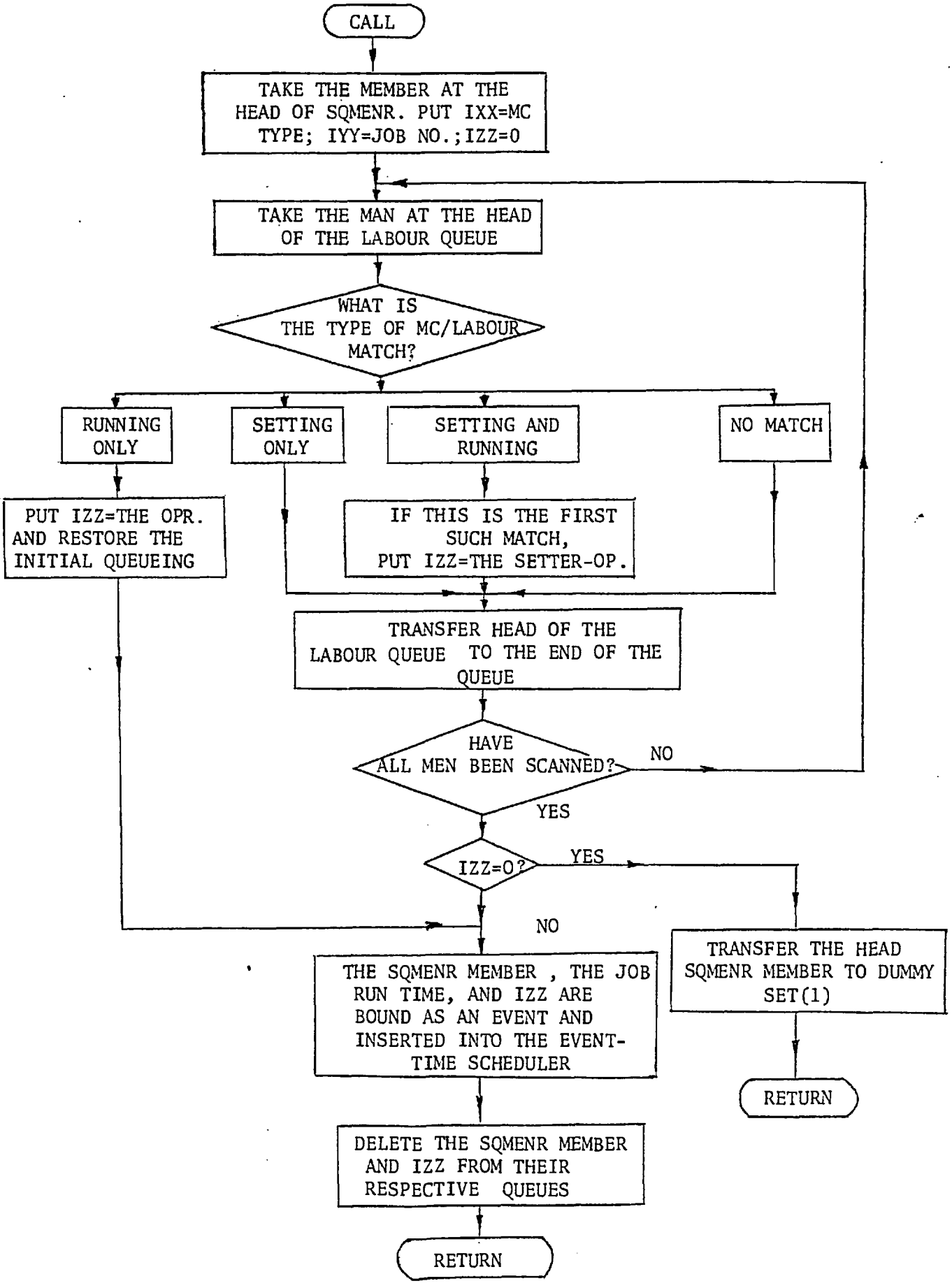


FIGURE 4.7(c) : FLOWCHART OF SEARCH PROCEDURE FOR A SETTER OR SETTER-OPERATOR

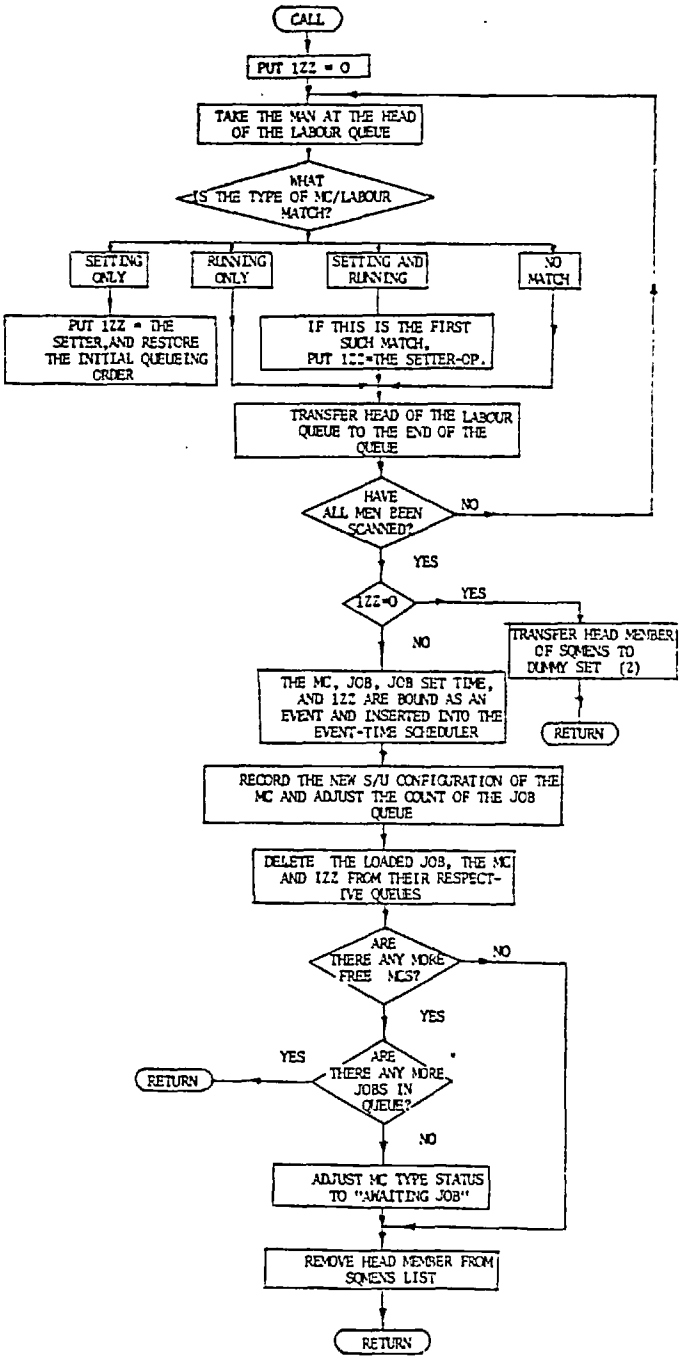
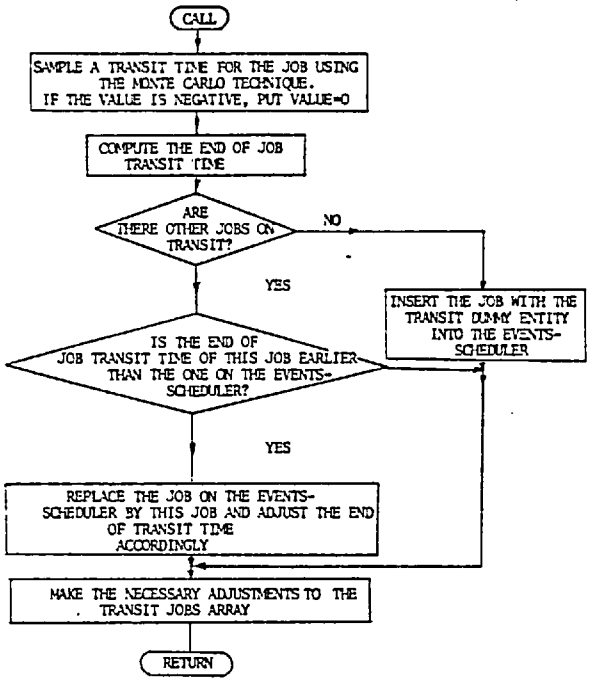


FIGURE 4.8 : PROCEDURES FOR JOBS ON INTER-OPERATIONAL TRANSIT

(a) FLOWCHART OF THE PROCEDURE FOR INITIATION OF A JOB ON TRANSIT




(b) EVENT - COMPLETION OF JOB INTER-OPERATION TRANSIT

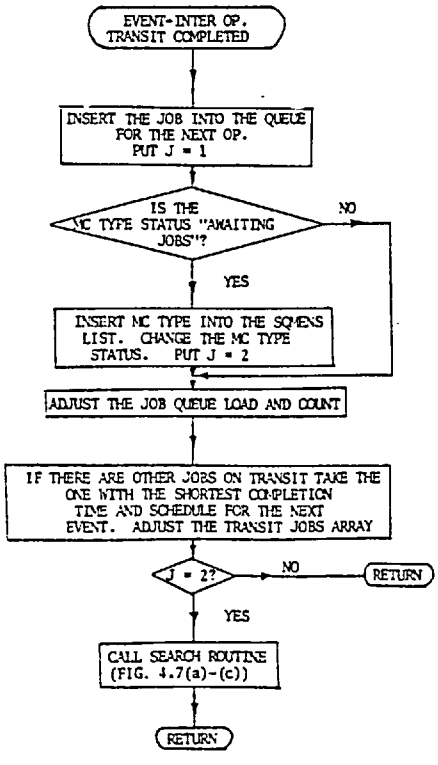


FIGURE 4.9 : A COMPUTER PRINT-OUT OF THE SYSTEM PERFORMANCE

| MC TYPE | MC TOOL ENGAGED SET | RUN | MC TOOL SET | RUN | AWAITS PART | PARTS QUE. TIME AVG | MAX | RECORD SIZE MAX | QUEUE IMME- DIATE | LOAD POTE- NTIAL |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.132 | 0.778 | 0.019 | 0.071 | 0.000 | 207 | 840 | 9 | 470 | 978 |
| 2 | 0.171 | 0.419 | 0.067 | 0.222 | 0.122 | 36 | 104 | 3 | 41 | 532 |
| 3 | 0.083 | 0.561 | 0.058 | 0.139 | 0.160 | 64 | 348 | 5 | 134 | 304 |
| 4 | 0.142 | 0.525 | 0.013 | 0.174 | 0.146 | 121 | 458 | 6 | 193 | 1096 |
| 5 | 0.156 | 0.574 | 0.028 | 0.060 | 0.183 | 118 | 762 | 5 | 38 | 453 |
| 6 | 0.181 | 0.637 | 0.041 | 0.099 | 0.042 | 84 | 312 | 7 | 209 | 625 |
| SHOP | 0.144 | 0.582 | 0.038 | 0.127 | 0.109 | 105 | | | 1085 | 3988 |

OPERATOR PERFORMANCE RECORD

| TYPE | SET | RUN | IDLE |
|---|---|---|---|
| 1 | 0.509 | 0.000 | 0.491 |
| 2 | 0.177 | 0.802 | 0.020 |
| 3 | 0.000 | 0.945 | 0.055 |

PARTS ROUTE TRACING

| FROM FINISH AT MC TYPE | TO START AT MC TYPE 1 | 2 | 3 | 4 | 5 | 6 | 0 |
|---|---|---|---|---|---|---|---|
| 0 | 6 | 6 | 8 | 3 | 10 | 3 | 0 |
| 1 | 0 | 6 | 4 | 6 | 4 | 7 | 3 |
| 2 | 5 | 0 | 5 | 3 | 2 | 3 | 4 |
| 3 | 10 | 3 | 0 | 2 | 2 | 9 | 2 |
| 4 | 3 | 5 | 4 | 0 | 3 | 6 | 1 |
| 5 | 5 | 2 | 3 | 7 | 0 | 2 | 2 |
| 6 | 7 | 1 | 6 | 4 | 1 | 0 | 6 |

PARTS INTAKE = 36 PARTS COMPLETED = 18 OPS. COMPLETED = 148

NO ENTRIES

PARTS TARDINESS

MEAN= 12.1917 SD= 8.1779 MAX= 28.7833 MIN= 1.0167 ENTRIES= 18

| % | 0.00 | 5.56 | 16.67 | 27.78 | 5.56 | 11.11 | 11.11 | 0.00 | 5.56 | 16.67 |
|---|---|---|---|---|---|---|---|---|---|---|
| HRS. | 0. | 3. | 6. | 9. | 12. | 15. | 18. | 21. | 24. | |

PARTS EARLINESS

MEAN= 12.1972 SD= 6.1084 MAX= 20.9167 MIN= 3.4667 ENTRIES= 18

| % | 0.00 | 0.00 | 22.22 | 22.22 | 5.56 | 11.11 | 16.67 | 22.22 | 0.00 | 0.00 |
|---|---|---|---|---|---|---|---|---|---|---|
| HRS. | 0. | 3. | 6. | 9. | 12. | 15. | 18. | 21. | 24. | |

PARTS THROUGHPUT

## Chapter 5 : Simulation Experiments


| | | | |
|---|---|---|---|
| 5.1 | Experiment 1 | : | Investigation of System Parameters. |
| 5.1.1 | Experiment 1(a) | : | Selection of the Job Due Date Parameter. |
| 5.1.2 | Experiment 1(b) | : | Comparative Analysis of Priority Despatching Rules. |
| 5.2 | Experiment 2 | : | Effect of Process Time Distributions. |
| 5.3 | Experiment 3 | : | Effect of Batch Size. |
| 5.3.1 | Case (1) | - | Constant Mean Process Load |
| 5.3.2 | Case (2) | - | Constant Mean Run Load. |
| 5.4 | Experiment 4 | : | Effect of Work in Progress Level. |
| 5.5 | Experiment 5 | : | Effect of the Job Inter-Operation Transit Time. |
| 5.6 | Experiment 6 | : | Effect of Number of Tool Set-Up Configurations. |
| 5.7 | Experiment 7 | : | Effect of Cell Size |
| 5.8 | Experiment 8 | : | Effect of Manning Level and Type. |

## 5.1 Experiment 1 : Investigation of System Parameters

In the examination into the background of job shop simulation studies in chapter two it was illustrated that unless the system parameters are chosen with a reasonable perception of the work flow conditions created the conclusions derived from the investigation may be misleading. Also, especially when attempting to compare the results from different sources, it is important to recognise that even when the overall conditions appear to be similar the simulated situations may be vastly different. For example, a ninety percent shop loading can be obtained by (i) a high job input rate with jobs of short operation times or (ii) a low job input rate with jobs of long operation durations. Furthermore, depending on whether the jobs are programmed to enter en masse into the system at the start of each period or individually at prescribed intervals the queue pattern at the machine groups will differ.

Mathematical methods have so far proved to be only applicable to trivially small job shop problems. Computer simulation, on the other hand, provides a great deal more flexibility and the size of the problem is limited solely by the computer core and execution time available. However, there is clear evidence that many investigators are concerned at the departure from the realm of mathematical exactitude and in an attempt to redeem the situation somewhat a set of norms has been established to render the experimentation statistically acceptable. Prominent among the conditions laid down is the use of a large job sample in a simulation run; of thousands or even tens of thousands of jobs. Unfortunately, the tremendous computing resources required to abide by this stipulation has resulted in the bulk of simulation work being of a highly restrictive nature; mainly the investigation of priority despatching rules.

As the objective of the present investigation is to perform a broader analysis of work flow it is necessary to incorporate greater versatility and complexity within the job shop model. This inevitably causes an escalation in the turn-around time. To further compound the matter the Cranfield ICL 1903T computer is under strain of heavy demand for its resources. In the light of all this and the large number

of simulation runs envisaged, it is imperative to drastically curtail the job sample size. It follows therefore, that one of the first requisites is to verify that even with relatively small job samples the results are nevertheless representative and valid.

### 5.1.1 Experiment 1(a) : Selection of the Job Due Date Parameter

In Chapter two we discussed the significance of the due date assignment method and the tightness of due dates. It was shown that the best performance is obtained when the flow allowance is allocated in proportion to the total job process time. Lagging slightly behind in effectiveness is the flow allowance in proportion to the number of operations method. Intuitively, one would have expected the order of merit to be the other way round since a greater percentage of the job throughput time is usually spent waiting in queues. It is not difficult, however, to unearth the likely cause of it not being so. A close scrutiny would reveal that the flow allowance in proportion to the process time assignment procedure has the effect of imparting more urgency (or less float) to the shorter jobs when a due date-based scheduling rule is employed. This as we have already established earlier results in a superior work flow characteristic. With job process times widely dispersed, as in an exponential distribution, the influence is particularly dominant. Following from this, an explanation is required as to why a commensurate deterioration in the lateness variance does not arise as it would for an SPT-type of effect under normal circumstances. The reason is simply that although the larger jobs are continually bypassed at the earlier stages when the slacks are high, the position is by no means stagnant. With the passage of time the initially generous slacks will be increasingly eroded causing a progressive tightening of the due dates and hence also the raising of the priority of these jobs. As manifested by various investigations this "push-pull" phenomenon has a very favourable overall impact on the mean job lateness variance.

We have gone to some length on the pros and cons of the SPT effect in Chapter two. For the purpose of avoiding the introduction of bias, rather than having taken any stand on the issue, it was decided against using the flow allowance in proportion to process time method for due date allocation in the experiments. As an alternative it is intended to determine the proficiency of an equation in which the flow allowance is the summation of the total job process time and a factor times the number of operations.

## Experimental Details

The job shop consists of six machine groups with one machine each. 9 jobs are generated at the start of each period and entered into the order book. The trigger-off level below which jobs are automatically released into the queues from the order book is set at 20 hr. for all machine types. Each job is designated 2-10 operations, routed randomly, the possibility of consecutive operations on the same machine group being excluded. For each operation a set-up configuration of 1-8 is assigned and the set and run times are sampled from exponentially distributed values with means of 12 and 36 min. respectively. The job inter-operation transit time is assumed to be similar between all machine groups and is taken from a normal distribution with a mean of 5 min. and standard deviation of 1 min.. To fill up the system 18 jobs are generated at the first period and the number of periods simulated is 13. Five types of job due date assignments are examined, viz :

Flow allowance = (1) sum of process times + 2 x number of ops.
(average allowance = 16.8 hr.)
(2) sum of process times + 3 x number of ops.
(average allowance = 22.8 hr.)
(3) sum of process times + 4 x number of ops.
(average allowance = 28.8 hr.)
(4) 4 x sum of process times
(average allowance = 19.2 hr.)
(5) 5 x sum of process times
(average allowance = 24.0 hr.)

The priority despatching rules used are FCFS, DDATE, SLACK(1), SPT, SLACK(1)/SPT and S(1)/SET/SPT. Further details of the experimental data are given in Appendix 5.1.

## Discussion of Results

The results of the experiment are given in Appendix 5.1.1. Considering first the mean job throughput times we note that for priority rules DDATE and SLACK(1) (i.e. the due date-based rules) due date assignment

types 4 and 5 provide a slightly better performance. This is largely as expected. To support the conjecture that this has arisen from an induced SPT effect the work content remaining per operation was calculated (Appendix 5.1.1(h)). Clearly the figures confirm that the flow allowance in proportion to the process time method causes a backlog of the longer duration jobs. To seek further evidence we refer to the average queue time figures. There is little doubt that due date assignment types 4 and 5 exhibit the other SPT characteristic of shorter average queue times. Before moving on to discuss the other performance measures it is necessary to explain the variations in the throughput times for assignment types 1 to 3 and types 4 and 5 respectively when the FCFS and SPT procedures are employed. The discrepancies have arisen because of the dual innovations in/simulation /the model that (1) jobs are queued in the order book on the criterion of increasing slack time and (2) jobs do not enter the shop directly on generation but are released only when the queue load at each group is below the specified level.

Next the relative merits of the two due date assignment methods are examined in terms of lateness performance. As assignment types 1 to 5 provide varying degrees of flow allowance the mean job lateness results need first to be standardized (see Appendix 5.1.1(j)). From the adjusted figures the benefit of assignment types 4 and 5 readily emerges. It is also worth observing that with an increased flow allowance (type 5) the SPT-like influence is more prominent and hence a better mean job lateness is produced. However, as shown in our findings this is not necessarily accompanied by a concomitant upsurge in the lateness variance. The reason is mainly due to the "push-pull" phenomenon mentioned above. The resultant job lateness variance obtained is dependent on the relative strengths of the detrimental effect of the SPT influence and the desirable quality of the progressive tightening of the slackness of the larger jobs.

The other system effectiveness features such as machine utilisation and work content remaining serve mainly to collaborate with our main conclusions. The better work flow distribution created by assignment types 4 and 5 makes possible a marginal improvement in the utilisation of the facilities and consequently leaves less work in progress at the end of the simulation runs.

Therefore to a large extent the results have supported our previous conjectures. The involuntarily introduced SPT effect causes the flow allowance in proportion to the process time assignment method to be slightly superior in respect of the throughput characteristics and mean lateness but the aspect of lateness variance is less distinctly resolved. Because of the relatively little advantage and the possibility of prejudicing the results of later experiments it was decided to adopt instead the due date assignment method where the allowance is taken as the sum of process time plus a prescribed queue time for each operation.

To observe the effect of varying degrees of due date tightness on the performance measures and to be able to arrive at suitable due date data for the later experiments the two-way layout distribution-free test (Hollander and Wolfe, 1973) and analysis of variance test (Bowker and Lieberman, 1972) were conducted on the results for due date assignment types 1 to 3. Details of the tests are given in Appendix 5.1.2 and a summary is reproduced in Table 5.1.1. In the case of the SLACK(1)/SPT queue discipline statistically significant differences are obtained between the three due date assignment types in all performance characteristics except the set/run time ratio. As expected, with decreasing pressure of dateline the throughput time, mean lateness and machine utilisation all show an improvement principally because of the greater scope for the SPT element of the hierarchic rule to act. However, with progressively tighter due dates the job lateness variance and the throughput of the larger jobs become better. Assignment type 2 appears to be the best choice for the due date assignment data from two considerations. Firstly, it combines the twin benefits of the good throughput and mean lateness of type 3 with the small job lateness variance of type 1 and secondly, the proportion of the tardy jobs is at a reasonable level.

The trend for the S(1)/SET/SPT priority rule is largely very similar. Other than for the set/run time ratio the order of merit of the 3 assignment types for each of the performance measures correspond to that of the SLACK(1)/SPT procedure. The proficiency of assignment type 2 in deriving the better aspects of both types 1 and 3 is even

more pronounced with this queue discipline, and is hence also a natural choice for the due date data.

One further point advocates on behalf of assignment type 2. Referring to Appendix 5.1.1(c) it is found that for the DDATE and SLACK(1) rules the lateness variance does not decrease monotonically with increasingly tighter due dates as for the above SPT-loaded hierarchic rules but rather a minimum is obtained for assignment type 2. This feature is also demonstrated in the graphs of Eilon and Chowdhury (1976).

### 5.1.2 Experiment 1(b) : Comparative Analysis of Priority Despatching Rules

It is long since recognised that the choice of the queue discipline has great significance on the flow of work through the shop. It follows naturally that numerous attempts have been made to determine the despatching rule that will present the best results in the desirable performance characteristics. Findings (see Chapter two) indicate that simple rules such as the SPT, SLACK or S/OPN tend to show promise only in certain effectiveness measures. To overcome this, moves have been made to investigate the efficacy of combining the basic rules in the form of composites or hierarchies. Of principal interest is the aim of merging the superior throughput qualities of the SPT rule and the more precise delivery keeping of job slack-orientated procedures. By regulating the degree of dominance of each of the constituent factors, the optimum overall performance can then be derived.

For the present study, it is intended to take a closer look at the SLACK(1)/SPT rule. In their assessment of a similar procedure (rule 12)* Eilon and Cotterill (1968) concluded that its merit is merely on par with the SPT/trunc procedure and further/more found that the lateness variance produced is higher than even the SPT rule. While both these assertions need examining, only the accuracy of the latter will be investigated.

* SLACK(1)/SPT differs from Rule 12 in that the delay allowance is not a constant but varies in proportion to the number of operations remaining.

Within the constraining influence of keeping the simulation model simple, the majority of investigators have ignored the relevance of tool resetting. There is little doubt that in practical situations a considerable amount of effort is taken to avoid, wherever possible, the need to reset for the next batch of work. It would therefore, be useful to examine the likely benefits that can be obtained when resetting is minimised. The adopted S(1)/SET/SPT rule is formulated by incorporating the resetting element in the SLACK(1)/SPT procedure.

## Experimental Details

The system parameters employed are as those given in Appendix 5.1. The due date data is assignment type 2 and priority rules examined are FCFS, DDATE, SLACK(1), SPT, SLACK(1)/SPT and S(1)/SET/SPT.

## Discussion of Results

Details of the analysis of the results are given in Appendix 5.1.3. For easier reference a summary is set out in Table 5.1.2. As can be observed, with the exception of the machine utilisation and set/run time ratio, a statistically significant variation exists between the six priority rules. For the set/run time ratio the lack of bias is clearly desirable.

The order of merit of the scheduling rules for the mean throughput time, mean lateness and average queue time characteristics conforms well to what is expected. Inevitably the SPT procedure emerges to be the most effective followed by due date-conscious methods such as DDATE and SLACK(1). The SLACK(1)/SPT procedure as predicted, attempts to bridge the gap between these two disciplines. Incorporating the resetting factor as an additional hierarchic stage brings forth sufficient advantage to almost match the SPT performance. Of least proficiency is the FCFS principle. This rule is nevertheless useful as it serves to show the possible benefits that could be obtained when considering more sophisticated loading procedures.

The reason for the lack of enthusiasm for the SPT rule from a practical viewpoint is clearly revealed in the job lateness variance. The figure is twice as high as those for the DDATE and SLACK(1) procedures. Merging the SPT with a SLACK(1) constituent brings the lateness variance down to a more acceptable level but at the expense of losing some of the throughput advantage. Showing good all round effectiveness is the S(1)/SET/SPT rule. The improvement produced in the work flow is accompanied by a better accuracy in meeting the job datelines. At the other end of the scale the FCFS/is not only inefficient in throughput /rule but proves to be equally poor in job completion. The explanation for this is not difficult. Although both the due date-orientated and the FCFS procedures are non-process time selective, the former has a greater propensity to expedite jobs from an earlier batch. This naturally leads to a better throughput as well as a lower lateness variance. Further substantiation of this point can be obtained by computing the operations/jobs completed ratio. For the FCFS rule the highest value is recorded, thus confirming that jobs tend to dwell longer within the system. The rule that has the best job turnover quality and hence the lowest operations/jobs completed value is DDATE. This method possesses the strongest inclination to dispose of jobs from earlier loading periods, a property also reflected in the relatively good mean job throughput times and high work content per job remaining. On its part the SLACK(1) rule is more "single-minded" in the strict adherence to delivering jobs in the proximity of their stipulated due date. Because of the lesser discrimination between work from different loading periods the mean throughput time and mean job lateness are slightly inferior to that of the DDATE discipline. Compensating for this is the improvement in the job lateness variance.

The undesirability of the large lateness variance for the SPT rule has already been mentioned. Comparing the work content per remaining operation for the six rules it is clear that the SPT method leaves a backlog of high-content jobs. The big job lateness variance indicates that a situation is created whereby small jobs are finished well ahead of their requirements while larger jobs are constantly lagging behind their deadlines. Attractive though the overall work flow may be, this condition cannot be tolerated both in terms of production control and the heavy tie-down in stock investment. With the amalgamation of the

SLACK(1) element which provides a "sweeping" function the arrears of larger jobs is reduced to a level that is only slightly higher than for the other rules. The distractive influence of the resetting factor on the clearance of the larger jobs in the case of the S(1)/SET/SPT procedure causes a small rise in the work content per remaining operation.

The machine utilisation results indicate that unless the queue discipline process-time discriminating a substantial variation is not likely to prevail. With the exclusion of the SPT and SPT-incorporated rules the differences were found to be refutable on statistical grounds.

Overall, the results correspond well to the findings from a number of other simulation studies. The differences between the despatching rules have been verified to be statistically significant and their pattern of behaviour and interaction is logically explicable. In addition to showing that the selected system parameters are acceptable, we have also illustrated that credible conclusions can be reached even when using relatively short and small job sample sizes. An important aspect in the validity of the present results is the use of the starting load of a higher volume of work into the system to bring it into a condition that would have otherwise taken much longer to achieve had the shop been simulated from an empty state.

Table 5.1.1

(A) Priority Rule : SLACK(1)/SPT

| Performance Measure | Due Date Assignment Type (1) | (2) | (3) |
|---|---|---|---|
| Mean throughput time (hr.) | 17.72 (3) | 16.06 (2) | 14.62 (1) |
| Mean lateness (hr.) | - 4.09 (3) | - 5.69 (2) | - 6.70 (1) |
| Std.dev. of lateness (hr.) | 4.62 (1) | 5.86 (2) | 8.34 (3) |
| Work content remaining (hr.) | 70.97 (3) | 60.60 (2) | 56.43 (1) |
| Machine utilisation (%) | 84.30 (3) | 85.50 (2) | 86.73 (1) |
| Set/run time ratio | 0.308(1) | 0.308(1) | 0.314(3) |
| Av.queue time (hr.) | 2.21 (3) | 1.89 (2) | 1.69 (1) |
| Work content per remaining operation (min.) | 47.27 (1) | 54.14 (2) | 58.94 (3) |
| Percentage of jobs tardy | 60.99 (3) | 14.08 (2) | 2.98 (1) |

| Performance Measure | Distribution-free test ALPHA level of significance | Analysis of variance T statistics | |
|---|---|---|---|
| | | D-d types | Samples |
| Mean throughput time | 0.005 | 13.12 | 15.52 |
| Mean lateness | 0.005 | 14.18 | 25.80 |
| Std.dev. of lateness | 0.042 | 18.22 | 0.60* |
| Work content remaining | 0.042 | 9.94 | 11.16 |
| Machine utilisation | 0.015 | 9.26 | 23.44 |
| Set/run time ratio | 0.811* | 1.04* | 4.11* |
| Av. queue time | 0.005 | 20.59 | 21.98 |
| Work content per remaining op. | 0.042 | 5.45 | 0.51* |

* case where the null hypothesis is accepted.

Table 5.1.1 (cont'd)

(B) Priority Rule : S(1)/SET/SPT

| Performance Measure | Due Date Assignment Type (1) | (2) | (3) |
|---|---|---|---|
| Mean throughput time (hr.) | 17.09 (3) | 14.56 (2) | 13.96 (1) |
| Mean lateness (hr.) | - 4.71 (3) | - 7.28 (2) | - 8.06 (1) |
| Std.dev. of lateness (hr.) | 4.54 (1) | 5.55 (2) | 8.14 (3) |
| Work content remaining (hr.) | 67.58 (3) | 43.67 (2) | 36.04 (1) |
| Machine utilisation (%) | 82.70 (3) | 84.50 (2) | 85.10 (1) |
| Set/run time ratio | 0.285(3) | 0.246(2) | 0.240(1) |
| Av. queue time (hr.) | 2.11 (3) | 1.67 (2) | 1.53 (1) |
| Work content per remaining operation (min.) | 46.52 (1) | 54.20 (2) | 58.03 (3) |
| Percentage of jobs tardy | 58.36 (3) | 3.79 (2) | 0.00 (1) |

| Performance Measure | Distribution-free test ALPHA level of significance | Analysis of variance T statistics | |
|---|---|---|---|
| | | D-d types | Samples |
| Mean throughput time (hr.) | 0.005 | 10.71 | 8.91 |
| Mean lateness | 0.005 | 14.61 | 10.37 |
| Std.dev. of lateness | 0.042 | 37.33 | 1.41* |
| Work content remaining | 0.042 | 12.34 | 2.77* |
| Machine utilisation | 0.042 | 8.39 | 3.56* |
| Set/run time ratio | 0.069* | 19.60 | 0.02* |
| Av. queue time | 0.005 | 17.08 | 12.25 |
| Work content per remaining op. | 0.005 | 9.83 | 5.43 |

* case where the null hypothesis is accepted.

Table 5.1.2

| Performance Measure | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
|---|---|---|---|---|---|---|
| Mean throughput time (hr.) | 19.68 (6) | 16.43 (4) | 17.85 (5) | 14.06 (1) | 16.06 (3) | 14.56 (2) |
| Mean lateness (hr.) | -1.44 (6) | -4.97 (4) | -3.68 (5) | -7.75 (1) | -5.69 (3) | -7.28 (2) |
| Std.dev. of lateness (hr.) | 7.06 (5) | 4.94 (2) | 4.12 (1) | 9.28 (6) | 5.86 (4) | 5.55 (3) |
| Work content remaining (hr.) | 70.83 (4) | 82.23 (6) | 75.87 (5) | 48.84 (2) | 60.60 (3) | 43.67 (1) |
| Machine Utilisation (%) | 84.70 (3) | 82.60 (6) | 83.30 (5) | 87.70 (2) | 85.70 (2) | 84.50 (4) |
| Set/run time ratio | 0.316(6) | 0.311(2) | 0.306(4.5) | 0.309(4.5) | 0.308(3) | 0.247(1) |
| Av. queue time (hr.) | 2.63 (6) | 2.09 (4) | 2.28 (5) | 1.58 (1) | 1.89 (3) | 1.67 (2) |
| Work content per job remaining (min.) | 179.50 (1) | 278.70 (6) | 238.10 (5) | 225.10 (4) | 216.50 (3) | 197.80 (2) |
| Work content per remaining operation (min.) | 51.12 (2) | 49.90 (1) | 51.02 (3) | 61.29 (6) | 54.14 (4) | 56.99 (5) |

| Performance Measure | Distribution-free test ALPHA level of significance | Analysis of variance T statistics | |
|---|---|---|---|
| | | Rules | Samples |
| Mean throughput time (hr.) | 0.035 | 19.81 | 16.77 |
| Mean lateness | 0.002 | 24.38 | 17.80 |
| Std.dev. of lateness | 0.017 | 14.24 | 3.85 |
| Work content remaining | <0.006 | 27.44 | 4.12 |
| Machine utilisation | 0.047 | 1.06* | 0.83* |
| Set/run time ratio | 0.461* | 0.94* | 5.04 |
| Average queue time | 0.001 | 25.59 | 18.21 |
| Work content per job remaining | 0.014 | 10.89 | 6.08 |
| Work content per remaining op. | 0.014 | 11.03 | 15.69 |
| Operations/jobs completed ratio | 0.020 | 12.81 | 15.59 |

*case where the null hypothesis is accepted.

## 5.2 Experiment 2 : Effect of Process Time Distributions

In job shop simulation studies it is commonly assumed that the job process times are exponentially distributed. The basis for this rests on the findings obtained from a number of practical situations (Reinitz 1963, Hollier 1964, Leigh 1974). Although it is known that on occasions the Erlang or Lognormal curves provide a better approximation these are seldom employed because of their much greater complexity in respect of the computational effort and number of parameters involved. Some results from investigations into the effect of process time variance (using the k-phase Erlang) on the mean job flow time indicate that the SPT rule is rather insensitive to the degree of variance whereas the FCFS procedure shows a marked improvement as the variance is reduced (Conway et al. 1967). This view is not entirely supported in a later study by Ashour and Vaswani(1972). Comparing the performances for k=4 and k=8 (i.e. with lower variance) it was observed that for the SPT discipline, an appreciable advantage in the job throughput time was realised in the case where the variance in the process time was lower. Similar benefits were derived for the mean and standard deviation of job lateness. For the S/OPN rule (non-process time dependent) greater effectiveness all round was also obtained when k=8.

Two other simple types of process time distributions that are also sometimes used in simulation work are the uniform and normal distributions. To assess the likely influence that different process time forms may have on work flow Conway et al. examined the differences obtained for the mean flow time between the uniform and exponential distributions for both the SPT and FCFS procedures. They found that a poorer performance was given by the FCFS rule in the case of the exponential distribution. The response of the SPT procedure varied with the shop loading. With loading below 90% better results were obtained for the uniformly distributed process times. Above that utilisation figure shorter throughput times were provided by the exponentially distributed process times.

For the present investigation the effect of the uniform, normal and exponential distributions on the system performance will be examined. The FCFS (non-process time dependent) and SLACK(1)/SPT (process time dependent) criteria will form the basis on which jobs are selected for loading.

### 5.2.1 Experimental Details

The system parameters are as those given in Appendix 5.1 except for the process time distributions which are as follows :

(1) Exponential : Set time - expected value = 12 min.
Run time - expected value = 36 min.

(2) Normal : Set time - mean = 12 min.;
std. dev. = 3 min.
Run time - mean = 36 min.;
std. dev. = 9 min.
coeff. of variance = 1/4 in both cases)

(3) Uniform : Set time - range : 2 to 22 min. (mean = 12 min.)
Run time - range : 6 to 66 min. (mean = 36 min.)

The run time distributions are plotted in Figure 5.2.1.

### 5.2.2 Discussion of Results

Details of the analysis of the results are given in Appendix 5.2.1 and a summary of the findings is produced in Table 5.2.1. For the SLACK(1)/SPT rule it is found that other than for the set/run time ratio there is no statistically acceptable difference between the 3 process time distributions. Nevertheless, the overall results indicate that with exponentially distributed process times the system responds less effectively. To investigate this point an "Equality of means test for paired observations" (Bowker and Lieberman 1972) was performed on the results for the exponential and normal distributions. The analysis showed that the suspicions are not supported (see Table 5.2.2).

For the FCFS rule the order of merit of the distributions is fairly consistent for most of the performance measures. Again, the exponentially distributed process times produce a poorer performance. In applying the Equality of means test for the exponential and normal distributions the difference is found to be statistically significant for the majority of the performance measures.

One notable feature about the results is the heavy prejudice in the set/run time ratio against the exponential distribution for both the FCFS and SLACK(1)/SPT rules. An investigation is made to determine the cause and its contribution to the poor performance of the exponentially distributed process times. First, it is determined if there is any possible discrepancy in the process time generation. For the exponential distribution a truncation point exists for values below 1.0 minute; the necessity for this is to prevent the generation of operations requiring zero process times as the computer programme has been written with attributes in the integer format. Referring to the exponential curve in Figure 5.2.1 it can be observed that the 0 to 1.0 minute range constitutes an important region of the curve; more so when the expected mean is low as in the case of the set times. Since sampled process times falling below 1.0 minute are rejected and re-generated this causes the actual mean time to be shifted above the expected mean value. As already stated the amount of the shift is inversely proportional to the expected mean value. Calculations indicate that for the set and run times the percentages of cases requiring re-sampling are approximately 8.0 and 2.7 respectively. A similar truncation of values below 1.0 minute is used for the normal variates. However, as illustrated in Figure 5.2.1 the proportion of generated data that is rejected is extremely small and the normally distributed process times are not subjected to the same degree of distortion as for the exponentially distributed times. The uniformly distributed process times are not affected since the generated process times do not fall below 1.0 minute.

For a confirmation of the above analysis a statistical check was made on the experimental data. Details are given in Appendix 5.2.3. As expected, there is good statistical evidence that the exponentially distributed set times are higher than those for the normal and uniform distributions. The discrepancy between the normally and uniformly distributed set times, however, needs some explanation. Arising from the restriction to work with integer numbers whereby the decimal part of a figure is automatically dropped, the exponential and normal distribution means will be lower than their respective expected values. This effect is enhanced when dealing with small numbers as is the case in the set times and probably caused the normally distributed set times to be lower than for the uniform distribution. It also follows that but for this effect the exponentially generated set times will be even higher than those shown in Table 5.2.3.

When the numbers involved are larger as for the run times both phenomena described above show relatively less influence and a statistically acceptable distinction between the process times generated by the 3 distribution forms is not produced. For the cumulative set and run times (total process times) a significant variation in rating between the 3 distributions is again observed. In the case of the set/run time ratio a significant difference in the figures was not obtained. The rankings were however, shown to be statistically acceptable.

Next, it is necessary to relate the above findings to the experimental results. Basically, the situation is that with the exponentially distributed process times the work load is on average about three percent higher. For both the SLACK(1)/SPT and the FCFS procedures it is found that the heavier loading has not produced a higher utilisation. Instead, at the end of the simulation run, the extra load is carried as work in progress. There is little doubt that the higher load would affect the mean job throughput time and mean lateness and although the precise effect cannot be ascertained it is suggested that it is unlikely to have contributed wholly to the poorer performance of the exponentially distributed process times. However, it may be concluded that the present results have confirmed the findings of Conway et al. that exponentially distributed process times are inferior to uniformly distributed times in system performance. Also, it has been found that the difference between normally and uniformly distributed times is not significant.

Table 5.2.1

(A) Scheduling Rule : SLACK(1)/SPT

| Performance Measure | Process Time Distribution | | |
|---|---|---|---|
| | Exponential | Normal | Uniform |
| Mean throughput time (hr.) | 16.06 (3) | 14.90 (1.5) | 14.99 (1.5) |
| Mean job lateness (hr.) | -5.69 (3) | -6.85 (1.5) | -6.61 (1.5) |
| Std.dev. of lateness (hr.) | 5.86 (2) | 5.67 (3) | 5.57 (1) |
| Work content remaining (hr.) | 60.60 (3) | 39.35 (1) | 44.80 (2) |
| Machine utilisation (%) | 85.70 (2) | 86.30 (1) | 85.60 (3) |
| Set/run time ratio | 0.308(3) | 0.286(1) | 0.296(2) |
| Average queue time (hr.) | 1.89 (3) | 1.65 (2) | 1.70 (1) |

| Performance Measure | Distribution-free test ALPHA level of significance | Analysis of variance T statistics | |
|---|---|---|---|
| | | Distributions | Samples |
| Mean throughput time | 0.653* | 3.27* | 15.43* |
| Mean job lateness | 0.653* | 3.31* | 20.51 |
| Std. dev. of lateness | 0.431* | 0.36* | 1.15* |
| Work content remaining | 0.042 | 5.08* | 0.29* |
| Machine utilisation | 0.431* | 0.38* | 8.28 |
| Set/run time ratio | 0.005 | 15.75 | 4.76 |
| Average queue time | 0.525* | 3.92* | 11.97 |

(B) Scheduling Rule : FCFS

| Performance Measure | Process Time Distribution | | |
|---|---|---|---|
| | Exponential | Normal | Uniform |
| Mean throughput time (hr.) | 19.68 (3) | 17.51 (1) | 18.11 (2) |
| Mean job lateness (hr.) | -2.79 (3) | -4.98 (1) | -4.33 (2) |
| Std. dev. of lateness (hr.) | 7.06 (3) | 5.16 (2) | 5.08 (1) |
| Work content remaining (hr.) | 70.83 (3) | 44.55 (1) | 51.05 (2) |
| Machine utilisation (%) | 84.70 (2.5) | 85.50 (1) | 84.90 (2.5) |
| Set/run time ratio | 0.316(3) | 0.286(1) | 0.294(2) |
| Average queue time (hr.) | 2.63 (3) | 2.07 (1) | 2.22 (2) |

* case where the null hypothesis is accepted.

| Performance Measure | Distribution-free test ALPHA level of significance | Analysis of variance T statistics | |
|---|---|---|---|
| | | Distributions | Samples |
| Mean throughput time | 0.042 | 9.78 | 13.37 |
| Mean job lateness | 0.042 | 13.62 | 48.49 |
| Std.dev. of lateness | 0.042 | 9.15 | 2.75* |
| Work content remaining | 0.125* | 9.18 | 0.83* |
| Machine utilisation | 0.653* | 1.39* | 14.16 |
| Set/run time ratio | 0.005 | 52.42 | 5.78 |
| Average queue time | 0.042 | 12.13 | 7.36 |

Table 5.2.2

| Performance Measure | T Statistics | |
|---|---|---|
| | SLACK(1)/SPT | FCFS |
| Mean throughput time | 1.97* | 4.70 |
| Mean job lateness | 2.20* | 7.57 |
| Std.dev. of lateness | 0.43* | 2.79* |
| Work content remaining | 2.91* | 3.59 |
| Machine utilisation | 0.69* | 2.38* |
| Set/run time ratio | 4.52 | 10.95 |
| Average queue time | 2.51* | 4.65 |

Table 5.2.3

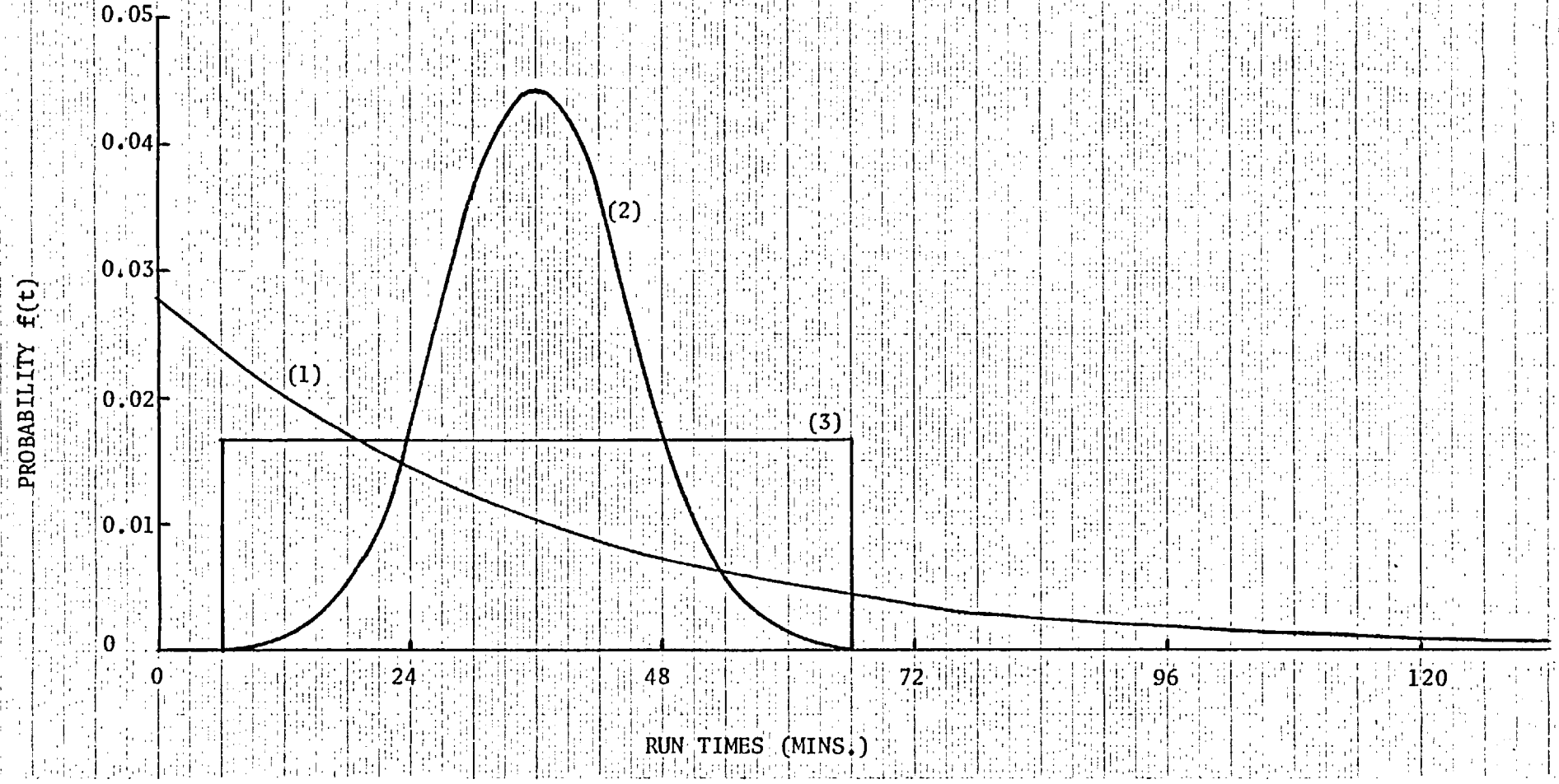
| | Process Time Distribution | | |
|---|---|---|---|
| | Exponential | Normal | Uniform |
| Set time (hr.) | 158.57 (1) | 145.58 (3) | 149.90 (2) |
| Run time (hr.) | 452.90 (1) | 447.72 (2) | 445.98 (3) |
| Total Process time (hr.) | 611.47 (1) | 593.30 (3) | 595.88 (2) |
| Set/run time ratio | 0.350(1) | 0.325(3) | 0.336(2) |

* case where the null hypothesis is accepted.

| | Distribution-free test ALPHA level of significance | Analysis of variance T Statistics | |
|---|---|---|---|
| | | Distributors | Samples |
| Set time | 0.005 | 20.41 | 8.64 |
| Run time | 0.431* | 2.63* | 4.10* |
| Total process time | 0.005 | 30.01 | 16.90 |
| Set/run time ratio | 0.042 | 3.38* | 6.01 |

* case where the null hypothesis is accepted.

FIG. 5.2.1 DISTRIBUTION OF RUN TIMES



## 5.3 Experiment 3 : Effect of Batch Size

The setting up of machine tools in preparation for a fresh batch of components has traditionally been regarded as a necessary evil. In an attempt to diminish the effect of this unproductive element a frequent action is to try to capitalize on it as fully as possible by inflating the batch size or alternatively in realising the same end by selecting, often out of turn, a batch that requires either the minimal or no resetting. It can be anticipated that the continual persuance of this practice would introduce some measures of inertia and disturbance into the system with the consequence of a more sluggish flow and a reduced reliability in the meeting of due dates. An impetus to rectify this situation has come from the group technology concept. Besides the formation of families of parts and grouping of facilities a careful survey of the case studies describing the implementation of cellular manufacture would reveal a perhaps more significant tendency towards the appreciation and adoption of the period batch control method for the determination of batch sizes. This batching strategy has long been advocated by Burbidge (1958, 1970). The well-established economic batch quantity theory is challenged on the ground that though providing a mathematical basis for the derivation of an optimal lot size in terms of cost or profit it is myopic through its total lack of consideration of the relationship between the batches in the shop as well as their relevance to the end product quantities. Symptomatic of the economic batch quantity strategy is the multitude of production control problems and a high inventory investment. While there is little doubt that it is in association with group technology that the period batch control method has received a wider degree of acceptance there are a number of other factors that are progressively working in its favour. The most compelling influence towards product - and not component-consciousness is the economic necessity to overcome the twin effects of escalating material costs and high interest rates. The trend towards a market of greater variety and the projected risk of stock obsolescence with the increasing pace in design and technology turnover also encourages the closer regulation of production to the order book. Finally, the ready availability of tool presetting, numerical control machine tools and setting aids such as the digital

readout advance the case further for the smaller batch.

### 5.3.1 Case (1) - Constant Mean Process Load

#### Experimental Details

The investigation consists of comparing the flow behaviour of 4 levels of batch sizes. To maintain the mean process load constant, the product of the job input rate and the mean batch size is kept the same for all cases. Since a common mean set time is assigned to each batch situation the smaller batches will have a proportional disadvantage in the set/run time ratio. Further details of the experimental data are given in Appendix 5.3.

#### Discussion of Results

The results of the simulation runs are presented in Figures 5.3.1 (a) to (i). In studying the graphs it is useful first to establish that an increasing job input rate is equivalent to a decrease in the batch size. From Figure 5.3.1(a) the machine utilisation for the FCFS and SLACK(1)/SPT rules improve as the batch size is reduced. This suggests that smaller batches are more readily distributed. A similar degree of increase in the machine utilisation is not recorded for the S(1)/SET/SPT discipline. The reason is that as the batch size is decreased there is a correspondingly greater number of jobs within the queues thus allowing the "SET" constituent of the hierarchic rule more opportunity to operate. The result is a lower incidence of re-setting necessary and hence also a reduction in the effective load. A demonstration of this phenomenon can be clearly seen from the set/run time ratio in Figure 5.3.1(b). A point that is of more fundamental interest is the extent this increase in utilisation is reflected in terms of the run or useful work achieved. Figure 5.3.1(c) shows that the outcome is not encouraging. However, this seems logical since there is basically less run load admitted into the system with the smaller batches. To assess the comparative work flow performance the graphs for the average queue time, mean job throughput time and mean job lateness are examined. There is little doubt that the smaller batches excel in all these measures. Another notable feature is the much greater proficiency of the S(1)/SET/SPT procedure when the batch sizes are small. The job lateness variance does not change significantly

with the batch quantity for the SLACK(1)/SPT and S(1)/SET/SPT rules while a downward trend is observed for the FCFS rule (Figure 5.3.1(i)).

Therefore the situation is such that although the smaller batches are better in most respects the amount of useful work obtained is unacceptably low. The next part of the investigation consists of studying the effect of using a constant mean run load instead of a constant mean process load; that is, a proportionally heavier load is imposed on the smaller batch.

### 5.3.2 Case (2) - Constant Mean Run Load

#### Experimental Details

The experimental parameters used are given in Appendix 5.3. For each of the four batch sizes the product of the job input rate and mean run time is kept constant. Consequently the load factors for the 6, 9, 12 and 18 Job Input Rate are 0.825, 0.9, 0.975 and 1.125 respectively.

#### Discussion of Results

Results of this investigation are plotted in Figures 5.3.2(a)-(i). With the higher effective load as the batches get smaller there is a corresponding increase in the machine utilisation. Figure 5.3.2(c) shows that the set/run time ratio disadvantage has to some extent been overcomed and the cumulative run time completed shows up favourably. The trend however, differs between the S(1)/SET/SPT and the other two despatching rules. The former provides a continuous improvement with a decreasing batch size whereas the FCFS and SLACK(1)/SPT procedure starts to decline beyond the 12 Job Input Rate point. The reason for this diversity is clearly illustrated by reference to the set/run time ratio (Figure 5.3.2(b)). It is basically the proficiency of the "SET" feature of the S(1)/SET/SPT procedure in off-setting the set/run time ratio effect. This characteristic applies equally for the work flow performance measures of the average queue time, mean throughput time and mean job lateness. For these measures the S(1)/SET/SPT discipline shows little sensitivity to variation in the batch size. In contrast, beyond the 12 Job Input Rate mark the effectiveness of the FCFS and the

SLACK(1)/SPT rules deteriorate noticeably. It is worth commenting that a proportionally greater difference is obtained between the batch sizes for the average queue times than the mean job throughput times. This has arisen from the shorter process times of the smaller batches countering somewhat the longer waiting times in the queues. It is also interesting that although a fair amount of variation is found in the mean job lateness this has not been reflected in the variance of job lateness (Figure 5.3.2(i)).

Overall the findings indicate that the case for the smaller batch is good. Even with the FCFS and SLACK(1)/SPT procedures, where no attempt is made to capitalize on the re-setting element enhanced by the greater number of jobs in the system with the smaller batches, the results for all performance measures used are promising provided the batch size is not reduced beyond a critical point. For the S(1)/SET/SPT discipline the situation is further improved. The next exercise is to ascertain the statistical significance of these trends. For this analysis the S(1)/SET/SPT rule is used. The details are given in Appendix 5.3.1 and an extract is presented in Table 5.3.1.

The outcome of the analysis leaves little doubt as to advantage of the smaller batch size. The progressively better performance of the throughput time, machine utilisation and cumulative run times completed with reducing batch quantities are all verified to be statistically significant.

Practical Evidence

As far as is known not many case studies have been conducted into the correlation between batch sizes and production flow, and fewer still have been published with sufficient details for possible comparison with these findings. However, one report of the results of planned production changes at Wickman Scrivener Ltd (Hawkins 1974) is relevant to the present investigation. Amongst other undertakings a study was made into effects of reducing the batch sizes below the economically established 'optimum' of 20. It was found that in decreasing the number to 12 (a 40% reduction) a 55% increase in production flow (number of batches) was derived for a 4% increase in cost and a 10% decrease in the number of components produced.

As shown in Table 5.3.2 the simulation results are in fair agreement with these figures. One other remark in connection with the table is that as the batch size is progressively reduced a diminishing benefit is achieved while the loss in cumulative run times rapidly mounts.

Table 5.3.2

(a) Increase in no. of jobs completed (%)*

| | Job Input Rate | | | |
|---|---|---|---|---|
| | 6 | 9 | 12 | 18 |
| FCFS | 54.0 | 61.8 | 39.8 | |
| SLACK(1)/SPT | 71.0 | 54.4 | 41.0 | |
| S(1)/SET/SPT | 69.8 | 58.4 | 44.2 | |
| Wickman Scrivener | | (55) | | |

(b) Increase in cumulative run times (components) produced (%)*

| | Job Input Rate | | | |
|---|---|---|---|---|
| | 6 | 9 | 12 | 18 |
| FCFS | -4.7 | -7.7 | -17.1 | |
| SLACK(1)/SPT | -1.6 | -8.2 | -17.5 | |
| S(1)/SET/SPT | -0.3 | -9.0 | -14.7 | |
| Wickman Scrivener | | (-10) | | |

* The figures are computed on the basis of a 40% reduction in the effective batch size.

Table 5.3.1

Scheduling Rule : S(1)/SET/SPT

| Performance Measure | Job Input Rate 6 | | | |
|---|---|---|---|---|
| Throughput time (hr.) | 17.56 (4) | 14.56 (3) | 14.54 (2) | 13.49 (1) |
| Mean job lateness (hr.) | -5.68 (4) | -7.28 (1) | -6.30 (2) | -6.51 (3) |
| Std.dev. of lateness (hr.) | 6.71 (4) | 5.55 (2) | 5.95 (3) | 5.25 (1) |
| Work content remaining (hr.) | 68.90 (4) | 43.67 (1.5) | 53.97 (3) | 52.77 (1.5) |
| Machine utilisation (%) | 75.80 (4) | 84.50 (3) | 88.00 (2) | 94.40 (1) |
| Set/run time ratio | 0.179(1) | 0.247(2) | 0.307(3) | 0.359(4) |
| Av. queue time (hr.) | 1.90 (4) | 1.67 (1) | 1.85 (3) | 1.83 (2) |
| Run time completed (hr.) | 401.23 (4) | 422.77 (2) | 420.27 (3) | 432.90 (1) |
| Percentage of jobs completed | 83.00 (4) | 89.30 (3) | 88.90 (2) | 90.40 (1) |

| Performance Measure | Distribution-free test ALPHA level of significance | Analysis of variance T statistics | |
|---|---|---|---|
| | | Input rates | Samples |
| Throughput time | 0.036 | 4.16 | 6.18 |
| Mean job lateness | 0.867* | 0.61* | 8.00 |
| Std.dev. of lateness | 0.006 | 2.50* | 2.37* |
| Work content remaining | 0.033 | 2.39* | 4.05 |
| Machine utilisation | 0.000 | 105.56 | 5.00 |
| Set/run time ratio | 0.000 | 76.40 | 1.82* |
| Av. queue time | 0.867* | 0.51* | 6.54 |
| Run time completed | 0.012 | 7.20 | 4.79 |
| Percentage of jobs completed | 0.190* | 2.76* | 1.75* |

* Case where the null hypothesis is accepted.

FIGURE 5.3.1 : EFFECT OF BATCH SIZE ON THE VARIOUS EFFECTIVENESS MEASURES - CASE (1) CONSTANT MEAN PROCESS LOAD

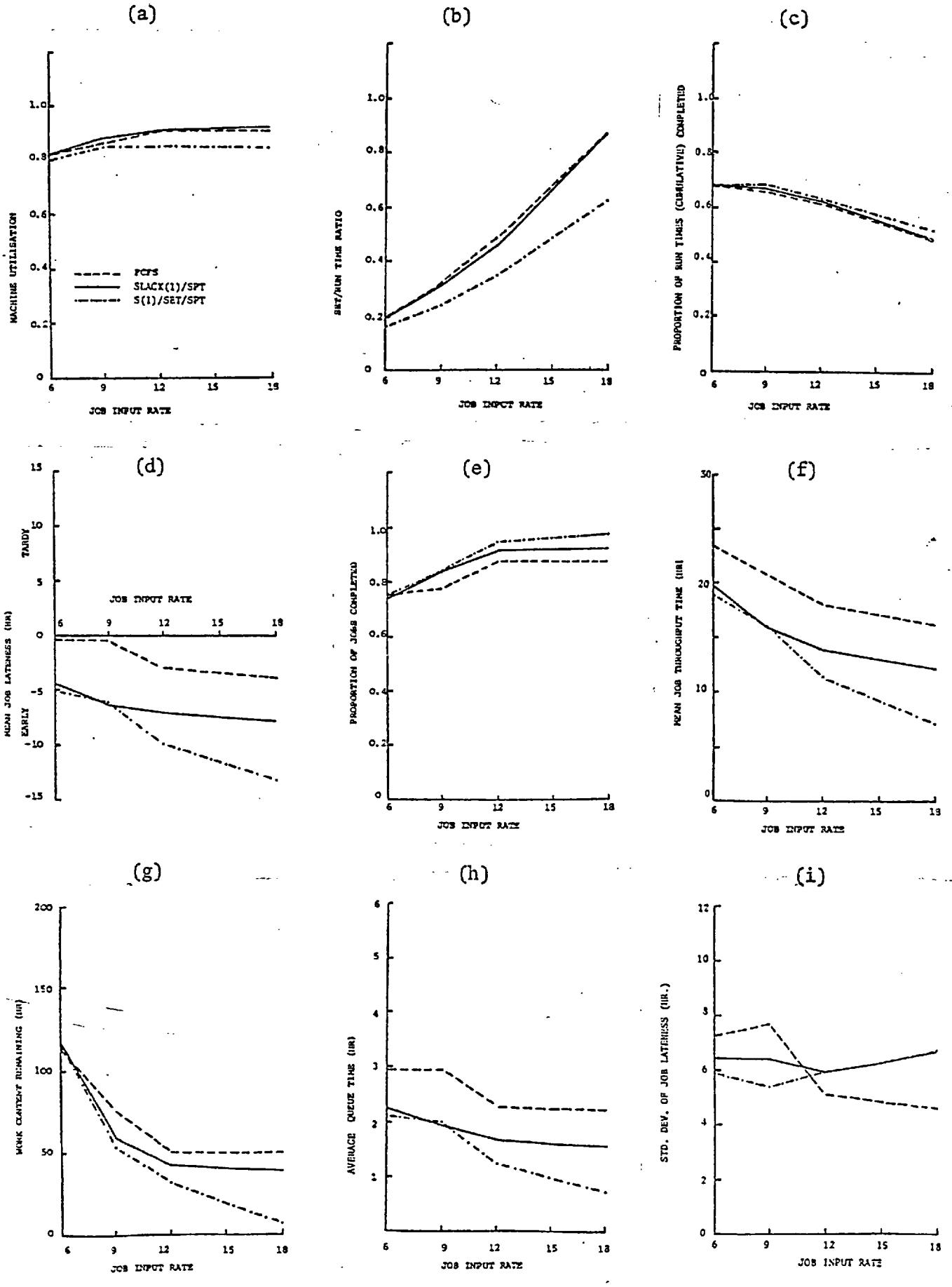
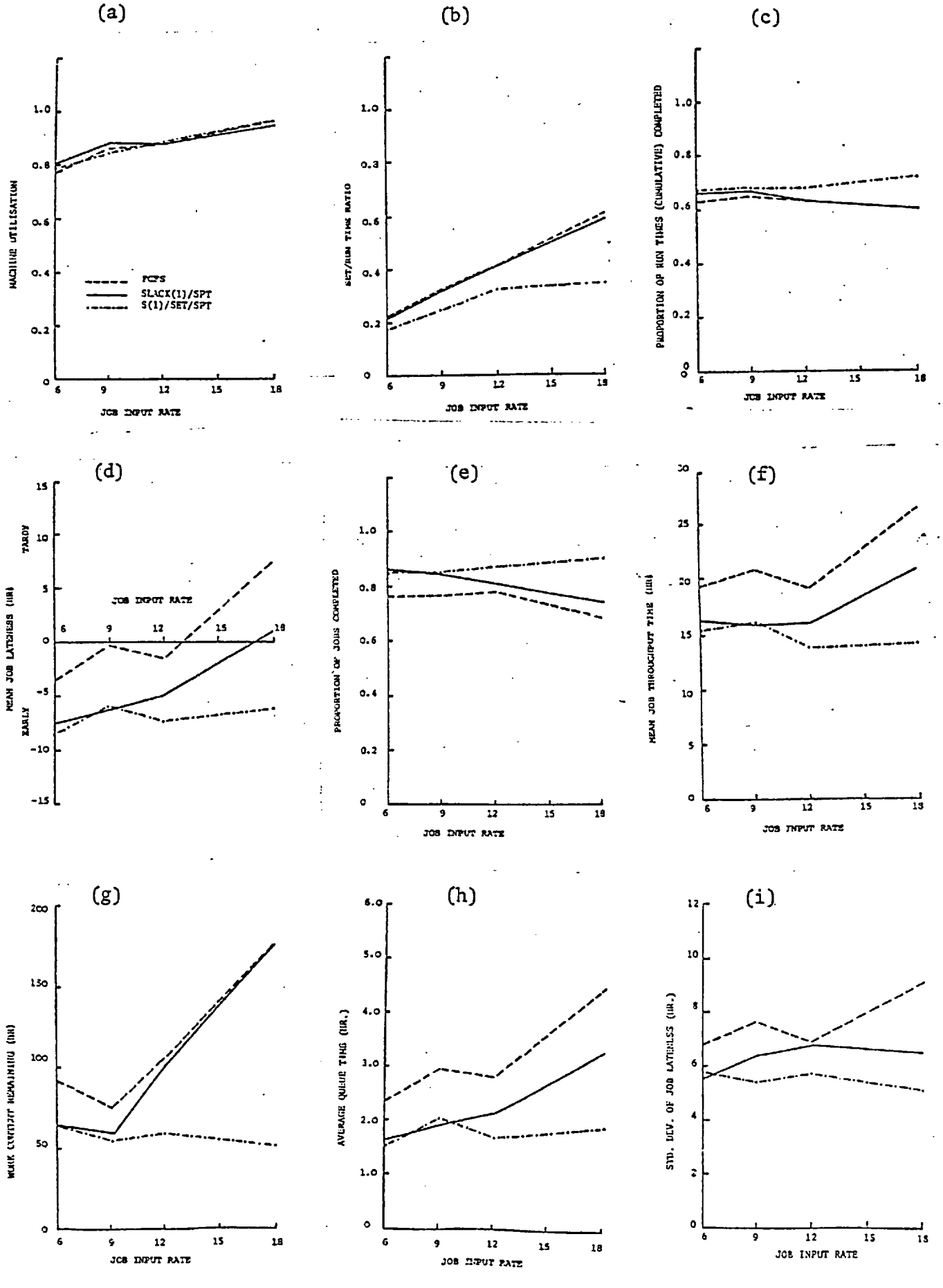


FIGURE 5.3.2 : EFFECT OF BATCH SIZE ON THE VARIOUS EFFECTIVENESS MEASURES - CASE (2) CONSTANT MEAN RUN LOAD



## 5.4 Experiment 4 : Effect of Work in Progress Level

In recent years the increasing cash flow pressures that many companies are facing has placed considerable importance on the work inventory situation. In presenting the 1971 Sir Alfred Herbert Paper, Harrison (1972) remarked that the average British manufacturing company turns its stock over twice per year. In comparison, the stock turnover rate for the German, American and Japanese firms is approximately double. The result is an extended lead time and twice as much working capital committed to stock. Interpreted in terms of figures Willetts suggested (separately - reported in Anon 1975) that should the general level of work in progress be reduced by say 15%, the balance of payments could be improved by around £4,000 million. Also, as far back as 1968 the British Productivity Council estimated that in British industry the value of stocks of finished products, piece parts, etc. totalled £12,000 million and the cost of maintaining those stocks was between £2,400 and £3,600 million each year (Anon 1970).

A further consequence of an extended work in progress level is the possible down-grading of the company's standing and competitiveness through the constant inability to meet its delivery commitments. In a survey by the British Institute of Management (Anon 1977) it was found that out of a total of 186 firms only four claimed a 100% on-time delivery record in 1975. Five companies failed to deliver anything by the time promised and 25% reported that they managed to deliver less than half of the customer's orders on time.

The fundamental motive for maintaining a high work in progress level is to achieve a high plant and labour utilisation. Unfortunately, it also has an adverse effect on the job throughput and delivery performances. The essence of good production planning and control is an efficient regulation of these two factors. From what has been shown above it is obvious that the majority of production managements have chosen to be more preoccupied with the better usage of the machines and workers. This is not surprising since this aspect has traditionally been regarded as their principal responsibility. As a measure of the situation it was established in the BIM survey already mentioned that there is on average a queue length of 4 to 5 jobs at each stage in a manufacturing

sequence. This is projected to be twice the number necessary for efficient utilisation of a facility; whether it is a machine or an operator.

Many other causes could contribute to the escalation in the work in progress. One of these is the ineffective use of the production resources. Studies conducted by Dudley (1970) over several years showed that machines and labour were employed productively for only approximately 40% and 50% respectively. Even then it was found that most machining operations were performed at cutting conditions below those considered to be optimum. Therefore, the situation is such that while ensuring that the facilities are well supplied with work there is little effort towards the quicker dispensation of the work. As a result it is not totally unexpected that no more than 20% of the time taken to progress materials through the shop is actually spent productively (Anon 1975 II).

A third factor likely to wield some influence on the work in progress condition is the method in which the batch sizes are determined and whether parts are made for stock, specific orders, or both. In going for larger batches to lower the unit cost the manufacturing cycle is effectively extended. If the components are produced predominantly for stock and the requirements are regular the schedules could be arranged to maintain the work in progress at a reasonable level. However, in practice demands are liable to be erratic and this often necessitates batch splitting, expedition of certain batches and other actions disrupting the orderly sequence of the work. The consequence could be the loss of the "re-setting" advantage of the larger batch leading to an increase in queueing time and an extended work in progress.

Fourthly, although production management is an important, challenging and difficult job it is ranked for complex social reasons as of secondary status only. It follows that the task is often carried out by under-qualified or under-staffed departments (Anon 1976). Substantiation of this position was obtained in a survey by members of PROMAG* which indicated that in UK companies the production managers are rarely in sufficient control.

* The Production Management Action Group.

It is relevant therefore in the present investigation to examine the effects of work in progress on the system performance and attempt wherever possible to relate our findings to some of the "general, and generally accepted" observations made in the reports quoted above.

Experimental Details

To simulate varying work in progress levels the system is preloaded with different numbers of jobs. The experimental parameters used are as those shown in Appendix 5.1. The job due dates are allocated by assignment type 3 and again the results are assessed for the FCFS, SLACK(1)/SPT and S(1)/SET/SPT despatching rules.

Discussion of Results

The results obtained are presented in Figures 5.4.1(a) - (g). The trend for the machine utilisation is very much as expected. Although different numbers of jobs are taken into the system to start with, the job input at subsequent periods is at a 90% load level. Since the effect of the initial assignment would have been largely worked off by the end of the simulation run and the utilisation values are taken as an average over the simulation period, the curve will rise with a diminishing gradient to the 100% mark. For the set/run time ratio we note that whereas the FCFS and SLACK(1)/SPT procedures only show statistically random fluctuations a distinct pattern can be discerned for the S(1)/SET/SPT rule. With increasing volume of work in progress the "SET" element comes more frequently into action and brings down the amount of setting up necessary. However, beyond the 36 job preload point the urgency to maintain good job deliveries predominates and the set/run time ratio mounts again. This characteristic is reflected in the average queue time, mean throughput time, work content remaining, and the mean and standard deviation of job lateness. From the 'work content remaining' graph a similar breakpoint appears to be at the 27 job preload for the FCFS and SLACK(1)/SPT rules but this is not shared by the other performance measures except the machine utilisation.

Now we will attempt to relate these results with some published figures discussed earlier. Consider first the suggestion in the BIM report that the average of 4 to 5 jobs in queue prevalent in industry at present could be cut to half without much adverse effect on facilities usage. From our results the best operational point corresponds to the 27 job preload situation. In Figure 5.4.1(g) a scale is included for the average queue time/ mean process time per operation; this is taken to be equivalent to the number of jobs in queue. At the 27 job preload point the average number of jobs in queue are 4.8, 3.3 and 2.8 for the FCFS, SLACK(1)/SPT and S(1)/SET/SPT disciplines respectively. This condition may be assumed to represent the preferred state of queues. To portray the present day situation the 45 job preload is used. This gives an average queue length of 7.6, 5.8 and 5.3 jobs respectively for the 3 scheduling rules. Comparing the 27 and 45 job preload cases it is evident that an endeavour to ensure the higher utilisation of the resources has serious detrimental consequences. For the FCFS rule a 5% improvement in utilisation is accompanied by a 40% rise in the mean job throughput time. The corresponding figures for the SLACK(1)/SPT procedure are 2% and 58% respectively.

Secondly, we examine the observation in Dudley's survey that less than 20% of the job lead time is spent productively. Again, assuming the 45 job preload case to represent the industrial situation as it is today, a throughput/mean process time ratio (see Figure 5.4.1(c)) of 7.6, 6.3 and 5.8 respectively are recorded for the FCFS, SLACK(1)/SPT and S(1)/SET/SPT rules. On reducing the work in progress equivalent to the 27 job preload case the corresponding figures are 5.4, 4.0 and 3.8 respectively. Therefore, although a fair improvement is obtained one must still expect jobs to spend more time waiting in queues than actually being attended to.

Finally, we consider the poor delivery statistics that is also contained in the BIM report. In practice the specification of delivery dates vary widely. In addition to the job characteristics such as complexity (i.e. number of operations required), size and batch quantities, the state of the workload in the shop, customer relationship and competitiveness of the product also impart some influence. Nevertheless, in many industrial situations the job characteristics still dictate the basis on

which due dates are derived. Reference to Figure 5.4.1(e) indicates that the mean job lateness rapidly worsens with higher work in progress. At the same time the job lateness variance rises. Thus jobs not only become increasingly late but the completion of work in relation to their required dates become more variable and less predictable.

FIGURE 5.4.1 : EFFECT OF WORK-IN-PROGRESS LEVEL ON THE VARIOUS EFFECTIVENESS MEASURES

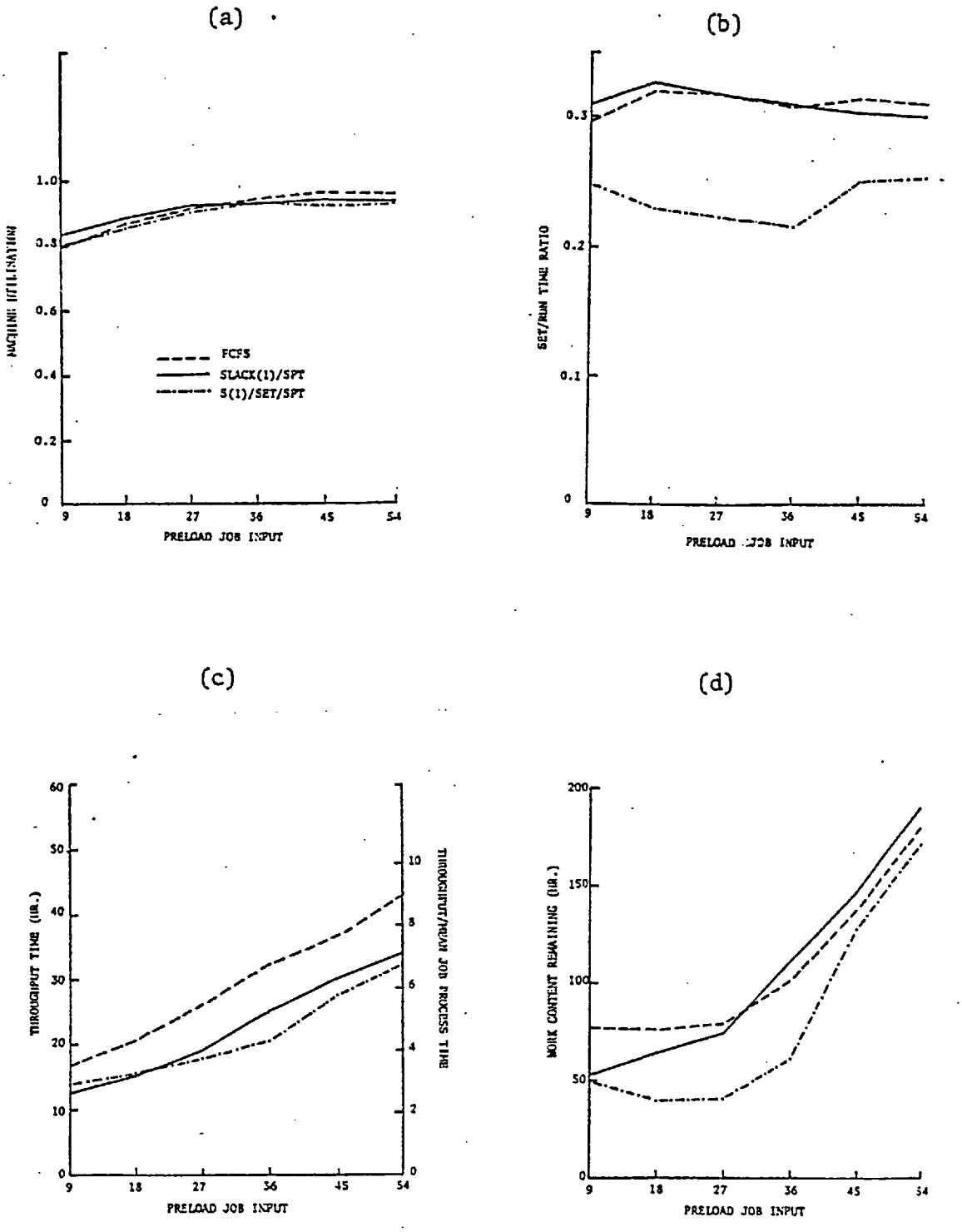
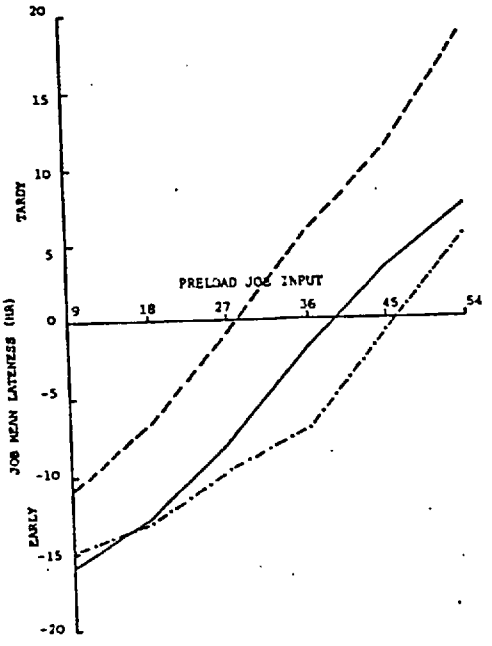
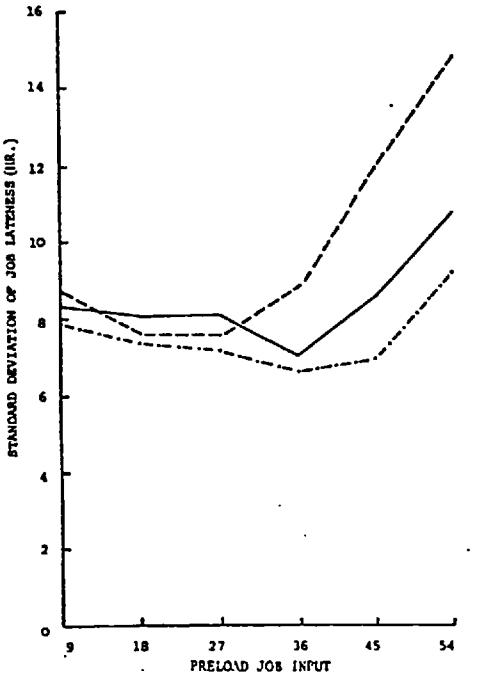


FIGURE 5.4.1 (CONT'D)

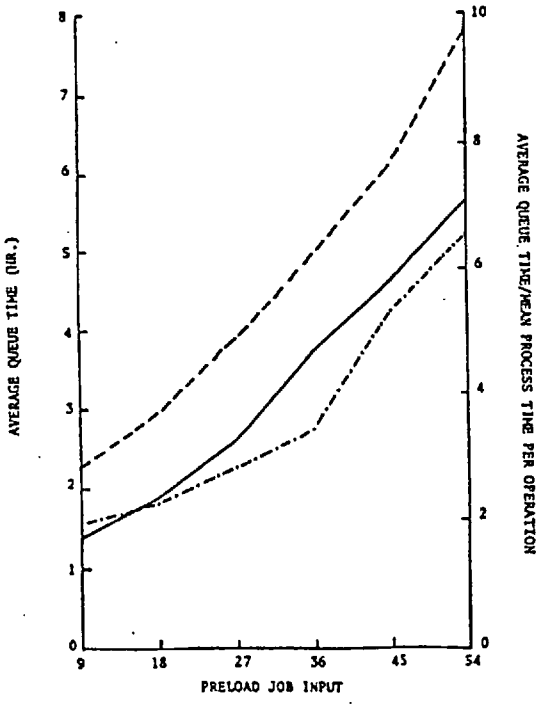
(e)




(f)




(g)



## 5.5 Experiment 5 : Effect of the Job Inter-Operation Transit Time

The time element in which jobs are transported between subsequent operations is one of the least discussed aspect of work flow. This is understandable in predominantly high work in progress situations, as it is relatively insignificant. However, transit time is inevitably an additional, non-productive element of lead time.

While factors such as the adequacy of transfer equipment and the size, shape and weight of the parts are likely to impose their influence, the main considerations in determining job transfer efficiency are the effectiveness of the production control and the facility of the plant layout in promoting a good work flow. An illustration of the benefits that could be derived from better production planning and control is the experience at Petbow Ltd, where the production management function has recently been computerised (Kellock 1976). It was worked out that using the conventional system of workpiece movement a minimum of 6 hours is usually allowed for the transfer between work centres. This period is essential for the issue of necessary instructions and for the uncertainty as to the work load of the person responsible for carrying out the move. With the new system the moving time assigned to every item is 6 minutes. Though it is appreciated that moving times cannot be estimated with much accuracy and will vary greatly with the distance involved it was felt that this target can be achieved on average. To increase the workability of this method it was decided that no machining operation will be scheduled to begin until one hour after the required move is planned to take place. The success rate claimed for this measure was 85%.

The conversion from the functional to the cellular mode of manufacture not only eradicates many of the production control problems, but with the work flow considerably streamlined and rationalised and the sequential machines in closer proximity the delays arising from work transfer is greatly reduced. Figures recorded at Elliot (Barker 1970) showed that with group technology the total distance travelled per batch was shortened by around 312 feet. Over a year the shortening of the inter-operation movement for a particular type of component was estimated to be as much as 161,400 feet or 30.6 miles. The segregation of parts

into families of different shapes and sizes also simplifies work handling. In many cases conveyor systems have been introduced and heavier equipment such as cranes need only traverse a smaller area of the shop. From his study of the economic aspect of group technology Knight (1974) concluded that some savings are obtained in the indirect labour and handling equipment costs. Another beneficial factor reported to result from the reduced transportation of parts is the lower incidence of accidental damage (Astrop 1973).

The present experiment examines the effects arising from varying inter-operation transit times.

## Experimental Details

The inter-operation transit times are sampled from normal distributions with different mean values but in each case the coefficient of variation (i.e. standard deviation/mean) is maintained at 0.2. For simplicity (though not an inherent restriction of the simulation model) it is assumed that the mean inter-operation transit time between all work centres is the same. The range of the mean values used are 0 to 70 minutes with intervals of 10 minutes. Due dates are fixed by assignment type 2 and the rest of the data are as shown in Appendix 5.1.

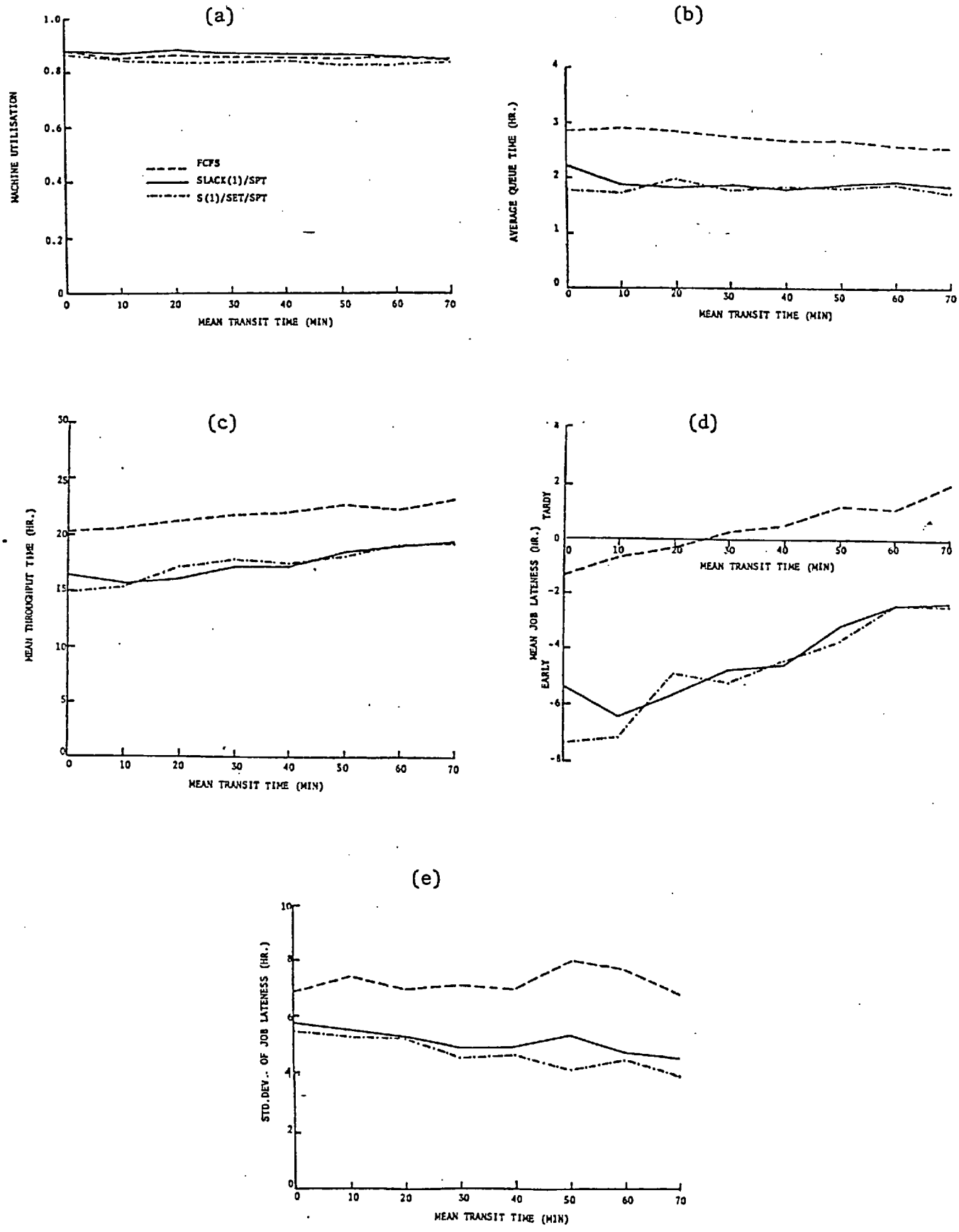
## Discussion of Results

The results from the experiment are presented in Figures 5.5.1(a) to (e). With longer inter-operation delays the number of jobs in queue at any time will be smaller and therefore the average queue time will fall. This is reflected in the average queue time curve for the FCFS rule but not however, in the trends for the SLACK(1)/SPT and S(1)/SET/SPT disciplines. The reason is that with a shorter queue length the SPT element of these disciplines becomes less effective, hence causing a rise in the average queue time. The result is the offsetting of one factor by the other and the average queue time curve shows relatively little sensitivity to changes in the mean inter-operation transit time. As the mean transit time is increased the probability of queues being depleted becomes higher and the machine utilisation will be expected to

fall. Figure 5.5.1(a) shows that although the average queue lengths for the FCFS, SLACK(1)/SPT and S(1)/SET/SPT rules are only 3.2, 2.3 and 2.2 respectively (at 70 minutes mean transit time) the fall in utilisation as the mean transit time is increased from 0 to 70 minutes (equivalent to 1.5 mean process time per operation) is small.

For the FCFS rule, the shorter average queue time is unable to compensate for the increase in the inter-operation transit time and as can be observed in Figure 5.5.1(c), the mean job throughput time rises with the mean transit time. The curves for the SLACK(1)/SPT and S(1)/SET/SPT are steeper since there is no corresponding advantage in the average queue time. The trend for the mean job lateness curves follow that of the mean job throughput time. Figure 5.5.1(e) demonstrates a point made earlier that the tightening of due dates have a beneficial effect on the job lateness variance. With an increase in the mean transit time it is found that there is a decrease in the job lateness variance for the SLACK(1)/SPT and S(1)/SET/SPT procedures. A similar performance is not obtained for the FCFS discipline which is not due-date orientated.

FIGURE 5.5.1 : EFFECT OF THE MEAN INTER-OPERATION TRANSIT TIME ON MACHINE UTILISATION, AVERAGE QUEUE TIME, MEAN JOB THROUGHPUT TIME, MEAN JOB LATENESS AND STANDARD DEVIATION OF JOB LATENESS



## 5.6 Experiment 6 : Effect of Number of Tool Set-Up Configurations

In his survey into the activities of machine tools Tinker (1966) reported that the time spent in setting and handling is approximately two-thirds of that engaged in cutting. This suggests that there is a great potential for raising productivity without necessarily resorting to investment in new capital equipment. There are two ways in which this can be achieved; both being largely complementary. The first method is to reduce the setting time as much as possible through the use of numerically-controlled machine tools, tool presetting, digital readouts, and the like. The second approach consists of taking measures to avoid as far as possible having to reset for a fresh batch of parts. One of these measures is a move towards less proliferation of designs for components of very similar function. It was estimated at Herbert (Anon 1974) that with a 25% reduction in variety at 10% increase in production could be obtained.

A second measure towards minimising resetting between batches is the use of the composite component concept. This technique entails basically the design of tooling arrangements and fixtures to incorporate the common features of a group of components broadly similar in shape and size or machining requirements. With the machine tool prepared for the composite component, which may be real or hypothetical, only minor adjustments, if any, will be necessary to accommodate all the components within the group. In one application (Sidders 1966) the benefits claimed were a 50% reduction in the setting times and a 40% improvement in the floor-to-floor times. A further advantage of the composite component innovation is the elimination of future proliferation of little used jigs, fixtures and too tooling. In a survey at a major British machine tool company (Grayson 1970) it was shown that on average a fixture was used for less than one day each year. With the use of group fixtures - in one case it was found that 189 individual jigs could be replaced by 14 group jigs - the considerable capital tied up in idle fixtures and jigs, stores area and personnel could be released for more profitable ventures.

Thirdly, setting times can be curtailed through careful planning of the sequence in which jobs are loaded. Using classification and coding (e.g. Opitz, Brisch) each part is assigned a code number depicting its

characteristics. In production the jobs are selected in ascending (or descending) order of these code values thus minimising the change in tool set-up configuration (Durie 1970, Barker 1970, Whitfield 1972). With this arrangement great savings in the setting times can be derived. For example, it was established that for one type of component the average setting time has been reduced from 240 to 45 minutes (Barker 1970). Unfortunately, this procedure also suffers from an inherent disadvantage; that is, the relative inflexibility of the job cycle time. An alternative strategy involving the use of the composite component concept together with a scheduling discipline such as the S(1)/SET/SPT is more adept at reaching the setting time and throughput time minimisation requirements.

Although generous claims have been made on the savings in setting time and costs possible with group technology it is necessary to appraise some of the more practical aspects. It is conceivable that in some situations the conversion from the functional to the cellular layout can actually cause a rise in the setting times due to the reduced matching opportunity of the component requirements to the machine facility (Craven 1974). Also despite what has been said above about the composite component it is necessary to consider a number of practical factors such as different sizes of collets being required for different sizes of bar, different sizes and settings of roller boxes being needed in turning different finished diameters, etc.

Early attempts at group technology often aimed to limit the number of families within a cellular group; the ultimate figure being one. This is usually not viable because the inhospitable characteristic of small cells causes the utilisation to be unacceptably low. For this experiment the effects of varying numbers of tool set-up configurations will be investigated. The queue length employed is low to simulate the conditions for cellular manufacture; the average number of jobs in queue for the FCFS, SLACK(1)/SPT and S(1)/SET/SPT rules being 2.95, 1.87 and 1.82 respectively.

## Experimental Details

The number of tool set-up configurations used are 1 to 8, 10, 15, 20 and

25. In each case the same number is applied to all the machine types (though not an inherent requirement of the simulation model). Each job operation is separately assigned a set-up configuration sampled from a uniform distribution. The rest of the experimental data are as those shown in Appendix 5.1.

Discussion of Results

The results for the machine utilisation, set/run time ratio and mean job throughput time are presented in Figures 5.6.1(a) to (c). With small numbers of tool Set-Up Configurations (SUC's) the effective loading is reduced because of the lower setting times and this is reflected in the machine utilisation. For the FCFS and SLACK(1)/SPT rules the machine utilisation rises quickly and reaches a steady value at SUC=5. In the case of the S(1)/SET/SPT procedure which consciously matches the job selected to the set-up type on the last job, the machine utilisation increases more slowly and does not taper off until at SUC=10. An insight into the savings in setting time is given by Figure 5.6.1(b). The set/run time ratio for the FCFS and SLACK(1)/SPT rules increases rapidly until SUC=5 and beyond SUC=10 the curves become insensitive to variations in the SUC's. The curve for the S(1)/SET/SPT rises more steadily and the increase is sustained beyond SUC=25. Figure 5.6.1(c) shows that above SUC=5 the mean job throughput times for all 3 rules remain relatively constant with respect to the number of set-up configurations.

It is interesting that at low SUC's the mean throughput time for the S(1)/SET/SPT rule is only marginally better than for the SLACK(1)/SPT procedure. This is because as the "SET" element becomes more active with higher set-up matching probabilities the "SPT" factor, which is proficient at low job throughput, becomes correspondingly less effective.

One factor that must be considered in relation to the results, in particular with respect to the S(1)/SET/SPT rule, is the queue length. The average queue lengths for the FCFS, SLACK(1)/SPT and S(1)/SET/SPT rules (at SUC=5) are 3.2, 2.3 and 2.2 respectively. As discussed in Experiment 4 these work-in-progress levels relate well to the "recommended" values.

Therefore the general conclusion that can be made is that when operating with a reasonable work-in-progress level the effect on the system performance rapidly decreases beyond very small numbers of different set-up types.

Next, an examination is made of the practice whereby tool setting minimisation is sought through carrying to great lengths the matching of the set-up configurations between consecutively loaded parts. Under such circumstances the queue length is often maintained at a higher level and this feature is incorporated in the present experiment. For comparison 2 sets of conditions are used. Case A represents the "normal" or control condition with the flow allowance allocated as the sum of process times + 4 x Number of operations in the job. For Case B the flow allowance is the sum of process times + 6 x Number of operations in the job. The higher flow allowance gives greater opportunity for the "SET" element of the S(1)/SET/SPT rule to operate, thus simulating the effect that is being investigated. The results from the experiment are presented in Figures 5.6.2(a)-(f).

The two curves show little difference in the machine utilisation. At low SUC's the reduced setting time is reflected in the slightly lower utilisation for case B. As the SUC increases the matching possibilities decrease and the now higher utilisation for case B is attributable to the more dominant effect of the SPT factor.

Figures 5.6.2(c) and (d) show that the throughput performance for case B is only slightly improved. The penalty for this advantage is the substantial deterioration in the reliability at meeting due dates, as illustrated by standard deviation of job lateness in Figure 5.6.2(e). An indication of the "queue length" (that is, average queue time/mean job process time per operation) for the experiment is given in Figure 5.6.2(f).

FIGURE 5.6.1 : EFFECT OF NUMBER OF SET-UP CONFIGURATIONS ON MACHINE UTILISATION, SET/RUN TIME RATIO AND MEAN JOB THROUGHPUT TIME

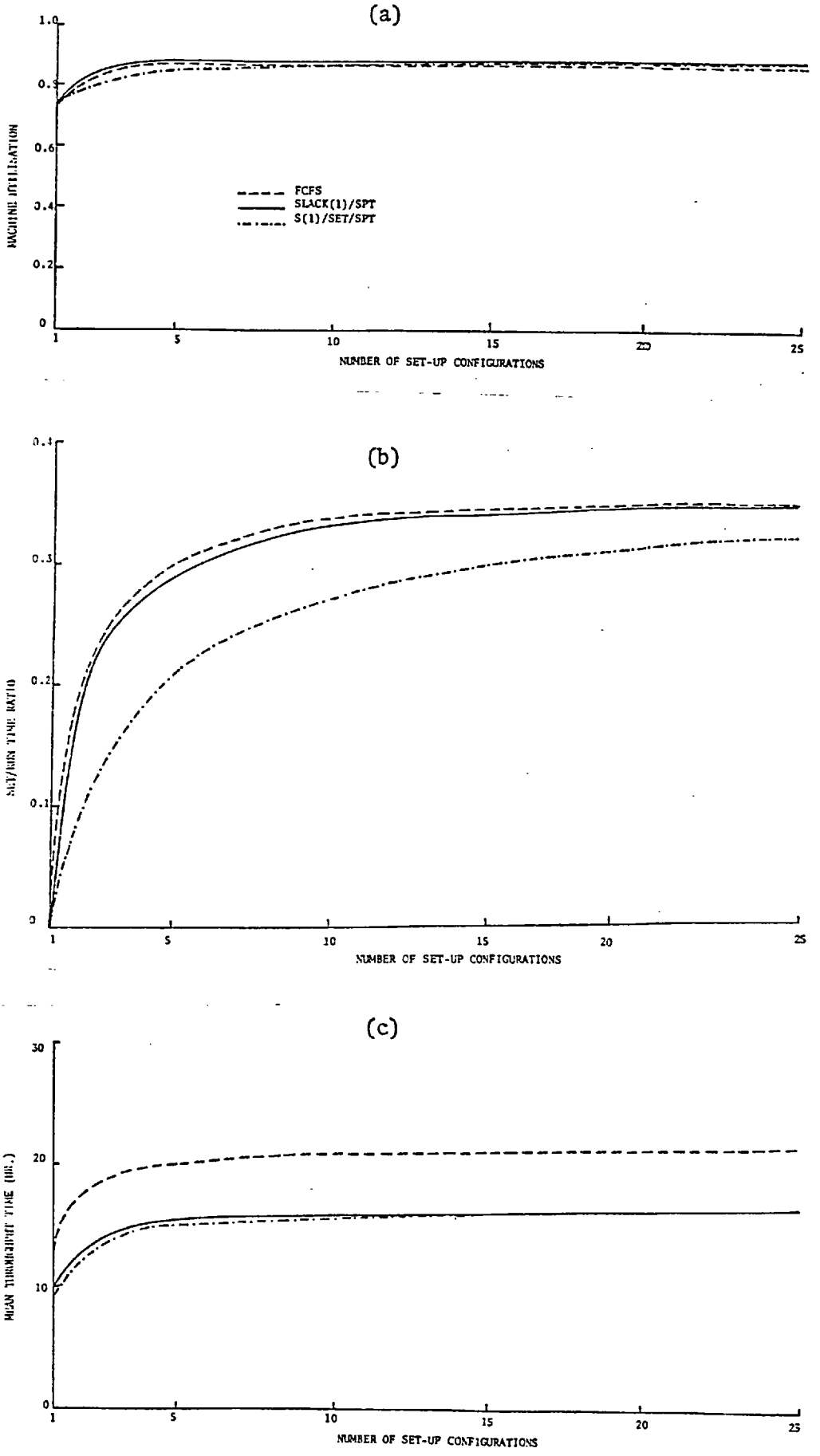
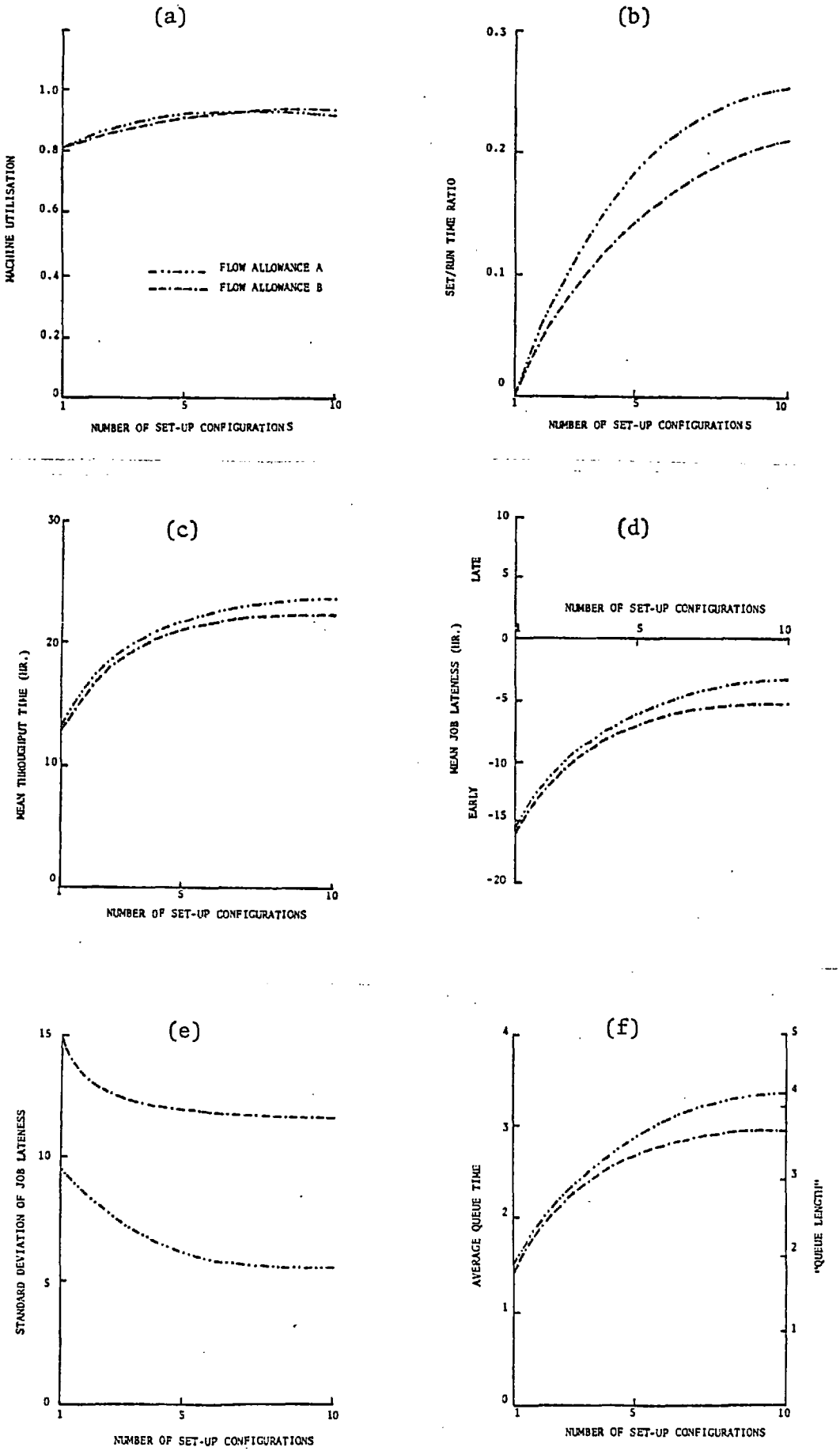


FIGURE 5.6.2 : EFFECT OF TOOL SETTING MINIMISATION ON THE VARIOUS EFFECTIVENESS MEASURES



## 5.7 Experiment 7 : Effect of Cell Size

Largely traceable to the manner in which group technology has developed, there are two distinct approaches in formulating the composition of manufacturing cells. The first strategy is closely allied to the earlier preoccupation with workpiece features and classification, and was conceived from an extension of Mitrofanov's work which is basically single machine-orientated. Here, schemes are devised whereby one or more families of parts are completely produced within a group of machines. This method is favoured where the establishment of pilot cells are contemplated, and in firms where a large proportion of their components fall into natural families and the demand for their products is steady. While pilot cells serve a useful purpose as some firms have decided to commit their facilities more fully to the cellular layout arising from the encouraging results therefrom, they should not be allowed to function in isolation for the longer term as consequences such as production imbalance and inflation of work in progress at the more expensive end of the production cycle may ensue (Edwards 1974). Characteristic of cells formed by the "part families approach" is that they are small and considerably specialised.

The second cell design procedure, usually regarded to be a more total venture, consists of the analysis of the parts flow routes. In this way, components which share common production processes but are dissimilar in physical features will be brought together. This gives the advantage of a better all-round usage of the machining resources. Although one may be sceptical at the loss of the setting advantage inherent in the "part families approach" this can actually, be recouped through the formation of composite set-ups. Typical of cells germinated from the parts flow concept is that they are fairly large and has a good measure of flexibility in the accommodation of parts.

While a rule of thumb may be used in deciding which of the two cell design methods is more suited to a particular industrial environment there are instances when both approaches can be simultaneously applied to good advantage. Examples of these are Ferranti (Allen

1973) and Herbert (Perrins 1972).

It is not unusual at the outset of the analysis to have certain preconceived requirements regarding the cell size, optimum number of operatives, and so on. However, resulting from the interaction between a multiplicity of factors such as the level of machine utilisation in the cells, work content imbalance between cells and restrictions pertaining to machine tool characteristics (e.g. automatics should be grouped together to minimise setting and also enable an operator to attend more than one machine), the best cellular groupings that are found may depart substantially from what is initially envisaged. Such is the experience at Short's (Tedford and Ferris 1976). In planning the production system for a new product based on group technology principles it was intended that the cells should, for sociological reasons, contain approximately ten operators each. At the end of the exercise the optimum arrangement is for six groups with operator numbers ranging from 22 to 30.

The survey by Pullen (1976) of manufacturing cells already operational reveal that there are on average 10.7 men and 14.0 machines to each cell. His observation of a sizeable proportion of very large (greater than 21 men) cells and very small (below 4 men) cells goes towards confirmation of the suggestion that different characteristics of cells are created by each of the two cell design methods. Although comments were made that very small cells cannot be expected to have long-term viability nor be significant units of production capacity, and large cells cannot be left to manage themselves nor can operators be expected to form a single social group there is no indication of how accurate these remarks are in relation to the existing cells. On the basis of this survey and some predominantly sociological considerations Pullen drew up a list of necessary and desirable qualities of a manufacturing cell (Hall 1975). The necessary cell size characteristic is stated to be 4 to 14 men with a desirable number of about 10.

In another survey (Dale and Willey 1977) - conducted by questionnaire - it was recorded that some of the reasons companies gave for not changing to group technology are :-

(1) the changing nature of demand
(2) the range of manufactured products, the complexity of operations involved and the variability of batch sizes, and
(3) the reductions in machine utilisation and the additional investment in new machines.

This clearly shows that a very incomplete view of the various group technology concepts has been put across despite the voluminous amount of literature published on the subject. To many, group technology is associated with part families, steady product demand, poor machine utilisation for secondary machines and cell inflexibility. This situation is characteristic of cells formed with the "part family approach" and the success enjoyed predominantly by the valve industry has received much exposure. Yet sufficient evidence has been forthcoming that with larger cells most of these problems will be weeded out. The rationalisation of work flow together with innovations such as the period batch control is potentially geared up to meet with conditions such as those listed above. The improved throughput and lower work in progress situation is ideally suited to a changing environment. Because of the hospitality afforded by the larger cells and the superior distribution property of the smaller batches the machine utilisation is unlikely to be worse off and with composite set-ups the setting time will be reduced. On the point of loss of effective control some of the firms have elected to implement a computerised production control system (Hollingum 1971, Kellock 1976).

For our present investigation we will study the differences in performance between one large cell and 3 smaller cells in parallel.

## Experimental Details

A 18-machine cell consisting of 3 units each of 6 types is used to represent the larger cell. For the smaller cells we have 3 cells in parallel with one each of the six machine types. The workload for the larger cell is split into three equal numbers of jobs and these are fed into each of the smaller cells. Two tool set-up configuration arrangements are employed in the case of the 6-machine

cells. For the first part the number of set-up configurations is taken to be 15, which is the same as for the larger cell. To simulate the setting advantage inherent in smaller cells, we also consider for the second part a set-up configuration number of 5 for the smaller cells. The rest of the experimental data used are as those listed in Appendix 5.1.

Discussion of Results

The results from the experiment are given in Table 5.7.1. For the 3 x 6-machine cells the average of the 3 cells have been computed. Details of the performance of each of the smaller cells are shown in Appendix 5.7.1. For easier comparison the percentage improvement of the larger cell over the smaller ones have been worked out and these are presented in Figure 5.7.2. Considering first the case when no setting advantage is allowed for the smaller cells we find the larger cell performs markedly better in all respects except the lateness variance for the SLACK(1)/SPT and S(1)/SET/SPT rules. The reason for the better figures of the smaller cell is once again due to the beneficial influence of the relatively tighter due dates arising from the poorer throughput. The key to the superiority of the larger cell is the improvement in the machine utilisation and average queue time. The multi-server situation has elevated the matching probability between machines and jobs thus resulting in a higher utilisation and a lower waiting time in the queues. For the S(1)/SET/SPT procedure the greater number of jobs queueing at each machine type - although the number of jobs/machine ratio is actually lower than for the smaller cells - gives better opportunity to obviate the need to reset for the next batch. Consequently the advantage over the smaller cells is further accentuated.

Next we examine the case when the smaller cells each has only one-third the number of set-up configurations of the larger cell (Figure 5.7.2(B)). We observe that while the position of the smaller cells has improved, the larger cell still emerges to be significantly better. The reduction in setting time has been translated in part into a greater capacity for running jobs (as

manifest by the lower work content remaining) and the average queue time is appreciably lower. Comparing cases (A) and (B) we note that the S(1)/SET/SPT rule does not show as great an improvement with the reduction in the number of set-up configurations as the other two disciplines. On close scrutiny of the results we find that a greater portion of the savings in setting time has been wasted as idle time. Furthermore, because of the enhanced effect of the "SET" element at the expense of the "SPT" constituent the throughput performance has suffered.

Here we have found the larger cell to be more proficient even when the smaller cells are favoured with the setting advantage. There is little doubt that the setting aspect is one of the central issues in the argument in support of the smaller cell. Referring back to Experiment 6 we recorded that a great advantage is derived for very small numbers of set-up configurations; such as below 5. Therefore if we have chosen a value of unity or near unity instead of 5 for case (B) we might have shown the smaller cells in a different light. However, from a practical viewpoint it is felt that the poor utilisation and low parts accessibility causes such arrangements to be hardly viable.

Table 5.7.1 : Results from Experiment 7

| | Priority Rule | | |
|---|---|---|---|
| | FCFS | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 18-Machine Cell | | | |
| Mean throughput time (hr.) | 14.12 | 11.20 | 9.23 |
| Mean job lateness (hr.) | -7.64 | -10.62 | -12.65 |
| Std.dev.of lateness (hr.) | 4.36 | 6.50 | 6.64 |
| Work content remaining (hr.) | 36.93 | 22.88 | 17.25 |
| Average queue time (hr.) | 1.50 | 1.02 | 0.73 |
| Machine utilisation (%) | 92.50 | 93.30 | 89.10 |
| Set/run time ratio | 0.314 | 0.318 | 0.253 |
| Jobs tardy (%) | 0.3- | 0 | 0 |
| 3 x 6-Machine Cells | | | |
| (15 set-up configurations) | | | |
| Mean throughput time (hr.) | 19.23 | 15.34 | 14.94 |
| Mean job lateness (hr.) | -1.63 | -5.88 | -6.42 |
| Std.dev.of lateness (hr.) | 6.16 | 5.79 | 5.61 |
| Work content remaining (hr.) | 192.49 | 166.25 | 147.61 |
| Average queue time (hr.) | 2.66 | 1.90 | 1.79 |
| Machine utilisation (%) | 84.50 | 86.20 | 85.40 |
| Set/run time ratio | 0.316 | 0.317 | 0.293 |
| Jobs tardy (%) | 34.90 | 12.40 | 8.40 |
| 3 x 6-Machine Cells | | | |
| (5 set-up configurations) | | | |
| Mean throughput time (hr.) | 17.49 | 13.70 | 13.84 |
| Mean job lateness (hr.) | -3.76 | -7.78 | -7.89 |
| Std.dev.of lateness (hr.) | 5.12 | 6.02 | 5.92 |
| Work content remaining (hr.) | 154.53 | 124.70 | 124.04 |
| Average queue time (hr.) | 2.28 | 1.61 | 1.59 |
| Machine utilisation (%) | 81.60 | 85.50 | 81.80 |
| Set.run time ratio | 0.277 | 0.274 | 0.218 |
| Jobs tardy (%) | 28.80 | 2.20 | 5.31 |

Table 5.7.2 : Comparison Between Cell Size *

| | Priority Rule | | |
|---|---|---|---|
| | FCFS | SLACK(1)/ SPT | S(1)/SET/ SPT |
| (A) 3 x 6-Machine Cells | | | |
| (15 set-up configurations) | | | |
| Mean throughput time (hr.) | 26.60 | 27.00 | 38.20 |
| Mean job lateness (hr.) | 368.70 | 80.60 | 97.00 |
| Std.dev.of lateness (hr.) | 29.20 | -12.30 | -18.40 |
| Work content remaining (hr.) | 80.80 | 86.20 | 88.30 |
| Average queue time (hr.) | 43.60 | 46.30 | 59.20 |
| Machine utilisation (%) | 9.50 | 8.20 | 4.30 |
| Set/run time ratio | 0.60 | -0.30 | 13.70 |
| Jobs tardy (%) | 99.10 | 100.00 | 100.00 |
| (B) 3 x 6-Machine Cells | | | |
| (5 set-up configurations) | | | |
| Mean throughput time (hr.) | 19.30 | 18.20 | 33.30 |
| Mean job lateness (hr.) | 103.20 | 36.50 | 60.30 |
| Std.dev.of lateness (hr.) | 17.40 | -8.00 | -12.20 |
| Work content remaining (hr.) | 76.10 | 81.70 | 86.10 |
| Average queue time (hr.) | 34.20 | 36.60 | 54.10 |
| Machine utilisation (%) | 13.40 | 9.10 | 8.90 |
| Set/run time ratio | -13.40 | -16.10 | -16.10 |
| Jobs tardy (%) | 99.00 | 100.00 | 100.00 |

* Values are in "percentage improvement" of the large cell over the three smaller cells in parallel.

## 5.8 Experiment 8 : Effect of Manning Level and Type

In the mass production sector great efforts have been directed at designing away the need for human intervention and where this is found to be infeasible work study methods are employed to bring the labour productivity to a level comparable to the mechanical precision of their machine counterparts. The efficiency of this mode of manufacture is already well proven; however, the social consequences have emerged to be one of its staunchest objectors. At the other end of the spectrum the relatively lesser discipline of the small batch situation provides a greater degree of job satisfaction but at the expense of an inferior performance effectiveness. Referring to the findings from Dudley's survey we observe that on average an operator in a machine shop only spends about 44% of his time productively. This position is likely to be improved with the introduction of group manufacture. In incorporating a tool bank complete with all the necessary cutting tools, fixtures and jigs within each cell and the upgrading of production information possible with the rationalised work flow and lower parts variety the amount of time that the operator takes in the preparation for his productive task can be drastically reduced.

For some cases (Marklew 1970, Dale and Willey 1977) the improvement in labour utilisation is stated to be one of the principal reasons for firms adopting group technology. In particular, at Ferranti the concern was at the shortage of skilled labour and ways were sought to upgrade the utilisation of the pool of workers they had. Taking first the question of the shortage of skilled labour it would be instructive to consult the results of the one-man survey conducted by Eastwood (1976). Here it was found that there is evidence to support the general feeling that craftsmen are being wastefully employed and furthermore, industry's perception of the shortage of craftsmen often conceals an ineffective and exaggerated demand for labour. Therefore, for the industry as a whole there are some employers who cannot get the skilled men they need while others do not make full use of those they have. Among the contributory factors given for the ineffective use of labour are restrictive union practices, poor management, and technological innovations such as

numerical control of machine tools. In previous sections we have discussed the savings in setting time that can be obtained with cellular manufacture. Projected in terms of manpower, there is a report of a particular application where the number of setters required is actually halved (Ivanov 1963). With the use of composite set-ups where only minor adjustments are necessary to accommodate a different component, a semi-skilled or even unskilled worker may be permitted this task.

Two firm characteristics of manufacturing cells are firstly, the number of men should be less than the number of machines and secondly, the men should have a reasonable measure of flexibility in operating different machines. On the first point, this is almost invariable so in the cells already implemented and Pullen's survey has revealed an average machine/man ratio of 1.3. The practice of labour flexibility has not received the same unanimous response. While union resistance forms the main contributory factor there are also some personal and technological problems involved. In some cases, a certain degree of labour flexibility is derived by transferring men between similar machines or skills in different cells (Barker 1970, Connolly et al. 1970).

For the present investigation we will examine the effects on system performance of varying levels of manning with different operator types.

Experimental Details

For this experiment we assume the men to be of two functional types. There are the setter-operators who both set and run machines, and the operators who are only capable of running a machine once it is set. A setter-operator would not normally run a machine unless a job is waiting to be run and there are no operators available at the time. Once the setter-operator is engaged in running a machine he will be bound to that task till completion. Six machine types of one unit each are used and the load factors together with the other experimental data are given in Appendix 5.8.

Discussion of Results

The results from the experiment are presented in Figures 5.8.1(a) to (h) and Table 5.8.1. Figures 5.8.1(b) and (c) give a breakdown of the causes for the machine idle time. The third possibility of machine idleness arising from awaiting to be run does not come about because of a condition incorporated within the simulation model that the running of machines takes priority over setting for a new batch.* A setter-operator on the completion of setting up a machine will proceed to run it if no operator is available at the time.

Before embarking on a discussion of the machine and labour utilisation it would be useful to establish that the input workload requirements for the setting and running manpower are 1.125 and 3.375 men respectively. From some savings in setting due to set-up matching between consecutive batches the former figure is likely to approach unity. In Figure 5.8.1(b) we observe that the proportion of machine idle time spent in waiting to be set rises well before the number of setter-operators is reduced to one. The explanation for this is that the computed value of 1.125 is the cumulative requirement of all six machine types. Therefore there will be periods when some machines need setting but all the assigned setter-operators are engaged on other machines. The position is appreciably aggravated by the imposed condition that once started on the running of a machine, a setter-operator is committed to that task till completion. Consequently a higher number of setter-operators are required to minimise the idle time occurring from this cause. The situation also improves as the number of men are increased from 4 to 6 or when a despatching rule such as the S(1)/SET/SPT is used to reduce the amount of setting required.

* This statement applies to the present experiment since only "operators" and "setter-operators" are assigned. If a third labour category of "setters"had also been employed there may then arise a proportion of idle time due to machines waiting to be run.

The contribution to the machine idle time due to queue depletion is shown in Figure 5.8.1(c). Here it is clear that as the manning capacity (both in terms of the number of men and the number of setter-operators) is reduced the queues are allowed to build up thus causing a fall in the proportion of idle time arising from machines waiting for jobs. Naturally the situation is dependent on the level of loading of the cell. Since in our case an overall load factor of 0.75 has been chosen there will be a reasonable proportion of machine idleness due to the shortage of work when the manning level is high but this will progressively fall as the number of men and/or number of setter-operators are trimmed.

The combined influence of the two aspects of machine idleness is recorded in Figure 5.8.1(a). We note that there is little difference whether 5 or 6 men are employed provided there is a sufficient number of setter-operators; which is 4 and 3 for the SLACK(1)/SPT and S(1)/SET/SPT procedures respectively. The 4 men situation manifestly represents undermanning as the total idle time can be traced to be almost completely caused by machines waiting to be set. Regarding the number of setter-operators required, the 6 men arrangement shows little sensitivity until the number is reduced to one. With 5 men a steady deterioration begins at a higher point (4 and 3 for the SLACK(1)/SPT and S(1)/SET/SPT rules respectively).

To a large extent the trends for the average job queue time, throughput time and mean job lateness follow that of the proportion of machine idle time awaiting setting. This is fairly predictable since the accummulation of jobs within queues inevitably results in an escalation in the queueing delays of jobs. Therefore, although in respect of the machine utilisation figures the 5 men situation is on occasions comparable to when 6 men are employed there is a penalty in the throughput and delivery performance. However, the gulf is measurably less when a priority rule such as the S(1)/SET/SPT is used.

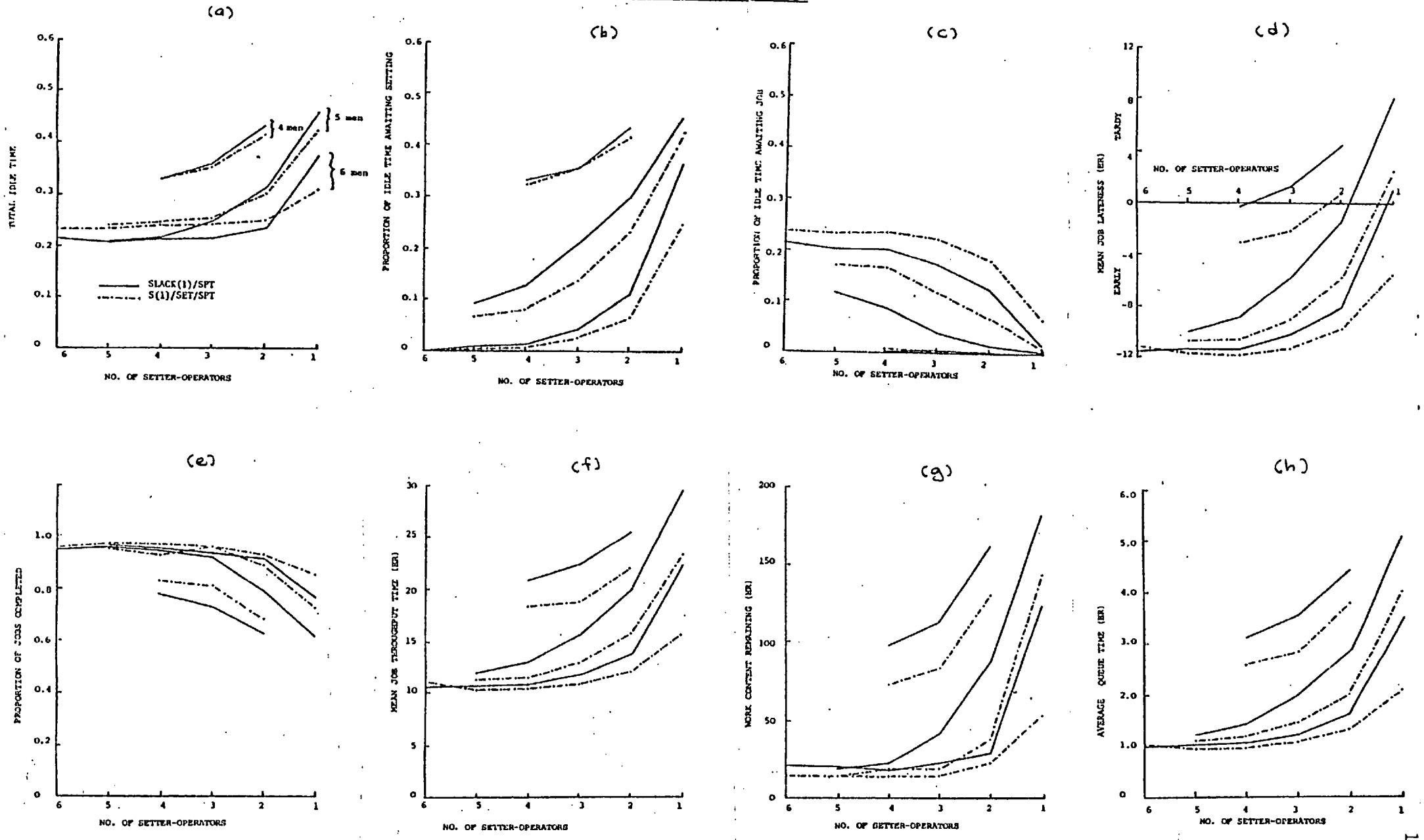
Table 5.8.1 : Results from Experiment 8
Percentage Labour Utilisation

| Manning Arrangement | Setter-operator | | | Operator | |
|---|---|---|---|---|---|
| | Set | Run | Idle | Run | Idle |
| (A) Scheduling Rule : SLACK(1)/SPT | | | | | |
| 6 setter-operators | 18.90 | 59.70 | 21.40 | - | - |
| 5 s/o, 1 operator | 23.40 | 55.00 | 21.60 | 82.60 | 17.40 |
| 4 s/o, 2 operators | 27.90 | 47.90 | 24.20 | 83.20 | 16.80 |
| 3 s/o, 3 operators | 38.10 | 39.90 | 22.00 | 78.50 | 21.50 |
| 2 s/o, 4 operators | 53.60 | 31.70 | 14.80 | 71.70 | 28.30 |
| 1 s/o, 5 operators | 87.80 | 11.20 | 1.00 | 54.50 | 45.50 |
| 5 setter-operators | 23.30 | 71.40 | 5.30 | - | - |
| 4 s/o, 1 operator | 28.60 | 67.90 | 3.40 | 82.00 | 18.00 |
| 3 s/o, 2 operators | 36.30 | 62.80 | 1.00 | 76.10 | 23.90 |
| 2 s/o, 3 operators | 48.50 | 50.80 | 0.70 | 70.60 | 29.40 |
| 1 s/o, 4 operators | 75.20 | 24.80 | 0 | 55.20 | 44.80 |
| 4 setter-operators | 23.70 | 76.30 | 0 | - | - |
| 3 s/o, 1 operator | 29.70 | 70.30 | 0 | 82.50 | 17.50 |
| 2 s/o, 2 operators | 39.40 | 60.60 | 0 | 68.90 | 31.10 |

Table 5.8.1 (Cont'd)

| Manning Arrangement | Setter-operator | | | Operator | |
|---|---|---|---|---|---|
| | Set | Run | Idle | Run | Idle |
| (B) Scheduling Rule : S(1)/SET/SPT | | | | | |
| 6 setter-operators | 16.20 | 60.10 | 23.70 | - | - |
| 5 s/o, 1 operator | 19.60 | 54.50 | 25.90 | 87.10 | 12.90 |
| 4 s/o, 2 operators | 23.50 | 47.30 | 29.20 | 85.50 | 14.50 |
| 3 s/o, 3 operators | 30.70 | 39.20 | 30.10 | 80.90 | 19.10 |
| 2 s/o, 4 operators | 47.00 | 26.20 | 26.80 | 75.60 | 24.40 |
| 1 s/o, 5 operators | 79.70 | 14.70 | 5.60 | 63.50 | 36.50 |
| 5 setter-operators | 19.10 | 71.90 | 9.00 | - | - |
| 4 s/o, 1 operator | 23.60 | 67.10 | 9.30 | 88.10 | 11.90 |
| 3 s/o, 2 operators | 30.20 | 63.90 | 5.90 | 81.80 | 18.20 |
| 2 s/o, 3 operators | 37.60 | 59.50 | 2.90 | 74.80 | 25.20 |
| 1 s/o, 4 operators | 72.40 | 27.60 | 0 | 60.80 | 39.20 |
| 4 setter-operators | 19.70 | 80.30 | 0 | - | - |
| 3 s/o, 1 operators | 24.10 | 75.90 | 0 | 85.30 | 14.70 |
| 2 s/o, 2 operators | 35.70 | 64.30 | 0 | 75.50 | 24.50 |

FIGURE 5.8.1 : EFFECTS OF MANNING LEVEL AND TYPE ON THE VARIOUS EFFECTIVENESS MEASURES



## Chapter 6 : Cellular Grouping Methods


| | |
|---|---|
| 6. | Introduction |
| 6.1.1 | The Component Classification Method |
| 6.1.2 | The Natural Families Method |
| 6.1.3 | The Machine Tool and Workpiece Statistics Method |
| 6.2.1 | Production Flow Analysis |
| 6.2.2 | Component Flow Analysis |
| 6.2.3 | Numerical Taxonomy |
| 6.2.4 | Combinatorial Analysis |
| 6.2.5 | The Graph-Theroretic Method |
| 6.3 | Concluding Remarks |

## 6. Introduction

Already burdened with the need to sift through a massive quantity of literature for his initiation into the subject, the would-be Group Technology convert is further misled and confused by a number of the exponents of cellular grouping techniques who adopt an uncompromising stand by claiming that his is the only creditable method. Yet the history and actual applications of grouping methods have shown that in many cases the various grouping strategies play a supportive role to one another. On delving into the background of the development of grouping methods we will find that the work flow approach has been introduced to overcome some of the inadequacies of the earlier components classification method. To suggest, however, that the classification method has been superseded is an exaggeration. There is ample evidence that in some situations component shapes and sizes provide the best basis on which cellular groups should be formed. Also, work flow analysis on its own, and without any due consideration of component features, may lead to the derivation of arrangements where the disadvantage of higher setting times may seriously overshadow the benefits obtained from an improved work flow.

Broadly, cellular grouping methods can be divided into two categories. The first line of approach is associated with the physical characteristics of the components and the cellular groups are obtained by :

(1) the formal classification of components
(2) the identification of naturally occurring families of components from the aspect of
    (i) general shapes and sizes
    (ii) specific features
(3) the use of workpiece and machine tool statistics.

The second technique involves an analysis of the process routes of the components and the various strategies advocated are :

(1) Production Flow Analysis

(2) Component Flow Analysis

(3) Numerical Taxonomy

(4) Combinatorial Analysis

(5) Graph-theoretic Approach.

### 6.1.1 The Component Classification Method

The design office is the'breeding ground'for components and the decisions made here, good or bad, infiltrate and affect the whole of the manufacturing cycle. It is important that adequate measures should be enforced to prevent the proliferation of design which in the normal sequence of events also causes a proliferation of the production methods and the associated jigs and fixtures. The situation is not helped by the common practice of naming components according to their functional purpose. In what must be considered to be an extreme case Brisch (1954) illustrated how a deceptively simple shaft-like component can be designated up to 38 different names. To remove a great deal of the ambiguity components can be classified and identified by means of numerical codes such as the Opitz, Brisch, VUOSO and PGM systems. A description of these and other classification systems is given by Gallagher and Knight (1973). It is generally acknowledged that the two principal benefits of a classification system are firstly, the standardization of component characteristics and secondly, the possibility of retrieval. Another important but seldom recognised aspect is that the adoption of a classification system actually allows the firm for the first time to take stock and reconcile the real needs of their component mix to the machine resources that they have built up over the years.

Disagreement exists between the exponents of certain classification systems as to whether additional features need to be incorporated to render the system suitable for determining groups or families of components with compatible production requirements. The Brisch workers pursue their "tailor-made" theme by maintaining that design-orientated and production-orientated systems should be developed separately. Their proposed solution consists of a mono-code and poly-code respectively (Gombinski 1969). Opitz (1969) contends, on the other hand, that his system serves equally well for both design and production requirements. In Table 6.1 are listed

some examples where classification systems have been employed for deriving component families.

From the classification process components with similar physical characteristics are drawn together. The formation of a cellular grouping now consists of scanning a specific portion of the coding chart to select components with common machining needs. This procedure involves a fair amount of "hash and rehash" until a satisfactory balance between the workload and the machine facilities for the group is found. One singular feature of the groupings obtained in the various applications is that they tend to be the more "obvious" groups within the component range. Also because of the greater bias of most classification systems towards rotational parts, most of the group constituents also pertain to this configuration. In situations where there is an absence of a multiplicity of workpieces for ready group composition classification systems will prove to be of little use (Tedford and Ferris 1976).

Table 6.1 : Some Examples of Firms using a Classification System For Establishing Part Families

| Classification System | Organisation | Source |
|---|---|---|
| Opitz | Rank Taylor Hobson | Haworth (1968) |
| Modified Opitz | Herbert | Perrins (1974) |
| Opitz | Matter & Platt | Caudwell (1973) |
| Opitz | Thomas Mercer | Whitfield (1972) |
| Opitz | Rotork Controls | Johnstone (1974) |
| Brisch | F.A.C.E. Jeumont | Sidders (1962) |
| Brisch | Sigmund Pulsometer | Garratt (1969) |

### 6.1.2 The Natural Families Method

Very often firms are able to identify a number of component groups by means of names, their shapes and sizes, and/or the compatibility of their production requirements. Some illustrations of these are given in Table 6.2. A necessary condition for such groups to be viable as a manufacturing cell is of course that the workload should be acceptable. An advantage

that can be claimed for cellular groups of this nature is that the high uniformity of the machining operations required provides for a great simplification of work handling and a substantial standardization of the tools and work holding devices.

Table 6.2 : Some Examples of Cellular Groups Formed by Means of Names, Shapes and Sizes, or Specialised Production Methods

| Groups | Organisation | Source |
|---|---|---|
| Beds, Headstocks, Gears | Herbert | Perrins (1974) |
| Cams | Wildt Mellor Bromley | Kruse et al. (1975) |
| According to shapes and sizes | Fluidair | Marklew (1972) |
| Armature shafts | Black & Decker | Marklew (1974) |
| Rings | Elliott | Barker (1970) |

### 6.1.3 The Machine Tool and Workpiece Statistics Method

It is suggested (Husain and Leonard 1975) that many organisations have been deterred from implementing the Group Technology mode of manufacture because of the heavy demand that is made on time and effort when attempting to form the cellular groups using either the component classification or work flow method. The proposed strategy based on workpiece statistics and the existing machine tool distribution is said to be able to overcome this. This approach differs from the other methods in that instead of the components, the machine tools are taken as the starting point in the cell formation procedure.

The composition of machines for the cellular groups is established by means of a number of empirical relationships obtained in previous surveys of workpiece and machine tool statistics. Briefly, the technique is applied as follows :

(1) The firm is required to provide 3 basic data :
   (a) the machines list
   (b) the percentage of rotational to non-rotational

parts (by time)

(c) the percentage of parts falling into each VUOSO class (by time).

(2) For the non-rotational parts the number of surfacing machines required = L/R
where R = the ratio of rotational/non-rotational parts
and L = the no. of lathes in the shop.

(3) The number of drilling/boring machines required for the non-rotational parts is equal to that of the surfacing machines, i.e. L/R.

(4) Any other machines that cater specifically for the non-rotational parts are allocated.

(5) Details of the surfacing machines :
Since planning and shaping machines are exclusively used for non-rotational parts they are invariably included. The balance of the surfacing machines to a total of L/R units consists of milling machines.

(6) Details of drilling/boring machines :
Boring machines are predominantly used for non-rotational parts. The balance of the drilling/boring machines to a total of L/R units consists of drilling machines. Some adjustments may be necessary at a later stage if it is found that a unit or more of boring machines are required for the rotational parts.

(7) The facilities for the rotational parts are obtained by subtracting the machines assigned to the non-rotational parts from the machines list in 1(a).

(8) Using the class designation within the VUOSO classification system cells of non-rotational and rotational parts are formulated. The machines of each type are divided in proportion to the number of parts falling into each of the proposed cells.

Reservations must be expressed as to whether the above exercise is able to furnish anything beyond what could be considered to be rough groupings. It was suggested that the foreman or production engineer should be consulted before deciding on the machine allocation for the cells but it is doubtful if the expertise and working knowledge of the production

personnel alone could achieve the large degree of refinement that is necessary to arrive at cellular arrangements that are viable in the longer run. In the case study that was given it was shown that the composition of the cells, especially for rotational parts, departs appreciably from those initially deduced from empirical relationships.

### 6.2.1 Production Flow Analysis

Burbidge's Production Flow Analysis (PFA), published in 1963, introduced a new dimension in the concept of cellular grouping. In shifting the classifying criterion from the geometric features of components to their process routes, components with similar machining requirements but different physical configurations can be brought together. One immediate advantage of PFA is that the basic data required for the analysis is already present in the form of job cards. Of greater and more fundamental significance is that PFA provides for a more total approach and commitment to cellular manufacture.

Production Flow Analysis involves "a progressive analysis of the information contained in the route cards for the components and assemblies ..... to find the natural division into groups and families ....." (Burbidge 1971). Two levels of analysis are carried out :

(1) the Factory Flow Analysis
(2) the Departmental Flow Analysis

Factory Flow Analysis is performed with the primary aim of simplifying the inter-departmental material flow. Burbidge also listed the following secondary aims :

(1) Each component, as far as possible, should be fully processed in one department only
(2) Each machine type, as far as possible, should exist in one department only
(3) Each department should have the minimum source/destination for their material/completed component respectively
(4) Incompatible processes should be separated from each other.

The procedures for the Factory Flow Analysis are :

(1) Divide the factory into departments on the basis of major processing differences

(2) Allocate plant to the departments on the basis of processing type and find the usage frequencies; where intermediate operations are required in some other department and the usage frequency warrants it, plant duplication may be considered at this point.

(3) Determine the Process Route Number (PRN) for each part; the PRN is a code number formed by listing in the correct sequence all the departments visited by the part.

(4) Analyse the parts by PRN. A list is made of all the different PRN's in use and the number of components with each PRN is counted.

(5) Draw the basic flow chart to illustrate the inter-departmental material flow system. Label the number of parts using each flow path and the number of parts finishing at each of the departments.

(6) Determine from the flow chart the parts to treat as exceptions; i.e. those parts requiring re-routing to fit the majority pattern.

(7) Eliminate the exceptions by :
   (a) re-allocation of plant between departments
   (b) re-routing operations to other machines already present in the department
   (c) change of method
   (d) change in design
   (e) purchase the part instead of making it.

(8) Check the machine loads for all machine types to be installed in more than one department to determine the number of units required in each department.

(9) Specify the standard inter-departmental flow system by documenting :
   (a) a basic flow chart
   (b) a plant list for each department
   (c) a list of parts processed in each department.

The next level of analysis - that is, the Departmental Flow Analysis - can be divided into the two consecutive stages of :

(A) Group Analysis
(B) Line Analysis

The objective of Group Analysis is to divide the components allocated to each department into families, and the plants assigned to each department into groups so that each family is completely processed by one group only. The procedures for Group Analysis consist of :

(1) Renumbering the operations on the route cards. Starting with Operation 1 each number denotes a machine type visited by the component. Re-visits to the same machine type will not be recorded. Also ignored are operations such as marking-off, deburring, etc. where no machines are involved.

(2) Sorting into packs components using the same plant in the same sequence. Components are first divided into packs corresponding to the various machine types required for Operation 1. Then each pack is progressively sub-divided into the machine types required for Operation 2, Operation 3, and so on.

(3) Drawing the pack/machine chart and finding the families and groups. In Figure 6.1(a) is shown an example of a pack/machine chart. By rearranging the order of the component and machine lists, and duplicating some machine types patterns for families and groups will emerge (Figure 6.1(b).

(4) Checking the load and allocating plant to the groups. For machine types which are required in more than one group, it is necessary to check the load.

(5) Investigating the exceptions and eliminating them by :
   (a) re-routing of operations to other machines already present in the group
   (b) duplicating machine types between groups

(c) changing the method of production

(d) changing the component design

(e) purchasing the part isntead of making it.

(6) Specifying the groups and families.

(7) Drawing the final flow system network and examining it for further possible simplications.

After the machine groups have been established the next phase is the Line Analysis where the best sequence of layout for the machines is determined. The steps suggested are :

(1) Renumber all the operations in sequence. This includes re-visits to the same machine types as well as manual operations such as marking-off, deburring, etc.

(2) Draw the machine/operation no. chart for each group showing the frequency each machine type or work centre is used for Operation 1, Operation 2, and so on.

(3) Arrange the machines in a sequence such that the top member has the highest frequency for early operations and the bottom member has the largest occurrence of the later operations. Number the machines in this sequence.

(4) Determine the Operation Route No. (ORN) of every component according to the numbering established in (3). Record the frequency of each ORN and prepare the ORN chart.

(5) Draw the flow network diagram for each group and examine for possible simplications.

Therefore we find that PFA lays out logically and at some considerable length the various stages and procedures necessary for a total approach to cellular grouping. However, PFA remained on the shelf until El-Essawy (1971) adopted the majority of its principles and applied it in an

industrial study. He coined his version the Component Flow Analysis.

### 6.2.2 Component Flow Analysis

Some protests were lodged as to whether it is justifiable that Component Flow Analysis (CFA) should be so called when it draws on so many of the concepts embodied within PFA. In its defence it was pointed out that CFA can be regarded as an approach in its own right since it "is a proven management tool .....(whereas).....PFA suffers from a lack of clearly defined methodology and the omission of basic data of major importance to any analysis of material flow patterns to determine plant and machine tool layout" (Torrance 1972).

In their paper El-Essawy and Torrance (1972) explained the technique behind CFA. First, the following basic data is required :

(1) Component identification; each component manufactured should have a unique identification number, not necessarily a code with digital significance

(2) Product Parts' list showing the explosion into assemblies, sub-assemblies and component parts

(3) Production Planning Data showing the process routes of each component as well as the operation-type, machine tool, set and run times for each operation

(4) The Plant List

(5) A reliable forecast of the demand pattern for each component.

It is stated that the quality of the analysis will deteriorate if one or more of the above information is inaccurate or not available. The second step is the analysis proper which can be split into 3 stages :

(1) The factory is divided into a number of broad sections. Each section contains all the plant necessary for the production

of a specific sector of the component mix. A computer programme has been written for this analysis.

(2) The results from (1) are scanned manually to obtain "rough" groupings of machine tools and equipment.

(3) Here the final structure of the production system is determined. Using the work demand figures the "rough" groups are examined for possible decomposition into less complex groups. After the nature of the cells have been decided upon the following are computed :

(a) the number of units of each machine type
(b) the feasibility of providing repeated machine types at different points
(c) the labour requirements

Clearly the techniques for CFA and PFA do not differ greatly. What distinguishes the two methods is the basis on which cellular groups are formed. PFA suggests that numerical counts of components using each process route would provide a sufficient indication of the material flow pattern. CFA maintains that while usage frequency is a useful guide it is essential that the volume of work flow should represent the criterion on which decisions are made.

Despite Torrance's claim CFA does not provide a "clearly defined methodology" for the derivation of cellular groups. The "rough" groups are obtained by manual "hash and rehashing" and this could be a long drawn process when a large amount of components is encountered. A number of techniques have been explored for the possibility of filling this gap and among these are the Numerical Taxonomy, Combinational Analysis, and Graph-theoretic methods.

### 6.2.3 Numerical Taxonomy

The application of Numerical Taxonomy and Cluster Analysis for the determination of cellular groups was first examined by McAuley(1972).

This work was further developed by Carrie (1973) who designed a suite of computer programmes for the analysis.

The Numerical Taxonomy method consists of 3 stages :

(1) The preparation of a data matrix which is basically the machine-component matrix showing which machines are required for the production of each component.

(2) The computation of similarity coefficient matrices for machines and components. A similarity coefficient is an indication of the strength of the link between two objects. There are many ways in which similarity coefficients can be formulated. The equation found to be the most appropriate for the present situation is given by :

$$S_{jk} = \frac{N_{JK}}{N_{JK}+N_{Jk}+N_{jK}}$$

where $S_{jk}$ is the similarity coefficient between machines (components) j and k

$N_{JK}$ is the number of components (machines) visiting (visited by) both j and k

$N_{Jk}$ is the number of components (machines) visiting (visited by) j but not k

$N_{jK}$ is the number of components (machines) visiting (visited by) k but not j.

(3) The performance of Cluster Analysis on the results from (2). Cluster Analysis examines the similarity between each pair of objects and forms groups of objects such that within each group the members are highly similar to each other. The method chosen is based on the three algorithms proposed by Ross (1969). The output from Carrie's programme is a machine/component or component/machine matrix where the machine and component sequences have been rearranged such that grouping patterns, if present, can be easily recognised. In his experience with a

number of practical cases Carrie concluded that the present approach is not always suitable for the formation of cellular groups because :

(a) there is a larger prevalence of "exceptions" than anticipated by Burbidge.
(b) there is no provision for duplication of machines between groups.
(c) some components appear to fit equally well to more than one family.

A second method using the algorithm suggested by Wishart (1969) was investigated and found to be promising. The algorithm commences by setting the similarity coefficient level initially to 1.0 and then the level is gradually reduced until all the components have been assigned to a group. To prevent the formation and analysis of a large number of very small groups a minimum number of members in a family is also stipulated. By examining the groupings and the machine load figures at successive levels of similarity coefficients viable cellular grouping can be arrived at.

### 6.2.4 Combinatorial Analysis

The Combinatorial Analysis approach is originated by Purcheck (1974) and the procedures for group formation are :

(1) Data Coding - Each component is assigned a code number of the form A B C $\cdots$ . a b c $\cdots$ . The string of numbers (or letters) on the left (i.e. A B C $\cdots$) is a list in numerical (or alphabetical) order of the set of facilities required by the component. The string of numbers on the right (i.e. a b c $\cdots$) denotes the sequence in which the set of facilities are used. For example, if 1 $\equiv$ broaching; 4 $\equiv$ milling; 5 $\equiv$ grinding; 6 $\equiv$ drilling, a code number 1456.24123 means that the component requires broaching, milling, grinding and drilling in the sequence mill; drill; broach; mill; and grind.

(2) Sorting - Since operation sequence is not considered at this phase of the analysis only the left hand string of numbers (or letters) is relevant. The components are first sorted into classes according to the number of facilities required. Next a re-coding is carried out whereby each machine type is assigned a number to the power-of-two; e.g. machine type a $\equiv 2^0$, b $\equiv 2^1$, c $\equiv 2^2$, etc. Therefore, a component requiring machine types a and c is re-coded 5(i.e. 1+4). Using these re-coded numbers components within each class is ordered in descending values. The purpose of the sorting into classes and ordering within the classes is to reduce the amount of searching necessary in (3) below.

(3) Grouping by Affiliation - The idea behind this procedure is to divide the components into two categories which are represented by the hosts and the guests. Hosts consist of components where the machine requirements are unique with respect to the other hosts. Guests, on the other hand, have machine requirements which form subsets of one or more hosts. The search procedure begins by designating all members in the class with the largest number of facilities as hosts. Then members in the next largest class are matched against each member already designated as a host. Each time a member is found to form a subset of a host a record is made for both the host and the member. When all the hosts have been scanned the member will be designated a host if it has not been found to be a subset of any host. Otherwise, it will be categorised as a guest. On completion of the scanning of all members in the class the search is continued for members of the next lower class until all given components have been catered for. At the end of the exercise a matrix is derived with the hosts forming the rows and guests forming the columns. A record is also on hand of the number of affiliated guests of each host and the number of hosts each guest is associated with. The hosts constitute the first groupings for possible viable cells pending upon the workload balance. When the workloads are insufficient for cells to be formed from the hosts the next stage is performed to obtain larger-sized groupings or superhosts.

(4) Merging by Affiliation - This procedure involves the matching of each pair of hosts to determine the differences in machine facilities between them. Priority for the formation of superhosts is given to those arrangements where the differences in facilities is minimal and where these differences occur most frequently for the same host; that is preference is given to the case(s) where with the addition of 1 or more facilities to a particular host, several other hosts can be merged with it. If required, superhosts can be further amalgamated into higher level superhosts until suitable groupings have been found. In later papers (Purcheck 1975, 1977) it is shown how the comparatively more sophisticated Backtracking with Branch-and-Bound method can be used to derive the superhosts.

(5) Distribution of the Guests among the Hosts - For each host the number of guests that affiliated to it is known. However, many of the guests are likely to be also associated with other hosts. To assist in the assessment of the likely workloads values are worked out when

(a) guests are assumed to be evenly distributed among the hosts and

(b) guests are exclusively assigned to each host.

These figures are taken to represent the minimum and maximum values of the "loading". Since units of components are considered these reflects the usage frequencies rather than the actual workload. For a more realistic estimation it is necessary to introduce statistical weightings based on the component requirements and operation times.

### 6.2.5 The Graph-theoretic Approach

The third method for the formation of cellular groupings is the Graph-theoretic Approach of Rajagopalan and Batra (1975). The analysis consists of three stages :

(1) Deriving the machine-graph and its cliques. The strength of

the links between machines is found by computing the similarity coefficients between pairs of machines using equation 6.1. For partitioning the links into "strong" and "weak" it is necessary to decide on a threshhold value T. It is suggested that T should be chosen such that there will be neither too many nor too few links. Alternatively, a graph can be plotted showing the number of links against the value of T, and T is taken where the curve is flat. If there is more than one flat region T, should again be chosen so that there is a reasonable number of links. For the case where there is no flat region, T is selected from a point on the minimum slope. Having decided on the value of T, the components associated with the "weak" links are examined for possible re-routing. After this exercise the similarity coefficients are again calculated since the link relationships would have changed. The next step is to look for groups of related machines or cliques. A clique is an arrangement where each machine (within the clique) bears a relationship stronger than T to all the other machines. A number of algorithms are available for finding the cliques (see Mulligan 1971).

(2) Forming machine cells. The cliques found in stage (1) can actually be considered for production cells. But due to the strong condition imposed on mutual relationship it is likely that there may be too many groups and the amount of duplication of machines between groups may be unacceptably high. It is proposed therefore that the cliques should be examined for possible merging into near-cliques. The procedures for this are :

(a) Start with the cliques as "cells".

(b) Allocate the components to the "cells". If a component cannot be completely processed by one cell, take the cell that is able to process the most number of operations starting from the first. Repeat this procedure for the remaining operations as if it were a separate component.

(c) Store components that cannot be completely processed by one cell in a "move matrix".

(d) Priority for the merging of "cells" is based on the number of inter-cell transfers.

(3) Allocating components to cells. If a component can be catered for by more than/cell allocate the component to the smallest / one cell with the required facilities. For components where the operations cannot be fully processed by one cell, the procedure in 2(b) is again followed. With the machine loads known, the number of units of each machine type required can be computed.

## 6.3 Concluding Remarks

As shown in Figure 6.2 there are three essential ingredients in the formation of viable and well-balanced production cells. The classification of components by their shapes and sizes serves three main purposes :

(a) to weed out proliferations in design and production methods thus contributing to a simpler work flow.

(b) to identify "obvious" component and machine groupings.

(c) to assist in the allocation of components to cells found by the production flow methods.

The grouping methods which are used for bringing together components with similar production methods but of different physical configurations can be divided into three types; that is, machine-orientated, component-orientated, or machine as well as component-orientated. The machine-orientated approach such McAuley's and Rajagopalan and Batra's is relatively less demanding in time and effort since the number of machine types is usually much smaller than the component population. However, the groupings formed are liable to cause some inter-cell transfers, a characteristic that is decidedly undesirable. The machine/component-orientated method of Carrie suffers from two disadvantages. Firstly, it is necessary to analyse the similarities between both the machines and the components, and secondly, there is no provision for machine duplication between groups. It appears, therefore, that the best grouping method available at the moment is Purcheck's Combinatorial Analysis. The PERA method (Lewis 1973) which is known to have been

applied to a number of companies has not been reviewed here since little have been published of its methodology.

Sufficiently accurate determination of the machine workloads should be made :

(a) to assist in the derivation of the final cellular groupings

(b) so that the requirements of the number of units of each machine type in the cells can be computed.

Therefore there is little doubt that the three factors perform a complementary function and any attempt to promote one at the exclusion of the others will not only lead to considerably more problems in arriving at the optimal cellular groupings but may also cause cells that are entirely unsuitable and will not stand the test of time.

Figure 6.2 : The Three Essential Factors for the Formation of Production Cells

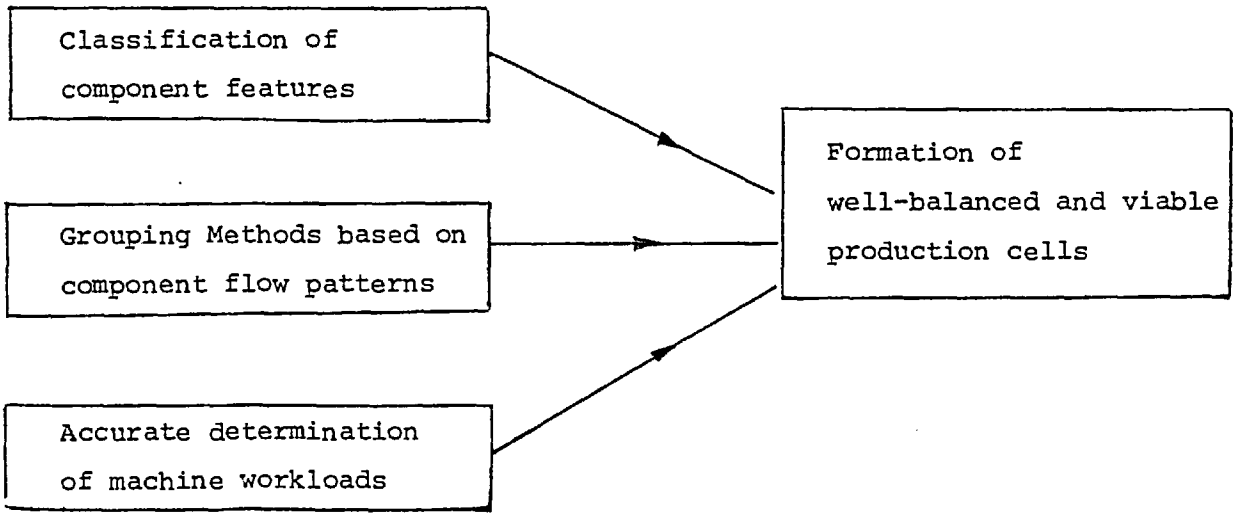


FIGURE 6.1(a) : The Pack/Machine Chart (Before Rearrangement)

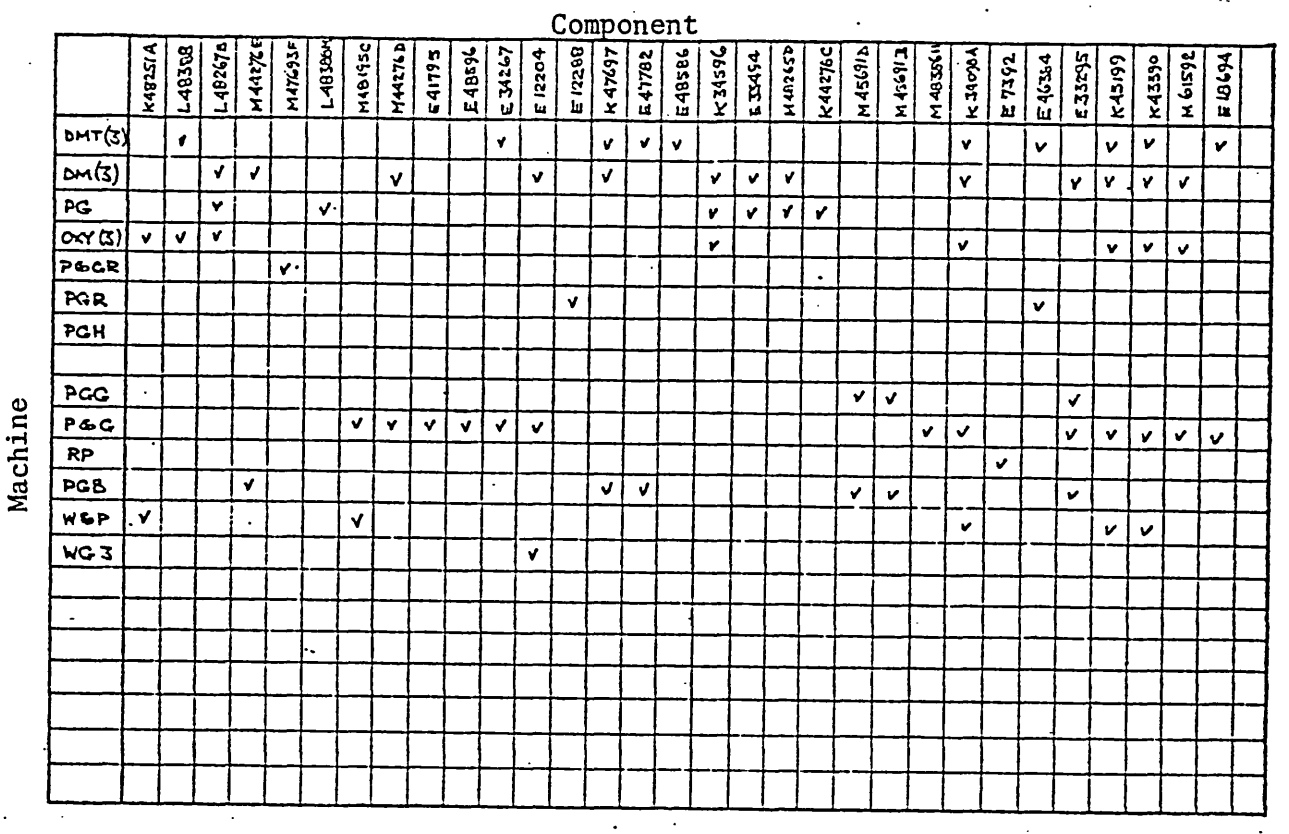
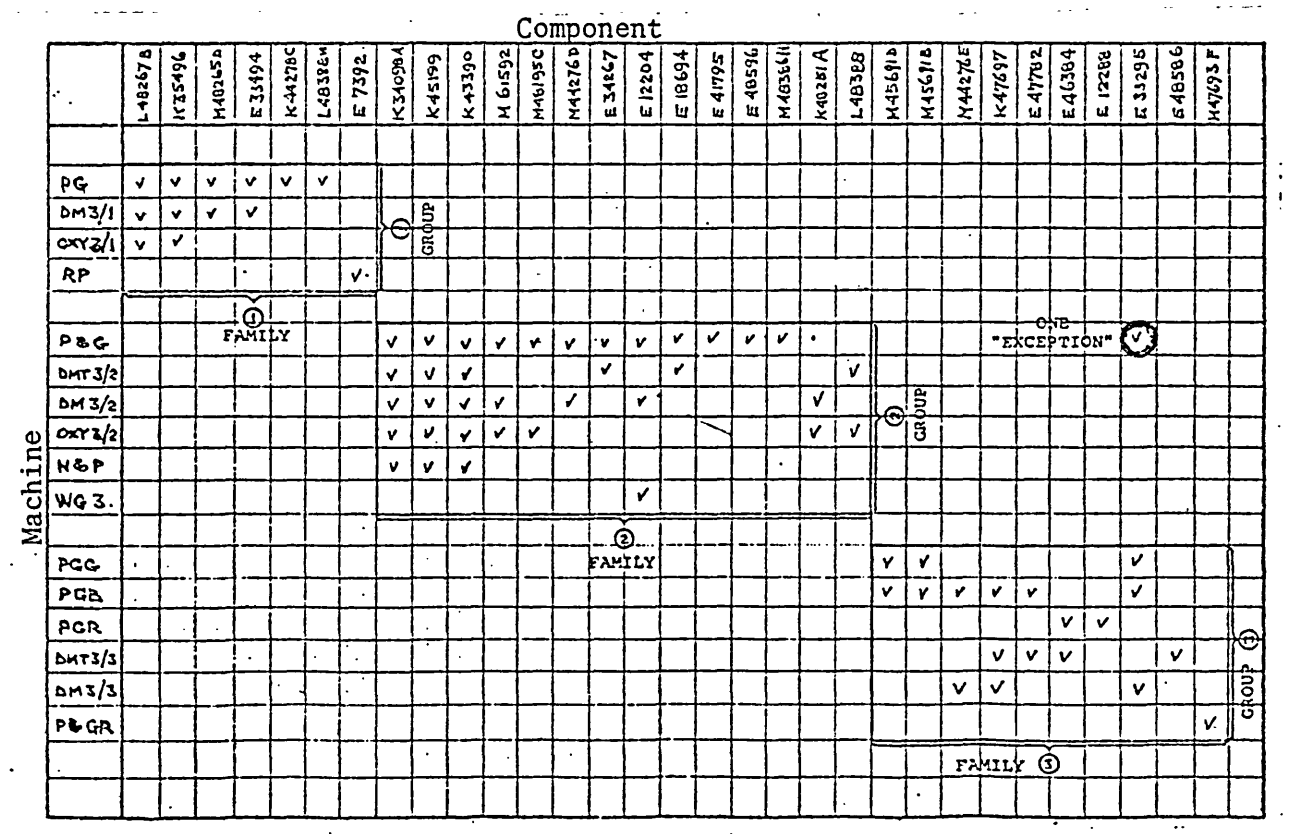



FIGURE 6.1(b) : The Pack/Machine Chart (After Rearrangement)



## Chapter 7 : Investigations into the Job Operation Time

7. Introduction
7.1 The Tool Life Equation
7.2 Sensitivity of the Cutting Cost Function
7.3 Operational Range of Cutting Conditions
7.4 Concluding Remarks

## 7. Introduction

Concern is often expressed at the gulf that exists between theoretical research and practical situations. This problem is well represented in the case of the determination of the optimum cutting conditions for machine tools. Investigations (Dudley 1970, Barr 1971) show that industry generally employs machining rates that are appreciably below the values established through research to be optimum with respect to the production cost or rate. In a comparative analysis of the recommended machining rates (based on figures from the US data bank) and those currently in use in British machine shops Barr recorded a ratio, on average, of 4:1. A conservative estimate suggests a potential savings in the national machining cost of around £70 million per annum.

A wide range of causes contribute to the theory-practice gap. Apart from the technical reasons which will be discussed later, some of the other factors include :

(1) the lack of firm control by management of the cutting conditions actually used

(2) union intervention

(3) the unavailability or inaccuracy of data for the machine rates, overheads, and tool change and reconstitution costs

(4) the computational complexity of the formulae for optimum conditions

(5) the unsuitability of the machine tools for reasons of rigidity, horsepower, speed range, etc.

A more basic contributory factor is actually the relatively little incentive for improving the machining times. The reason for this is that the average proportion of time that a machine is engaged in

productively cutting metal is only in the region of 30% (Tinker 1966, Moreton 1974). Consequently, changes made to the machining times have comparatively little effect on the manufacturing cycle. By taking measures to remove some of the unproductive elements of the machine time, such as with the introduction of group manufacture and/or numerically controlled machine tools, the need for the improvement of the machining rates will become much more significant.

## 7.1 The Tool Life Equation

To determine the optimum cutting conditions it is necessary to have a reliable tool life equation. F W Taylor (1907) has long established the following empirical relationship :

$$VT^n = C \qquad (7.1)$$

where V = cutting speed (m/min)
T = tool life (min)
n,C = constants

To include the effects of the feedrate and depth of cut Gilbert (1950) extended the formula to :

$$VT^n s^m a^p = \lambda \qquad (7.2)$$

where s = feedrate (mm/rev)
a = depth of cut (mm)
m,p,$\lambda$ = constants

Since the metal removal rate is proportional to Vsa and generally $p < m < 1$ it can be easily deduced that for optimum cutting conditions - whether it is with respect to minimum cost, maximum production rate or maximum profit - the largest values of feedrate and depth of cut, subject to the constraints defined by the performance envelope (Crookall 1969), should be taken. The tool life analysis therefore reverts back to considering the relationship between the tool life and the cutting speed.

Machine shops often do not have testing facilities of their own but rely

mainly on tool manufacturers and machining handbooks for their cutting data. As will be shown, considerable discrepancies can arise when laboratory-derived data are applied to the machine shop situation.

(1) The Tool Life Criterion

The tool wear mechanism is highly complex and tool deterioration can be caused by flank wear, cratering of the rake face, chipping due to mechanical impact, deformation due to high stress and temperature, and cracking due to thermal stress. However, with the selection of the correct tool material and operating conditions the incidence of tool failure caused by chipping, deformation and cracking will be largely avoided and therefore tool life criteria are based mainly on flank wear and crater wear. For high speed steel tools, material build-up on the tool makes measurement difficult and tool failure is widely accepted as the tool life criterion. As shown in Table 7.1 a similar measure of consensus is not found for the carbide and ceramic tools. The principal tool wear criterion is based on flank wear and for carbide and ceramic tools the adopted mean flank wear lands (VB) at "failure" can range from 0.15mm to 0.75mm and 0.13mm to 0.40mm respectively. At higher cutting speeds cratering wear becomes more dominant and is included by some investigators as a second tool life criterion. Here, there is a lack of agreement as to whether the degree of cratering wear should be based on the maximum crater depth (KT) or the cratering ratio (K)*.

The important consideration is the effect of different tool life criteria on the values of "n" and "C" in the Taylor equation. In assuming different wear levels the tool life is changed for a given cutting speed and consequently there will also be a change in the value of "C" and/or "n". To keep "n" constant the two necessary conditions, as illustrated in Figure 7.1 are :

(i) the wear rate curves must be linear on log-log paper

(ii) the wear rate curves must be parallel for different cutting speeds.

* An explanation of the notations used in this chapter is given in Appendix 7.1.

Tool wear shows (a) a primary rapid wear zone, (b) a secondary wear zone and (c) a temperature sensitive accelerated wear zone. Since tool "failure" points are almost invariably taken on the secondary wear zone which in most cases have been found to be linear on log-log paper conditions (i) is therefore usually satisfied. The fulfilment of condition (ii) is more variable. Some results (Koenig and Diederich 1969 , Bhattacharyya et al. 1970) indicate that flank wear curves are parallel for different cutting speeds whereas others (Koenig and Diederich, Hastings and Oxley 1976) do not reflect a similar trend. Hence with varying tool life criteria the derived values for "n" as well as "C" may be different.

(2) The Tool Life Test Method

The demand on time and material by the conventional tool life test method has led to the use of a number of short time tests such as the facing test, taper turning test, variable rate test, and radioactive tracer test. Thomas and Lambert (1975) compared the results of some of these tests with those obtained by the conventional method. An extract of the findings is given in Table 7.2.

Table 7.2 : Tool Life Parameters for Conventional and Accelerated Testing Methods

| Testing Method | Initially Sharp Tools | | Initially Prehoned Wearland Tools | |
|---|---|---|---|---|
| | n | C | n | C |
| Conventional | 0.3890 | 1118 | 0.3770 | 783 |
| Facing | 0.2130 | 733 | 0.3520 | 990 |
| Taper turning | 0.1678 | 821 | 0.3592 | 1099 |

There is little doubt that the tool life test method has a pronounced effect on the tool life parameters obtained although the situation is greatly improved when the tool wearland is first prehoned to 0.05mm. Assessments by Cook and Lang (1963) and Opitz (1963) on the compatibility between the results from radioactive tracer tests and conventional tests produced inconclusive results. The correlation was found to range from good to poor depending on the cutting conditions used.

Investigations were also conducted by Thomas and Lambert (1972) into the effect of intermittently removing the tool for measurement as is required in tool life testing. For their experiments the intermittent method consisted of cutting for 8 minutes with the tool stopped after each minute and the continuous method (portraying production situations) involved non-stop cuts for 4, 6 or 8 minutes. The Taylor parameters obtained were :

| | | |
|---|---|---|
| Intermittent method | n = 0.348 | C = 740 |
| Continuous method | n = 0.636 | C = 1250 |

Similar discrepancies have also been reported in other studies (Barrow and Spencer 1970).

(3) The Machining System

Machining system characteristics such as rigidity and the resistance to thermo-electric current path have been found to have an effect on tool wear. Investigations by Merchant (1961) and Pilafidas (1971) revealed that rigidity has a significant effect on tool wear but the trend appears to be inconsistent. Kuljanic (1975), on the other hand, concluded that tool life increases monotonically with lower stiffness. In their research, Ellis and Barrow (1969) determined that the flow of electric current through the contact zone between steel workpiece material and carbide cutting tools can appreciably influence tool life. They suggested that since the outer part of the thermo-electric circuit contributed by the machine structure can vary considerably from machine to machine under similar cutting conditions this may account for the relatively large difference in tool life reported. Taking up this investigation, Barrow and Spencer (1970) found that although thermo-electric tool wear can affect the results when tool life tests are conducted on different lathes, a more dominant factor causing the variation is attributable to the dynamic characteristics of the lathe-tool-workpiece system.

## (4) The Interpretation of Tool Life Test Results

In tool life tests a certain amount of scatter of the points between tool life and the cutting speed is invariably produced. The Taylor parameters are determined by applying a statistical regression analysis. Depending on whether the regression is taken of the tool life on the cutting speed or the cutting speed on the tool life different results will be obtained. A literature search shows that both interpretations have been used in the analysis of tool life test results. Kuljanic (1976) performed an assessment of the effects of these alternative interpretations and some of his findings are given in Table 7.3.

Table 7.3 : Discrepancies Arising From Alternative Regression Analysis Of Tool Life Test Results

| | Regression | n | C |
|---|---|---|---|
| Face milling | T vs V | 0.566 | 2441 |
| P30/Ck 45 steel | V vs T | 0.527 | 1991 |
| Turning | T vs V | 0.520 | 850 |
| Ceramics/16Mn Cr 5 steel | V vs T | 0.444 | 728 |

That cutting data which has been proven on the shopfloor is what industry really needs was clearly confirmed in a joint MTIRA/PERA study (Barr 1971, Tilsley 1972). A survey by Tilsley (1973) showed that this situation is shared by many of the CIRP member countries. For improving the current machining practice the MTIRA group recommended (i) the establishment of a machining data service to collate the data obtained from industry and publications of the U.S.A.F. machining data centre, Metcut and other research institutions, and (ii) the compilation of a machining data handbook to widen the circulation of these data.

On their part firms should have their own data banks so that :

(i) cutting data that are frequently used are stored as such, thus eliminating errors inherent in the conversion from exponent values to the cutting condition data

(ii) there is a standardisation in the machining conditions employed by different operators

(iii) the record of previous experiences provides a good basis for possible improvement of the machining rates.

Next, an examination will be made into the sensitivity of the optimum cutting speed and machining cost to the accurate determination of the Taylor parameters.

## 7.2 Sensitivity of the Cutting Cost Function

For a single point tool the production cost per workpiece is given by :

$$C_p = R_1 t_h + \frac{\pi DLR_1}{1000sV} + \frac{\pi DL(R_1 t_w + W)V^{1/n-1}}{1000sC^{1/n}} \qquad (7.3)*$$

where $R_1$ = total overhead, machine-rate and direct labour rate (m.u./min.)

$W$ = tool cost per tool change (m.u.)

$t_h$ = handling and fast traverse times (min.)

$t_w$ = tool change time (min.)

$D$ = diameter of workpiece (mm)

$L$ = length of cut (mm)

The cutting speed at minimum production cost can be easily determined to be :

$$V_{mc} = \frac{C}{(1/n - 1)^n \ (t_w + W/R_1)^n} \qquad (7.4)$$

* see Wu and Ermer (1966)

In Figure 7.2 the values of $V_{mc}/C$ are plotted against n for $t_e$ = 1,2,5 and 10 (solid lines), where $t_e = t_w + W/R_l$.

The curves reflect the following characteristics :

(i) as n increases the tool life becomes less sensitive to changes in the cutting speed

(ii) since C is assumed to be constant a higher n value also means a shorter tool life for a given cutting speed and

(iii) the balance between (i) and (ii) is greatly influenced by the tool change time equivalent, $t_e$.

The feature that is of particular relevance when considering the effect of discrepancies in the derived n value on the optimum cutting speed is the shifting of the flat or relatively insensitive region of the curves along the "n" axis as $t_e$ is increased. To obtain an assessment of the comparative influence of variations in C, two curves (dotted lines) representing a 20% increase and decrease respectively in the value of C have been included. Since, from the previous section it was found that variations in C is likely to be large it is expected that C would generally exert a more dominant influence than n on the optimum cutting speed.

By substituting equation 7.4 into equation 7.3, the minimum production cost is obtained as :

$$C_{pmc} = R_l t_h + \frac{\pi DL}{1000s} \cdot \frac{1}{C} \cdot \left(\frac{1}{1-n}\right) \left(\frac{1-n}{n}\right)^n t_e^{\,n} \qquad (7.5)$$

Figure 7.3 illustrates the effects of n, C and $t_e$ on C X $C'_{pmc}$, where $C'_{pmc} = (1/1-n)(1-n/n)^n t_e^{\,n}/C$. Clearly, $t_e$ imposed a strong influence on the sensitivity of the cost curves to changes in n. Comparing Figures 7.2 and 7.3 it is found that when $t_e$ is low,higher n values allow a considerable improvement in the production rate with only a small increase

in the cost. However, for large $t_e$ values, an increase in the n value would result in operations that are both slow and costly.

To assess the cost penalty for the employment of inaccurate tool life parameters it would be necessary to determine the sensitivity of the production cost curve. By applying the Taylor expansion series around the minimum cost point the following relationship is derived :

$$\Delta C_p = \frac{\pi DLR_1 (\Delta V)^2 (1/n - 1)^{3n} t_e^{3n}}{2000nsC^3} \qquad (7.6)*$$

where $\Delta C_p$ = an increase in the cost over the minimum production cost

and $\Delta V$ = the deviation in the cutting speed away from the minimum cost cutting speed

Putting $n' = (1/n - 1)^{3n} t_e^{3n}$, n' is plotted against n for different values of $t_e$ in Figure 7.4. For small values of $t_e$, the sensitivity of the cost equation decreases monotonically with n. But when $t_e$ is large a peak sensitivity occurs at the medium range of the n values.

From Figures 7.2, 7.3 and 7.4 the simultaneous effects on the cutting speed sensitivity, production cost sensitivity and production cost of n and $t_e$ are compiled in Table 7.4.

Table 7.4 : Effects of n and $t_e$ on Cutting Speed Sensitivity, Production Cost Sensitivity and Production Cost

| $t_e$ | n | Cutting Speed Sensitivity | Production Cost Sensitivity | Production Cost |
|---|---|---|---|---|
| small | small | low** | high | low |
| | medium | medium | medium | medium |
| | large | high | low | medium |
| large | small | low | low | low |
| | medium | medium | high | medium |
| | large | high | low | high |

* Details of the derivation is given in Appendix 7.2.

** These designations are taken to reflect the trend rather than the absolute values.

(i) When $t_e$ is small : For all values of n, the situations are well balanced. For example, when n is small, variations in n produce little changes in the optimum cutting speed and hence the high production cost sensitivity is relatively unimportant. Conversely, the large deviation in cutting speed caused by varying the n value, when n is large, is moderated by the low production cost sensitivity.

(ii) When $t_e$ is large : For low values of n, variations in n have comparatively little effect both on the cutting speed and production cost. When n is at the medium range any variation would result in a fairly large change in the optimum cutting speed and since the production cost is very sensitive to changes in the cutting speed there would be a serious escalation in the cost. In the case when n is large the high cutting speed sensitivity is balanced by the relatively low cost sensitivity. But since the production cost is high, the increase in the production cost, in absolute terms, may still be high.

## 7.3 Operational Range of Cutting Conditions

So far the analysis has been confined to cutting conditions based on the minimum production cost. For work scheduling it is desirable to have a range of operating conditions so that depending on the work flow situation, a suitable machining rate can be selected. It is already well established that this operational range is between the conditions for minimum cost and maximum production rate. To observe the measure of scheduling flexibility provided, the ratio of the production time at minimum cost to maximum production rate is derived (see Appendix 7.3). This ratio (ignoring the $t_h$ term) is given as :

$$R'_t = \frac{t'_{pmc}}{t'_{pmt}} = \left(\frac{t_e}{t_w}\right)^n \frac{[1 + t_w/t_e(1/n - 1)]}{[1 + 1/(1/n - 1)]} \qquad (7.7)$$

In Figure 7.5 $R'_t$ is plotted against n for $t_e/t_w$ = 2, 5, 10 and 15 (solid lines). When $t_e/t_w$ is small the range of operating conditions is also small for all values of h. For large $t_e/t_w$ values the amount of flexibility in the job operation time increases rapidly with higher n values.

To observe the corresponding cost penalty for operating at the maximum production rate instead of at the minimum cost, the ratio of the cost of maximum production rate to minimum cost is determined (see Appendix 7.4) and found to be (ignoring the $R_l t_h$ term) :

$$R'_c = \frac{C'_{pmt}}{C'_{pmc}} = \left(\frac{t_w}{t_e}\right)^n \frac{[1 + t_e/t_w(1/n - 1)]}{[1 + 1/(1/n - 1)]} \qquad (7.8)$$

The values of $R'_c$ for n = 0.1 to 0.7 and $t_e/t_w$ = 2, 5, 10 and 15 are plotted in Figure 7.5 (dotted lines). The first interesting observation is the cross-over point between $R'_t$ and $R'_c$ at n = 0.5 irrespective of the value of $t_e/t_w$. This means that at this point the proportional improvement in the production time is equal to the proportional increase in the production cost. Above n = 0.5, $R'_c$ becomes increasingly lower than $R'_t$ whereas below n = 0.5, $R'_e$ is always greater than $R'_t$.

A third criterion often proposed for the optimisation of cutting conditions is the maximisation of the profit rate (Armarego and Russell 1966, Wu and Ermer 1966). If I is the unit revenue and M is the material cost per piece, the profit rate $P_r$ is $(I-M-C_p)/t_p$ and the maximum profit rate cutting condition is represented by :

$$(1-n)\ [Wt_h + (I-M)t_w]\ V_{mp}^{1/n} + \frac{\pi DLWV_{mp}^{1/n-1}}{1000s} - n(I-M)C^{1/n} = 0 \qquad (7.9)$$

where $V_{mp}$ is the cutting speed at maximum profit rate.

Since the solution of equation 7.9 would normally require the use of an iterative procedure such as the Newton-Raphson method, the likelihood of its being adopted in an industrial situation is small. Nevertheless, profit rate maximisation is often the management objective and hence,

it would be useful to observe some of the salient features associated with it :

(i) When the profit is non-negative the maximum profit rate cutting speed lies between the minimum cost and maximum production rate cutting speeds

(ii) An increase in the unit revenue shifts the cutting speed nearer the value for the maximum production rate

(iii) Unless the profit is set at a very high level the maximum profit cutting speed is nearer the value for minimum production cost

(iv) The profit curve is steeper at cutting speeds above the maxima than below

Therefore, we find that an increase in the profit rate provides further incentive for operating above the minimum cost conditions although some fall in the profit rate is generally expected when approaching the maximum production machining rates.

## 7.4 Concluding Remarks

Provided industry is supplied with accurate tool life data, a concerted effort is made by management, and with union support, considerable improvements in the machining rates can be obtained. In addition to the reduction in the production cost of the components, the increased productivity of machines and labour provides for the creation of extra capacity without investment in more machines and man power. This feature is of particular significance in times of erratic market trends and tight cash flows.

It is normal shop practice to employ a single set of cutting conditions for a particular job, based mainly on the minimum cutting cost criterion. While this appears sensible especially when it is also known in most cases to approximate the maximum profit rate situation this actually

provides only a sub-optimal solution since the optimising objective function does not include considerations for the state of the work flow or penalties for job lateness and excessive queue times. To cater for these factors and allow for more scheduling flexibility it would be desirable to have a range of cutting conditions from which the parameters for the job is selected to suit the prevailing work flow situation.

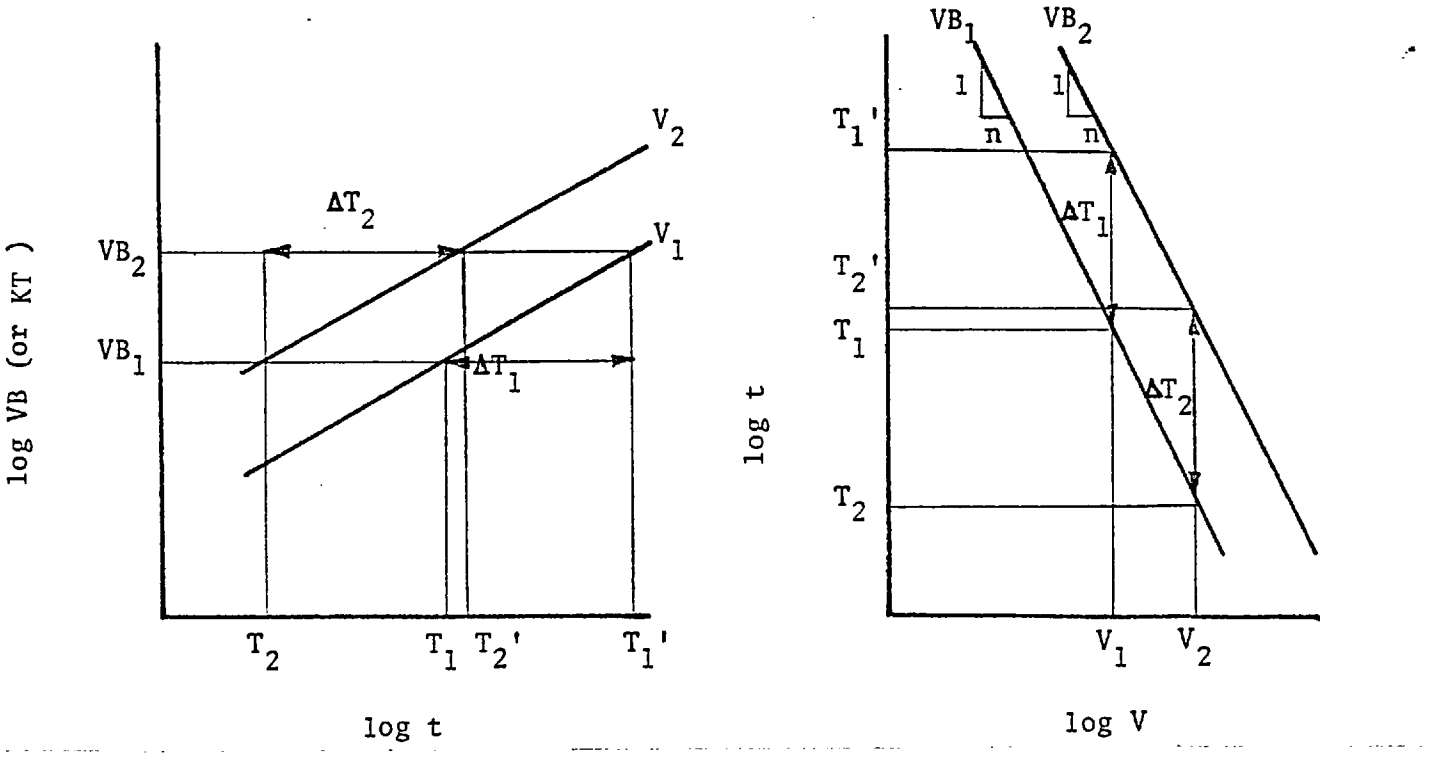



Figure 7.1 : Conditions for "n" to be Constant when Different Wear Levels ($VB_1$, $VB_2$) are used as the Tool Life Criterion

Table 7.1 : Some Tool Life Criteria and Cutting Conditions Used in Tool Life Testing

| Tool Life Criterion | Tool/ Workpiece | Cutting Conditions | Source |
|---|---|---|---|
| VB = 0.38mm or failure | Carbide 78B/ AISI 4147H and 4340H | V = 15-76m/min<br>s = 0.13-0.48mm/rev<br>a = 2.54mm. | Zlatin and Gould (1959) |
| VB = 0.76mm<br>KT = 0.25mm | Carbide/SAE 104.5 | V = 91-183m/min<br>s = 0.30mm/rev<br>a = 3.18mm | Kececioglu and Sorensen (1962) |
| VB = 0.61mm | Carbide P10/ Heat resistant alloy | V = 5-274m/min<br>s = 0.10-0.61mm/rev<br>a = 0.51-2.54mm | Takeyama and Murata (1963) |
| VB = 0.20mm | Carbide K20/ G18B and FC30 cast iron | | |
| VB = 0.76mm | Carbide K2S/ steel | V = 91-305m/min<br>s = 0.12 mm/rev<br>a = 2.54 mm | Cook and Lang (1963) |
| VB = 0.76mm | Carbide 78B/ SAE 1018 | V = 101-213m/min<br>s = 0.25-0.56mm/rev<br>a = 1.24-2.54mm | Wu (1964) |
| VB = 0.25mm | Carbide grade R cutanit/steel | V = 61-305m/min<br>s = 0.20-0.36mm/rev<br>a = 5.08mm | Heginbotham and and Pandey (1966) |
| VB = 0.20mm<br>VBMAX = 0.30 mm<br>K = 0.1 | Carbide P10,P20, P30/AISI8640 and 1030 | V = 100,180m/min<br>s = 0.01,0.29mm/rev<br>a = 2.5mm | Filippi and Ippolito (1969) |
| VB = 0.25mm<br>KT = 0.15mm | Carbide K11/ EN9 | V = 91m/min<br>s = 0.20mm/rev<br>a = 2.03mm | Ellis and Barrow (1969) |
| VB = 0.20mm | Carbide K11/ XC45N | V = 30m/min<br>s = 0.15mm/rev<br>a = 1.27mm | Barrow and Spencer (1970) |
| VB = 0.20mm<br>K = 0.1 | Carbide P10/ XC45 | V = 160-200m/min<br>s = 0.13-0.32mm/rev<br>a = 3.00mm | Gibson (1971) |

Table 7.1 (Cont'd)

| Tool Life Criterion | Tool Workpiece | Cutting Conditions | Source |
|---|---|---|---|
| | Carbide P30/ XC45 | V = 100-160m/min<br>s = 0.26-0.50mm/rev<br>a = 3.00mm | |
| VB = 0.30mm or burnishing due to oxidation wear | Carbide P15/ Cm55N | V = 80-200m/min<br>s = 0.63-1.25mm/rev<br>a = 2.50mm | Colding and Koenig (1971) |
| | Carbide P10/ SIS 1550 | V = 50-470m/min<br>s = 0.12-1.56mm/rev<br>a = 2.50mm | |
| VB = 0.13mm | Ceramics/Gray cast iron | V = 274-457m/min<br>s = 0.25mm/rev<br>a = 2.54mm | Ham and Narutaki (1973) |
| VB = 0.76mm | Carbide C6/ C4145 steel | V = 61-168m/min<br>s = 0.26-0.65mm/rev<br>a = 1.91mm | Groover (1975) |
| VB = 0.40mm | Carbide P25/ CK55N | V = 110-280m/min<br>s = 0.25 mm/rev<br>a = 2.00mm | Koenig (1975) |
| | Carbide K10/ GG30 | V = 70-120m/min<br>s, a as above | |
| | Ceramic/GG30 | V = 400-900m/min<br>s = 0.16mm/rev<br>a = 2.00mm | |
| VB = 0.15mm | Carbide DO-16/ SAE 1020 | V = 156-259m/min<br>s = 0.10mm/rev<br>a = 2.54mm | Thomas and Lambert (1975) |
| VB = 0.30mm | Ceramics/ AISI 4340 | V = 230-370m/min<br>s = 0.36mm/rev<br>a = 2.5mm | Kuljanic (1976) |

FIGURE 7.2 : EFFECT ON THE MINIMUM COST CUTTING SPEED OF TAYLOR "n" AND "C"

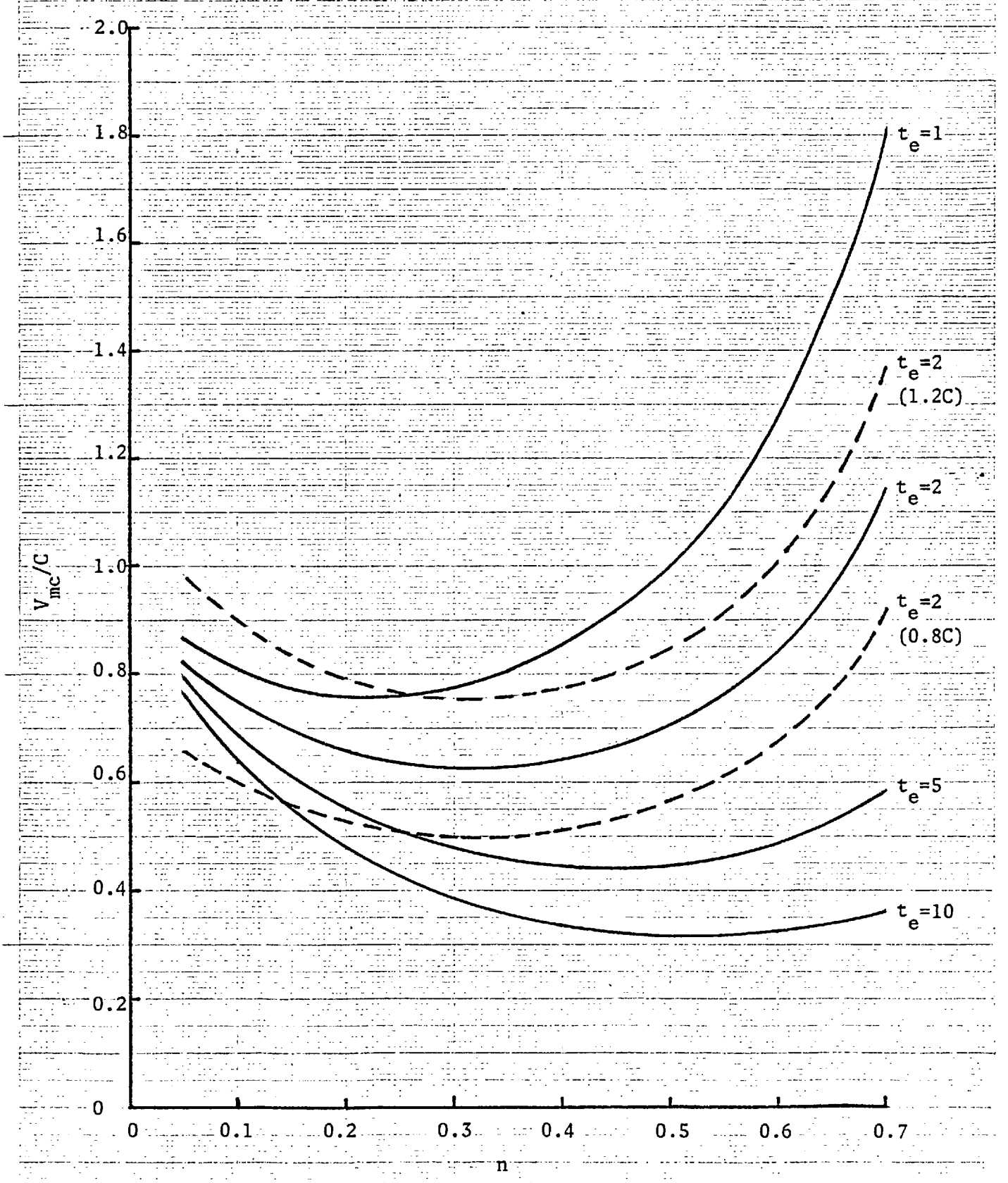


FIGURE 7.3 : EFFECTS OF n AND C ON $C'_{pmc}$

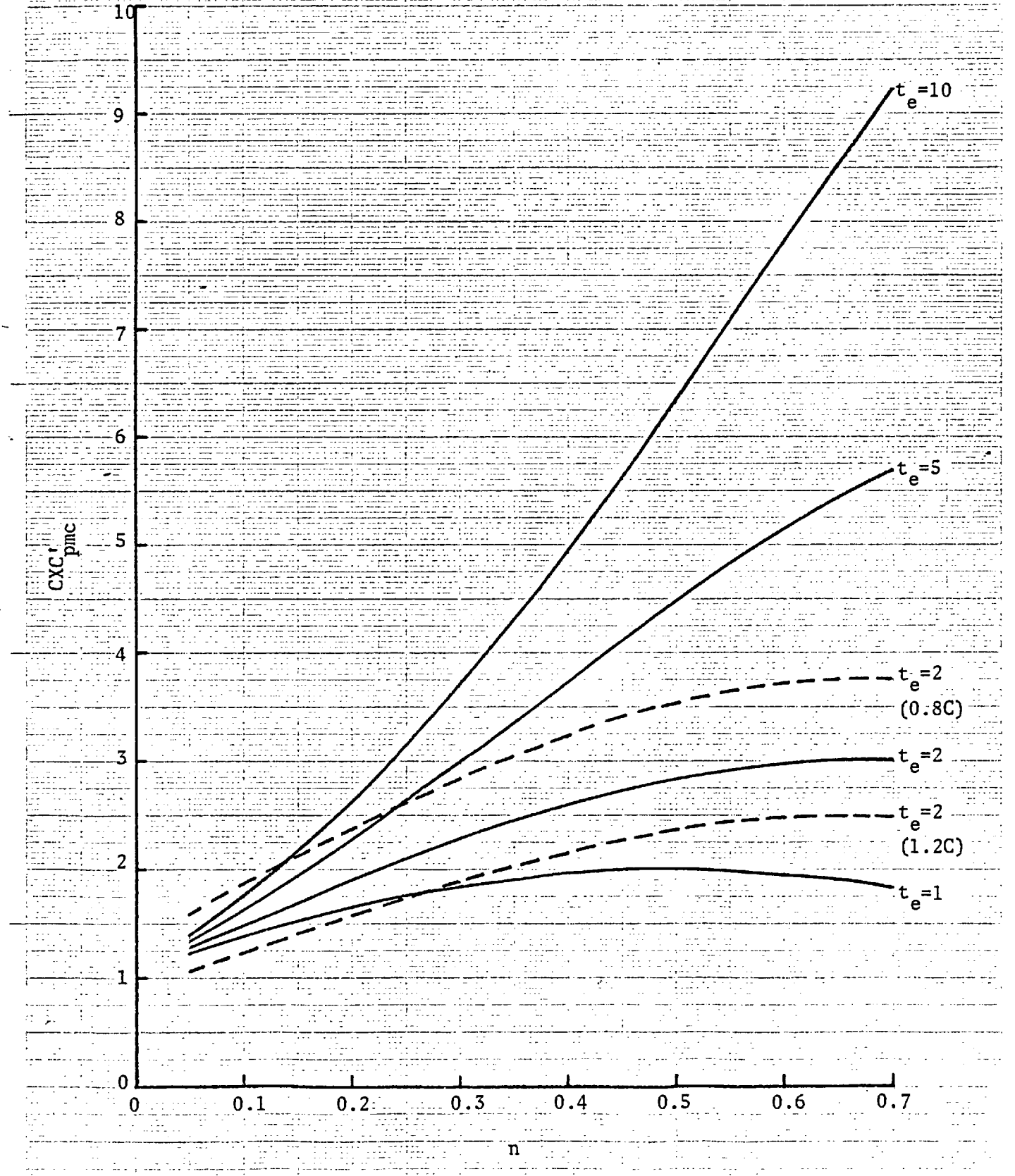


FIGURE 7.4 : SENSITIVITY OF THE COST EQUATION TO $t_e$ AND n

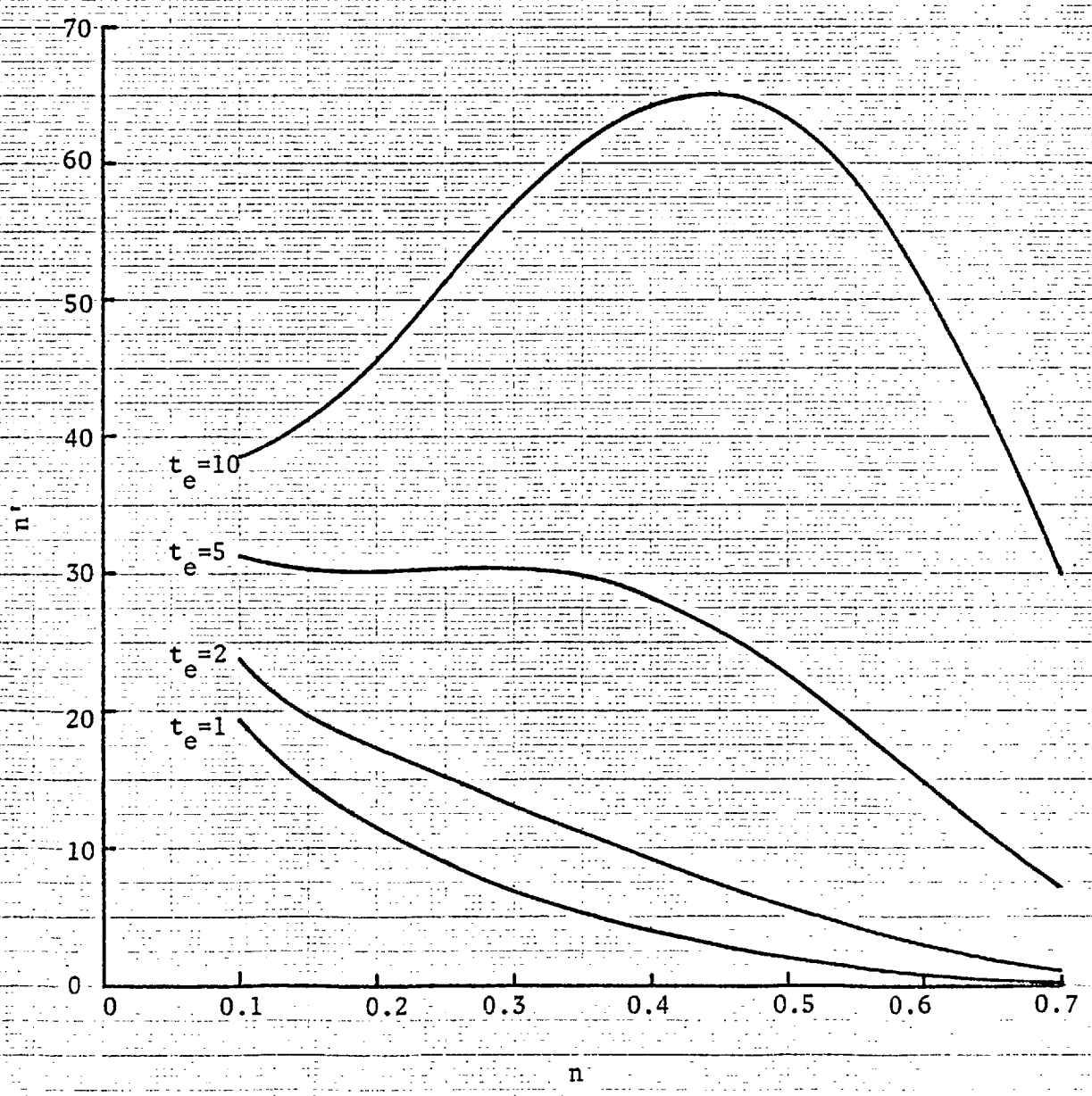
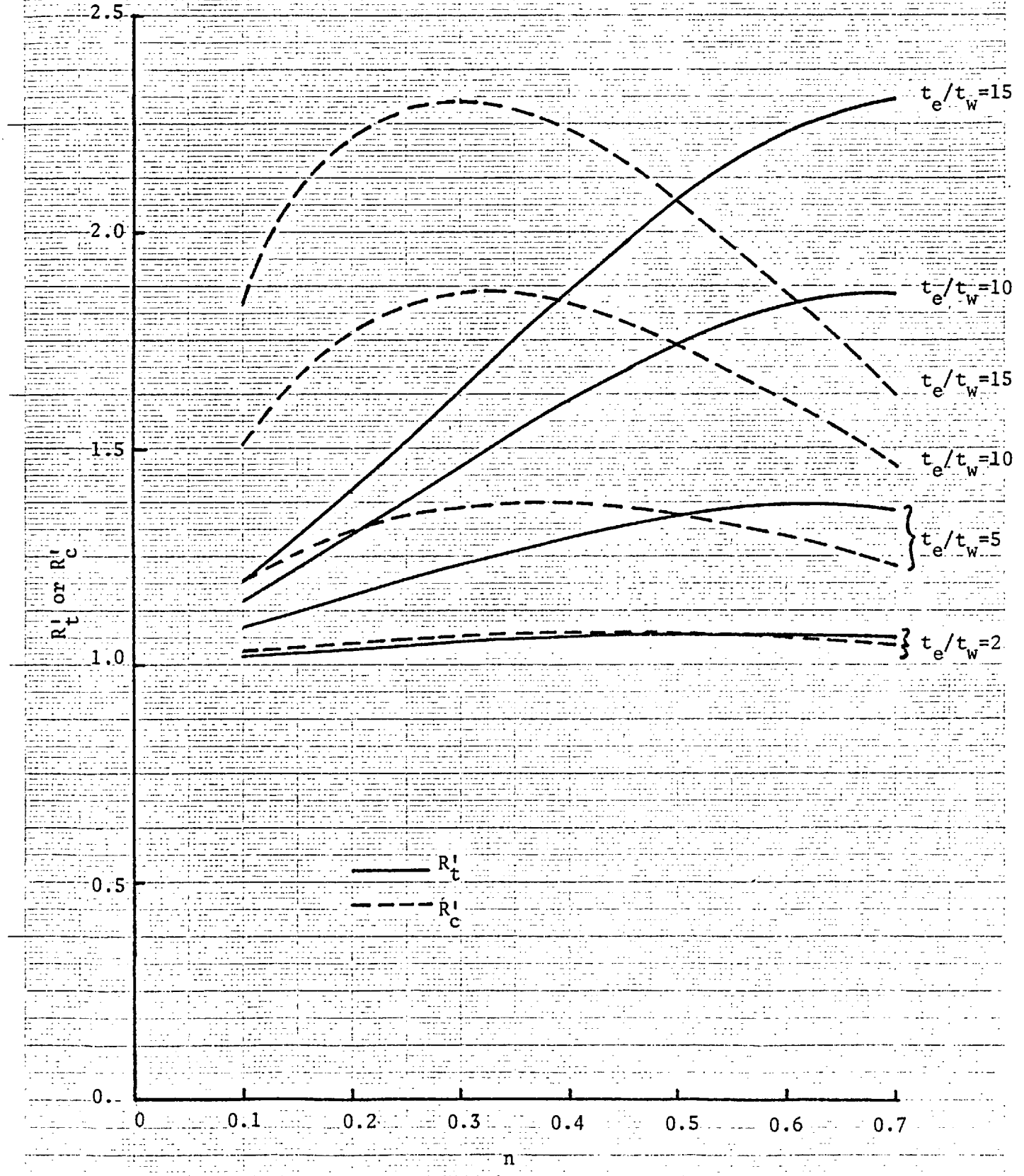


FIGURE 7.5 : EFFECTS OF n AND $t_e/t_w$ ON $R_t'$ AND $R_c'$



Chapter 8

# 8. Conclusions

Computer simulation offers an important approach for the performance analysis of manufacturing systems. Using a simulation model, one can obtain a positive knowledge of cause and effect and above the level of supposition, "experience" and numerical data.

Priority rules have a significant influence on the system performance. Cost-based rules, though intuitively preferred, suffer from considerable practical difficulties in cost attribution and computational effort. Simple rules such as the SPT and SLACK-orientated disciplines are proficient in certain effectiveness measures but poor in others. A better all-round performance is derived by combining the SPT and SLACK rules in the form of hierarchies. Additional benefits are often obtained by incorporating further a tool-resetting-minimisation factor viz. S(1)/SET/SPT.

It is commonly assumed that by keeping batch sizes large, the savings in setting time will create extra capacity and hence the system will behave more effectively. Results show that the converse is true. Smaller batches are more readily distributed and the higher machine utilisation derived is able to recompense for the extra setting time. The most outstanding advantage is found in the superior job throughput characteristics.

Evidence elsewhere indicates that in the preoccupation to ensure a high utilisation of the resources, a frequent practice is to inflate the work in progress level in the system. It is estimated that on average the queue lengths are maintained at 4-5 whereas a projected level of 2-3 is suggested to suffice. In investigating this point it was found with the lower work in progress level a substantial improvement in the work flow was obtained at the expense of only a slight drop in the machine utilisation.

Cellular manufacture provides a favourable environment for achieving a better work flow. The grouping method employed influences greatly the size and nature of cells formed; the cells being generally small and relatively more specialised with the parts classification method, and

larger and more "hospitable" with the process routes analysis approach. In addition to the greater viability in the longer-term larger cells have been shown to perform more effectively. Results also indicate that when operating with a reasonable queue length (that is 2-3 jobs) the benefits derived from reduced setting rapidly decrease as the number of set-up configurations is increased. Above 5 set-up configurations the throughput performance becomes insensitive to the number of set-up types. Movement of labour among machines in a cell is advocated for raising manpower utilisation. Experiments conducted show that provided there is a good balance between setters and operators the machine utilisation will be little affected but some deterioration in the job lead times will arise.

Examination into the organic aspects of Group Technology shows that in most respects a more enriched and satisfying work situation is possible. Studies of conditions at existing GT cells indicate that the social needs of the workers have received low priority. In some cases the social circumstances of the workers are actually worse off with GT.

Despite extensive studies in the determination of optimum cutting conditions the benefits from these researches are not evident in the prevailing machining practice. The reason can be traced to the infeasibility of direct practical application of many of the findings and also to the lack of managerial effort and trade union co-operation. Improvement in the cutting conditions is clearly desirable since it represents the derivation of extra machining capacity with the present level of investment. Use should also be made of the process time flexibility between the minimum cost (or maximum profit rate) condition and the maximum production rate condition to plan the schedule according to the level of work demand.

Increasing number of companies are incorporating computer facilities in their production function but mainly for the purpose of control and administration. This study shows that computer simulation can be a very versatile and effective management technique.

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Appendix 2.1 : Explanation of Notations for Priority Rules

| Notation | Description |
|---|---|
| DDATE | Jobs are selected in order of the earliest due date. |
| FASFS | Jobs are selected in order of arrival in the shop |
| FCFS | Jobs are selected in order of arrival at the queue |
| FOPNR | Jobs are selected in order of the fewest operations remaining |
| LPT | Jobs are selected in order of the longest process time |
| LWKR | Jobs are selected in order of the least work (process times) remaining |
| MOPNR | Jobs are selected in order of the most operations remaining |
| MWKR | Jobs are selected in order of the most work remaining |
| S/OPN | Jobs are selected in order of the ratio of the slack time to the no. of ops. remaining |
| S(U)/SET/SPT | Jobs are queued according to the amount of slack time. If jobs have negative slacks the job at the head of the queue is selected. Otherwise form two queues on the basis of whether or not resetting is required. If |

| | |
|---|---|
| | the non-resetting queue is not empty select the job with the shortest process time; otherwise select the SPT job from the other queue. |
| SLACK(U) | Jobs are selected in order of the slack time remaining; a queue allowance of U time units is provided for each remaining operation. |
| SLACK(U)/SPT | Jobs are queued according to the amount of slack time. If jobs have negative slacks the job at the head of the queue is selected. Otherwise take the shortest process time job. |
| SPT | Jobs are selected in order of the shortest process time. |
| WINQ | Jobs are selected in order of the least work in the next operation queue. |
| OPNDD | Jobs are selected in order of earliest operation due date. The flow allowance is divided equally among operations. |
| SET | Jobs are selected which require no (or in other cases, the minimal) setting (time). |

APPENDIX 4.1(a) : QUESTIONS ENCOUNTERED IN THE JOB GENERATION PROGRAMME

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NO. OF MC TYPES?
RANDOM NO. GENERATION STREAM...TYPE IN  1 TO 10

TYPE OF DISTRIBUTION      (1) SPECIFIED(CONTINUOUS)
                          (2) SPECIFIED(DISCRETE)
                          (3) NORMAL
                          (4) OP. TIMES : EXPONENTIAL   OR,
                              DUE DATE : NON-DISTRIBUTION

     FOR....SET TIME?
     FOR....RUN TIME?
     FOR....TOOL S/U?
     FOR....LOT SIZE?
     FOR....   VALUE?
     FOR....DUE DATE?
     FOR....     ESD?
MAX. NO. OF OPS.?
TYPE IN DISTRIBUTION FOR NO. OF OPS.
TYPE IN DISTRIBUTION FOR OP. NO.  1
TYPE IN DISTRIBUTION FOR OP. NO.  2
TYPE IN DISTRIBUTION FOR OP. NO.  3
TYPE IN DISTRIBUTION FOR OP. NO.  4
TYPE IN DISTRIBUTION FOR OP. NO.  5
TYPE IN DISTRIBUTION FOR OP. NO.  6
TYPE IN DISTRIBUTION FOR OP. NO.  7
TYPE IN DISTRIBUTION FOR OP. NO.  8
TYPE IN DISTRIBUTION FOR OP. NO.  9
TYPE IN DISTRIBUTION FOR OP. NO. 10
TYPE IN MEAN VALUE FOR SET TIME FOR MC TYPE  1
TYPE IN MEAN VALUE FOR SET TIME FOR MC TYPE  2
TYPE IN MEAN VALUE FOR SET TIME FOR MC TYPE  3
TYPE IN MEAN VALUE FOR SET TIME FOR MC TYPE  4
TYPE IN MEAN VALUE FOR SET TIME FOR MC TYPE  5
TYPE IN MEAN VALUE FOR SET TIME FOR MC TYPE  6
TYPE IN MEAN VALUE FOR RUN TIME FOR MC TYPE  1
TYPE IN MEAN VALUE FOR RUN TIME FOR MC TYPE  2
TYPE IN MEAN VALUE FOR RUN TIME FOR MC TYPE  3
TYPE IN MEAN VALUE FOR RUN TIME FOR MC TYPE  4
TYPE IN MEAN VALUE FOR RUN TIME FOR MC TYPE  5
TYPE IN MEAN VALUE FOR RUN TIME FOR MC TYPE  6
TYPE IN DISTRIBUTION FOR TOOL S/U FOR MC TYPE  1
TYPE IN DISTRIBUTION FOR TOOL S/U FOR MC TYPE  2
TYPE IN DISTRIBUTION FOR TOOL S/U FOR MC TYPE  3
TYPE IN DISTRIBUTION FOR TOOL S/U FOR MC TYPE  4
TYPE IN DISTRIBUTION FOR TOOL S/U FOR MC TYPE  5
TYPE IN DISTRIBUTION FOR TOOL S/U FOR MC TYPE  6
TYPE IN DISTRIBUTION FOR LOT SIZE
TYPE IN DISTRIBUTION FOR    VALUE
DUE DATE....(1) FACTOR * NO. OF OPS.
            (2) FACTOR * JOB OP. TIMES
            (3) OP. TIMES + FACTOR * NO. OF OPS.
FACTOR?
TYPE IN DISTRIBUTION FOR      ESD
TYPE IN DISTRIBUTION FOR EXT. PRIORITY
NO. OF PARTS TO BE GENERATED?
```

## APPENDIX 4.1(b) : SAMPLE DATA INPUT INTO THE JOB GENERATION PROGRAMME

```
6
2
4
4
1
2
2
4
2
10
  1   2 11   3 22   4 33   5 44   6 56   7 67   8 78   9 89 10100
 11   1 17   2 34   3 50   4 67   5 84   6100
 12   1 17   2 34   3 50   4 67   5 84   6100
 13   1 17   2 34   3 50   4 67   5 84   6100
 14   1 17   2 34   3 50   4 67   5 84   6100
 15   1 17   2 34   3 50   4 67   5 84   6100
 16   1 17   2 34   3 50   4 67   5 84   6100
 17   1 17   2 34   3 50   4 67   5 84   6100
 18   1 17   2 34   3 50   4 67   5 84   6100
 19   1 17   2 34   3 50   4 67   5 84   6100
 20   1 17   2 34   3 50   4 67   5 84   6100
12
12
12
12
12
12
36
36
36
36
36
36
151   1   0   8100
152   1   0   8100
153   1   0   8100
154   1   0   8100
155   1   0   8100
156   1   0   8100
201   1100
202  10100
3
4
204   0100
205   1100
126
```

## APPENDIX 4.2 : SAMPLE OF THE JOBS GENERATED

Job Details : Job No./Batch Size/Value/Flow Allow./ESD/Ext.Priority/No.of Ops.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Job.No. | 1 | 1 | 10 | 24 | 0 | 1 | 5 |
| Op.No.1 | 4 | 15 | 86 | 2 | (Op.Type/Set Time/Run Time/Set-Up | | |
| Op.No.2 | 6 | 20 | 38 | 1 | | | Configuration) |
| Op.No.3 | 4 | 26 | 4 | 1 | | | |
| Op.No.4 | 1 | 9 | 31 | 3 | | | |
| Op.No.5 | 5 | 23 | 32 | 1 | | | |
| Job.No. | 2 | 1 | 10 | 13 | 0 | 1 | 3 |
| | 6 | 3 | 17 | 3 | | | |
| | 4 | 5 | 33 | 5 | | | |
| | 5 | 19 | 6 | 7 | | | |
| | 3 | 1 | 10 | 22 | 0 | 1 | 5 |
| | 4 | 6 | 52 | 1 | | | |
| | 6 | 14 | 5 | 4 | | | |
| | 5 | 6 | 24 | 4 | | | |
| | 1 | 4 | 2 | 3 | | | |
| | 2 | 7 | 24 | 8 | | | |
| | 4 | 1 | 10 | 28 | 0 | 1 | 6 |
| | 5 | 8 | 49 | 2 | | | |
| | 1 | 24 | 14 | 2 | | | |
| | 5 | 3 | 31 | 2 | | | |
| | 4 | 19 | 64 | 6 | | | |
| | 3 | 16 | 41 | 2 | | | |
| | 1 | 6 | 1 | 8 | | | |
| | 5 | 1 | 10 | 24 | 0 | 1 | 5 |
| | 2 | 47 | 67 | 3 | | | |
| | 6 | 9 | 50 | 1 | | | |
| | 3 | 1 | 4 | 7 | | | |
| | 4 | 11 | 52 | 1 | | | |
| | 2 | 9 | 32 | 7 | | | |
| | 6 | 1 | 10 | 23 | 0 | 1 | 5 |
| | 4 | 5 | 54 | 7 | | | |
| | 6 | 13 | 8 | 6 | | | |
| | 2 | 22 | 1 | 7 | | | |
| | 6 | 9 | 5 | 7 | | | |
| | 2 | 5 | 82 | 7 | | | |
| | 7 | 1 | 10 | 34 | 0 | 1 | 7 |
| | 2 | 1 | 24 | 4 | | | |
| | 6 | 3 | 8 | 6 | | | |
| | 2 | 16 | 30 | 2 | | | |
| | 5 | 9 | 96 | 7 | | | |
| | 6 | 3 | 28 | 5 | | | |
| | 5 | 27 | 30 | 7 | | | |
| | 1 | 13 | 86 | 2 | | | |
| | 8 | 1 | 10 | 39 | 0 | 1 | 8 |
| | 1 | 1 | 41 | 6 | | | |
| | 5 | 6 | 100 | 6 | | | |
| | 4 | 10 | 19 | 5 | | | |
| | 3 | 51 | 9 | 7 | | | |
| | 1 | 3 | 137 | 2 | | | |
| | 6 | 15 | 9 | 3 | | | |
| | 1 | 8 | 3 | 3 | | | |
| | 2 | 9 | 34 | 1 | | | |

## APPENDIX 4.3 : QUESTIONS ENCOUNTERED IN THE MAIN SIMULATION PROGRAMME

```
NO. OF MC TYPES?
NO. OF MC TYPE  1?
NO. OF MC TYPE  2?
NO. OF MC TYPE  3?
NO. OF MC TYPE  4?
NO. OF MC TYPE  5?
NO. OF MC TYPE  6?
NO. OF OPERATOR TYPES?
NO. OF OPR. TYPE  1?
NO. OF OPR. TYPE  2?
NO. OF OPR. TYPE  3?
MACHINE-OPERATOR MATCH.....(0) NO MATCH
                            (1) SETTING ONLY
                            (2) RUNNING ONLY
                            (3) SETTING AND RUNNING
MC TYPE  1/OPR. TYPE  1?
MC TYPE  1/OPR. TYPE  2?
MC TYPE  1/OPR. TYPE  3?
MC TYPE  2/OPR. TYPE  1?
MC TYPE  2/OPR. TYPE  2?
MC TYPE  2/OPR. TYPE  3?
MC TYPE  3/OPR. TYPE  1?
MC TYPE  3/OPR. TYPE  2?
MC TYPE  3/OPR. TYPE  3?
MC TYPE  4/OPR. TYPE  1?
MC TYPE  4/OPR. TYPE  2?
MC TYPE  4/OPR. TYPE  3?
MC TYPE  5/OPR. TYPE  1?
MC TYPE  5/OPR. TYPE  2?
MC TYPE  5/OPR. TYPE  3?
MC TYPE  6/OPR. TYPE  1?
MC TYPE  6/OPR. TYPE  2?
MC TYPE  6/OPR. TYPE  3?
PARTS PRIORITY RULE       (1) FIFO
                          (2) EARLIEST DUE DATE
                          (3) EARLIEST SHOP ARRIVAL DATE
                          (4) LEAST SLACK
                          (5) LEAST REMAINING PROCESS TIME
                          (6) MOST REMAINING PROCESS TIME
                          (7) FEWEST OPERATIONS REMAINING
                          (8) MOST OPERATIONS REMAINING
                          (9) SHORTEST PROCESS TIME
                         (10) LONGEST PROCESS TIME
                         (11) LEAST SLACK/SPT
                         (12) LEAST SLACK/TSU/SPT
?
QUEUE TIME FOR EACH OP.?
PARTS SHOP ENTRY MODE     (1) FIRST OP. QUEUE LENGTH
                          (2) FIRST OP. QUEUE LOAD
?
TRIGGER OFF VALUE FOR MC TYPE  1?
TRIGGER OFF VALUE FOR MC TYPE  2?
TRIGGER OFF VALUE FOR MC TYPE  3?
TRIGGER OFF VALUE FOR MC TYPE  4?
TRIGGER OFF VALUE FOR MC TYPE  5?
TRIGGER OFF VALUE FOR MC TYPE  6?
PART INTER-MACHINE TRANSIT TIME
FROM MC TYPE  1 TO MC TYPE  2...MEAN/STD. DEV.??
FROM MC TYPE  1 TO MC TYPE  3...MEAN/STD. DEV.??
FROM MC TYPE  1 TO MC TYPE  4...MEAN/STD. DEV.??
FROM MC TYPE  1 TO MC TYPE  5...MEAN/STD. DEV.??
FROM MC TYPE  1 TO MC TYPE  6...MEAN/STD. DEV.??
FROM MC TYPE  2 TO MC TYPE  1...MEAN/STD. DEV.??
FROM MC TYPE  2 TO MC TYPE  3...MEAN/STD. DEV.??
FROM MC TYPE  2 TO MC TYPE  4...MEAN/STD. DEV.??
FROM MC TYPE  2 TO MC TYPE  5...MEAN/STD. DEV.??
FROM MC TYPE  2 TO MC TYPE  6...MEAN/STD. DEV.??
FROM MC TYPE  3 TO MC TYPE  1...MEAN/STD. DEV.??
FROM MC TYPE  3 TO MC TYPE  2...MEAN/STD. DEV.??
FROM MC TYPE  3 TO MC TYPE  4...MEAN/STD. DEV.??
FROM MC TYPE  3 TO MC TYPE  5...MEAN/STD. DEV.??
FROM MC TYPE  3 TO MC TYPE  6...MEAN/STD. DEV.??
FROM MC TYPE  4 TO MC TYPE  1...MEAN/STD. DEV.??
FROM MC TYPE  4 TO MC TYPE  2...MEAN/STD. DEV.??
FROM MC TYPE  4 TO MC TYPE  3...MEAN/STD. DEV.??
FROM MC TYPE  4 TO MC TYPE  5...MEAN/STD. DEV.??
FROM MC TYPE  4 TO MC TYPE  6...MEAN/STD. DEV.??
FROM MC TYPE  5 TO MC TYPE  1...MEAN/STD. DEV.??
FROM MC TYPE  5 TO MC TYPE  2...MEAN/STD. DEV.??
FROM MC TYPE  5 TO MC TYPE  3...MEAN/STD. DEV.??
FROM MC TYPE  5 TO MC TYPE  4...MEAN/STD. DEV.??
FROM MC TYPE  5 TO MC TYPE  6...MEAN/STD. DEV.??
FROM MC TYPE  6 TO MC TYPE  1...MEAN/STD. DEV.??
FROM MC TYPE  6 TO MC TYPE  2...MEAN/STD. DEV.??
FROM MC TYPE  6 TO MC TYPE  3...MEAN/STD. DEV.??
FROM MC TYPE  6 TO MC TYPE  4...MEAN/STD. DEV.??
FROM MC TYPE  6 TO MC TYPE  5...MEAN/STD. DEV.??
HISTOGRAM SCALES(HRS.):
PARTS DELIVERY(TARDINESS).....INITIAL VALUE/INTERVAL??
PARTS DELIVERY(EARLINESS).....INITIAL VALUE/INTERVAL??
PARTS THROUGHPUT.....INITIAL VALUE/INTERVAL??
SIMULATION PERIOD(DAYS)?
SIMULATION DETAILS?
```

## Appendix 4.4 : Details of the Recording of the System Performance Measures

(a) Machine utilisation : For each machine type or group and for the "shop" (averaged over the machine types) the proportion of time spent in each of the 5 activity states is recorded. Since the programme is interactive and allows a series of simulation periods to be run in one session these figures represent the values to-date or for the last simulation period only, depending on the recording mode specified at the beginning of each simulation period.

(b) Job queue : Over the recorded period the queue situation for each machine type is monitored through :-

(i) the average time (in minutes) that jobs remain in the queue before being loaded

(ii) the longest time that a job remained in the queue

(iii) the largest queue count.

Information is also provided for the state of queueing at the time of reporting via :

(i) the workload (in minutes) in queue at each machine type

(ii) the workload for each machine type in the "shop" (that is, that in queue as well as imminent).

(c) Labour utilisation : For each labour type the proportion of time spent in setting machines, running machines and idle is recorded.

(d) Job process routing : A chart in the form of a matrix displays the frequency in which jobs are transfered from one machine type to another for subsequent operations. The entries for "from

finish at machine type 0 .... to start at machine type n" indicate the number of jobs having machine type n for its first operation. Entries for "from finish at machine type n .... to start at machine type 0" show the number of jobs having the last operation at machine type n.

(e) Job tardiness, job earliness and job throughput : For the jobs completed over the recorded period the following aspects of the above measures are given :

(i) the mean
(ii) the standard deviation
(iii) the maximum
(iv) the minimum

A histogram shows the distribution of the entries.

(f) Also provided are :

(i) the number of jobs taken into the system
(ii) the number of jobs completed
(iii) the number of operations completed

over the recorded period.

For the experiments in Chapter 5 the results are recorded for one 13-day period run and the performance measures are taken from the output at the end of this simulation period.

APPENDIX 5.1 : Data for Experiment 1(a)

| | | |
|---|---|---|
| No. of machine groups | : | 6 |
| No. of machines/group | : | 1 |
| Manning arrangement | : | 1 setter-operator at each machine |
| Job input rate | : | 9 (18 in the first period to load up system) jobs/period |
| Job characteristics | : | |
| No. of ops. | : | Uniformly distributed; 2-10 ops. |
| Routing | : | Random-consecutive ops. on the |
| | : | same machine group disallowed |
| Set-up configuration | : | Uniformly distributed; 1-8 |
| Set times | : | Exponentially distributed; mean=12min. |
| Run times | : | Exponentially distributed; mean=36min. |
| Earliest start date | : | On generation |
| External Priority | : | All jobs normal |
| Batch size | : | 1 |
| Value | : | Not used |
| Due Date | : | (1) Sum of process times+2 x No. of ops. |
| | | (2) Sum of process times+3 x No. of ops. |
| | | (3) Sum of process times+4 x No. of ops. |
| | | (4) 4 x sum of process times |
| | | (5) 5 x sum of process times |
| Inter-operation transit time | : | Normally distributed; mean=5min. std. dev. = 1 min. |
| Trigger off value (from order book to queue) | : | 20 hr. |
| Priority Despatching Rule | : | (1) FCFS |
| | | (2) DDATE |
| | | (3) SLACK(1) |
| | | (4) SPT |
| | | (5) SLACK(1)/SPT |
| | | (6) S(1)/SET/SPT |
| No. of periods simulated | : | 13 |

Appendix 5.1(a) : Aspects of the simulation run length

It has been fairly general practice in job shop simulation studies that long run lengths are advocated because :

(i) the initial portion of the simulation run which is in the transient "build-up" state can be discarded,
and
(ii) the performance measures recorded as an average of a larger sample size will minimise the random variability effects.

This approach has resulted in something of a convention in which simulation runs are usually performed using thousands or even tens of thousands of jobs.

The intention in the present investigation has been to examine broadly the batch manufacturing area in terms of the variety of relevant factors to be taken into account. This, together with the more restrictive computer resources available in the phase of the work carried out at the Cranfield Institute of Technology, dictated that job sample size must be kept manageably small. However, rather than representing a limitation on the results and their validity that can be achieved, this led to an exploration of the positive steps which can be taken to improve the "efficiency" of computer usage in simulation studies, and to measure the significance of the results. The procedure adopted was as follows :

(a) to avoid the initial period in which the queue is allowed to build up the system is "preloaded" with the required queue level.

(b) the short run length subsequently used will inevitably be greatly affected by random variability in the job sample used. Therefore, firstly, each experiment is conducted with 4 independent job samples. Secondly, a statistical ranking test is applied to assess the consistency of the relative merits of various courses of action.

The advantage of using the pseudo-random number generator is that with a particular seed, an identical set of jobs is generated for each run. Therefore, for each experimental condition tested the same workload is injected on each occasion.

One question that remains relates to the matter of transient behaviour. It must be acknowledged that the system performance measures are taken in a non-steady-state condition. But reflecting on the actual job-shop environment, which is in reality in a perpetual transient state, the results are deemed to be more realistically representative of the practical situation.

Preliminary experiments conducted indicated that using a job intake arrangement of 18 jobs on the first period and 9 jobs per period on subsequent periods provides a satisfactory queue level and machine utilisation. Using a simulation run length of 13 days provided results which satisfy the statistical ranking tests and are comparable with the findings of other simulation studies.

APPENDIX 5.1.1 : Results from Experiment 1(a)

| Priority Rule | Due Date Assignment Type (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| (a) Throughput times (hr.) | | | | | |
| FCFS | 20.77 | 20.77 | 20.77 | 19.85 | 20.08 |
| DDATE | 16.41 | 15.61 | 15.69 | 15.72 | 14.96 |
| SLACK(1) | 18.97 | 17.47 | 17.35 | 16.76 | 16.06 |
| SPT | 14.02 | 14.02 | 14.02 | 15.09 | 15.09 |
| SLACK(1)/SPT | 17.04 | 15.88 | 15.17 | 15.99 | 15.27 |
| S(1)/SET/SPT | 17.13 | 16.00 | 15.57 | 14.94 | 15.91 |
| (b) Mean lateness (hr.) | | | | | |
| FCFS | 5.01 | - 0.36 | - 6.60 | 1.83 | - 2.86 |
| DDATE | 0.25 | - 6.02 | -11.70 | - 2.61 | - 7.77 |
| SLACK(1) | 2.94 | - 4.22 | - 9.97 | - 1.67 | - 6.94 |
| SPT | - 2.17 | - 8.15 | -14.13 | - 3.72 | - 8.52 |
| SLACK(1)/SPT | 1.13 | - 6.30 | -12.78 | - 2.52 | - 7.77 |
| S(1)/SET/SPT | 1.11 | - 6.07 | -12.94 | - 3.59 | - 7.81 |
| (c) Std.dev. of lateness (hr.) | | | | | |
| FCFS | 7.79 | 7.67 | 7.68 | 8.19 | 9.09 |
| DDATE | 4.33 | 3.60 | 4.98 | 4.10 | 4.36 |
| SLACK(1) | 4.72 | 3.86 | 4.14 | 3.83 | 3.33 |
| SPT | 7.08 | 7.81 | 9.28 | 6.99 | 7.88 |
| SLACK(1)/SPT | 4.32 | 6.39 | 8.10 | 4.03 | 6.75 |
| S(1)/SET/SPT | 4.62 | 5.40 | 7.43 | 3.91 | 6.32 |
| (d) Work content remaining (hr.) | | | | | |
| FCFS | 75.20 | 75.20 | 75.20 | 71.90 | 67.15 |
| DDATE | 90.72 | 80.72 | 87.28 | 85.43 | 83.17 |
| SLACK(1) | 83.25 | 80.83 | 80.18 | 72.57 | 74.77 |
| SPT | 53.70 | 53.70 | 53.70 | 49.88 | 49.88 |
| SLACK(1)/SPT | 69.45 | 59.75 | 64.43 | 64.47 | 58.85 |
| S(1)/SET/SPT | 77.78 | 53.85 | 39.92 | 52.13 | 44.88 |

| Priority Rule | Due Date Assignment Type | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| (e) Machine utilisation(%) | | | | | |
| FCFS | 86.50 | 86.50 | 86.50 | 87.00 | 87.10 |
| DDATE | 85.00 | 84.90 | 84.40 | 84.50 | 85.00 |
| SLACK(1) | 85.20 | 85.60 | 85.20 | 86.80 | 86.70 |
| SPT | 89.50 | 89.50 | 89.50 | 89.70 | 89.70 |
| SLACK(1)/SPT | 86.50 | 88.20 | 88.50 | 87.50 | 88.30 |
| S(1)/SET/SPT | 84.20 | 84.90 | 85.90 | 86.50 | 86.20 |
| (f) Set/run time ratio | | | | | |
| FCFS | 0.319 | 0.319 | 0.319 | 0.319 | 0.314 |
| DDATE | 0.316 | 0.310 | 0.313 | 0.314 | 0.317 |
| SLACK(1) | 0.317 | 0.315 | 0.309 | 0.326 | 0.320 |
| SPT | 0.322 | 0.322 | 0.322 | 0.323 | 0.323 |
| SLACK(1)/SPT | 0.311 | 0.312 | 0.327 | 0.322 | 0.314 |
| S(1)/SET/SPT | 0.295 | 0.243 | 0.231 | 0.268 | 0.255 |
| (g) Average queue time (hr.) | | | | | |
| FCFS | 2.95 | 2.95 | 2.95 | 2.75 | 2.77 |
| DDATE | 2.15 | 2.08 | 2.10 | 2.00 | 1.92 |
| SLACK(1) | 2.52 | 2.37 | 2.37 | 2.12 | 2.02 |
| SPT | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 |
| SLACK(1)/SPT | 2.27 | 1.93 | 1.87 | 1.98 | 1.83 |
| S(1)/SET/SPT | 2.27 | 2.02 | 1.82 | 1.77 | 1.85 |
| (h) Percentage of jobs tardy | | | | | |
| FCFS | 74.20 | 43.30 | 17.50 | 55.60 | 38.80 |
| DDATE | 50.00 | 1.90 | 0 | 23.10 | 2.80 |
| SLACK(1) | 75.50 | 14.60 | 0 | 34.60 | 0 |
| SPT | 27.30 | 14.50 | 4.50 | 22.30 | 8.00 |
| SLACK(1)/SPT | 61.20 | 12.30 | 0.90 | 28.70 | 0.90 |
| S(1)/SET/SPT | 59.80 | 5.60 | 0 | 6.30 | 2.70 |

| Priority Rule | Due Date Assignment Type (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| (i) Work content per remaining operation(min.) | | | | | |
| FCFS | 48.52 | 48.52 | 48.52 | 48.47 | 47.96 |
| DDATE | 49.48 | 45.26 | 48.04 | 55.12 | 55.44 |
| SLACK(1) | 47.57 | 49.49 | 46.26 | 55.11 | 55.38 |
| SPT | 57.54 | 57.54 | 57.54 | 62.35 | 62.35 |
| SLACK(1)/SPT | 51.44 | 47.17 | 55.23 | 50.89 | 60.88 |
| S(1)/SET/SPT | 48.61 | 52.97 | 53.22 | 61.33 | 56.10 |
| (j) Mean lateness - standardized(hr.) | | | | | |
| FCFS | -0.99 | -0.36 | -0.60 | -1.77 | -1.66 |
| DDATE | -5.75 | -6.02 | -5.70 | -6.21 | -6.57 |
| SLACK(1) | -3.06 | -4.22 | -3.97 | -5.27 | -5.74 |
| SPT | -8.17 | -8.15 | -8.13 | -7.32 | -7.32 |
| SLACK(1)/SPT | -4.87 | -6.30 | -6.78 | -6.12 | -6.57 |
| S(1)/SET/SPT | -4.89 | -6.07 | -6.94 | -7.19 | -6.61 |

APPENDIX 5.1.2 : Analysis of Results from Experiment 1(a)

(A) Priority Rule : SLACK(1)/SPT

(a) Throughput time (hr.)

(i) Two-way layout distribution-free test

| Sample | Due Date Assignment Type (1) | (2) | (3) |
|---|---|---|---|
| 1 | 17.04(3) | 15.88(2) | 15.17(1) |
| 2 | 14.85(3) | 13.05(2) | 12.57(1) |
| 3 | 18.21(3) | 17.19(2) | 15.47(1) |
| 4 | 20.77(3) | 18.10(2) | 15.28(1) |
| | 17.72(12) | 16.06(8) | 14.62(4) |

Friedman's Statistic $$S \doteq \left[ \frac{12}{nk(k+1)} \sum_{j=1}^{k} Rj^2 \right] - 3n(k+1)$$

where n = number of samples = 4

k = number of due date types = 3

$R_1$ = 12, $R_2$ = 8 and $R_3$ = 4

$$\therefore \quad S = \frac{12}{4x3x4}\left[12^2 + 8^2 + 4^2\right] - 3 \times 4 \times 4$$

$$= 8$$

For S = 8, the ALPHA level of significance that $H_o$ be rejected is 0.005

(ii) Analysis of variance
(Two-way classification, one observation per combination)

| | Due Date Assignment Type | | | |
|---|---|---|---|---|
| Sample | (1) | (2) | (3) | Total($R_i$) |
| 1 | 17.04 | 15.88 | 15.17 | 48.09 |
| 2 | 14.85 | 13.05 | 12.57 | 40.47 |
| 3 | 18.21 | 17.19 | 15.47 | 50.87 |
| 4 | 20.77 | 18.10 | 15.28 | 54.15 |
| Total($C_j$) | 70.87 | 64.22 | 58.49 | 193.58 |

(1) $R_1$ = 48.09, $R_2$ = 40.47, $R_3$ = 50.87, $R_4$ = 54.15

(2) $C_i$ = 70.87, $C_2$ = 64.22, $C_3$ = 58.49

(3) T = 193.58

(4) $\sum_{i=1}^{r} \sum_{j=1}^{c} X_{ij}^2 = 3180.40$

(5) $\sum_{i=1}^{r} \frac{R_i^2}{c} = 3156.82$

(6) $\sum_{j=1}^{c} \frac{C_j^2}{r} = 3141.96$

(7) $T^2/rc = 3122.77$

(8) $SS_4$ = (6) - (7) = 19.19

(9) $SS_3$ = (5) - (7) = 34.05

(10) SS = (4) - (7) = 57.63

(11) $SS_2$ = (10) - (9) - (8) = 4.39

| Source | Sum of Squares | Degrees of freedom | Mean Square | Test |
|---|---|---|---|---|
| Between due date assignment types | 19.19 | 2 | 9.60 | 13.12 |
| Between samples | 34.05 | 3 | 11.35 | 15.52 |
| Residual | 4.39 | 6 | 0.73 | |
| Total | 57.63 | 11 | | |

Test of hypothesis on due date assignment types :

$F_{0.05,2,6}$ = 5.14 < 13.12. ∴. Null hypothesis is rejected.

Test of hypothesis on samples :

$F_{0.05,3,6}$ = 4.76 < 15.52. ∴. Null hypothesis is rejected.

(b) Mean lateness - standardized (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | -4.87(3) | -6.30(2) | -6.78(1) |
| 2 | -6.92(3) | -8.66(2) | -8.81(1) |
| 3 | -3.46(3) | -4.22(2) | -5.54(1) |
| 4 | -1.11(3) | -3.58(2) | -5.65(1) |
| | -4.09(12) | -5.69(8) | -6.70(4) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 13.81 | 2 | 6.90 | 14.18 |
| Between samples | 37.69 | 3 | 12.56 | 25.80 |
| Residual | 2.92 | 6 | 0.49 | |
| Total | 54.52 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 14.18$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 25.80$.

$\therefore$ Null hypothesis is rejected.

(c) Std. dev. of lateness (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 4.32(1) | 6.39(2) | 8.10(3) |
| 2 | 3.93(1) | 5.73(2) | 7.60(3) |
| 3 | 3.86(1) | 5.26(2) | 8.91(3) |
| 4 | 6.36(2) | 6.05(1) | 8.75(3) |
| | 4.62(5) | 5.86(7) | 8.34(12) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between D-d types | 29.80 | 2 | 14.90 | 18.22 |
| Between samples | 1.48 | 3 | 0.49 | 0.60 |
| Residual | 4.91 | 6 | 0.82 | |
| Total | 36.18 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 18.22$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 > 0.60$.

$\therefore$ Null hypothesis is accepted.

(d) Work content remaining (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 69.45(3) | 59.75(1) | 64.43(2) |
| 2 | 60.43(3) | 46.28(2) | 41.57(1) |
| 3 | 74.98(3) | 72.15(2) | 64.12(1) |

| | | | |
|---|---|---|---|
| 4 | 79.00(3) | 64.18(2) | 55.58(1) |
| | 70.97(12) | 60.60(7) | 56.43(5) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 448.53 | 2 | 224.27 | 9.94 |
| Between samples | 755.24 | 3 | 251.75 | 11.16 |
| Residual | 135.41 | 6 | 22.57 | |
| Total | 1339.18 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 9.94$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4,76 < 11.16$.

$\therefore$ Null hypothesis is rejected.

(e) Machine utilisation(%)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 86.5(3) | 88.2(2) | 88.5(1) |
| 2 | 85.2(3) | 87.5(2) | 87.9(1) |
| 3 | 82.4(2.5) | 82.4(2.5) | 83.7(1) |
| 4 | 83.1(3) | 83.7(2) | 86.8(1) |
| | 84.3(11.5) | 85.5(8.5) | 86.73(4) |

As there is a tie in sample 3 an alternative method is required to calculate the Friedman's statistic.

$$S' = \frac{12 \sum_{j=1}^{k} (R_j - nR..)^2}{nk(k+1) - [1/(k-1)] \sum_{i=1}^{n} \left\{ \left( \sum_{j=1}^{g_i} t^3_{i,j} \right) - k \right\}}$$

where n, k and $R_j$ are as defined before

$R_{..}$ = (k+1)/2 = 2

i = 3 (i.e. tie at sample 3)

$g_3$ = no.of groups in sample 3 = 2

$t_{3,1}$ = no.of members in group 1 = 2

$t_{3,2}$ = no.of members in group 2 = 1

$$\sum_{j=1}^{2} (2^3 + 1^3) - 3 = 6$$

$$\therefore S' = \frac{12[ (11.5-8)^2 + (8.5 -8)^2 + (4-8)^2 ]}{48 - 1/2 \times 6}$$

$$= 7.6$$

For S' = 7.6, the ALPHA level of significance that $H_o$ be rejected is 0.015.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 11.77 | 2 | 5.89 | 9.26 |
| Between samples | 44.70 | 3 | 14.90 | 23.44 |
| Residual | 3.82 | 6 | 0.64 | |
| Total | 60.29 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 9.26$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 23.44$.

$\therefore$ Null hypothesis is rejected.

(f) Set/run time ratio

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 0.311(1) | 0.312(2) | 0.327(3) |
| 2 | 0.311(2) | 0.322(3) | 0.318(2) |
| 3 | 0.306(2) | 0.296(1) | 0.310(3) |
| 4 | 0.307(3) | 0.301(1.5) | 0.301(1.5) |
| | 0.309(7) | 0.308(7.5) | 0.314(9.5) |

For S' = 0.93, the ALPHA level of significance that $H_o$ be rejected is 0.811.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 0.0000902 | 2 | 0.0000451 | 1.04 |
| Between samples | 0.0005350 | 3 | 0.0001783 | 4.11 |
| Residual | 0.0002605 | 6 | 0.0000434 | |
| Total | 0.0008857 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 > 1.04$.

∴. Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 > 4.11$.

∴. Null hypothesis is accepted.

(g) Average queue time (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 2.27(3) | 1.93(2) | 1.87(1) |
| 2 | 1.75(3) | 1.40(2) | 1.32(1) |
| 3 | 2.17(3) | 2.00(2) | 1.75(1) |
| 4 | 2.65(3) | 2.22(2) | 1.82(1) |
| | 2.21(12) | 1.89(8) | 1.69(4) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 0.551 | 2 | 0.276 | 20.59 |
| Between samples | 0.883 | 3 | 0.294 | 21.98 |
| Residual | 0.080 | 6 | 0.013 | |
| Total | 1.514 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 20.59$.

∴. Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 21.98$.

∴ Null hypothesis is rejected.

(h) Work content per remaining operation(min.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 51.44(2) | 47.17(1) | 55.23(3) |
| 2 | 49.67(1) | 56.67(2) | 56.68(3) |
| 3 | 43.68(1) | 57.72(2) | 66.33(3) |
| 4 | 44.30(1) | 55.01(2) | 57.50(3) |
| | 47.27(5) | 54.14(7) | 58.94(12) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 273.81 | 2 | 136.91 | 5.45 |
| Between samples | 38.66 | 3 | 12.89 | 0.51 |
| Residual | 150.77 | 6 | 25.13 | |
| Total | 463.24 | 11 | | |

Due Date assignment types : $F_{0.05,2,6} = 5.14 < 5.45$.

∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 > 0.51$.

∴ Null hypothesis is accepted.

(B) Priority Rule : S(1)/SET/SPT

(a) Throughput time (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 17.13(3) | 16.00(2) | 15.57(1) |
| 2 | 13.95(3) | 12.58(2) | 12.24(1) |
| 3 | 17.04(3) | 14.02(2) | 13.33(1) |
| 4 | 20.22(3) | 15.63(2) | 14.71(1) |
| | 17.09(12) | 14.56(8) | 13.96(4) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected, is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 21.99 | 2 | 11.00 | 10.71 |
| Between samples | 27.44 | 3 | 9.15 | 8.91 |
| Residual | 6.16 | 6 | 1.03 | |
| Total | 55.59 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 10.71$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 8.91$.

$\therefore$ Null hypothesis is rejected.

(b) Mean lateness-standardized (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | -4.89(3) | -6.07(2) | -6.94(1) |
| 2 | -7.77(3) | -9.41(2) | -9.82(1) |
| 3 | -4.48(3) | -7.61(2) | -8.18(1) |
| 4 | -1.70(3) | -6.02(2) | -7.29(1) |
| | -4.71(12) | -7.28(8) | -8.06(4) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 24.54 | 2 | 12.27 | 14.61 |
| Between samples | 26.13 | 3 | 8.71 | 10.37 |
| Residual | 5.04 | 6 | 0.84 | |
| Total | 55.71 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 14.61$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 10.37$.

$\therefore$ Null hypothesis is rejected.

(c) Std. dev. of lateness (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 4.62(1) | 5.40(2) | 7.43(3) |
| 2 | 3.99(1) | 5.65(2) | 8.12(3) |
| 3 | 3.65(1) | 5.45(2) | 8.51(3) |
| 4 | 5.90(2) | 5.69(1) | 8.51(3) |
| | 4.54(5) | 5.55(7) | 8.14(12) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 27.64 | 2 | 13.82 | 37.33 |
| Between samples | 1.57 | 3 | 0.52 | 1.41 |
| Residual | 2.22 | 6 | 0.37 | |
| Total | 31.43 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 37.33$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 > 1.41$.

$\therefore$ Null hypothesis is accepted.

(d) Work content remaining (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 77.78(3) | 53.85(2) | 39.92(1) |
| 2 | 43.07(3) | 37.92(2) | 32.17(1) |
| 3 | 73.58(3) | 45.68(1) | 46.83(2) |
| 4 | 75.92(3) | 37.20(2) | 25.25(1) |
| | 67.58(12) | 43.67(7) | 36.04(5) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 2167.41 | 2 | 1083.71 | 12.34 |
| Between samples | 728.80 | 3 | 242.94 | 2.77 |
| Residual | 527.01 | 6 | 87.84 | |
| Total | 3423.22 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 12.34$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 > 2.77$.

$\therefore$ Null hypothesis is accepted.

(e) Machine utilisation (%)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 84.2(3) | 84.9(2) | 85.9(1) |
| 2 | 83.2(3) | 83.8(2) | 85.0(1) |
| 3 | 81.6(3) | 83.7(1) | 83.2(2) |
| 4 | 81.8(3) | 85.4(2) | 86.1(1) |
| | 82.7(12) | 84.5(7) | 85.1(5) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 11.93 | 2 | 5.96 | 8.39 |
| Between samples | 7.59 | 3 | 2.53 | 3.56 |
| Residual | 4.27 | 6 | 0.71 | |
| Total | 23.79 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 8.39$.

$\therefore$ Null hypothesis is rejected.

Samples $F_{0.05,3,6} = 4.76 > 3.56$.

$\therefore$ Null hypothesis is accepted.

(f) Set/run time ratio

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 0.295(3) | 0.243(2) | 0.231(1) |
| 2 | 0.270(3) | 0.251(1) | 0.252(2) |
| 3 | 0.287(3) | 0.241(1) | 0.245(2) |
| 4 | 0.286(3) | 0.250(2) | 0.232(1) |
| | 0.285(12) | 0.246(6) | 0.240(6) |

For S = 6.0, the ALPHA level of significance that $H_o$ be rejected is 0.069.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 0.0046432 | 2 | 0.0023216 | 19.60 |
| Between samples | 0.0000069 | 3 | 0.0000023 | 0.02 |
| Residual | 0.0007108 | 6 | 0.0001185 | |
| Total | 0.0053609 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 19.61$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 > 0.02$.

$\therefore$ Null hypothesis is accepted.

(g) Average queue time (hr.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 2.27(3) | 2.02(2) | 1.82(1) |
| 2 | 1.60(3) | 1.33(2) | 1.25(1) |
| 3 | 2.02(3) | 1.53(2) | 1.43(1) |
| 4 | 2.55(3) | 1.78(2) | 1.60(1) |
| | 2.11(12) | 1.67(8) | 1.53(4) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 0.746 | 2 | 0.373 | 17.08 |
| Between samples | 0.803 | 3 | 0.268 | 12.25 |
| Residual | 0.131 | 6 | 0.022 | |
| Total | 1.681 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 17.08$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 12.25$.

$\therefore$ Null hypothesis is rejected.

(h) Work content per remaining operation(min.)

(i) Two-way layout distribution-free test

| | Due Date Assignment Type | | |
|---|---|---|---|
| Sample | (1) | (2) | (3) |
| 1 | 48.61(1) | 52.97(2) | 53.22(3) |
| 2 | 49.30(1) | 56.88(2) | 64.23(3) |
| 3 | 45.99(1) | 62.30(2) | 62.44(3) |
| 4 | 42.18(1) | 44.64(2) | 52.24(3) |
| | 46.52(4) | 54.20(8) | 58.03(12) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between d-d types | 274.92 | 2 | 137.46 | 9.83 |
| Between samples | 227.59 | 3 | 75.86 | 5.43 |
| Residual | 83.87 | 6 | 13.98 | |
| Total | 586.38 | 11 | | |

Due date assignment types : $F_{0.05,2,6} = 5.14 < 9.83$.

$\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 5.43$.

$\therefore$ Null hypothesis is rejected.

APPENDIX 5.1.3 : Analysis of Results from Experiment I(b)

(a) Throughput time (hr.)

(i) Two-way layout distribution-free test

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Samples | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 20.77(6) | 15.61(2) | 17.47(5) | 14.02(1) | 15.88(3) | 16.00(4) |
| 2 | 17.88(6) | 15.72(5) | 15.42(4) | 13.12(3) | 13.05(2) | 12.58(1) |
| 3 | 18.88(6) | 15.39(3) | 17.90(5) | 13.05(1) | 17.19(4) | 14.02(2) |
| 4 | 21.19(6) | 19.00(4) | 20.62(5) | 16.03(2) | 18.10(3) | 15.63(1) |
| | 19.68(24) | 16.43(14) | 17.85(19) | 14.06(7) | 16.06(12) | 14.56(8) |

Excluding FCFS from the analysis, Friedman's S statistic = 9.4.

For S = 9.4, the ALPHA level of significance that $H_o$ be rejected is 0.035.

(ii) Analysis of variance

| Source | Sum of Squares | Degrees of Freedom | Mean Square | Test |
|---|---|---|---|---|
| Between rules | 87.49 | 5 | 17.50 | 19.81 |
| Between samples | 44.43 | 3 | 14.81 | 16.77 |
| Residual | 13.25 | 15 | 0.88 | |
| Total | 145.17 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 19.81$. $\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 16.77$.. $\therefore$ Null hypothesis is rejected.

(b) Mean lateness (hr.)

(i) Two-way layout distribution-free test

| Samples | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | -0.36(6) | -6.02(4) | -4.22(5) | 8.15(1) | -6.30(2) | -6.07(3) |
| 2 | -3.52(6) | -5.74(5) | -6.13(4) | -8.79(2) | -8.66(3) | -9.41(1) |
| 3 | -2.13(6) | -5.79(3) | -3.37(5) | -8.45(1) | -4.22(4) | -7.61(2) |
| 4 | 0.24(6) | -2.32(4) | -0.99(5) | -5.59(2) | -3.58(3) | -6.02(1) |
| | -1.44(24) | -4.97(16) | -3.68(19) | -7.75(6) | -5.69(12) | -7.28(7) |

Excluding FCFS from the analysis, Friedman's S statistic = 12.6.

For S = 12.6, the ALPHA level of significance that $H_o$ be rejected is 0.002.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 109.99 | 5 | 22.00 | 24.38 |
| Between samples | 48.18 | 3 | 16.06 | 17.80 |
| Residual | 13.53 | 15 | 0.90 | |
| Total | 171.70 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 24.38..$. Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 17.80..$. Null hypothesis is rejected.

(c) Std. dev. of lateness (hr.)

(i) Two-way layout distribution-free test

| Samples | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 7.67(5) | 3.60(1) | 3.86(2) | 7.81(6) | 6.39(4) | 5.40(3) |
| 2 | 5.44(3) | 4.91(2) | 3.58(1) | 7.77(6) | 5.73(5) | 5.65(4) |
| 3 | 6.39(5) | 4.05(2) | 3.98(1) | 10.70(6) | 5.26(3) | 5.45(4) |
| 4 | 8.73(5) | 7.21(4) | 5.04(1) | 10.85(6) | 6.05(3) | 5.69(2) |
| | 7.06(18) | 4.94(9) | 4.12(5) | 9.28(24) | 5.86(15) | 5.55(13) |

Excluding SPT from the analysis, Friedman's S statistic = 10.4.

For S = 10.4, the ALPHA level of significance that $H_o$ be rejected is 0.017.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 66.73 | 5 | 13.35 | 14.24 |
| Between samples | 10.82 | 3 | 3.61 | 3.85 |
| Residual | 14.06 | 15 | 0.94 | |
| Total | 91.61 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 14.24$ ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 3.85$ ∴ Null hypothesis is rejected.

(d) Work content remaining (hr.)

(i) Two-way layout distribution-free test

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Samples | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 75.20(4) | 80.72(5) | 80.83(6) | 53.70(1) | 59.75(3) | 53.85(2) |
| 2 | 62.73(4) | 84.48(6) | 65.47(5) | 42.57(2) | 46.28(3) | 37.92(1) |
| 3 | 68.77(3) | 78.23(6) | 77.67(5) | 53.72(2) | 72.15(4) | 45.68(1) |
| 4 | 76.63(4) | 85.47(6) | 79.50(5) | 45.38(2) | 64.18(3) | 37.20(1) |
| | 70.83(15) | 82.23(23) | 75.87(21) | 48.85(7) | 60.60(13) | 43.67(5) |

For S = 18.71, the ALPHA level of significance that $H_o$ be rejected is 0.006.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 4698.1 | 5 | 939.6 | 27.44 |
| Between samples | 423.2 | 3 | 141.1 | 4.12 |
| Residual | 513.7 | 15 | 34.2 | |
| Total | 5635.0 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 27.44$ .·. Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 4.12$ .·. Null hypothesis is rejected.

(e) Utilisation (%)

(i) Two-way layout distribution-free test

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Sample | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 86.5(2) | 84.9(4.5) | 85.6(3) | 89.5 | 88.2(1) | 84.9(4.5) |
| 2 | 84.8(2) | 81.5(5) | 84.0(3) | 87.8 | 87.5(1) | 83.8(4) |
| 3 | 83.5(2) | 81.6(5) | 81.8(4) | 85.5 | 82.4(3) | 83.7(1) |
| 4 | 83.8(3) | 82.2(4) | 81.6(5) | 88.0 | 84.8(2) | 85.4(1) |
| | 84.7(9) | 82.6(18.5) | 83.3(15) | 87.7 | 85.7(7) | 84.5(10.5) |

Excluding SPT from the analysis, Friedman's S' statistics = 8.86.
For S' = 8.86, the ALPHA level of significance that $H_o$ be rejected is 0.047.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 28.60 | 5 | 5.72 | 1.06 |
| Between samples | 13.45 | 3 | 4.48 | 0.83 |
| Residual | 81.06 | 15 | 5.40 | |
| Total | 123.11 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 > 1.06$. .·. Null hypothesis is accepted.

Samples : $F_{0.05,3,15} = 3.29 > 0.83$. .·. Null hypothesis is accepted.

(f) Set/run time ratio

(i) Two-way layout distribution-free test

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Sample | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 0.319(4) | 0.310(1) | 0.315(3) | 0.322(5) | 0.312(2) | 0.243 |
| 2 | 0.322(4.5) | 0.314(1) | 0.317(3) | 0.315(2) | 0.322(4.5) | 0.251 |
| 3 | 0.311(5) | 0.301(3) | 0.306(4) | 0.290(1) | 0.296(2) | 0.242 |
| 4 | 0.313(4) | 0.317(5) | 0.285(1) | 0.309(3) | 0.301(2) | 0.250 |
| | 0.316(17.5) | 0.311(10) | 0.306(11) | 0.309(11) | 0.308(10.5) | 0.247 |

Excluding S(1)/SET/SPT from the analysis, Friedman's S'statistic=3.9. For S' = 3.9, the ALPHA level of significance that $H_o$ be rejected is 0.461.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 0.0002533 | 4 | 0.0000633 | 0.94 |
| Between samples | 0.0010246 | 3 | 0.0003415 | 5.04 |
| Residual | 0.0008127 | 12 | 0.0000677 | |
| Total | 0.0020906 | 19 | | |

Rules : $F_{0.05,4,12} = 3.26 > 0.94$. ∴ Null hypothesis is accepted.

Samples : $F_{0.05,3,12} = 3.49 < 5.04$. ∴ Null hypothesis is rejected.

(g) Average queue time (hr.)

(i) Two-way layout distribution-free test

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Sample | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 2.95(6) | 2.08(4) | 2.37(5) | 1.67(1) | 1.93(2) | 2.02(3) |
| 2 | 2.28(6) | 2.00(5) | 1.87(4) | 1.38(1) | 1.40(3) | 1.33(2) |
| 3 | 2.40(6) | 1.82(3) | 2.18(5) | 1.42(1) | 2.00(4) | 1.53(2) |
| 4 | 2.88(6) | 2/47(4) | 2.68(5) | 1.85(2) | 2.22(3) | 1.78(1) |
| | 2.63(24) | 2.09(16) | 2.28(19) | 1.58(5) | 1.89(12) | 1.67(8) |

Excluding FCFS from the analysis, Friedman's S statistic = 13.0
For S = 13.0, the ALPHA level of significance that $H_o$ be rejected is 0.001.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 3.106 | 5 | 0.621 | 25.59 |
| Between samples | 1.327 | 3 | 0.442 | 18.21 |
| Residual | 0.365 | 15 | 0.024 | |
| Total | 4.797 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 25.59$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 18.21$. ∴ Null hypothesis is rejected.

(h) Work content per job remaining (min.)

(i) Two-way layout distribution-free test

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Sample | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 155.6(1) | 254.9(6) | 210.9(5) | 201.4(4) | 179.3(3) | 170.1(2) |
| 2 | 198.1(3) | 281.6(6) | 231.1(5) | 196.5(2) | 213.6(4) | 189.6(1) |
| 3 | 187.5(1) | 293.4(6) | 245.3(4) | 293.0(5) | 216.5(2) | 228.4(3) |
| 4 | 176.8(1) | 284.9(6) | 265.0(5) | 209.5(3) | 256.7(4) | 202.9(2) |
| | 179.5(6) | 278.7(24) | 238.1(19) | 225.1(14) | 216.5(13) | 197.8(8) |

Excluding DDATE from the analysis, Friedman's S statistic = 10.6.
For S = 10.6, the ALPHA level of significance that $H_o$ be rejected is 0.014.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 23619.9 | 5 | 4724.0 | 10.89 |
| Between samples | 7911.0 | 3 | 2637.0 | 6.08 |
| Residual | 6509.8 | 15 | 434.0 | |
| Total | 38040.6 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 10.89$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 6.08$. ∴ Null hypothesis is rejected.

(i) Work content per remaining operation (min.)

(i) Two-way layout distribution-free test.

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Samples | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 48.52(3) | 45.26(1) | 49.49(4) | 57.54(6) | 47.17(2) | 52.97(5) |
| 2 | 47.05(2) | 46.50(1) | 49.72(3) | 58.05(6) | 56.67(4) | 56.88(5) |
| 3 | 58.94(4) | 56.55(2) | 53.56(1) | 71.62(6) | 57.72(3) | 62.30(5) |
| 4 | 49.98(1) | 51.28(2) | 51.29(3) | 57.94(6) | 55.01(4) | 55.80(5) |
| | 51.12(10) | 49.90(6) | 51.02(11) | 61.29(24) | 54.14(13) | 56.99(20) |

Excluding SPT from the analysis, Friedman's S statistic = 10.6.

For S = 10.6, the ALPHA level of significance that $H_o$ be rejected is 0.014.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 384.16 | 5 | 76.83 | 11.03 |
| Between samples | 327.88 | 3 | 109.29 | 15.69 |
| Residual | 104.50 | 15 | 6.97 | |
| Total | 816.54 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 11.03$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 15.69$. ∴ Null hypothesis is rejected.

(j) Operations/Jobs completed ratio

(i) Two-way layout distribution-free test

| | Despatching Rules | | | | | |
|---|---|---|---|---|---|---|
| Sample | FCFS | DDATE | SLACK(1) | SPT | SLACK(1)/ SPT | S(1)/SET/ SPT |
| 1 | 7.03(1) | 6.24(6) | 6.57(4) | 6.54(5) | 6.59(3) | 6.67(2) |
| 2 | 6.45(1) | 6.12(6) | 6.34(5) | 6.42(2) | 6.38(4) | 6.40(3) |
| 3 | 6.56(1) | 6.08(6) | 6.21(3.5) | 6.15(5) | 6.39(2) | 6.21(3.5) |
| 4 | 6.67(1) | 6.10(6) | 6.17(5) | 6.30(2) | 6.21(4) | 6.25(3) |
| | 6.68(4) | 6.14(24) | 6.32(17.5) | 6.35(14) | 6.39(13) | 6.38(11.5) |

Excluding DDATE from the analysis, Friedman's S'statistic = 10.08.
For S' = 10.08, the ALPHA level of significance that $H_o$ be rejected is 0.020.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between rules | 0.611 | 5 | 0.122 | 12.81 |
| Between samples | 0.446 | 3 | 0.149 | 15.59 |
| Residual | 0.143 | 15 | 0.010 | |
| Total | 1.200 | 23 | | |

Rules : $F_{0.05,5,15} = 2.90 < 12.81$. $\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,15} = 3.29 < 15.59$. $\therefore$ Null hypothesis is rejected.

## Appendix 5.2.1 : Analysis of Results for Experiment 2

(A) Scheduling Rule : SLACK(1)/SPT

(a) Throughput times (hr.)

(i) Two-way layout distribution-free test

| | Process Time Distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | 15.88(3) | 14.01(1) | 15.20(2) |
| 2 | 13.05(1) | 13.62(3) | 13.18(2) |
| 3 | 17.19(3) | 15.25(2) | 14.84(1) |
| 4 | 18.10(3) | 16.71(1) | 16.72(2) |
| | 16.06(10) | 14.90(7) | 14.99(7) |

For S = 1.5, the ALPHA level of significance that $H_o$ be rejected is 0.653.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 3.33 | 2 | 1.67 | 3.27 |
| Between samples | 23.62 | 3 | 7.87 | 15.43 |
| Residual | 3.07 | 6 | 0.51 | |
| Total | 30.02 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 > 3.27$. $\therefore$ Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 < 15.43$. $\therefore$ Null hypothesis is rejected.

(b) Mean lateness (hr.)

(i) Distribution-free test.

| | Process Time Distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | -6.30(3) | -8.09(1) | -6.81(2) |
| 2 | -8.66(1) | -8.30(3) | -8.38(2) |
| 3 | -4.22(3) | -6.14(2) | -6.42(1) |
| 4 | -3.58(3) | -4.85(1) | -4.81(2) |
| | -5.69(10) | -6.85(7) | -6.61(7) |

For S = 1.5, the ALPHA level of significance that $H_o$ be rejected is 0.653.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 2.97 | 2 | 1.49 | 3.31 |
| Between samples | 27.69 | 3 | 9.23 | 20.51 |
| Residual | 2.71 | 6 | 0.45 | |
| Total | 33.37 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 > 3.31$. ∴. Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 < 20.51$.. ∴. Null hypothesis is rejected.

(c) Standard deviation of lateness (hr.)

(i) Distribution-free test

| | Process Time Distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | 6.39(3) | 5.69(2) | 5.65(1) |
| 2 | 5.73(1) | 6.12(3) | 5.92(2) |
| 3 | 5.26(1) | 5.96(3) | 5.82(2) |
| 4 | 6.05(3) | 4.92(2) | 4.89(1) |
| | 5.86(8) | 5.67(10) | 5.57(6) |

For S = 2.0, the ALPHA level of significance that $H_o$ be rejected is 0.431.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 0.17 | 2 | 0.085 | 0.36 |
| Between samples | 0.80 | 3 | 0.267 | 1.15 |
| Residual | 1.40 | 6 | 0.233 | |
| Total | 2.37 | 11 | | |

Distributions : $F_{0,05,2,6} = 5.14 > 0.36$. ∴. Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 > 1.15$. ∴. Null hypothesis is accepted.

(d) Work content remaining (hr.)

(i) Distribution-free test

| | Process Time Distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | 59.75(3) | 32.47(1) | 38.73(2) |
| 2 | 46.28(2) | 46.05(1) | 56.77(3) |
| 3 | 72.15(3) | 38.43(1) | 38.97(2) |
| 4 | 64.18(3) | 40.43(1) | 44.70(2) |
| | 60.60(11) | 39.35(4) | 44.80(9) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 974.24 | 2 | 487.12 | 5.08 |
| Between samples | 84.42 | 3 | 28.14 | 0.29 |
| Residual | 575.84 | 6 | 95.97 | |
| Total | 1634.50 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 > 5.08$. ∴. Null hypothesis is accepted.

Samples : $F_{0.05,2,6} = 4.76 > 0.29$. ∴. Null hypothesis is accepted.

(e) Utilisation (%)

(i) Distribution-free test

| | Process Time Distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | 88.2(2) | 88.9(1) | 88.0(3) |
| 2 | 87.5(1) | 86.2(2) | 84.8(3) |
| 3 | 82.4(3) | 84.8(2) | 85.1(1) |
| 4 | 84.8(2) | 85.1(1) | 84.5(3) |
| | 85.7(8) | 86.3(6) | 85.6(10) |

For S = 2.0, the ALPHA level of significance that $H_o$ be rejected is 0.431.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 0.96 | 2 | 0.48 | 0.38 |
| Between samples | 31.81 | 3 | 10.60 | 8.28 |
| Residual | 7.69 | 6 | 1.28 | |
| Total | 40.46 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 > 0.38$. $\therefore$ Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 < 8.28$. $\therefore$ Null hypothesis is rejected.

(f) Set/run time ratio

(i) Distribution-free test

| | Process Time Distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | 0.312(3) | 0.291(1) | 0.303(2) |
| 2 | 0.322(3) | 0.287(1) | 0.299(2) |
| 3 | 0.296(3) | 0.285(1) | 0.295(2) |
| 4 | 0.301(3) | 0.279(1) | 0.286(2) |
| | 0.308(12) | 0.286(4) | 0.296(8) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 0.0009922 | 2 | 0.0004961 | 15.75 |
| Between samples | 0.0001892 | 3 | 0.0001498 | 4.76 |
| Residual | 0.0001892 | 6 | 0.0000315 | |
| Total | 0.0016307 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 15.75$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 = 4.76$. ∴ Null hypothesis is rejected.

(g) Average queue time (hr.)

(i) Distribution-free test

| | Process time distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | 1.93(3) | 1.53(1) | 1.77(2) |
| 2 | 1.40(1) | 1.48(3) | 1.43(2) |
| 3 | 2.00(3) | 1.63(2) | 1.62(1) |
| 4 | 2.22(3) | 1.97(1.5) | 1.97(1.5) |
| | 1.89(10) | 1.65(7.5) | 1.70(6.5) |

For S' = 1.73, the ALPHA level of significance that $H_o$ be rejected is 0.525.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 0.124 | 2 | 0.062 | 3.92 |
| Between samples | 0.570 | 3 | 0.190 | 11.97 |
| Residual | 0.095 | 6 | 0.0156 | |
| Total | 0.790 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 > 3.92$. ∴ Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 < 11.97$. ∴ Null hypothesis is rejected.

(B) Scheduling Rule : FCFS

(a) Throughput time (hr.)

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 20.77(3) | 17.39(1) | 18.06(2) |
| 2 | 17.88(3) | 15.69(1) | 16.87(2) |
| 3 | 18.88(3) | 17.74(2) | 16.78(1) |
| 4 | 21.19(3) | 19.21(1) | 20.72(2) |
| | 19.68(12) | 17.51(5) | 18.11(7) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | | | | |
|---|---|---|---|---|
| Between distributions | 10.07 | 2 | 5.04 | 9.78 |
| Between samples | 20.64 | 3 | 6.88 | 13.37 |
| Residual | 3.09 | 6 | 0.52 | |
| Total | 33.81 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 9.78$. ∴. Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 13.37$. ∴. Null hypothesis is rejected.

(b) Mean lateness (hr.)

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | -3.52 | -5.94(1) | -4.78(2) |
| 2 | -5.74(3) | -7.81(1) | -7.17(2) |
| 3 | -2.13(3) | -3.59(2) | -4.61(1) |
| 4 | 0.24(3) | -2.59(1) | -0.76(2) |
| | -2.79(12) | -4.98(5) | -4.33(7) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 10.16 | 2 | 5.08 | 13.62 |
| Between samples | 54.28 | 3 | 18.09 | 48.49 |
| Residual | 2.24 | 6 | 0.37 | |
| Total | 66.68 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 13.62$. ∴. Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 48.49$. ∴. Null hypothesis is rejected.

(c) Standard deviation of lateness (hr.)

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 7.67(3) | 4.75(1) | 5.02(2) |
| 2 | 5.44(3) | 4.67(2) | 4.37(1) |
| 3 | 6.39(3) | 5.71(2) | 5.47(1) |
| 4 | 8.73(3) | 5.49(2) | 5.44(1) |
| | 7.06(12) | 5.16(7) | 5.08(5) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 10.08 | 2 | 5.04 | 9.15 |
| Between samples | 4.54 | 3 | 1.51 | 2.75 |
| Residual | 3.31 | 6 | 0.55 | |
| Total | 17.92 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 9.15$. ∴. Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 > 2.75$. ∴. Null hypothesis is accepted.

(d) Work content remaining (hr.)

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 75.20(3) | 36.70(1) | 46.28(2) |
| 2 | 62.73(2) | 56.65(1) | 65.75(3) |
| 3 | 68.77(3) | 43.62(2) | 40.43(1) |
| 4 | 76.63(3) | 41.23(1) | 51.72(2) |
| | 70.83(11) | 44.55(5) | 51.05(8) |

For S = 4.5, the ALPHA level of significance that $H_o$ be rejected is 0.125.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 1499.41 | 2 | 749.70 | 9.18 |
| Between samples | 204.36 | 3 | 68.12 | 0.83 |
| Residual | 490.10 | 6 | 81.68 | |
| Total | 2193.87 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 9.18$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 > 0.83$. ∴ Null hypothesis is accepted.

(e) Utilisation (%)

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 86.5(3) | 88.1(1) | 87.7(2) |
| 2 | 84.8(1) | 84.7(2) | 83.5(3) |
| 3 | 83.5(3) | 84.3(2) | 85.0(1) |
| 4 | 83.8(2) | 84.9(1) | 83.3(3) |
| | 84.7(9) | 85.5(6) | 84.9(9) |

For S = 1.5, the ALPHA level of significance that $H_o$ be rejected is 0.653.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 1.55 | 2 | 0.78 | 1.39 |
| Between samples | 23.71 | 3 | 7.90 | 14.16 |
| Residual | 3.35 | 6 | 0.56 | |
| Total | 28.61 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 > 1.39$. ∴ Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 < 14.16$. ∴ Null hypothesis is rejected.

(f) Set/run time ratio

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 0.319(3) | 0.288(1) | 0.299(2) |
| 2 | 0.322(3) | 0.289(1) | 0.302(2) |
| 3 | 0.311(3) | 0.289(1) | 0.294(2) |
| 4 | 0.313(3) | 0.279(1) | 0.280(2) |
| | 0.316(12) | 0.286(4) | 0.294(8) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 0.0019500 | 2 | 0.0009750 | 52.42 |
| Between samples | 0.0003229 | 3 | 0.0001076 | 5.78 |
| Residual | 0.0001114 | 6 | 0.0000186 | |
| Total | 0.0023843 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 52.42$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 5.78$. ∴ Null hypothesis is rejected.

(g) Average queue time (hr.)

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 2.95(3) | 2.07(1) | 2.23(2) |
| 2 | 2.28(3) | 1.83(1) | 2.05(2) |
| 3 | 2.40(3) | 2.08(2) | 1.92(1) |
| 4 | 2.88(3) | 2.30(1) | 2/67(2) |
| | 2.63(12) | 2.07(5) | 2.22(7) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 0.67 | 2 | 0.33 | 12.13 |
| Between samples | 0.61 | 3 | 0.20 | 7.36 |
| Residual | 0.17 | 6 | 0.03 | |
| Total | 1.44 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 12.13$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 7.36$. ∴ Null hypothesis is rejected.

Appendix 5.2.2 : Test of Variance Between the Exponential and Normal Distributions

Equality of means test for paired observations.

(A) Scheduling Rule : SLACK(1)/SPT

(a) Throughput time

| Sample | Exponential | Normal | Difference($D_i$) |
|---|---|---|---|
| 1 | 15.88 | 14.01 | +1.87 |
| 2 | 13.05 | 13.62 | -0.57 |
| 3 | 17.19 | 15.25 | +1.94 |
| 4 | 18.10 | 16.71 | +1.39 |
| | | | +4.63 |

$$\bar{D} = \frac{\sum_{i=1}^{n} D_i}{n} = \frac{4.63}{4} = 1.1575$$

Estimate of the variance $$S_D = \sqrt{\frac{\sum_{i-1}^{n} (D_i - \bar{D})^2}{n-1}} = 1.177$$

Test statistic t $$= \frac{\bar{D}\sqrt{n}}{S} = \frac{1.1575 \times 2}{1.177} = 1.967$$

For 5% level of significance $t_{\alpha/2;n-1} = t_{0.025;3} = 3.182$

∴ Since $1.967 < 3.182$ the null hypothesis is accepted.

(b) Mean lateness

$\overline{D} = 1.155; \quad S_D = 1.048; \quad \therefore \quad t = 2.204$

Since $2.204 < 3.182$ the null hypothesis is accepted.

(c) Std.dev. of lateness

$\overline{D} = 0.185; \quad S_D = 0.870 \quad \therefore \quad t = 0.425$

Since $0.425 < 3.182$ the null hypothesis is accepted.

(d) Work content remaining

$\overline{D} = 21.245; \quad S_D = 14.605; \quad \therefore \quad t = 2.909$

Since $2.909 < 3.182$ the null hypothesis is accepted.

(e) Utilisation

$\overline{D} = 0.525; \quad S_D = 1.520; \quad \therefore \quad t = 0.691$

Since $0.691 < 3.182$ the null hypothesis is accepted.

(f) Set/run time ratio

$\overline{D} = 0.02225; \quad S_D = 0.00984; \quad \therefore \quad t = 4.522$

Since $4.522 > 3.182$ the null hypothesis is rejected.

(g) Average queue time

$\overline{D} = 0.235; \quad S_D = 0.187; \quad \therefore \quad t = 2.513$

Since $2.513 < 3.182$ the null hypothesis is accepted.

(B) Scheduling Rule : FCFS

(a) Throughput time

$\overline{D}$ = 2.1725; $S_D$ = 0.924; $\therefore$ t = 4.702

Since 4.702 > 3.182 the null hypothesis is rejected.

(b) Mean lateness

$\overline{D}$ = 2.195; $S_D$ = 0.580; $\therefore$ t = 7.569

Since 7.569 > 3.182 the null hypothesis is rejected.

(c) Std. dev. of lateness

$\overline{D}$ = 1.9025; $S_D$ = 1.366; $\therefore$ t = 2.786

Since 2.786 < 3.182 the null hypothesis is accepted.

(d) Work content remaining

$\overline{D}$ = 26.2825; $S_D$ = 14.627; $\therefore$ t = 3.594

Since 3.594 > 3.182 the null hypothesis is rejected.

(e) Utilisation

$\overline{D}$ = 0.85; $S_D$ = 0.714; $\therefore$ t = 2.381

Since 2.381 < 3.182 the null hypothesis is accepted.

(f) Set/run time ratio

$\overline{D}$ = 0.030; $S_D$ = 0.00548; $\therefore$ t = 10.949

Since 10.949 > 3.182 the null hypothesis is rejected.

(g) Average queue time

$\overline{D} = 0.5575$; $S_D = 0.240$; $\therefore$ $t = 4.65$

Since $4.65 > 3.182$ the null hypothesis is rejected.

## Appendix 5.2.3 : Analysis of Process Time Data for Experiment 2

(A) Set time (hr.)

(i) Distribution-free test

| | Process Time Distribution | | |
|---|---|---|---|
| Sample | Exponential | Normal | Uniform |
| 1 | 167.70(1) | 149.02(3) | 155.38(2) |
| 2 | 160.97(1) | 146.37(3) | 150.78(2) |
| 3 | 148.18(1) | 142.73(3) | 145.77(2) |
| 4 | 157.43(1) | 144.20(3) | 147.65(2) |
| | 158.57(4) | 145.58(12) | 149.90(8) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 350.15 | 2 | 175.08 | 20.41 |
| Between samples | 222.29 | 3 | 74.10 | 8.64 |
| Residual | 51.49 | 6 | 8.58 | |
| Total | 623.93 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 20.41$. $\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 8.64$. $\therefore$ Null hypothesis is rejected.

(B) Run time (hr.)

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 459.42(1) | 453.88(3) | 454.95(2) |
| 2 | 445.90(3) | 451.65(1) | 448.33(2) |
| 3 | 452.40(1) | 440.85(2) | 438.48(3) |
| 4 | 453.87(1) | 444.48(2) | 442.17(3) |
| | 452.90(6) | 447.72(8) | 445.98(10) |

For S = 2.0, the ALPHA level of significance that $H_o$ be rejected is 0.431.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 103.6 | 2 | 51.8 | 2.63 |
| Between samples | 242.4 | 3 | 80.8 | 4.10 |
| Residual | 118.1 | 6 | 19.7 | |
| Total | 464.1 | 11 | | |

Distributions : $F_{0.05,2,6}$ = 5.14 > 2.63. ∴ Null hypothesis is accepted.

Samples : $F_{0.05,3,6}$ = 4.76 > 4.10. ∴ Null hypothesis is accepted.

(C) Total process time (hr.)

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 627.12(1) | 602.90(3) | 610.33(2) |
| 2 | 606.87(1) | 598.02(3) | 599.11(2) |
| 3 | 600.58(1) | 583.58(3) | 584.25(2) |
| 4 | 611.30(1) | 588.68(3) | 589.89(2) |
| | 611.47(4) | 593.30(12) | 595.88(8) |

For S = 8.0, the ALPHA level of significance that $H_o$ be rejected is 0.005.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 914.1 | 2 | 457.1 | 30.01 |
| Between samples | 772.5 | 3 | 257.5 | 16.90 |
| Residual | 91.4 | 6 | 15.2 | |
| Total | 1778.0 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 < 30.01$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,6} = 4.76 < 16.90$. ∴ Null hypothesis is rejected.

(D) Set/run time ratio

(i) Distribution-free test

| Sample | Exponential | Normal | Uniform |
|---|---|---|---|
| 1 | 0.365(1) | 0.328(3) | 0.342(2) |
| 2 | 0.361(1) | 0.324(3) | 0.336(2) |
| 3 | 0.328(2) | 0.324(3) | 0.332(1) |
| 4 | 0.347(1) | 0.324(3) | 0.334(2) |
| | 0.350(5) | 0.325(12) | 0.336(7) |

For S = 6.5, the ALPHA level of significance that $H_o$ be rejected is 0.042.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between distributions | 0.0004803 | 2 | 0.0002402 | 3.38 |
| Between samples | 0.0012822 | 3 | 0.0004274 | 6.01 |
| Residual | 0.0004265 | 6 | 0.0000711 | |
| Total | 0.0021890 | 11 | | |

Distributions : $F_{0.05,2,6} = 5.14 > 3.38$. ∴ Null hypothesis is accepted.

Samples : $F_{0.05,3,6} = 4.76 < 6.01$. ∴ Null hypothesis is rejected.

Appendix 5.3 : Data for Experiment 3 - Case (1) Constant Mean Process Time

| Job input rate | 6 | 9 | 12 | 18 |
|---|---|---|---|---|
| Set time (min.) | 12 | 12 | 12 | 12 |
| Run time (min.) | 60 | 36 | 24 | 12 |
| Set/run time ratio | 0.20 | 0.33 | 0.50 | 1 |
| Load factor | 0.9 | 0.9 | 0.9 | 0.9 |

The load factor is calculated from input rate x process time/capacity. The set and run times are exponentially distributed. At the start of each simulation run the system is preloaded with twice the job input rate. The rest of the data used are as those given in Appendix 5.1. For queue discipline are the FCFS, SLACK(1)/SPT and S(1)/SET/SPT rule and assignment type (2) was employed for job due date allocation.

Data for Experiment 3 - Case (2) Constant Mean Run Time

| Job input rate | 6 | 9 | 12 | 18 |
|---|---|---|---|---|
| Set time (min.) | 12 | 12 | 12 | 12 |
| Run time (min.) | 54 | 36 | 27 | 18 |
| Set/run time ratio | 0.22 | 0.33 | 0.44 | 0.67 |
| Load factor | 0.825 | 0.9 | 0.975 | 1.125 |

The remarks for Case (1) pertains also for this case.

Appendix 5.3.1 : Analysis of Results for Experiment 3(b)

Scheduling Rule : S(1)/SET/SPT

(a) Throughput time (hr.)

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 15.35(3) | 16.00(4) | 13.93(1) | 14.22(2) |
| 2 | 15.32(4) | 12.58(2) | 13.12(3) | 12.19(1) |
| 3 | 15.83(4) | 14.02(3) | 12.88(2) | 12.75(1) |
| 4 | 23.75(4) | 15.63(2) | 18.22(3) | 14.79(1) |
| | 17.56(15) | 14.56(11) | 14.54(9) | 13.49(5) |

For S = 7.8, the ALPHA level of significance that $H_o$ be rejected is 0.036.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 37.03 | 3 | 12.35 | 4.16 |
| Between sanples | 55.05 | 3 | 18.35 | 6.18 |
| Residual | 26.74 | 9 | 2.97 | |
| Total | 118.82 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 < 4.16$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,9} = 3.86 < 6.18$. ∴ Null hypothesis is rejected.

(b) Mean lateness (hr.)

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | -8.41(1) | -6.07(4) | -7.31(2) | -6.25(3) |
| 2 | -8.07(2.5) | -9.41(1) | -7.72(4) | -8.07(2.5) |
| 3 | -6.97(4) | -7.61(2) | -7.85(1) | -7.44(3) |
| 4 | 0.72(4) | -6.02(1) | -2.30(3) | -4.27(2) |
| | -5.68(11.5) | -7.28(8) | -6.30(10) | -6.51(10.5) |

For S' = 1.0, the ALPHA level of significance that $H_o$ be rejected is 0.867.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 5.203 | 3 | 1.734 | 0.61 |
| Between samples | 67.856 | 3 | 22.619 | 8.00 |
| Residual | 25.453 | 9 | 2.828 | |
| Total | 98.512 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 > 0.61$. ∴ Null hypothesis is accepted.

Samples : $F_{0.05,3,9} = 3.86 < 8.00$. ∴ Null hypothesis is rejected.

(c) Standard deviation of lateness (hr.)

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 5.70(3) | 5.40(2) | 5.76(4) | 5.09(1) |
| 2 | 6.04(4) | 5.65(2) | 5.80(3) | 5.33(1) |
| 3 | 5.79(4) | 5.45(3) | 5.39(2) | 5.32(1) |
| 4 | 9.30(4) | 5.69(2) | 6.83(3) | 5.27(1) |
| | 6.71(15) | 5.55(9) | 5.95(12) | 5.25(4) |

For S = 9.9, the ALPHA level of significance that $H_o$ be rejected is 0.006.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 4.769 | 3 | 1.590 | 2.50 |
| Between samples | 4.537 | 3 | 1.512 | 2.37 |
| Residual | 5.733 | 9 | 0.637 | |
| Total | 15.038 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 > 2.50$. ∴ Null hypothesis is accepted.

Samples : $F_{0.05,3,9} = 3.86 > 2.30$. ∴ Null hypothesis is accepted.

(d) Work content remaining (hr.)

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 64.85(4) | 53.85(2) | 59.02(3) | 51.02(1) |
| 2 | 58.10(4) | 37.92(1) | 53.60(3) | 47.45(2) |
| 3 | 46.32(4) | 45.68(3) | 28.03(1) | 41.47(2) |
| 4 | 106.33(4) | 37.20(1) | 75.20(3) | 71.10(2) |
| | 68.90(16) | 43.67(7) | 53.97(10) | 52.77(7) |

For S = 8.1, the ALPHA level of significance that $H_o$ be rejected is 0.033.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 1310.89 | 3 | 436.96 | 2.39 |
| Between samples | 2224.77 | 3 | 741.59 | 4.05 |
| Residual | 1646.34 | 9 | 181.93 | |
| Total | 5182.00 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 > 2.39$. $\therefore$ Null hypothesis is accepted.

Samples $F_{0.05,3,9} = 3.86 < 4.05$. $\therefore$ Null hypothesis is rejected.

(e) Utilisation (%)

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 78.7(4) | 84.9(3) | 90.1(2) | 97.0(1) |
| 2 | 76.4(4) | 83.8(3) | 87.3(2) | 94.2(1) |
| 3 | 75.9(4) | 83.7(3) | 88.6(2) | 95.6(1) |
| 4 | 72.2(4) | 85.4(3) | 85.9(2) | 90.8(1) |
| | 75.8(16) | 84.5(12) | 88.0(8) | 94.4(4) |

For S = 12.0, the ALPHA level of significance that $H_o$ be rejected is 0.000.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 721.72 | 3 | 240.57 | 105.56 |
| Between samples | 34.19 | 3 | 11.40 | 5.00 |
| Residual | 20.51 | 9 | 2.28 | |
| Total | 776.42 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 < 105.56$. $\therefore$ Null hypothesis is rejected.

Samples : $F_{0.05,3,9} = 3.86 < 5.00$. $\therefore$ Null hypothesis is rejected.

(f) Set/run time ratio

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 0.176(1) | 0.243(2) | 0.325(3) | 0.343(4) |
| 2 | 0.181(1) | 0.251(2) | 0.295(3) | 0.336(4) |
| 3 | 0.180(1) | 0.242(2) | 0.277(3) | 0.354(4) |
| 4 | 0.178(1) | 0.250(2) | 0.330(3) | 0.401(4) |
| | 0.179(4) | 0.247(8) | 0.307(12) | 0.359(16) |

For S = 12.0, the ALPHA level of significance that $H_o$ be rejected is 0.000.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 0.07214 | 3 | 0.02405 | 76.40 |
| Between samples | 0.00172 | 3 | 0.00057 | 1.82 |
| Residual | 0.00283 | 9 | 0.00031 | |
| Total | 0.07669 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 < 76.40$. ∴ Null hypothesis is rejected.

Samples : $F_{0.05,3,9} = 3.86 > 1.82$. ∴ Null hypothesis is accepted.

(g) Average queue time (hr.)

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 1.53(1) | 2.02(4) | 1.68(2) | 1.88(3) |
| 2 | 160(3) | 1.33(1) | 1.65(4) | 1.57(2) |
| 3 | 1.63(2) | 1.53(1.5) | 1.53(1.5) | 1.68(3) |
| 4 | 2.83(4) | 1.78(1) | 2.52(3) | 2.17(2) |
| | 1.90(10) | 1.67(7.5) | 1.85(10.5) | 1.83(10) |

For S' = 1.0, the ALPHA level of significance that $H_o$ be rejected is 0.867.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 0.120 | 3 | 0.040 | 0.51 |
| Between samples | 1.551 | 3 | 0.517 | 6.54 |
| Residual | 0.711 | 9 | 0.079 | |
| Total | 2.383 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 > 0.51$. ∴. Null hypothesis is accepted.

Samples : $F_{0.05,3,9} = 3.86 < 6.54$. ∴. Null hypothesis is rejected.

(h) Run time completed (hr.)

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 418.08(4) | 426.20(2) | 424.95(3) | 450.53(1) |
| 2 | 403.10(4) | 418.08(3) | 420.58(2) | 439.92(1) |
| 3 | 401.23(4) | 420.58(3) | 432.43(2) | 436.80(1) |
| 4 | 382.52(4) | 426.20(1) | 403.10(3) | 404.35(2) |
| | 401.23(16) | 422.77(9) | 420.27(10) | 432.90(5) |

For S = 9.3, the ALPHA level of significance that $H_o$ be rejected is 0.012.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 2201.50 | 3 | 733.83 | 7.20 |
| Between samples | 1465.30 | 3 | 488.43 | 4.79 |
| Residual | 917.40 | 9 | 101.93 | |
| Total | 4584.20 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 < 7.20$. ∴. Null hypothesis is rejected.

Samples : $F_{0.05,3,9} = 3.86 < 4.79$. ∴. Null hypothesis is rejected.

(i) Percentage of jobs completed

(i) Two-way layout distribution-free test

| | Job Input Rate | | | |
|---|---|---|---|---|
| Sample | 6 | 9 | 12 | 18 |
| 1 | 85.7(3) | 84.9(4) | 87.5(2) | 90.1(1) |
| 2 | 83.3(4) | 90.4(2) | 87.5(3) | 91.7(1) |
| 3 | 90.5(3) | 90.4(4) | 92.9(1) | 91.3(2) |
| 4 | 72.6(4) | 91.3(1) | 87.5(3) | 88.5(2) |
| | 83.0(14) | 89.3(11) | 88.9(9) | 90.4(6) |

For S = 5.1, the ALPHA level of significance that $H_o$ be rejected is 0.190.

(ii) Analysis of variance

| Source | SS | DOF | MS | Test |
|---|---|---|---|---|
| Between input rates | 130.96 | 3 | 43.65 | 2.76 |
| Between samples | 83.09 | 3 | 27.69 | 1.75 |
| Residual | 142.54 | 9 | 15.83 | |
| Total | 365.59 | 15 | | |

Input rates : $F_{0.05,3,9} = 3.86 > 2.76$. $\therefore$. Null hypothesis is accepted.

Samples : $F_{0.05,3,9} = 3.86 > 1.75$. $\therefore$. Null hypothesis is accepted.

Appendix 5.3.2 : Computation of Results for Comparison with Data from Wickman Scrivener

| Job input rate | 6 | 9 | 12 | 18 |
|---|---|---|---|---|
| Mean run time (min.) | 60 | 36 | 24 | 12 |
| Effective reduction in batch size (%) | | 40.0 | 33.3 | 50.0 |
| (i) FCFS | | | | |
| No. of jobs completed | 63 | 97 | 147 | 220 |
| Cumulative run times completed(proportional) | 0.687 | 0.655 | 0.613 | 0.482 |
| Inc.in no. of jobs completed (%) | | 54.0 | 51.5(61.8) | 49.7(39.8) |
| Inc.in run times completed (%) | | -4.7 | - 6.4(-7.7) | -21.4(-17.1) |
| (ii) SLACK(1)/SPT | | | | |
| No. of jobs completed | 62 | 106 | 154 | 233 |
| Cumulative run times completed(proportional) | 0.684 | 0.673 | 0.627 | 0.490 |
| Inc.in no. of jobs completed (%) | | 71.0 | 45.3(54.4) | 51.3(41.0) |
| Inc.in run times completed (%) | | -1.6 | -6.8(-8.2) | -21.9(-17.5) |
| (iii) S(1)/SET/SPT | | | | |
| No. of jobs completed | 63 | 107 | 159 | 247 |
| Cumulative run times completed(proportional) | 0.685 | 0.683 | 0.632 | 0.516 |
| Inc.in no. of jobs completed (%) | | 69.8 | 48.6(58.4) | 55.3(44.2) |
| Inc.in run times completed (%) | | -0.3 | -7.5(-9.0) | -18.4(-14.7) |

Note : Figures in brackets denote values adjusted to a 40% reduction in the effective batch size.

Appendix 5.7.1 : Results for the 6-machine Cells

(No. of Set-Up Configurations = 15)

(1) Scheduling Rule : FCFS

| | Cell | | | |
|---|---|---|---|---|
| Performance measure | (1) | (2) | (3) | Mean |
| Throughput time (hr.) | 21.16 | 22.08 | 14.44 | 19.23 |
| Mean job lateness (hr.) | -0.17 | 0.58 | -5.31 | -1.63 |
| Std.dev. of lateness (hr.) | 7.74 | 6.00 | 4.73 | 6.16 |
| Work content remaining (hr.) | 76.15 | 96.47 | 19.87 | 192.49 |
| Av. queue time (hr.) | 3.03 | 3.18 | 1.77 | 2.66 |
| Machine utilisation (%) | 87.00 | 85.40 | 81.10 | 84.50 |
| Set/run time ratio | 0.332 | 0.302 | 0.315 | 0.316 |
| Jobs tardy (%) | 41.2 | 53.1 | 10.3 | 34.9 |

(2) Scheduling Rule : SLACK(1)/SPT

| | Cell | | | |
|---|---|---|---|---|
| Performance measure | (1) | (2) | (3) | Mean |
| Throughput time (hr.) | 16.45 | 18.36 | 11.22 | 15.34 |
| Mean job lateness (hr.) | -5.40 | -3.63 | -8.62 | -5.88 |
| Std.dev. of lateness(hr.) | 5.67 | 6.02 | 5.68 | 5.79 |
| Work content remaining (hr.) | 74.55 | 81.77 | 9.93 | 166.25 |
| Av. queue time (hr.) | 2.15 | 2.33 | 1.22 | 1.90 |
| Machine utilisation (%) | 87.8 | 88.2 | 82.6 | 86.2 |
| Set/run time ratio | 0.332 | 0.310 | 0.309 | 0.317 |
| Jobs tardy (%) | 10.7 | 25.7 | 0.8 | 12.4 |

(3) Scheduling Rule : S(1)/SET/SPT

| | Cell | | | |
|---|---|---|---|---|
| Performance measure | (1) | (2) | (3) | Mean |
| Throughput time (hr.) | 16.30 | 17.37 | 11.16 | 14.94 |
| Mean job lateness (hr.) | -5.96 | -4.63 | -8.68 | -6.42 |
| Std.dev.of lateness (hr.) | 5.53 | 5.88 | 5.41 | 5.61 |
| Work content remaining (hr.) | 57.50 | 78.68 | 11.43 | 147.61 |
| Av. queue time (hr.) | 1.97 | 2.17 | 1.22 | 1.79 |
| Machine utilisation (%) | 88.4 | 86.9 | 81.0 | 85.4 |
| Set/run time ratio | 0.310 | 0.280 | 0.290 | 0.293 |
| Jobs tardy (%) | 5.7 | 19.4 | 0 | 8.4 |

Appendix 5.8 : Data for Experiment 8

No. of machine groups : 6

No. of machines/group : 1

Manning arrangement :
(1) 6 setter-operators
(2) 5 setter-operators, 1 operator
(3) 4 setter-operators, 2 operators
(4) 3 setter-operators, 3 operators
(5) 2 setter-operators, 4 operators
(6) 1 setter-operator, 5 operators
(7) 5 setter-operators
(8) 4 setter-operators, 1 operator
(9) 3 setter-operators, 2 operators
(10) 2 setter-operators, 3 operators
(11) 1 setter-operator, 4 operators
(12) 4 setter-operators
(13) 3 setter-operators, 1 operator
(14) 2 setter-operators, 2 operators.

Job input rate and job characteristics are as for Appendix 5.1 except :

Routing :

| M/c type | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Probability | 0.21 | 0.21 | 0.16 | 0.16 | 0.13 | 0.13 |
| Load factor | 0.945 | 0.945 | 0.720 | 0.720 | 0.585 | 0.585 |

(Overall load factor = 0.75)

Set times : Exponentially distributed; mean = 10 min.

Run times : Exponentially distributed; mean = 30 min.

Due date : Sum of process times + 3 x no. of ops.

Inter-operation transit time and trigger-off value are as for Appendix 5.1.

Priority rules : (1) FCFS
(2) SLACK(1)/SPT
(3) S(1)/SET/SPT

No. of periods simulated = 13.

## Appendix 7.1 : Notations

| | |
|---|---|
| $V$ | cutting speed (m/min) |
| $T$ | tool life (min) |
| $n, C$ | constants (Taylor tool life equation) |
| $s$ | feedrate (mm/rev) |
| $a$ | depth of cut (mm) |
| $m, p, \lambda$ | constants (extended Taylor tool life equation) |
| $C_p$ | production cost per piece (m.u.) |
| $R_1$ | total overhead, machine-rate and direct labour rate (m.u./min) |
| $W$ | tool cost per tool change (m.u.) |
| $t_h$ | handling and fast traverse times (min) |
| $t_w$ | tool change time (min) |
| $D$ | diameter of workpiece (mm) |
| $L$ | length of workpiece |
| $V_{mc}$ | minimum cost cutting speed (m/min) |
| $t_e$ | tool change time equivalent ($=t_w + W/R_1$) |
| $C_{pmc}$ | minimum production cost (m.u.) |
| $\Delta C_p$ | an increment of the minimum production cost |
| $t_{pmc}$ | production time at minimum cost (min) |
| $t_{pmt}$ | minimum production time |
| $VB$ | average flank wear (mm) |
| $KT$ | maximum crater depth (mm) |
| $KM$ | distance from unworn cutting edge to point of maximum crater depth (mm) |
| $K$ | $KT/KM$ (%) |

## Appendix 7.2 : Derivation of Equation for Production Cost Function Sensitivity

$$C_{pmc} = R_1 t_h + A/V_{mc} + BV_{mc}^{1/n-1} \quad \text{(A7.1)}$$

where $A = \pi DLR_1/1000s$ (A7.2a)

and $B = \pi DL(R_1 t_w + W)/1000sC^{1/n}$ (A7.2b)

$$C'_{pmc}(V_{mc}) = -A/V_{mc}^{2} + (1/n - 1)BV_{mc}^{1/n-2} \quad \text{(A7.3)}$$

$$C''_{pmc}(V_{mc}) = 2A/V_{mc}^{3} + (1/n - 1)\ (1/n - 2)BV_{mc}^{1/n-3} \quad \text{(A7.4)}$$

Applying the Taylor expansion series :

$$\Delta C_p = C_{pmc}(V_{mc} + \Delta V) - C_{pmc}(V_{mc})$$

$$= (\Delta V)^2 C''_{pmc}(V_{mc})/2! + (\Delta V)^3 C'''_{pmc}(V_{mc}) + .... \quad \text{(A7.5)}$$

Neglecting the 3rd and other higher derivatives and substituting equation A7.4 into A7.5 :

$$\Delta C_p = 1/2(\Delta V)^2 [2A/V_{mc}^{3} + (1/n - 1)\ (1/n - 2)BV_{mc}^{1/n-3}]$$

Since $V_{mc}^{1/n} = \dfrac{A}{B(1/n-1)}$ ,

$$\Delta C_p = \frac{(\Delta V)^2}{2V_{mc}^{3}} [2A + \cancel{(1/n-1)}\ (1/n - 2).\ \frac{\cancel{B}A}{\cancel{B(1/n-1)}}]$$

Simplifying:

$$\Delta C_p = \frac{B(\Delta V)^2}{2V_{mc}^{3}} = \frac{A(\Delta V)^2}{2n} . [B(1/n - 1)/A]^{3n}$$

$$\therefore \Delta C_p = \frac{\pi DLR_1(\Delta V)^2 (1/n - 1)^{3n} t_e^{3n}}{2000snC^{3}} \quad \text{(A7.6)}$$

## Appendix 7.3 : Deriving the Ratio of the Production Time at Minimum Cost to the Production Time at Maximum Production Rate

$$t_p = t_h + \frac{\pi DL}{1000sV}\left[1 + \frac{t_w V^{1/n}}{C^{1/n}}\right] \qquad (A7.7)$$

Substituting $V = V_{mc}$ into equation A7.7 :

$$t_{pmc} = t_h + \frac{\pi DLt_e^{\,n}(1/n - 1)^n}{1000sC}\left[1 + \frac{t_w}{(1/n - 1)t_e}\right] \qquad (A7.8)$$

Similarly, substituting $V = V_{mt} = \dfrac{C}{(1/n - 1)t_w^{\,n}}$ into equation A7.7 :

$$t_{pmt} = t_h + \frac{\pi DLt_w^{\,n}(1/n - 1)^n}{1000sC}\left[1 + \frac{1}{(1/n - 1)}\right] \qquad (A7.9)$$

Ignoring the $t_h$ term in both equations A7.8 and A7.9 :

$$R'_t = \frac{t'_{pmc}}{t'_{pmt}} = \left(\frac{t_e}{t_w}\right)^n \frac{[1 + t_w/t_e\,(1/n - 1)]}{[1 + 1/(1/n - 1)]} \qquad (A7.10)$$

## Appendix 7.4 : Deriving the Ratio of the Production Cost at Maximum Production Rate to the Minimum Production Cost

Substituting $V = Vmt$ into equation 7.3 :

$$C_{pmt} = R_1 t_h + \frac{DLR_1 t_w^{\,n}(1/n - 1)^n}{1000sC}\left[1 + \frac{t_e}{t_w(-/n - 1)}\right] \qquad (A7.11)$$

Also,

$$C_{pmc} = R_1 t_h + \frac{DLR_1 t_e^{\,n}(1/n - 1)^n}{1000sC}\left[1 + \frac{1}{1/n - 1}\right] \qquad (A7.1a)$$

Ignoring the $R_1 t_h$ term in both equations A7.11 and A7.1a :

$$R'_c = \frac{C'_{pmt}}{C'_{pmc}} = \left(\frac{t_w}{t_e}\right)^n \frac{[1 + t_e/t_w(1/n - 1)]}{[1 + 1/(1/n - 1)]} \qquad (A7.12)$$

```
      PROGRAM (P50G)
      INPUT 5 = CR0
      OUTPUT 6 = LP0
      OUTPUT 3 = LP1
      COMPACT DATA
      END
      MASTER DATGEN
      INTEGER DNO(25),DOS(25,12),DOT(25,3,6),DMS(25,6),
     @ RAN(10),IDIS(7),NST(10),SAMP,FDD
      COMMON DNO,DOS,DOT,DMS,RAN,IDIS,NST,NMT,NPN,FDD
      NPN = 0
      DO 300 I = 1, 10
      RAN(I) = 100*I + 1
  300 CONTINUE
      WRITE (6,200)
  200 FORMAT (1X,16HNO. OF MC TYPES?)
      READ (5,100) NMT
  100 FORMAT (I0)
      WRITE (6,210)
  210 FORMAT (1X,47HRANDOM NO. GENERATION STREAM...TYPE IN  1 TO 10)
      READ (5,100) IS
      NST(1) = IS
      DO 310 I = 2, 10
      IS = IS + 1
      IF (IS .GT. 10) IS = 1
      NST(I) = IS
  310 CONTINUE
      CALL DSTRBS
      CALL PAGEN
      STOP
      END
      SUBROUTINE PAGEN
      INTEGER DNO(25),DOS(25,12),DOT(25,3,6),DMS(25,6),
     @ RAN(10),IDIS(7),NST(10),SAMP,FDD
      INTEGER P(100)
      COMMON DNO,DOS,DOT,DMS,RAN,IDIS,NST,NMT,NPN,FDD
      WRITE (6,200)
  200 FORMAT (1X,29HNO. OF PARTS TO BE GENERATED?)
      READ (5,100) NPG
  100 FORMAT (I0)
      DO 300 I = 1, NPG
      NPN = NPN + 1
      P(1) = NPN
      DO 301 J = 1, 4
      M = IDIS(J+3)
      GO TO (11,11,12,301,301,301),M
   11 P(J+1) = SAMP(DMS(1,J),25,NST(J),M)
      GO TO 301
   12 P(J+1) = IFIX(DNORM(DMS(1,J),DMS(2,J),NST(J)))
  301 CONTINUE
      P(6) = SAMP(DMS(1,5),25,NST(5),2)
      P(7) = SAMP(DNO,25,NST(6),2)
      N = 0
      DO 302 J = 1, P(7)
      KK = 8 + 4 * (J-1)
  401 P(KK) = SAMP(DOS,25,NST(7),2)
      IF (J .EQ.  1) GO TO 400
      IF (P(KK) .EQ. JLAST) GO TO 401
  400 DO 303 K = 1, 3
      M = IDIS(6)
      GO TO (21,21,22,23),M
   21 P(KK+K)  = SAMP(DOT(1,K,P(KK)),25,NST(K+7),M)
      GO TO 303
   22 P(KK+K) = IFIX(DNORM(DOT(1,K,P(KK)),DOT(2,K,P(KK)),NST(K+7)))
      GO TO 303
   23 P(KK+K) = IFIX(DEXP(DOT(1,K,P(KK)),NST(K+7)))
  303 CONTINUE
      IF (IDIS(6) .LT. 4) GO TO 410
      N = N + P(KK+1) + P(KK+2)
  410 JLAST = P(KK)
  302 CONTINUE
      IF (IDIS(6) .LT. 4) GO TO 420
      M = IDIS(6) - 3
      GO TO (31,32,33),M
   31 P(4) = FDD * P(7)
      GO TO 420
   32 P(4) = (FDD*N) / 60
      GO TO 420
   33 P(4) = N/60 * FDD * P(7)
  420 WRITE (3,202) (P(J),J=1,7)
  202 FORMAT (1X,7I17,1X))
      DO 304 J = 1, P(7)
      KK = 7 + 4 * (J-1)
      WRITE (3,203) (P(KK+K),K=1,4)
  203 FORMAT (1X,4(I7,1X))
  304 CONTINUE
  300 CONTINUE
      RETURN
      END
      SUBROUTINE DSTRBS
      INTEGER DNO(25),DOS(25,12),DOT(25,3,6),DMS(25,6),
     @ RAN(10),IDIS(7),NST(10),SAMP,FDD
      COMMON DNO,DOS,DOT,DMS,RAN,IDIS,NST,NMT,NPN,FDD
      DIMENSION STR(7)
      DATA STR/8HSET TIME,8HRUN TIME,8HTOOL S/U,8HLOT SIZE,
     @ 8H      VALUE,8HDUE DATE,8H      ESD/
      WRITE (6,200)
  200 FORMAT(/1X,20HTYPE OF DISTRIBUTION,5X,25H(1) SPECIFIED(CONTINUOUS)
     @ /26X,23H(2) SPECIFIED(DISCRETE)/26X,10H(3) NORMAL/26X,
     @ 33H(4) OP. TIMES : EXPONENTIAL   OR,/30X,
     @ 27HDUE DATE : NON-DISTRIBUTION)
      DO 300 I = 1, 7
      WRITE (6,201) STR(I)
  201 FORMAT (6X,7HFOR....,A8,1H?)
      READ (5,100) IDIS(I)
  100 FORMAT (I0)
  300 CONTINUE
      WRITE (6,202)
  202 FORMAT (1X,17HMAX. NO. OF OPS.?)
      READ (5,100) MAXOP
      WRITE (6,203)
  203 FORMAT (1X,36HTYPE IN DISTRIBUTION FOR NO. OF OPS.)
      CALL DSTRI(DNO,25,1)
      DO 301 I = 1, MAXOP
      WRITE (6,204) I
  204 FORMAT (1X,32HTYPE IN DISTRIBUTION FOR OP. NO.,I3)
      CALL DSTRI(DOS(1,I),25,I*10)
  301 CONTINUE
      DO 302 I = 1, 3
      M = IDIS(I)
      DO 303 J = 1, NMT
      GO TO (11,11,12,13),M
   11 WRITE (6,205) STR(I),J
  205 FORMAT (1X,25HTYPE IN DISTRIBUTION FOR ,A8,12H FOR MC TYPE,I3)
      CALL DSTRI(DOT(1,I,J),25,I*50+J)
      GO TO 303
   12 WRITE (6,206) STR(I),J
  206 FORMAT (1X,27HTYPE IN MEAN/STD. DEV. FOR ,A8,12H FOR MC TYPE,I3)
      READ (5,101) DOT(1,I,J),DOT(2,I,J)
  101 FORMAT (2I0)
      GO TO 303
   13 WRITE (6,207) STR(I), J
  207 FORMAT (1X,23HTYPE IN MEAN VALUE FOR ,A8,12H FOR MC TYPE,I3)
      READ (5,100) DOT(1,I,J)
  303 CONTINUE
  302 CONTINUE
      DO 305 I = 4, 7
      M = IDIS(I)
      N = I - 3
      GO TO (21,21,22,23),M
   21 WRITE (6,208) STR(I)
  208 FORMAT (1X,25HTYPE IN DISTRIBUTION FOR ,A8)
      CALL DSTRI(DMS(1,N),25,200+N)
      GO TO 305
   22 WRITE (6,209) STR(I)
  209 FORMAT (1X,27HTYPE IN MEAN/STD. DEV. FOR ,A8)
      READ (5,101) DMS(1,N),DMS(2,N)
      GO TO 305
   23 WRITE (6,211)
  211 FORMAT (1X,36HDUE DATE....(1) FACTOR * NO. OF OPS,/13X,
     @ 26H(2) FACTOR * JOB OP. TIMES/13X,
     @ 36H(3) OP. TIMES * FACTOR * NO. OF OPS.)
      READ (5,100) M
      IDIS(6) = M + 3
      WRITE (6,212)
  212 FORMAT (1X,7HFACTOR?)
      READ (5,100) FDD
  305 CONTINUE
      WRITE (6,210)
  210 FORMAT (1X,39HTYPE IN DISTRIBUTION FOR EXT. PRIORITY)
      CALL DSTRI(DMS(1,5),25,205)
      RETURN
      END
      SUBROUTINE DSTRI(IA,IM,IN)
      DIMENSION IA(IM)
      READ (5,100) IA(IM), (IA(I), I = 1, IM-1)
  100 FORMAT (25I3)
      IF (IA(IM) - IN) 10, 20, 10
   10 WRITE (6,200) IA(IM), IN
  200 FORMAT (1H0,16HERROR - DISTRIB,,I4,19HREAD IN IN PLACE OF,I4)
      CALL EXIT
   20 RETURN
      END
      INTEGER FUNCTION SAMP(IA,IM,NS,IC)
      DIMENSION IA(IM)
C     IC     = 1(CONTINUOUS)      = 2(DISCRETE)
      CALL RANA(NS,10)
      GO TO (409,401),IC
  401 DO 300 I = 2, IM-1, 2
      IF (10 - IA(I)) 10, 300, 300
  300 CONTINUE
   10 SAMP = IA(I-1)
      RETURN
  400 DO 301 I = 4, IM-1, 2
      IF (10 - IA(I)) 20, 301, 301
  301 CONTINUE
   20 SAMP = IA(I-3) + (10 - IA(I-2)) * (IA(I-1) - IA(I-3) + 1) /
     @ (IA(I) - IA(I-2))
      RETURN
      END
      SUBROUTINE RANA(NS,NN)
      INTEGER DNO(25),DOS(25,12),DOT(25,3,6),DMS(25,6),
     @ RAN(10),IDIS(7),NST(10),SAMP,FDD
      COMMON DNO,DOS,DOT,DMS,RAN,IDIS,NST,NMT,NPN,FDD
      X = 100. * RANGRAN(NS))
      NN = IFIX(X)
      RETURN
      END
      FUNCTION RANG(N)
      N = N * 125
      N = N - 65536 * (N/65536)
      RANG = FLOAT(N)/65536.
      RETURN
      END
      FUNCTION DNORM(JM,JSD,NS)
      INTEGER DNO(25),DOS(25,12),DOT(25,3,6),DMS(25,6),
     @ RAN(10),IDIS(7),NST(10),SAMP,FDD
      COMMON DNO,DOS,DOT,DMS,RAN,IDIS,NST,NMT,NPN,FDD
   31 M = 0
      Y = RANGRAN(NS))
      IF (Y - 0.5) 11,12,12
   11 Y = 1. - Y
      M = 1
   12 Y = (-2.0 * ALOG(1.-Y+0.00002))**0.5
      X = Y - ((2.5753+0.27061*Y)/(1.+0.99229*Y+0.04481*Y*Y))
      IF (M) 21,21,22
   22 X = -X
   21 RM = FLOAT(JM)
      RSD = FLOAT (JSD)
      DNORM = RM + X*RSD
      IF (DNORM) 31,32,32
   32 RETURN
      END
      FUNCTION DEXP(JM,NS)
      INTEGER DNO(25),DOS(25,12),DOT(25,3,6),DMS(25,6),
     @ RAN(10),IDIS(7),NST(10),SAMP,FDD
      COMMON DNO,DOS,DOT,DMS,RAN,IDIS,NST,NMT,NPN,FDD
      RM = FLOAT(JM)
   11 Y = RANGRAN(NS))
      DEXP = -RM * ALOG(1.-Y)
      IF (DEXP .LT. 1.0) GO TO 11
      RETURN
      END
      FINISH
```

**** END OF STREAM  PR134S  3861

```
      LIBRARY(SUBGROUPNAGF)
      PROGRAM (P50A)
      INPUT 5 = CR0
      OUTPUT 3 = LP0
      OUTPUT 6 = LP1
      COMPACT DATA
      COMPRESS INTEGER AND LOGICAL
      END
      MASTER SIMLOD
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
  491 CALL RESET(1)
      CALL EVENT(ELIMIT,LIMIT,1)
  492 CALL INOB
      DO 399 IXX = 1, NMT
      CALL INSHOP(IQ)
  399 CONTINUE
      CALL SEARCH
  499 CALL FAZEA(IXX)
      IF (IXX .GT. NMT) GO TO 400
      J = MEMNU(MEMBE)
      IF (MCCD(J,IXX) .EQ. 2) GO TO 410
C     SETTING COMPLETED
      IYY = BSORT(STATE,2)
      LINE = BSORT(PB(4,IYY),1)
      N = BSORT(PA(1,LINE),2)
      MCLDQ(IXX) = MCLDQ(IXX) - N
      MCLDP(IXX) = MCLDP(IXX) - N
      L = MEMBE * 1000 + IYY
      CALL ADDLA(L,SQMENR)
      MC(J,IXX) = CLOCK
      MCCD(J,IXX) = 4
      L = BSORT(STATE,1)
      N = BSORT(STATE,3)
      M = BSORT(STATE,4)
      IF (INF .EQ. 2) CALL WRIINF(11,J,N,M)
      MN(M,N) = CLOCK
      MNCD(M,N) = 3
      CALL ADDLA(L,SMN)
      CALL INSHOP(IQ)
      CALL SEARCH
      GO  TO 499
C     OPERATION COMPLETED
C     THE MC TOOL
  410 CALL ADDLA(MEMBE,SMC(IXX))
      MC(J,IXX) = CLOCK
      MCCD(J,IXX) = 3
      IF (MCID(IXX) .NE. 0) GO TO 420
      IF (SIZEO(SPA(IXX)) .EQ. 0) GO TO 430
      MCID(IXX) = 2
      CALL ADDLA(IXX,SQMENS)
      GO TO 420
  430 MCID(IXX) = 1
C     THE OPERATOR
  420 L = BSORT(STATE,1)
      CALL ADDLA(L,SMN)
      L = BSORT(STATE,3)
      M = BSORT(STATE,4)
      MN(M,L) = CLOCK
      MNCD(M,L) = 3
C     THE PART
      IYY = BSORT(STATE,2)
      IF (INF .EQ. 2) CALL WRIINF(12,J,L,M)
      M = ASORT(PB(1,IYY),2)
      N = ASORT(PB(2,IYY),2) + 1
      LINE = BSORT(PB(4,IYY),1)
      L = BSORT(PA(1,LINE),1)
      MCLDQ(IXX) = MCLDQ(IXX) - L
      MCLDP(IXX) = MCLDP(IXX) - L
      IF (M .EQ. N) GO TO 440
      PB(2,IYY) = PB(2,IYY) + 1
      IF (IPP .GT. 10) CALL PAPRI(2)
C     REMOVAL OF COMPLETED OPERATION DETAILS
  440 LINE = BSORT(PB(4,IYY),1)
      J = PA(3,LINE)
      PA(3,LINE) = NSL
      NSL = LINE
      NOC = NOC + 1
      IF (N .EQ. M) GO TO 450
      PB(4,IYY) = PB(4,IYY) + (J-LINE) * 1000
      CALL MOVEPA
      GO TO 441
  450 M = IXX + 1
      MOV1(M,7) = MOV1(M,7) + 1
      M = PB(3,IYY) - CLOCK
      V = FLOAT(M) / 60.
      IF (V) 451,452,452
  451 CALL ADDHIS(V,HDELT,HDT)
      GO TO 453
  452 CALL ADDHIS(V,HDELE,HDE)
  453 M = ASORT(PB(2,IYY),1)
      M = CLOCK - M
      V = FLOAT(M) / 60.
      CALL ADDHIS(V,HTRU,HT)
      PB(3,IYY) = -10
      IF (INF .EQ. 3) CALL WRIINF(31,0,0,0)
  441 CALL INSHOP(IQ)
      CALL SEARCH
      GO TO 499
  400 M = IXX - NMT
      GO TO (490,480,492),M
C     PART ARRIVAL AT A QUEUE
  480 CALL ENDTPA
      GO TO 499
  490 J = CLOCK / NMPD
      WRITE (6,290) J
  290 FORMAT (1X,19HREADY - END OF DAY ,I3)
      CALL TIDYUP
      CALL CONTRL(J)
      GO TO (499,491,492,499,499),J
      STOP
      END
      SUBROUTINE CONTRL(J)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
  499 WRITE (6,200)
  200 FORMAT (1X,7HREPORT?,6X,8H(1) NONE/14X,15H(2) FULL REPORT/14X,
     @ 23H(3) MC TOOL PERFORMANCE/14X,
     @ 24H(4) OPERATOR PERFORMANCE/14X,
     @ 23H(5) PARTS ROUTE TRACING/14X,28H(6) PARTS DELIVERY HISTOGRAM/
     @ 14X,30H(7) PARTS THROUGHPUT HISTOGRAM/1X,1H?)
      READ (5,100) J
  100 FORMAT (I0)
      GO TO (10,20,30,30,30,40,50),J
   30 J = J - 2
      CALL REPORT(J)
      GO TO 499
   20 DO 300 I = 1, 3
      CALL REPORT(I)
  300 CONTINUE
   40 CALL WRIHIS(HDELT,HDT)
      WRITE (6,210)
  210 FORMAT (32X,15HPARTS TARDINESS)
      CALL WRIHIS(HDELE,HDE)
      WRITE (6,211)
  211 FORMAT (32X,15HPARTS EARLINESS)
      IF (J .EQ. 6) GO TO 499
   50 CALL WRIHIS(HTRU,HT)
      WRITE (6,220)
  220 FORMAT (32X,16HPARTS THROUGHPUT)
      IF (J .EQ. 7) GO TO 499
   10 WRITE (6,230)
  230 FORMAT (1X,10HWHAT NEXT?,6X,24H(1) TERMINATE SIMULATION/17X,
     @ 39H(2) RESIMULATE WITH MC/OPERATOR CHANGES/17X,
     @ 42H(3) RESIMULATE WITH NO MC/OPERATOR CHANGES/17X,
     @ 40H(4) CONTINUE SIMULATION WITH NEW RECORDS/17X,
     @ 41H(5) CONTINUE SIMULATION WITH SAME RECORDS/1X,1H?)
      READ (5,100) J
      GO TO (11,12,13,13,13),J
   11 J = 0
      WRITE (3,240) J
  240 FORMAT (1X,I6)
      CALL EXIT
   13 CALL RESET(J-1)
      I = LIMIT
      CALL READIN(8)
      CALL EVENT(ELIMIT,LIMIT,1)
      IF (J .EQ. 5) LIMIT = LIMIT + I
  400 WRITE (6,231)
  231 FORMAT (1X,8HCHANGES?,6X,8H(1) NONE/15X,
     @ 23H(2) MANNING ARRANGEMENT/15X,
     @ 23H(3) PARTS PRIORITY RULE/15X,
     @ 37H(4) SHOP ENTRY MODE/TRIGGER OFF VALUE/15X,
     @ 36H(5) PARTS INTER-MACHINE TRANSIT TIME/15X,
     @ 20H(6) HISTOGRAM SCALES/1X,1H?)
      READ (5,100) I
      IF (I .EQ. 1) RETURN
      I = I + 1
      CALL READIN(I)
      IF (I .EQ. 4) CALL REALLO(0)
      GO TO 400
   12 RETURN
      END
      SUBROUTINE RESET(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      GO TO (10,20,30,40),IA
   10 MAXPA = 120
      NMPD = 480
      DO 300 I = 1, 8
      CALL READIN(I)
  300 CONTINUE
   20 I = IFIX(G05BAF(10.))
      CLOCK = 0
      LMM = 0
      NOC = 700
      NPC = 0
      NSL = 1
      PCMX = 40
      DO 310 I = 1, MAXPA
      PB(3,I) = -10
  310 CONTINUE
      DO 320 I = 1, NMT
      WIQ(I) = 0
      MCLDQ(I) = 0
      MCLDP(I) = 0
  320 CONTINUE
      DO 340 I = 1, NOC
      PA(3,I) = I + 1
  340 CONTINUE
      CALL ENTSET
      CALL PRIME(1)
   30 INPA = 0
      DO 350 I = 1, NMT
      NPAI(I) = 0
      PTIT(I) = 0
      PTITMX(I) = -99
      WIQMX(I) = -99
      GO TO (31,31,32),IA
   31 DO 351 J = 1, 2
      MCWT(J,I) = 0
  351 CONTINUE
      GO TO 430
   32 DO 352 J = 1, 2
      MCWT(J,I) = MCWA(J,I)
  352 CONTINUE
  430 DO 353 J = 1, 2
      MCWA(J,I) = 0
  353 CONTINUE
      DO 354 J = 1, 3
      MCIT(J,I) = 0
  354 CONTINUE
  350 CONTINUE
      DO 360 I = 1, NOPT
      MNIT(I) = 0
      GO TO (41,41,42),IA
   41 DO 361 J = 1,2
      MNWT(J,I) = 0
  361 CONTINUE
      GO TO 440
   42 DO 362 J = 1, 2
      MNWT(J,I) = MNWA(J,I)
  362 CONTINUE
  440 DO 363 J = 1, 2
      MNWA(J,I) = 0
  363 CONTINUE
  360 CONTINUE
      DO 370 I = 1,7
      DO 371 J = 1,7
      MOV1(J,I) = 0
  371 CONTINUE
  370 CONTINUE
      CALL HIST(HDELT,HDT,DELT1,DELT2)
      CALL HIST(HDELE,HDE,DELE1,DELE2)
      CALL HIST(HTRU,HT,TRU1,TRU2)
      RETURN
   40 DO 380 I = 1, NMT
      DO 381 J = 1, 2
      MCWA(J,I) = 0
  381 CONTINUE
  380 CONTINUE
      DO 390 I = 1, NOPT
      DO 391 J = 1, 2
      MNWA(J,I) = 0
  391 CONTINUE
  390 CONTINUE
      RETURN
      END
      SUBROUTINE READIN(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      DATA AA/1HY/
      GO TO (10,20,30,40,50,60,70,80),IA
   10 WRITE (6,210)
  210 FORMAT (1X,16HNO. OF MC TYPES?)
      READ (5,100) NMT
  100 FORMAT(I0)
      DO 310 I = 1, NMT
      WRITE (6,211) I
  211 FORMAT (1X,15HNO. OF MC TYPE ,I2,1H?)
      READ (5,100) NMC(I)
  310 CONTINUE
      RETURN
   20 WRITE (6,220)
  220 FORMAT (1X,22HNO. OF OPERATOR TYPES?)
      READ (5,100) NOPT
      DO 320 I = 1, NOPT
      WRITE (6,221) I
  221 FORMAT (1X,17HNO. OF OPR. TYPE ,I2,1H?)
      READ (5,100) NMN(I)
  320 CONTINUE
      RETURN
   30 WRITE (6,230)
  230 FORMAT (1X,40HMACHINE-OPERATOR MATCH......(0) NO MATCH/
     @ 29X,16H(1) SETTING ONLY/29X,16H(2) RUNNING ONLY/
     @ 29X,23H(3) SETTING AND RUNNING)
      DO 330 I = 1, NMT
      DO 331 J = 1, NOPT
      WRITE (6,231) I, J
  231 FORMAT (1X,8HMC TYPE ,I2,11H/OPR. TYPE ,I2,1H?)
      READ (5,100) MCMN(J,I)
  331 CONTINUE
  330 CONTINUE
      RETURN
   40 WRITE (6,240)
  240 FORMAT (1X,19HPARTS PRIORITY RULE,6X,8H(1) FIFO/26X,
     @ 21H(2) EARLIEST DUE DATE/26X,
     @ 30H(3) EARLIEST SHOP ARRIVAL DATE/26X,15H(4) LEAST SLACK/26X,
     @ 32H(5) LEAST REMAINING PROCESS TIME/26X,
     @ 31H(6) MOST REMAINING PROCESS TIME/26X,
     @ 31H(7) FEWEST OPERATIONS REMAINING/26X,
     @ 29H(8) MORE OPERATIONS REMAINING/26X,
     @ 25H(9) SHORTEST PROCESS TIME/25X,
     @ 25H(10) LONGEST PROCESS TIME/25X,
     @ 20H(11) LEAST SLACK/SPT/25X,24H(12) LEAST SLACK/TSU/SPT/1X,1H?)
      READ (5,100) IPP
      IPQ = 0
      IF (IPP .LT. 11) GO TO 440
      IPQ = IPP - 10
      IPP = 4
  440 IF (IPP .GT. 3) IPP = IPP + 7
      IF (IPP .NE. 11) RETURN
      WRITE (6,241)
  241 FORMAT (1X,24HQUEUE TIME FOR EACH OP.?)
      READ (5,100) QTIME
      QTIME = QTIME * 60
      RETURN
   50 WRITE (6,250)
  250 FORMAT (1X,21HPARTS SHOP ENTRY MODE,6X,
     @ 26H(1) FIRST OP. QUEUE LENGTH/28X,
     @ 24H(2) FIRST OP. QUEUE LOAD/1X,1H?)
      READ (5,100) IQ
      DO 350 I = 1, NMT
      WRITE (6,251) I
  251 FORMAT (1X,30HTRIGGER OFF VALUE FOR MC TYPE ,I2,1H?)
      READ (5,100) QTRIG(I)
      IF (IQ .GT. 1) QTRIG(I) = QTRIG(I) * 60
  350 CONTINUE
      RETURN
   60 WRITE (6,260)
  260 FORMAT (1X,31HPART INTER-MACHINE TRANSIT TIME)
      DO  360 I = 1, NMT
      DO 361 J = 1, NMT
      IF (J .EQ. I) GO TO 361
      WRITE (6,261) I, J
  261 FORMAT (1X,12HFROM MC TYPE,I3,11H TO MC TYPE,I3,
     @ 19H...MEAN/STD. DEV.??)
      READ (5,101) TTM(J,I),TTSD(J,I)
  101 FORMAT(2I0)
  361 CONTINUE
  360 CONTINUE
      RETURN
   70 WRITE (6,270)
  270 FORMAT (1X,23HHISTOGRAM SCALES(HRS.):/1X,
     @ 54HPARTS DELIVERY(TARDINESS).....INITIAL VALUE/INTERVAL??)
      READ (5,103) DELT1,DELT2
  103 FORMAT (2F0.0)
      WRITE (6,271)
  271 FORMAT (1X,
     @ 54HPARTS DELIVERY(EARLINESS).....INITIAL VALUE/INTERVAL??)
      READ (5,103) DELE1,DELE2
      WRITE (6,272)
  272 FORMAT (1X,45HPARTS THROUGHPUT.....INITIAL VALUE/INTERVAL??)
      READ (5,103) TRU1,TRU2
      RETURN
   80 WRITE (6,280)
  280 FORMAT (1X,24HSIMULATION PERIOD(DAYS)?)
      READ (5,100) LIMIT
      LIMIT = LIMIT * NMPD
      WRITE (6,281)
  281 FORMAT (1X,19HSIMULATION DETAILS?)
      READ (5,102) AB
  102 FORMAT (A1)
      I = 1
      CALL COMP(I,AA,I,AB,I)
      INF = I + 1
      IF (INF .EQ. 1) RETURN
      WRITE (6,282)
  282 FORMAT (1X,23HDETAILS....(1) ANALYSIS/12X,11H(2) TESTING/1X,1H?)
      READ (5,100) I
      INF = I + 1
      RETURN
      END
      SUBROUTINE ENTSET
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
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     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      CALL SIMON
      DO 300 I = 1, NMT
      CALL GROUP(GMC(1,I),NMC(I),I)
  300 CONTINUE
      CALL ENTITY(ELIMIT,NMT+1)
      CALL ENTITY(ETPA,NMT+2)
      CALL ENTITY(EPAGEN,NMT+3)
      DO 310 I = 1, NMT
      CALL SET(SMC(I))
      CALL SET(SPA(I))
      CALL SET(SOB(I))
  310 CONTINUE
      CALL SET(SMN)
      CALL SET(SQMENS)
      CALL SET(SQMENR)
      CALL SET(SUTIL1)
      CALL SET(SUTIL2)
      CALL SET(SUTIL3)
      RETURN
      END
      SUBROUTINE PRIME(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IF (IA .EQ. 2) GO TO 400
C     STARTING WITH AN EMPTY SHOP
      DO 300 I = 1, NMT
      DO 301 J = 1, NMC(I)
      CALL ADDLA(MC(J,I),SMC(I))
      TSU(J,I) = 0
      MC(J,I) = CLOCK
      MCCD(J,I) = 3
  301 CONTINUE
      MCID(I) = 1
  300 CONTINUE
      DO 310 I = 1, NOPT
      DO 311 J = 1, NMN(I)
      M = I * 100 + J
      CALL ADDLA(M,SMN)
      MNCD(J,I) = 3
      MN(J,I) = CLOCK
  311 CONTINUE
  310 CONTINUE
  400 RETURN
      END
      SUBROUTINE TIDYUP
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      DO 300 I = 1, NMT
      DO 301 J = 1, NMC(I)
      M = MCCD(J,I)
      GO TO (10,10,20,30),M
C     MC - SETTING/RUNNING
   10 MCWA(M,I) = MCWA(M,I) + TIMEV(GMC(J,I)) - CLOCK
      GO TO 301
C     MC - AWAITS RUN
   30 M = 2
      GO TO 400
C     MC - AWAITS SET/PART
   20 M = 5 - 2 * MCID(I)
  400 MCIT(M,I) = MCIT(M,I) + CLOCK - MC(J,I)
      MC(J,I) = CLOCK
  301 CONTINUE
  300 CONTINUE
      DO 310 I = 1, NOPT
      DO 311 J = 1, NMN(I)
      M = MNCD(J,I)
      IF (M .EQ. 3) GO TO 410
C     OPERATOR - SETTING/RUNNING
      N = BSORT(M,1)
      M = BSORT(M,2)
      MNWA(M,I) = MNWA(M,I) + TIMEV(N) - CLOCK
      GO TO 311
  410 MNIT(I) = MNIT(I) + CLOCK - MN(J,I)
      MN(J,I) = CLOCK
  311 CONTINUE
  310 CONTINUE
      RETURN
      END
      SUBROUTINE INOB
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      READ (5,100) N
  100 FORMAT (I10)
      J = 0
      DO 300 I = 1, N
      READ (5,101) (IY(K), K = 1, 7)
  101 FORMAT (7I10)
  410 LMM = LMM + 1
      IF (LMM .GT. MAXPA) LMM = 1
C     CHECK IF PART LMM IS STILL IN CIRCULATION
      IF (PB(3,LMM) .LT. 0) GO TO 400
      IF (LMM .EQ. J) CALL SLIP(0,5,0,0)
      IF (J .EQ. 0) J = LMM
      GO TO 410
C     PART LMM ACCEPTED - ALLOCATE PART DETAILS
  400 PB(1,LMM) = IY(2) * 100 + IY(7)
      PB(2,LMM) = (IY(5)*NMPD)/8 + CLOCK
      PB(3,LMM) = (IY(4)*NMPD)/8 + CLOCK
      PB(4,LMM) = NSL + 1000 * IY(3)
      PB(5,LMM) = IY(6) + 2000000
      PB(6,LMM) = IY(1)
      IY(6) = PB(3,LMM)
      M = 0
      DO 310 L = 1, IY(7)
      IF (NOC .EQ. 0) CALL SLIP(0,6,0,0)
      READ (5,102) (IY(K), K = 1,4)
  102 FORMAT (4I10)
      IY(3) = IY(3) + IY(6)
      M = M + IY(2) + IY(3)
      PA(1,NSL) = IY(3) + 1000 * IY(2)
      PA(2,NSL) = IY(4) + 1000 * IY(1)
      NSL = PA(3,NSL)
      NOC = NOC - 1
  310 CONTINUE
      M = M - PB(3,LMM)
      PB(5,LMM) = PB(5,LMM) + M
      LINE = BSORT(PB(4,LMM),1)
      IXX = BSORT(PA(2,LINE),1)
      CALL QUEUP(-LMM,SOB(IXX))
  300 CONTINUE
      READ (5,100) N
      N = N * NMPD
      CALL EVENT(EPAGEN,N,1)
      RETURN
      END
      SUBROUTINE INSHOP(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
  499 GO TO (10,20),IA
   10 M = WIQ(IXX)
      GO TO 400
   20 M = MCLDQ(IXX)
  400 IF (M .GE. QTRIG(IXX)) GO TO 498
  411 IF (SIZEO(SOB(IXX)) .EQ. 0) GO TO 498
      IYY = HEADO(SOB(IXX))
      IF (PB(2,IYY) .GT. CLOCK) GO TO 410
      CALL BEHEA(SOB(IXX))
      PB(2,IYY) = CLOCK + 100
      CALL REALLO(IYY)
      CALL QUEUP(IYY,SPA(IXX))
      IF (MCID(IXX) .NE. 1) GO TO 430
      MCID(IXX) = 2
      CALL ADDLA(IXX,SQMENS)
      DO 310 I = 1, SIZEO(SMC(IXX))
      M = HEADO(SMC(IXX))
      M = MEMNU(M)
      MCIT(3,IXX) = MCIT(3,IXX) + CLOCK - MC(M,IXX)
      MC(M,IXX) = CLOCK
      CALL ROTAT(SMC(IXX),1)
  310 CONTINUE
  430 WIQ(IXX) = WIQ(IXX) + 1
      INPA = INPA + 1
      IF (WIQ(IXX) .GT. WIQMX(IXX)) WIQMX(IXX) = WIQ(IXX)
      MOV1(1,IXX) = MOV1(1,IXX) + 1
      IF (INF .EQ. 3) CALL WRIINF(20,0,0,0)
      PT(IYY) = CLOCK
      L = ASORT(PB(1,IYY),2)
      LINE = BSORT(PB(4,IYY),1)
      DO 300 I = 1, L
      J = BSORT(PA(1,LINE),1) + BSORT(PA(1,LINE),2)
      IF (I .NE. 1) GO TO 420
      MCLDQ(IXX) = MCLDQ(IXX) + J
      M = IXX
      GO TO 421
  420 M = BSORT(PA(2,LINE),2)
  421 MCLDP(M) = MCLDP(M) + J
      LINE = PA(3,LINE)
  300 CONTINUE
      GO TO 499
  410 CALL ADDLA(IYY,SUTIL3)
      CALL BEHEA(SOB(IXX))
      GO TO 411
  498 IF (SIZEO(SUTIL3) .EQ. 0) RETURN
      M = TAILO(SUTIL3)
      CALL ADDFI(M,SOB(IXX))
      CALL BETAI(SUTIL3)
      GO TO 498
      END
      SUBROUTINE MAPRI(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      GO TO (10,20),IA
   10 ISET = SQMENS
      GO TO 11
   20 ISET = SQMENR
   11 L = SIZEO(ISET)
      IF (L .EQ. 0) RETURN
      J = 0
      K = -10
      DO 300 I = 1, L
      M = HEADO(ISET)
      IF (IA .EQ. 1) GO TO 400
      M = BSORT(M,1)
      M = REFNU(M)
  400 N = MCLDQ(M)
      IF (N .LE. K) GO TO 410
      J = I
      K = N
  410 CALL ROTAT(ISET,1)
  300 CONTINUE
      CALL ROTAT(ISET,J-1)
      RETURN
      END
      SUBROUTINE PASEL(M)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IYY = HEADO(SPA(IXX))
      IF (IPQ .EQ. 0) GO TO 400
      IF (PB(5,IYY) .GT. 3000000) GO TO 400
      J = PB(5,IYY) - 2000000 + CLOCK
      IF (J .GE. 0) GO TO 400
      LL1 = 99999
      LL2 = 99999
      M = 0
      DO 310 I = 1, SIZEO(SPA(IXX))
      K = HEADO(SPA(IXX))
      LINE = BSORT(PB(4,K),1)
      IF (IPQ .EQ. 1) GO TO 22
      LPSU = BSORT(PA(2,LINE),1)
      IF (LPSU) 21,22,23
C     NO SETTING RED'D
   21 L = BSORT(PA(1,LINE),1)
      IF (L .GE. LL2) GO TO 430
      LL2 = L
      K2 = K
      GO TO 430
C     SETING REQ'D
   22 L = BSORT(PA(1,LINE),1) + BSORT(PA(1,LINE),2)
      IF (L .GE. LL1) GO TO 430
      LL1 = L
      K1 = K
      GO TO 430
   23 DO 320 II = 1, SIZEO(SMC(IXX))
      N = HEADO(SMC(IXX))
      N = MEMNU(N)
      IF (LPSU .EQ. TSU(N,IXX)) GO TO 21
      CALL ROTAT(SMC(IXX),1)
  320 CONTINUE
      GO TO 22
  430 CALL ROTAT(SPA(IXX),1)
  310 CONTINUE
      IF (IPQ .EQ. 1) GO TO 440
      IF (LL2 .EQ. 99999) GO TO 440
      K1 = K2
      LL1 = LL2
      M = 2
  440 IF (K1 .EQ. IYY) GO TO 450
      IF (LL1+J) 460,460,400
  460 CALL DELET(K1,SPA(IXX))
      CALL ADDFI(K1,SPA(IXX))
      IYY = K1
  450 IF (IPQ .EQ. 1) GO TO 400
      IF (M .EQ. 0) M = 1
      RETURN
  400 LINE = BSORT(PB(4,IYY),1)
      M = BSORT(PA(2,LINE),1)
      IF (M) 10,20,30
   10 M = 2
      RETURN
   20 M = 1
      RETURN
   30 DO 300 I = 1, SIZEO(SMC(IXX))
      N  = HEADO(SMC(IXX))
      N = MEMNU(N)
      IF (M .EQ. TSU(N,IXX)) GO TO 10
      CALL ROTAT(SMC(IXX),1)
  300 CONTINUE
      M= 1
      RETURN
      END
      SUBROUTINE QUEUP(M,ISET)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IF (M .LT. 0) GO TO 421
      N = 0
  420 L  = SIZEO(ISET)
      IF (L .EQ. 0) GO TO 400
      DO 300 I = 1, L
      J = HEADO(ISET)
      IF (IPP .GT. 10) GO TO 410
      GO TO (13,12,12),IPP
  410 K = IPP - 10
      GO TO (13,12,13,12,13,12,13),K
   12 IF (PB(5,M) .GT. 3000000) GO TO 430
      IF (PB(5,J) .GT. 3000000) GO TO 412
  431 IF (PB(5,M) - PB(5,J)) 411,412,412
  430 IF (PB(5,J) .GT. 3000000) GO TO 431
      GO TO 411
   13 IF (PB(5,M) - PB(5,J)) 412,412,411
  412 CALL ROTAT(ISET,1)
  300 CONTINUE
  400 CALL ADDLA(M,ISET)
      IF (N .NE. 0) IPP = N
      RETURN
  421 M = -M
      N = IPP
      IPP = 1
      GO TO 420
  411 CALL ADDFI(M,ISET)
      IF (I .EQ. 1) GO TO 413
      CALL ROTAT(ISET,L+2-I)
  413 IF (N .NE. 0) IPP = N
      RETURN
      END
      SUBROUTINE PAPRI(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IF (IA .EQ. 2) GO TO 400
C     ALLOCATION OF PRIORITY
      IF (IPP .GT. 10) GO TO 410
      GO TO (11,12,13),IPP
   12 J = PB(3,IYY)
      GO TO 499
   13 J = ASORT(PB(2,IYY),1)
      GO TO 499
  410 M = IPP - 10
      GO TO (21,21,21,21,21,23,23),M
   21 J = 0
      N = ASORT(PB(1,IYY),2)
      L = ASORT(PB(1,IYY),1)
      IF (M .GT. 3) GO TO 22
      LINE = BSORT(PB(4,IYY),1)
      DO 300 I = 1, L
      J = J + BSORT(PA(1,LINE),1) + BSORT(PA(1,LINE),2)
      LINE = PA(3,LINE)
  300 CONTINUE
      IF (M .NE. 1) GO TO 499
      J = J + QTIME * L - PB(3,IYY)
      GO TO 499
   22 J = L
      GO TO 499
   23 LINE = BSORT(PB(4,IYY),1)
  420 J = BSORT(PA(1,LINE),1) + BSORT(PA(1,LINE),2)
  499 PB(5,IYY) = PB(5,IYY) + J
   11 RETURN
C     ADJUSTMENT OF PRIORITY ON COMPLETION OF AN OPERATION
  400 LINE = BSORT(PB(4,IYY),1)
      M = IPP - 10
      GO TO (31,31,31,32,32,31,31),M
   31 J = BSORT(PA(1,LINE),1) + BSORT(PA(1,LINE),2)
      GO TO (41,42,42,43,43,44,44),M
   41 J = J + QTIME
   42 PB(5,IYY) = PB(5,IYY) - J
   43 RETURN
   44 PB(5,IYY) = PB(5,IYY) - J
      LINE = PA(3,LINE)
      GO TO 420
   32 J = 1
      GO TO 42
      END
      SUBROUTINE SEARCH
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IF (SIZEO(SMN) .EQ. 0) RETURN
      L = SIZEO(SQMENR)
      IF (L .EQ. 0) GO TO 400
      DO 300 I = 1, L
      CALL MAPRI(2)
      CALL LOKOPR(2)
      IF (SIZEO(SMN) .EQ. 0) GO TO 430
  300 CONTINUE
  430 L = SIZEO(SUTIL1)
      IF (L .EQ. 0) GO TO 401
      DO 301 I = 1, L
      M = HEADO(SUTIL1)
      CALL ADDLA(M,SQMENR)
      CALL BEHEA(SUTIL1)
  301 CONTINUE
  401 IF (SIZEO(SMN) .EQ. 0) RETURN
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  400 IF (SIZEO(SQMENS) .EQ. 0) RETURN
  441 CALL MAPRI(1)
      IXX = HEADO(SQMENS)
      CALL PASEL(M)
      IF (M .EQ. 1) GO TO 410
C     SETTING UP NOT REQD.
      N = HEADO(SMC(IXX))
      M = MEMNU(N)
      MCIT(1,IXX) = MCIT(1,IXX) + CLOCK - MC(M,IXX)
      MC(M,IXX) = CLOCK
      MCCD(M,IXX) = 4
      WIQ(IXX) = WIQ(IXX) - 1
      LINE = BSORT(PB(4,IYY),1)
      M = BSORT(PA(1,LINE),2)
      MCLDQ(IXX) = MCLDQ(IXX) - M
      MCLDP(IXX) = MCLDP(IXX) - M
      PT(IYY) = -PT(IYY)
      N = N * 1000 + IYY
      CALL ADDFI(N,SQMENR)
      CALL BEHEA(SMC(IXX))
      CALL DELET(IYY,SPA(IXX))
      CALL INSNOP(IQ)
      IF (SIZEO(SMC(IXX)) .EQ. 0) GO TO 420
      IF (SIZEO(SPA(IXX)) .NE. 0) GO TO 422
      MCID(IXX) = 1
      DO 330 J = 1, SIZEO(SMC(IXX))
      M = HEADO(SMC(IXX))
      M = MEMNU(M)
      MCIT(1,IXX) = MCIT(1,IXX) + CLOCK - MC(M,IXX)
      MC(M,IXX) = CLOCK
      CALL ROTAT(SMC(IXX),1)
  330 CONTINUE
  421 CALL BEHEA(SQMENS)
  422 CALL LOKOPR(2)
      L = SIZEO(SUTIL1)
      IF (L .EQ. 0) GO TO 423
      M = HEADO(SUTIL1)
      CALL ADDLA(M,SQMENR)
      CALL BEHEA(SUTIL1)
      GO TO 440
C     SETTING UP REQD.
  410 CALL LOKOPR(1)
  423 IF (SIZEO(SMN) .EQ. 0) GO TO 442
      GO TO 440
  420 MCID(IXX) = 0
      GO TO 421
  440 IF (SIZEO(SQMENS) .NE. 0) GO TO 441
  442 L = SIZEO(SUTIL2)
      IF (L .EQ. 0) RETURN
      DO 340 I = 1, L
      M = HEADO(SUTIL2)
      CALL ADDLA(M,SQMENS)
      CALL BEHEA(SUTIL2)
  340 CONTINUE
      RETURN
      END
      SUBROUTINE LOKOPR(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IF (IA .EQ. 1) GO TO 400
      J = HEADO(SQMENR)
      IYY = BSORT(J,2)
      L = BSORT(J,1)
      IXX = REFNU(L)
      IZZ = 0
      DO 300 I = 1, SIZEO(SMN)
      K = HEADO(SMN) * 1000
      N = BSORT(K,3)
      M = MCMN(N,IXX) + 1
      GO TO (11,11,12,13),M
   13 IF (IZZ .NE. 0) GO TO 11
      IZZ = K
   11 CALL ROTAT(SMN,1)
  300 CONTINUE
      IF (IZZ .EQ. 0) GO TO 410
  411 LINE = BSORT(PB(4,IYY),1)
      BIND = BSORT(PA(4,LINE),1)
      IF (PT(IYY) .GE. 0) GO TO 412
      M = CLOCK + PT(IYY) + 1
      PTIT(IXX) = PTIT(IXX) + M
      IF (M .GT. PTITMX(IXX)) PTITMX(IXX) = M
      NPAI(IXX) = NPAI(IXX) + 1
  412 M = IYY + IZZ
      CALL EVENT(L,BIND,M)
      M = MEMNU(L)
      MCCD(M,IXX) = 2
      MCIT(2,IXX) = MCIT(2,IXX) + CLOCK - MC(M,IXX)
      MCWT(2,IXX) = MCWT(2,IXX) + BIND
      N = BSORT(IZZ,3)
      J = BSORT(IZZ,4)
      MNCD(J,N) = L * 1000 + 2
      IF (INF .EQ. 2) CALL WRIINF(2,M,N,J)
      MNIT(N) = MNIT(N) + CLOCK - MN(J,N)
      MNWT(2,N) = MNWT(2,N) + BIND
      IZZ = IZZ / 1000
      CALL DELET(IZZ,SMN)
      CALL BEHEA(SQMENR)
      RETURN
   12 IF (I .NE. 1) CALL ROTAT(SMN,-(I-1))
      IZZ = K
      GO TO 411
  410 CALL ADDLA(J,SUTIL1)
      CALL BEHEA(SQMENR)
      RETURN
  400 IZZ = 0
      DO 320 I = 1, SIZEO(SMN)
      K = HEADO(SMN) * 1000
      N = BSORT(K,3)
      M = MCMN(N,IXX) + 1
      GO TO (21,22,21,23),M
   23 IF (IZZ .NE. 0) GO TO 21
      IZZ = K
   21 CALL ROTAT(SMN,1)
  320 CONTINUE
      IF (IZZ .EQ. 0) GO TO 420
  421 LINE = BSORT(PB(4,IYY),1)
      BIND = BSORT(PA(1,LINE),2)
      L = HEADO(SMC(IXX))
      M = IYY + IZZ
      CALL EVENT(L,BIND,M)
      M = MEMNU(L)
      MCCD(M,IXX) = 1
      J = BSORT(PA(2,LINE),1)
      TSU(M,IXX) = J
      MCIT(1,IXX) = MCIT(1,IXX) + CLOCK - MC(M,IXX)
      MCWT(1,IXX) = MCWT(1,IXX) + BIND
      N = BSORT(IZZ,3)
      J = BSORT(IZZ,4)
      MNCD(J,N) = L * 1000 + 1
      IF (INF .EQ. 2) CALL WRIINF(1,M,N,J)
      MNIT(N) = MNIT(N) + CLOCK - MN(J,N)
      MNWT(1,N) = MNWT(1,N) + BIND
      WIQ(IXX) = WIQ(IXX) - 1
      M = CLOCK - PT(IYY)
      IF (M .GT. PTITMX(IXX)) PTITMX(IXX) = M
      NPAI(IXX) = NPAI(IXX) + 1
      PTIT(IXX) = PTIT(IXX) + M
      CALL DELET(IYY,SPA(IXX))
      K = IZZ / 1000
      CALL DELET(K,SMN)
      CALL BEHEA(SMC(IXX))
      IF (SIZEO(SMC(IXX)) .EQ. 0) GO TO 430
      IF (SIZEO(SPA(IXX)) .NE. 0) RETURN
      MCID(IXX) = 1
      DO 330 J = 1, SIZEO(SMC(IXX))
      M = HEADO(SMC(IXX))
      M = MEMNU(M)
      MCIT(1,IXX) = MCIT(1,IXX) + CLOCK - MC(M,IXX)
      MC(M,IXX) = CLOCK
      CALL ROTAT(SMC(IXX),1)
  330 CONTINUE
  441 CALL BEHEA(SQMENS)
      RETURN
   22 IF (I .NE. 1) CALL ROTAT(SMN,-(I-1))
      IZZ = K
      GO TO 421
  420 CALL ADDLA(IXX,SUTIL2)
      CALL BEHEA(SQMENS)
      RETURN
  430 MCID(IXX) = 0
      GO TO 441
      END
      SUBROUTINE REALLO(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IF (IA .NE. 0) GO TO 450
      DO 300 I = 1, NMT
      DO 301 J = 1, NMC(I)
      IF (MCCD(J,I) .GT. 2) GO TO 301
      N = BOUND(GMC(J,I))
      IYY = BSORT(N,2)
      K = 1
  420 IF (PB(5,IYY) .GT. 3000000) GO TO 400
      PB(5,IYY) = 2000000
      GO TO 410
  400 PB(5,IYY) = 4000000
  410 CALL PAPRI(1)
      GO TO (301,430,440,330,451),K
  301 CONTINUE
      L = SIZEO(SPA(I))
      IF (L .EQ. 0) GO TO 300
      DO 310 J = 1, L
      IYY = HEADO(SPA(I))
      K = 2
      GO TO 420
  430 CALL ROTAT(SPA(I),1)
  310 CONTINUE
  300 CONTINUE
      L = SIZEO(SQMENR)
      IF (L .EQ. 0) GO TO 431
      DO 320 I = 1, L
      N = HEADO(SQMENR)
      IYY = BSORT(N,2)
      K = 3
      GO TO 420
  440 CALL ROTAT(SQMENR,1)
  320 CONTINUE
  431 IF (NPC .EQ. 0) RETURN
      DO 330 I = 1, NPC
      IYY = BSORT(PC(1,I),2)
      K = 4
      GO TO 420
  330 CONTINUE
      RETURN
  450 K = 5
      GO TO 420
  451 RETURN
      END
      INTEGER FUNCTION ASORT(IA,IB)
      ASORT = IA / 100
      IF (IB .EQ. 1) RETURN
      ASORT = IA - ASORT * 100
      RETURN
      END
      INTEGER FUNCTION BSORT(IA,IB)
      BSORT = IA / 1000
      GO TO (10,20,30,40),IB
   20 BSORT = IA - BSORT * 1000
      BSORT = IABS(BSORT)
   10 RETURN
   30 BSORT = BSORT / 100
      RETURN
   40 M = BSORT / 100
      BSORT = BSORT - M * 100
      RETURN
      END
      SUBROUTINE REPORT(IA)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      DIMENSION Y(6),SUM(5),ISUM(3)
      GO TO (10,20,30),IA
   10 WRITE (6,200)
  200 FORMAT (/7X,7HMC TOOL,25X,17HPARTS QUE. RECORD,2X,
     @ 10HQUEUE LOAD/1X,2HMC,4X,7HENGAGED,6X,16HMC  TOOL  AWAITS,
     @ 5X,4HTIME,5X,4HSIZE,4X,5HIMME-,1X,5HPOTE-/1X,4HTYPE,2X,
     @ 29HSET   RUN    SET   RUN    PART,4X,3HAVG,2X,3HMAX,3X,3HMAX,
     @ 4X,5HDIATE,1X,5HNTIAL/)
      DO 303 I = 1, 5
      SUM(I) = 0.0
  303 CONTINUE
      DO 304 I = 1, 3
      ISUM(I) = 0
  304 CONTINUE
      DO 300 I = 1, NMT
      Y(1) = FLOAT(LIMIT*NMC(I))
      DO 301 J = 1, 2
      Y(J+1) = FLOAT(MCWT(J,I)-MCWA(J,I))/Y(1)
      SUM(J) = SUM(J) + Y(J+1)
  301 CONTINUE
      DO 302 J = 1, 3
      Y(J+3) = FLOAT(MCIT(J,I))/Y(1)
      SUM(J+2) = SUM(J+2) + Y(J+3)
  302 CONTINUE
      IF (NPAI(I) .EQ. 0) GO TO 400
      M = PTIT(I) / NPAI(I)
      ISUM(1) = ISUM(1) + M
      ISUM(2) = ISUM(2) + MCLDQ(I)
      ISUM(3) = ISUM(3) + MCLDP(I)
      GO TO 410
  400 M = 0
  410 WRITE(6,210)I,(Y(J),J=2,6),M,PTITMX(I),WIQMX(I),MCLDQ(I),MCLDP(I)
  210 FORMAT (1X,I2,4X,2(F5.3,1X),1X,3(F5.3,1X),1X,2(I4,1X),I4,
     @ 5X,2(I4,2X))
  300 CONTINUE
      Y(1) = FLOAT(NMT)
      DO 305 I = 1, 5
      SUM(I) = SUM(I) / Y(1)
  305 CONTINUE
      ISUM(1) = ISUM(1) / NMT
      WRITE (6,211) (SUM(I),I=1,5),(ISUM(I),I=1,3)
  211 FORMAT (1X,4HSHOP,2X,2(F5.3,1X),1X,3(F5.3,1X),1X,I4,15X,
     @ 2(I4,2X))
      RETURN
   20 WRITE (6,206)
  206 FORMAT (/1X,27HOPERATOR PERFORMANCE RECORD//1X,4HTYPE,4X,
     @ 3HSET,4X,3HRUN,4X,4HIDLE)
      DO 310 I = 1, NOPT
      Y(1) = FLOAT(LIMIT*NMN(I))
      DO 311 J = 1, 2
      Y(J+1) = FLOAT(MNWT(J,I)-MNWA(J,I))/Y(1)
  311 CONTINUE
      Y(4) = FLOAT(MNIT(I))/Y(1)
      WRITE (6,220) I, (Y(J), J = 2,4)
  220 FORMAT (1X,I2,6X,3(F5.3,2X))
  310 CONTINUE
      RETURN
C     PARTS ROUTE TRACING
   30 WRITE (6,230)
  230 FORMAT (/22X,19HPARTS ROUTE TRACING//16X,8HTO START/16X,
     @ 10HAT MC TYPE,6X,19H1  2  3  4  5  6  0/
     @ 1X,11HFROM FINISH/1X,10HAT MC TYPE)
      N = 0
      DO 330 I = 1, NMT + 1
      M = I - 1
      WRITE (6,231) M,(MOV1(I,J),J=1,7)
  231 FORMAT (5X,I2,23X,7I3)
      IF (I .EQ. 1) GO TO 330
      DO 331 J = 1, 7
      N = N + MOV1(I,J)
  331 CONTINUE
  330 CONTINUE
      M = HDELT(11) + HDELE(11)
      WRITE (6,232) INPA,M,N
  232 FORMAT (/1X,14HPARTS INTAKE =,I4,4X,17HPARTS COMPLETED =,
     @ I4,4X,16HOPS. COMPLETED =,I4)
      RETURN
      END
      SUBROUTINE HIST(IH,H,A,B)
      DIMENSION IH(11),H(6)
      DO 300 I = 1, 11
      IH(I) = 0
  300 CONTINUE
      H(1) = 0.0
      H(2) = 0.0
      H(3) = -9999.
      H(4) = 9999.
      H(5) = A
      H(6) = B
      RETURN
      END
      SUBROUTINE ADDHIS(A,IH,H)
      DIMENSION IH(11),H(6)
      V = H(5)
      DO 300 I = 1, 9
      IF (V - A) 400,401,401
  401 IH(I) = IH(I) + 1
      GO TO 410
  400 V = V + H(6)
  300 CONTINUE
      IH(10) = IH(10) + 1
  410 IH(11) = IH(11) + 1
      H(1) = H(1) + A
      H(2) = H(2) + A * A
      IF (A .GT. H(3)) H(3) = A
      IF (A .LT. H(4)) H(4) = A
      RETURN
      END
      SUBROUTINE WRIHIS(IH,H)
      DIMENSION IH(11),H(6),Y(10)
      IF (IH(11) .EQ. 0) GO TO 401
      SD = 999.
      E = FLOAT (IH(11))
      AM = H(1) / E
      IF (IH(11) .EQ. 1) GO TO 410
      Y1 = H(2)/E - (AM*AM)
      Y1 = (Y1*E)/(E-1.)
      IF (Y1 .LT. 0) GO TO 410
      SD = SQRT(Y1)
  410 WRITE (6,220) AM,SD,H(3),H(4),IH(11)
  220 FORMAT (/1X,5HMEAN=,F8.4,3X,3HSD=,F8.4,3X,4HMAX=,F8.4,3X,
     @ 4HMIN=,F8.4,3X,8HENTRIES=,I3/)
      DO 300 I = 1, 10
      Y(I) = FLOAT(IH(I)) * 100. / E
  300 CONTINUE
      WRITE (6,221) (Y(I), I = 1, 10)
  221 FORMAT (1X,1H%,2X,10(F6.2,1X))
      DO 320 I = 1, 9
      Y(I) = H(5) + FLOAT(I-1) * H(6)
  320 CONTINUE
      WRITE (6,210) (Y(I),I= 1,9)
  210 FORMAT (1X,4HHRS.,3X,9(F4.0,3X))
      RETURN
  401 WRITE (6,230)
  230 FORMAT (/33X,10HNO ENTRIES/)
      RETURN
      END
      SUBROUTINE MOVEPA
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      IF (NPC .EQ. PCMX) GO TO 420
      LINE = BSORT(PB(4,IYY),1)
      M = BSORT(PA(2,LINE),2)
      Y1 = FLOAT(TTM(M,IXX))
      Y2 = FLOAT(TTSD(M,IXX))
      M = IFIX(G05AEF(Y1,Y2))
      IF (M .LT. 0) M = 0
      M = M + CLOCK
      IF (NPC .EQ. 0) GO TO 400
      DO 300 I = 1, NPC
      IF (M .LT. PC(2,I)) GO TO 410
  300 CONTINUE
  411 NPC = NPC + 1
      PC(1,NPC) = IYY + IXX * 1000
      PC(2,NPC) = M
      RETURN
  410 IF (I .EQ. 1) GO TO 430
  431 K = NPC - I + 1
      DO 310 J = 1, K
      L = NPC + 1 - J
      PC(1,L+1) = PC(1,L)
      PC(2,L+1) = PC(2,L)
  310 CONTINUE
      PC(1,I) = IYY + IXX * 1000
      PC(2,I) = M
      NPC = NPC + 1
      RETURN
  400 N = M - CLOCK
      CALL EVENT(ETPA,N,1)
      GO TO 411
  430 CALL DELET(ETPA,TIMES)
      NEWTI = M - CLOCK
      CALL EVENT(ETPA,NEWTI,1)
      GO TO 431
  420 WRITE (6,200)
  200 FORMAT (1X,25HERROR - PC ARRAY OVERFLOW)
      CALL EXIT
      END
      SUBROUTINE ENDTPA
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      J = 1
      IYY = BSORT(PC(1,1),2)
      LINE = BSORT(PB(4,IYY),1)
      IXX = BSORT(PA(2,LINE),2)
      CALL QUEUP(IYY,SPA(IXX))
      M = BSORT(PC(1,1),1) + 1
      MOV1(M,IXX) = MOV1(M,IXX) + 1
      IF (INF .EQ. 3) CALL WRIINF(21,0,0,0)
      IF (MCID(IXX) .NE. 1) GO TO 400
      MCID(IXX) = 2
      CALL ADDLA(IXX,SQMENS)
      DO 310 I = 1, SIZEO(SMC(IXX))
      M = HEADO(SMC(IXX))
      M = MEMNU(M)
      MCIT(3,IXX) = MCIT(3,IXX) + CLOCK - MC(M,IXX)
      MC(M,IXX) = CLOCK
      CALL ROTAT(SMC(IXX),1)
  310 CONTINUE
      J = 2
  400 WIQ(IXX) = WIQ(IXX) + 1
      IF (WIQ(IXX) .GT. WIQMX(IXX)) WIQMX(IXX) = WIQ(IXX)
      MCLDQ(IXX) = MCLDQ(IXX)+BSORT(PA(1,LINE),1)+BSORT(PA(1,LINE),2)
      PT(IYY) = CLOCK
      NPC = NPC - 1
      IF (NPC .EQ. 0) GO TO 320
      DO 300 I = 1, NPC
      PC(1,I) = PC(1,I+1)
      PC(2,I) = PC(2,I+1)
  300 CONTINUE
      M = PC(2,1) - CLOCK
      CALL EVENT(ETPA,M,1)
  320 IF (J .EQ. 2) CALL SEARCH
      RETURN
      END
      SUBROUTINE LOKSET(ISET)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      L = SIZEO(ISET)
      IF (L .EQ. 0) RETURN
      DO 300 I = 1, L
      M = HEADO(ISET)
      WRITE (6,200) M
  200 FORMAT (1X,I7)
      CALL ROTAT(ISET,1)
  300 CONTINUE
      RETURN
      END
      SUBROUTINE WRIINF(IA,IB,IC,ID)
      INTEGER TAILM,MAST1(400),MAST2(400),STATE,TIMES,CLOCK,
     + SIZEO,HEADO,TAILO,REFNU,BOUND,TIMEV,ASORT,BSORT,
     + PA(3,700),PB(6,120),PC(2,40),GMC(4,6),ETPA,ELIMIT,EPAGEN,
     + SMC(6),SPA(6),SOB(6),SMN,SQMENS,SQMENR,SUTIL1,SUTIL2,SUTIL3,
     + MC(4,6),MCCD(4,6),MCID(6),WIQ(6),WIQMX(6),MCLDQ(6),MCLDP(6),
     + MCLDA(6),QTRIG(6),NMC(6),MCWT(2,6),MCIT(3,6),MCWA(2,6),TSU(4,6),
     + MN(6,12),MNCD(6,12),NMN(12),MNWT(2,12),MNIT(12),MNWA(2,12),
     + MCMN(12,6),PT(120),PTIT(6),PTITMX(6),NPAI(6),HDELT(11),
     + HDELE(11),HTRU(11),TTM(6,6),TTSD(6,6),MOV1(7,7),
     + ALT(2,6,6),IY(10),BIND,QTIME,PCMX
      DIMENSION HDT(6),HDE(6),HT(6)
      COMMON NIM,TAILM,MAST1,MAST2,STATE,NAME,TIMES,CLOCK,MEMBE,
     + PA,PB,PC,GMC,ETPA,ELIMIT,EPAGEN,SMC,SPA,SOB,SMN,SQMENS,SQMENR,
     + SUTIL1,SUTIL2,SUTIL3,MC,MCCD,MCID,WIQ,WIQMX,MCLDQ,MCLDP,MCLDA,
     + QTRIG,NMC,MCWT,MCIT,MCWA,TSU,MN,MNCD,NMN,MNWT,MNIT,MNWA,
     + MCMN,PT,PTIT,PTITMX,NPAI,HDELT,HDELE,HTRU,ALT,MOV1,IY,BIND,
     + IXX,IYY,IZZ,INPA,IQ,LMM,NMT,NOPT,MAXPA,NMPD,LINE,NSL,NOC,
     + LIMIT,IPP,IPQ,NPC,INF,TTM,TTSD,QTIME,PCMX,LF1,LF2,LF3
      COMMON HDT,HDE,HT,DELT1,DELT2,DELE1,DELE2,TRU1,TRU2
      WRITE (3,200) IA,IXX,IB,IC,ID,PB(6,IYY),CLOCK
  200 FORMAT (1X,7I6)
      RETURN
      END

*** END OF STREAM  PR134S       5431
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