COPPEAD/UFRJ

RELATÓRIO COPPEAD Nº 12

AN EXPERIMENTAL INVESTIGATION OF PRIORITY DISPATCHING RULES FOR A SHOE BATCH PRODUCTION SYSTEM

Paulo F. Fleury*

November, 1977

* COPPEAD-Federal University of Rio de Janeiro. This paper draws from my Ph.D. dissertation of Loughborough University of Technology. I am grateful to Dr. E. A. Roberts my research supervisor for our lengthy discussions and his suggestions.

I. INTRODUCTION

The problem of dispatching in batch or job shop systems has atracted the attention of research workers over the years.

Among the many approaches tried, the development of simple priority rules has received special attention. In order to test the efficiency of those rules a number of computer simulation experiments have been conducted, in which the performances of the rules were compared, using different shop characteristics. Examples of such studies can be found in Conway (1960, 1962, 1964), Hollier (1968), Eilon and Coterill (1968), Agarwal et al (1973), Oral and Malouin(1973), Eilon and Hodgson (1967), Berry (1972), Rochette and Sadowski (1976), to name only a few.

Most of the earlier work were based in abstract models which were designed to represent a general class of batch or job shop production systems. This was done in order to allow the results of those studies to be transferable to as wide a range of situations as possible. Unfortunately some batch production systems have characteristics so different from the ones assumed in those abstract models, that conclusions obtained from them cannot be easily transferable. For this reason, other investigations were conducted, using more specific models. This is the case with this investigation, which presents the results of experiments conducted through a computer simulation model, of a class of production systems, producing in batches, and having unique characteristics.

Three of the major characteristics which make this class of production systems unique among the general class of batch production systems are:

(i) The pattern of demand, which is characterized by the fact that orders arriving at the system require the production and quick delivery of a multi-size product range. The quantities required for individual product sizes being different from each other.

(ii) The manufacturing units composed of multiple station machines which are able to manufacture different products at a time, and which require setting up.

(iii) The tooling requirement which is characterized by the fact that every product requires a special tool (mould). This, combined with the fact that the system manufactures a multi-style, multi-size product range, makes availability of tools a major constraint.

This type of system can be found for example in the shoe industry, for the manufacture of injection moulded shoes or shoe components.

II. DESCRIPTION OF THE PRODUCTION SYSTEM

Although the model was developed to represent a class of production systems, the original information which led to its construction was obtained from a particular company within the shoe industry which manufactures shoe components viz. Insoles, by an injection moulding process (For technical description of the product see Johnson, 1974).

In order to better describe the model, the original production system, as it was in the particular company described above, will be described first. For this purpose it can be divided into three major components: the products, the production units and the demand or order input.

The products are injection moulded shoe insoles, produced in different shapes and sizes. Each particular shape is called a style and is made up of a range consisting of up to 13 different sizes. This range results in the need for a corresponding range of injection moulds.

Because of design characteristics it is possible to manufacture the 13 products belonging to a range with only six corresponding moulds.

The production units consist of multiple station injection machines, each having twelve stations, laid out on a circular turntable which moves around its axe, and requiring one operator only. Each station is able to receive any mould, meaning that a machine can manufacture at the same time products of different sizes and style. Each mould when adjusted to the machine requires a substancial setup time.

The demand or order input Whose major characteristic is the fact that when a customer order a product of a certain style, he usually requires the full size range, with varying quantities for each size. Because there is a policy of starting production only after firm customer order, this means that each order implies the manufacture and joint delivery of up to 13 different batches of components.

Previous studies (McKay, 1929) showed that the distribution of foot sizes for adult men and women follow a normal distribution, and so it would be expected that the statistics for demand according to shoe sizes, should also fit a normal curve. However when actual data from sales were plotted and compared with data from actual foot sizes distribution it showed a drop in demand for half sizes, when compared with full sizes. These results agree with a similar comparison for men's shoes made by McKay (1929).

III. DESCRIPTION OF THE MODEL

The model being described was programmed in CSL, which is a general purpose simulation language provided by ICL. The use of this language made it possible to build a fairly flexible model in respect to the variables influencing the system, which can be easily varied. Its basic components are as follows:

a) The generation of orders is made independently for each product style. First the next arrival time is generated, followed by the generation of the total quantity Q, which will be required for that order. At arrival, this total quantity Q is divided among different product sizes in accordance with a distribution of proportional demand for the different sizes.

b) The machine shop is represented in the model by machines, moulds and a queue of 'jobs' waiting to be processed.
The main characteristics of the machines are the following:

(i) All machines have twelve stations, and the total number of machines is a parameter which can be varied in the model.

(ii) Any machine can operate both fully loaded (all 12 stations loaded), or it can operate partially loaded (at least one station unloaded).

(iii) Each machine is operated by a single operator, which is always available. It is also assumed that machines never break down.

(iv) Machines have a fixed cycle time, but they can be delayed by the operator whose cycle (load and unload the station) time is variable. For detailed description of cycle time generation, see Fleury, 1976 (1).

The main characteristics of the moulds are the following:

(i) Each mould is represented as an independent entity, which is able. to manufacture specific product sizes of a given style.

(ii) Any mould can be setup in any station of any machine, independent of what the other stations are producing.

(iii) Every time a new mould is setup in a station, a setup time is generated from a probability distribution and its value is added to the expected completion time of all 'jobs' already loaded in the other stations of the same machine.

(iv) the total number of moulds is a parameter of the model.

It is also assumed that all 'jobs' in the shop join the same 'queue', if they cannot be loaded at any station, at the time of their arrival. Each individual 'job' belongs to an 'order' which has a fixed delivery date and which can be delivered only when it is fully completed.

c) Priority scheduling rules are used in connection with the process of selecting 'jobs' from queue in order to 'load' them into machines. The model provides for the use of eight priority rules. Three of them, namely SPT, SLACK and FIFO are well known rules, and the other five, viz. FIFOM, FIFOB, FIFOMB, SPTM and SLACKM are modifications of the original three. (For description of the rules, see FLEURY.1976(2).

d) A facility for splitting jobs into smaller batches is provided by the model. This facility is controled by a variable (MAXLOT) which establishes a limit, such that any job whose batch size is bigger than MAXLOT, is split into smaller batches.

e) A series of variables are output by the model. Those variables can be divided into two groups. One is made up of variables which measure the internal behaviour of the system such as average number of 'jobs' in queue, actual average load factor, machine idle time, etc. The other is made of variables which measure the performance of the system in terms of delivery. Six variables belongs to this group, viz.

(i) Average delivery delay of orders ('order delay')

(ii) Average delivery delay of 'production' ('production delay')

(iii) Percentage of orders late ('orders late')

(iv) Tardiness index of orders ('tardiness of orders')

(v) Percentage of 'production delivered late ('production late')

(vi) Tardiness index of'production '('tardiness of production')

Where:

(i) Average delivery delay of orders is calculated from the samples obtained by measuring, for each order which is completed, the time elapsed from the arrival of the order at the system, to its delivery. The delivery corresponds to the completion of the last 'job' belonging to that order.

(ii) Average delivery delay of 'production' is a weighted measure of the delivery delay of orders. For each order which is delivered, the model measures the time it spent on the system, and weights this measure by the total quantity delivered with that order. At the end of the simulation, the weighted measures are averaged.

(iii) Percentage of late orders is calculated by the ratio between the number of orders delivered after the due date, and the total number of delivered orders.

(iv) Tardiness index of orders is a measure of lateness dispersion. It is the summation of the products of the proportions of orders late and the number of days late.

If d = promised delivery delay (lead time in days)

i = actual delivery delay (days)

$p(i)$ = proportion of orders with delivery delay equal to i days, then:

$$\text{Tardiness index of orders} = \sum_{i=d+1}^{\infty} (i - d) * p(i)$$

(v) Percentage of 'production' delivered late is a 'weighted' measure of the percentage of orders delivered late. It is calculated by the ratio between the number of items (size of orders) delivered after their due date, and the total amount of delivered items.

(vi) Tardiness index of 'production' is a weighted measure of lateness dispersion. It is calculated in the same way as the tardiness index of orders, with each order weighted by the total quantity delivered.

The measures of performance; percentage of late orders; tardiness index of orders; percentage of 'production' delivered late; and tardiness index of 'production' are calculated as a function of a delivery promise (lead time), which is always the same for all orders. The value of these promises however, can be varied from, say, eight days for all orders to, say, ten days for all orders, and in fact the model calculates the above measures of performance for seven different values of the delivery promises (lead times).

IV. PRELIMINARY INVESTIGATION AND EXPERIMENTAL DESIGN

The investigation carried out with the model can be divided into two phases. The first phase (in which empirical data obtained in a particular company was used), was exploratory in nature. The main objectives of this phase were to validate the model and identify the major characteristics of the system, in order to determine typical values for the parameters, and work out possible control rules which might be appropriate to the characteristics of the system under study.

The second phase of the investigation consisted of a more formal set of experiments, which were designed with the objective of generating information which could lead to a more general set of conclusions about this class of production systems.

The two phases of the investigation complemented each other, in the sense that the choice of parameters and the experimental designs of the second phase were largely based on the informations obtained from the first phase of the investigation.

Some of the parameters used in the preliminary investigation were:

a) Products. There were threee classes of styles, where two were made uf of eleven sizes and one made up of thirteen sizes. The mean value of interarrival were 11.6 days, 6.07 days and 4.10 days, respectively, while the average size of orders were equal to 2404, 1971 and 1611 items respectively.

b) Machines. There was one twelve station machine. The value of average 'process cycle time' is given by PCT = (3,0 + 0.1 (NSL)) minutes, where NSL represents the number of stations actually loaded at the machine.

c) Moulds. There were 26 moulds covering the three classes of styles.

d) Setup time: the mean value of setup time was 8 minutes.

e) Working hours: normal working hours were 5 shifts of 9 hours (45 hours) per week.

f) Due date: due dates were established in accordance with a fixed lead time which meant that any order which spent more than eight days in the machine shop was considered late.

Because no formal priority rule was in operation in the company, it was decided to use the FIFO rule in the initial runs. It was also decided not to give much consideration to tactical problems in these initial runs, and a single long run, equivalent to a period of three years was used, in which statistics obtained from the first eight weeks of simulation were discarded, to allow for stabilization of the model.

The preliminary investigation provided useful information about the behaviour of the system. These informations included the histograms of mean waiting time in queue, and mean processing time of 'jobs', the level of mould utilization, the percentage of time spent setting up the machine, and the level of delivery performance obtained by the system.

The histograms of mean processing time of 'jobs' and mean waiting time in queue are shown respectively in figures1 and 2.

Each figure shows three histograms, where each histogram represents the range of shoe sizes belonging to a particular shoe style. As should be expected, all three histograms of figure 1 have bell shaped formats, similar to the distributions of demand for the shoe sizes in a style. On the other hand, the histograms of figure 2 differ markedly from each other. The histogram for the product sizes of style one, is similar to what would be expected from the use of FIFO priority rule. This priority scheme means that 'jobs' representing the larger product sizes would tend to wait longer in queue, than 'jobs' representing the smaller product sizes in the same order. This effect is confirmed by the first histogram which represents product sizes of style one. However the other two histograms (for styles two and three) do not show the same effect. Although there is still a tendency for longer waiting times for the larger sizes, the two histograms do not follow the same smooth pattern as histogram one. What characterizes those two histograms is the fact that a few product sizes in each style (4-1/2 and 6-1/2 for style two; 4-1/2 and 7 for style three) have distinguishably longer waiting time in queue than the other product sizes. The reasons behind this effect were shown to be related to the restricted number of moulds for those particular sizes.

The'percentage of machine idle time due to setup' proved to be relatively small, representing only three percent of machine time. On the other hand the 'machine idle time due to lack of work' was relatively high representing thirty pertence of all machine time. It is interesting to note that although there seemend to be plenty of spare plant capacity, the delivery performance was relatively poor, twenty percent of all orders were late, with a 'tardiness index of orders' equal to 0.73.

V. DEVELOPMENT AND TEST OF PRIORITY SCHEDULING RULES

In view of the information obtained from the initial runs, it was decided that more experiments should be made in order to test the possible effects of different operation control procedures, on the behaviour of the system. One obvious alternative was the use of priority scheduling rules better suited to the characteristics of this production system. To this end three modified version of the FIFO rule (FIFOB, FIFOM, and FIFOMB) were devised and later compared against two well known priority rules (SPT and SLACK) and modified versions of them (SPTM and SLACKM).

A few comments should be made on the reasons behind the modifications introduced to the FIFO rules, which were later partially extended to the SPT and SLACK rules. The idea behind the FIFOM rule, and by extension, the SPTM and SLACKM, was to reduce the amount of time lost with setting up (changing moulds), by giving an extra priority to 'jobs' which could be 'loaded' in a machine without the need of changing moulds. The idea behind the FIFOB rule was to give priority to 'jobs' with larger batch sizes, over their companion 'jobs' in the same order, which have smaller 'batch sizes'. This procedure would tend to reduce the waiting time in queue for the 'jobs' belonging to the high demand (large batches) product sizes, with a possible reduction of their average throughput time.

To check the veracity of this assumption a simulation run was made with the FIFOB rule, in which the histograms of mean waiting time in queue were analysed.

Figure 3 shows the there histograms of average waiting time in queue, each corresponding to a different product style.

A comparison between figure 2 and 3 shows that the use of FIFOB rule has caused a desirable modification in the shape of the histogram for style one.

The new histogram is now U shaped, with the high demand (high processing times) product sizes having a smaller mean waiting time is queue, and the low demand. (low processing time) product sizes, having larger waiting time in queue. This U shaped waiting time histogram, combined with a bell shaped processing time histogram, would tend to create a more uniform histogram of average throughput times. For style two and three however, due to mould restriction, the U shaped effect did not occur, and their histogram have maintained their original shape.

The FIFOMB priority rule was designed in order to combine the characteristics of both FIFOB and FIFOM priority rules.

The preliminary investigation with the priority scheduling rule, consisted of running the model 8 times, each time with a different priority rule, but maintaining constant all the other variables in the model.

Table 1 presents the results of delivery performance and percentage of idle time due to setup, for each of the eight rules. The results indicate that the modified FIFO rules could bring some improvement to the performance of such a system.

All theree modified versions, FIFOB, FIFOM, and FIFOMB have produced slightly better results than the FIFO rule in all measures of performance, with FIFOMB producing the best results among them. The differences however are relatively small and might not be statistically significant. When FIFOMB is compared with the other rules (SPT, SLACK and SLACKM) it performs quite well.

Apart from the result of percentage of late orders, in which it comes third to SPTM and SPT, the FIFOMB rule comes first in all the other measures of performance.

It is interesting to note that although SPT and SPTM did well in relation to percentage of late orders, they did particularly badly in terms of lateness dispersion (tardiness index of order, and tardiness index of production), which indicates their tendency to delay certain 'jobs' for a very long time.

Additional information obtained during this preliminary investigation , includes the effects of splitting jobs into smaller batches, extra machines, additional moulds, and a different demand pattern. Those information were very usefull in designing the next series if experiments.

VI. EXPERIMENTAL DESIGN FOR THE SECOND PHASE

One of the main restriction of the preliminary investigation is the fact that it was conducted using a single system configuration, which means that any firm conclusion which might be reached, would be restricted to that particular situation. Ideally one would like to test the priority schedulling rules under as many different system configuration as possible. For example, one would like to see how the rules behave for different values of setup times, different load factors, different number of moulds, etc. As far as the model is concerned, it would be possible to analyse the priority rules for an almost limitless number of system configuration. However, because of time and cost considerations one has to limit the number of experiments to a manageable size. As Bonini (1963) points out, when the number of changes that can be made is quite large, one must select some for study and ignore the others, having to decide in many times through a personal judgement.

Judgement was used in this study to select the variables whose values were to be changed. After considering such aspects as the amount of time and experimental effort which would be required, the information available from industrial data, and the usefulness of the conclusions which might be obtained, it was decided that the priority scheduling rules should be tested for a number of system configurations, which would be obtained by varying six of the system's variables, each variable having two levels. This would permit to analyse the effect of changes in the variables on the performance of the priority rules. The variables and their levels are the following:

(i) the load factor on the system: a low average load factor (65%) against a higher average load factor (85%).

(ii) the man value of the distribution of setup times: a lower value (8 min) against a higher value (16 min).

(iii) <u>the number of moulds</u>: A medium number of moulds (27 moulds) against a large number of moulds (42 moulds).

(iv) <u>the mean value of the total quantity demanded per order</u>: A lower (1000 items), against a higher value (1600 items).

(v) <u>the value of 'MAXLOT' for splitting jobs</u>: The two situations tested were:

first - 'jobs' were never split (MAXLOT = ∞)

second- 'jobs' bigger than 450 were split (MAXLOT = 450).

(vi) <u>the ratio between number of styles and number of machines</u>: A lower ratio (3:2) against a higher ratio (3:1). Because in this case the number of styles is maintained constant (three) it is possible to express the variation in the ratio by the variation in the number of machines (2 and 1).

Having decided about the variables to be changed, a experimental design had to be chosen. A possible approach could be a factorial design in which priority rules and the six variables would be the factors, and their values, the levels of the factors (Davies, 1967 (1)). A full factorial experiment for this case would require a total of 512 experiments($2^6 \times 8$), which would be too large a number as far as time and computer resources availability were concerned. For this reason consideration was given to another experimental design which could economize on the number of experiments, such that the study be kept within manageable size, and still generate sufficient information.

In order to plan a more economical experimental design, two questions had to be asked:

(i) is it necessary to test all the eight priority scheduling rules?

(ii) is it necessary to compare the priority scheduling rules for all the possible system configurations which will be generated from a full factorial design?

The answer to both questions were negative, as discussed in Fleury, 1976(3). It was decided that only six priority scheduling rules should be tested (FIFOB, FIFOMB, SPT, SPTM, SLACK and SLACKM), in a set of situations representing a 'sample' of the total number of system configurations which would be generated by a full factorial design.

In order to make further references and manipulations easier, the variables and their value will be tabulated and associated with letters and abbreviated names, as shown on the table below

Variables to be changed	Symbol	Values of the variables	
		Standard (0)	Alternative (1)
A - nominal load factor	a	65%	85%
B - setup time	b	8 min	16 min
C - number of moulds	c	42	27
D - size of orders	d	1000	1600
E - splitting of jobs	e	450	∞
F - number of machines	f	2	1

Using the notation above a system configuration where A = 85, B = 16, C = 27, D = 1600, E = ∞, and F = 1, will be denoted as abcdef (all the variables are in their alternative value 1).

Alternatively if A = 65, B = 8, C = 42, D = 1000, E = 450 and F = 2, the system configuration will be denoted (I) (all the variables are in the standard value 0). For further reference to this notation see Davies, 1967 (2).

It should be noted that the parameters of the variables were divided in such way that (I) and abcdef would represent respectively the most 'loose' system configuration (low load factor; low setup time; large number of moulds; small size for the orders; more favourable ratio style/machine), and the most 'tight' system configuration (high load factor; high setup time; smaller number of moulds; large size for the orders; less favourable ratio style/machine).

Based on the above arguments it was decided to test the priority rules for six system configurations which would include the two extreme cases, (I) and abcdef, and some 'intermediate' cases obtained by the joint variation of some of the variables. The six system configurations, chosen as a 'sample' of the universe of sixty four (2^6) possible system configurations are:

i) (I)

ii) abc

iii) def

iv) bdf

v) ace

vi) abcdef

Each one of the six priority scheduling rules, were tested for each of the above six system configurations, giving a total of thirty six experiments. Each one of the thirty six experiments were carried out using the same sampling procedure, which consisted of having six pairs of antithetic runs. This sampling procedure was the results of an exhaustive analysis, carried out through a series of pilot runs as described in Fleury, 1976 (4).

VII. PRESENTATION OF RESULTS

As described earlier the model outputs six variables related to delivery performance where three of them are 'weighted' measures of performance, and the other three are 'unweighted' measures. The variables 'orders late', 'production late', 'tardiness of orders' and 'tardiness of production' are functions of due date. The procedure for determining due date is based on a constant 'lead time', which is fixed at a number D of days. In order to analyse the influence of D on the performance of the priority rules, the model calculates the values of the above four variables for different values of D, equal to eight, ten, twelve, fourteen, sixteen, eighteen and twenty days respectively.

For the sake of analysis, the thirty six experiments were divided into six blocks of six experiments, where each block consists of the results obtained by applying the six priority rules to a specific system configuration.

As far as delivery performance is concerned, the priority scheduling rules were compared to each other by the use of graphs and by statistical analysis.

The graphs were organized by plotting the values of 'orders late', 'tardiness of orders', 'production late' and 'tardiness of production', obtained from each rule as a function of D. In this way twenty four graphs were generated and analysed. Figures 4(a), 4(b), 4(c) and 4(d) are example of such graphs, which show the delivery performance of the six priority rules, as function of 'lead time' D, and for system configuration bdf.

The statistical analysis consisted of the application of a 'F test' followed by a 'multiple comparison test' (Dunnet, 1955), on the results of the priority rules, with the objective of identifying which differences are statistically significant for D = 8 days. Table 2 gives an example of such analysis for the case of system configuration bdf.

Apart from the measures of delivery performance the model also outputs all the other measures of internal behaviour which were described in an earlier paragraph. Some of those variables were also taken into consideration when analysing performances of the priority rules.

VIII. DISCUSSION OF RESULTS

The results obtained for the different system configuration were mixed as far as the performance of individual rules are concerned. The relative performance of the rules is affected by the system configuration; by the way in which delivery performance is measured; and by the value of D (lead time used to fix due dates). However a detailed analysis of the data showed some clear points. The first point to be noted is the consequences of incorporating in the priority rules the procedure for reducing the amount of time spent in the setting up. Comparisons between FIFOB vs. FIBOMB; SLACK vs. SLACKM; SPT vs. SPTM indicated that in general the introduction of the procedure is beneficial to the performance of the rules. In the case of FIFOB vs. FIFOMB, for example, from the 36 results of delivery performance (six system configurations X six measures of performance), FIFOMB produced lower results than FIFOB in 25 occasions. In the other 11 cases the differences were in favour of FIFOB, but those differences did not show any statistically significant differences at 0.01 level.

Similar comparisons made between SLACK and SLACKM, and SPT and SPTM gave similar results.

In relation to the measures of internal behaviour, FIFOB, SLACK and SPT consistently produced the highest values for the 'idle time due to setup' and 'process cycle time'. As far as the 'remaining content' is concerned there are no clear differences between the two groups of priority rules.

A second point to be observed relates to the relative behaviour of FIFOMB, SLACKM and SPTM (similarly FIFOB, SLACK and SPT). A close examination of the results showed that the behaviour of FIFOMB and SLACKM are very similar for all configurations, while the behaviour of SPTM is quite distinct from the other two. The relative performance of FIFOMB and SLACKM did not seem to be influenced by the value of D, but the performance of SPTM in relation to FIFOMB and SLACKM is clearly influenced by the value of D. This was confirmed by the fact that initial advantages of SPTM over the other two rules were reversed as the value of D increased. This characteristic of SPT rule is in accordance with the results obtained from previous studies of priority rules in more traditional job shop and batch manufacturing systems (Conway and Maxwell, 1962; Eilon and Coterill, 1968; Oral and Malouin, 1973), which indicated that SPT rules tend to generate distributions of throughput times with high variance and skewness.

Another important point to be discussed refers to the relative efficiency of the priority rules in terms of performance. The comparisons will concentrate on the relative performance of FIFOMB, SLACKM and SPTM, due to the observations made before. In general it can be said that SPTM tends to perform better for the unweighted measures of performances 'order delay' and 'orders late', and performs particularly badly in terms of the 'weighted' measures of delivery performance 'production delay' and 'tardiness of production'. The performances of FIFOMB and SLACKM are in general very similar, with FIFOMB producing lower (better) values than SLACKM. If their results are compared it can be seen that FIFOMB produced lower values than SLACKM on 33 occasions out of 36. However the differences between them are in general very small and as far as the multiple comparison tests are concerned, very few are significant.

In order to have a more clear picture of the relative performance of the rules, a further analysis was made on the delivery performance data. It consisted of comparing the rules in relation to their average performance over the six system configurations. Table 3 shows the average results of each rule for each of the six measures of delivery performance, for D = 8 days and 20 days, with each rule ranked in accordance with the results obtained. The results of table

3 confirms some of the observations made before. For D = 8 days, SPTM produced the lowest average result for the 'unweighted' measures of performance 'order delay', 'tardiness of order' and 'orders late', while FIFOMB produced the lowest values for the 'weighted' measures of delivery performance 'production delay', 'tardiness of production' and 'production late'. In all cases SLACKM came behind FIFOMB, although very close in most cases.

For D = 20 days, the advantages of SPTM were reversed in favour of FIFOMB, which produced the lowest value for all measures of delivery performance.

IX. CONCLUSIONS

In general the results indicated the following main conclusions:

(i) Both the absolute and relative performance of the priority rules are affected by the system configuration; by the way in which delivery performance are measured; and by the lead time used to fix due dates.

(ii) Overall, the priority rules designed to avoid setup times (FIFOMB, SLACKM, SPTM) were shown to be superior to equivalent rules (FIFOB, SLACK, SPT) which do not try to avoid setup.

(iii) The performance of SLACKM and FIFOMB were very similar, but FIFOMB produced overall better results for the measures of delivery performance. The differences however are very small and in the majority of the cases were not statistically significant.

(iv) The SPTM (and SPT) rule seems to perform better for the unweighted measures of delivery performance, 'average delay of orders' and 'percentage of late orders' and for tight due dates. However it tends to lose its advantages over the other rules (FIFOMB, and SLACKM) when the due dates get less tight, and to perform badly in respect to the weighted measures of delivery performance, 'average delay of production' and 'tardiness index of production'.

In view of the reported results and analysis it is possible to conclude that FIFOMB seems to be the most appropriate of all six priority rules, as far as this class of production systems is concerned. This conclusion is even more strong if one considers that the weighted measures of delivery performances are more relevant than the unweighted measures, as they take into consideration not only the number of orders delivered, but also their intrinsic value, which is represented by their batch size. Is should also be pointed out that from a practical point of view, FIFOMB has the advantage of being much easier to operate than both SLACKM and SPTM. This can be a significant aspect in the case of real production systems, particularly those which do not have a sophisticated production control department.

TABLE 1

RESULTS OBTAINED BY THE USE OF DIFFERENT PRIORITY SCHEDULING RULES

RULE	PERCENTAGE OF LATE ORDERS	TARDINESS INDEX OF ORDERS	PERCENTAGE OF LATE PRODUCTION	TARDINESS INDEX OF PRODUCTION	IDLE TIME DUE TO SET UP (%)
FIFO	21.02	0.73	35.31	1.17	3.15
FIFOB	19.28	0.71	33.77	1.14	3.11
FIFOM	20.83	0.71	34.38	1.15	2.80
FIFOMB	18.88	0.67	31.11	1.05	2.81
SPT	18.76	1.06	37.38	2.28	3.37
SPTM	15.00	0.79	31.66	1.72	2.82
SLACK	22.04	0.73	33.28	1.09	3.17
SLACKM	22.02	0.80	34.18	1.20	2.88

TABLE 2

SYSTEM CONFIGURATION bdf

MEAN VALUES - D = 8 DAYS

PRIORITY RULE	ORDER DELAY	PRODUCTION DELAY	TARDINESS OF ORDER	ORDERS LATE	TARDINESS OF PRODUCTION	PRODUCTION LATE
FIFOB	** 4.085	5.570	0.323	** 11.22	0.562	** 18.22
FIFOMB	(1) 3.723	(1) 5.253	(1) 0.262	(1) 8.01	(1) 0.490	14.24
SLACK	** 4.503	** 5.843	* 0.438	** 13.91	0.633	** 19.47
SLACKM	* 3.935	5.353	0.308	8.91	0.513	(1) 14.01
SPT	** 4.875	** 8.712	** 1.182	** 15.64	** 3.275	** 34.10
SPTM	* 3.900	** 6.422	** 0.563	* 10.35	** 1.298	** 21.90
RESULTS OF 'F TEST'						
FS	** 64.69	** 163.36	** 41.77	** 18.07	** 113.15	** 50.71
F	3.85	3.85	3.85	3.85	3.85	3.85
MULTIPLE COMPARISON TEST - (CRITICAL VALUE FOR DIFFERENCES)						
$D^{*}_{0.05}$	0.18	0.34	0.18	2.30	0.34	3.46
$D^{**}_{0.01}$	0.24	0.45	0.23	3.04	0.45	4.57

Convention:
- (1) - Smallest value for the measure of performance (control)
- * - Significant at 0.05 level
- ** - Significant at 0.01 level
- FS - 'F ratio' calculated from data
- F - Critical value for 'F ratio'
- $D^{*}_{0.05}$ - Critical value for differences between each contrast (priority rules) and the 'control' at 0.05 level
- $D^{**}_{0.01}$ - Critical value for difference between each contrast (priority rules) and the 'control' at 0.01 level

TABLE 3

RESULTS OF THE AVERAGE DELIVERY PERFORMANCE OF PRIORITY RULES OVER THE SIX SYSTEM CONFIGURATIONS

D = 8 Days

PRIORITY RULE	ORDER DELAY (DAYS)	PRODUCTION DELAY (DAYS)	TARDINESS OF ORDER	ORDERS LATE (%)	TARDINESS OF PRODUCTION	PRODUCTION LATE (%)
FIFOB	(4) 5.183	(3) 6.568	(4) 1.152	(4) 20.19	(3) 1.532	(3) 26.03
FIFOMB	(3) 4.908	(1) 6.316	(2) 1.018	(3) 18.33	(1) 1.389	(1) 24.29
SLACK	(6) 5.709	(4) 6.853	(6) 1.442	(6) 23.65	(4) 1.691	(5) 27.72
SLACKM	(5) 5.271	(2) 6.473	(5) 1.213	(5) 20.68	(2) 1.470	(2) 25.08
SPT	(2) 4.797	(6) 8.275	(3) 1.026	(2) 15.38	(6) 3.116	(6) 30.95
SPTM	(1) 4.456	(5) 7.267	(1) 0.828	(1) 13.74	(5) 2.267	(4) 26.70

D = 20 Days

PRIORITY RULE	ORDER DELAY (DAYS)	PRODUCTION DELAY (DAYS)	TARDINESS OF ORDER	ORDERS LATE (%)	TARDINESS OF PRODUCTION	PRODUCTION LATE (%)
FIFOB	SAME AS FOR 8 DAYS	SAME AS FOR 8 DAYS	(2) 0.112	(2) 1.95	(3) 0.169	(3) 2.85
FIFOMB			(1) 0.101	(1) 1.76	(1) 0.146	(1) 2.49
SLACK			(5) 0.151	(5) 2.76	(4) 0.189	(4) 3.33
SLACKM			(4) 0.122	(3) 2.06	(2) 0.153	(2) 2.54
SPT			(6) 0.178	(6) 3.16	(6) 1.019	(6) 8.27
SPTM			(3) 0.115	(4) 2.26	(5) 0.571	(5) 5.92

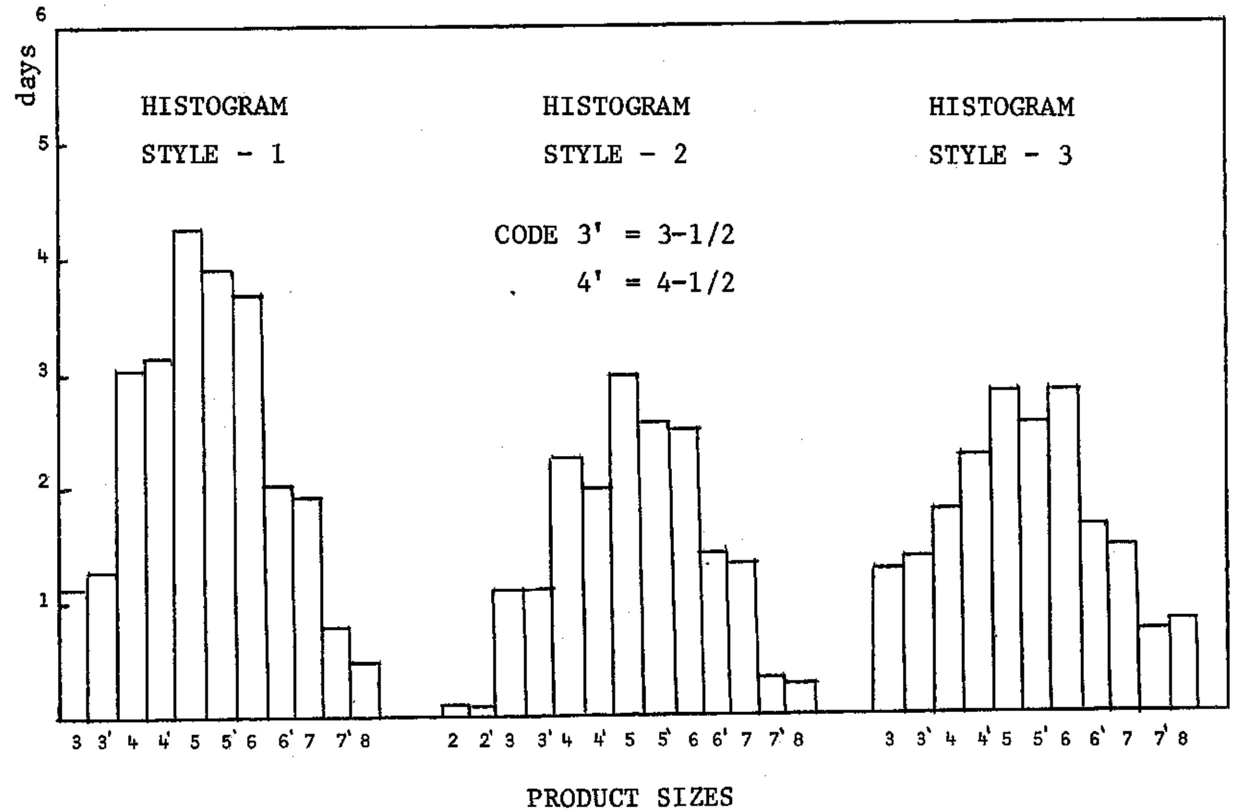


FIGURE 1

HISTOGRAMS OF MEAN PROCESSING TIME OF 'JOBS' (PRIORITY FIFO)

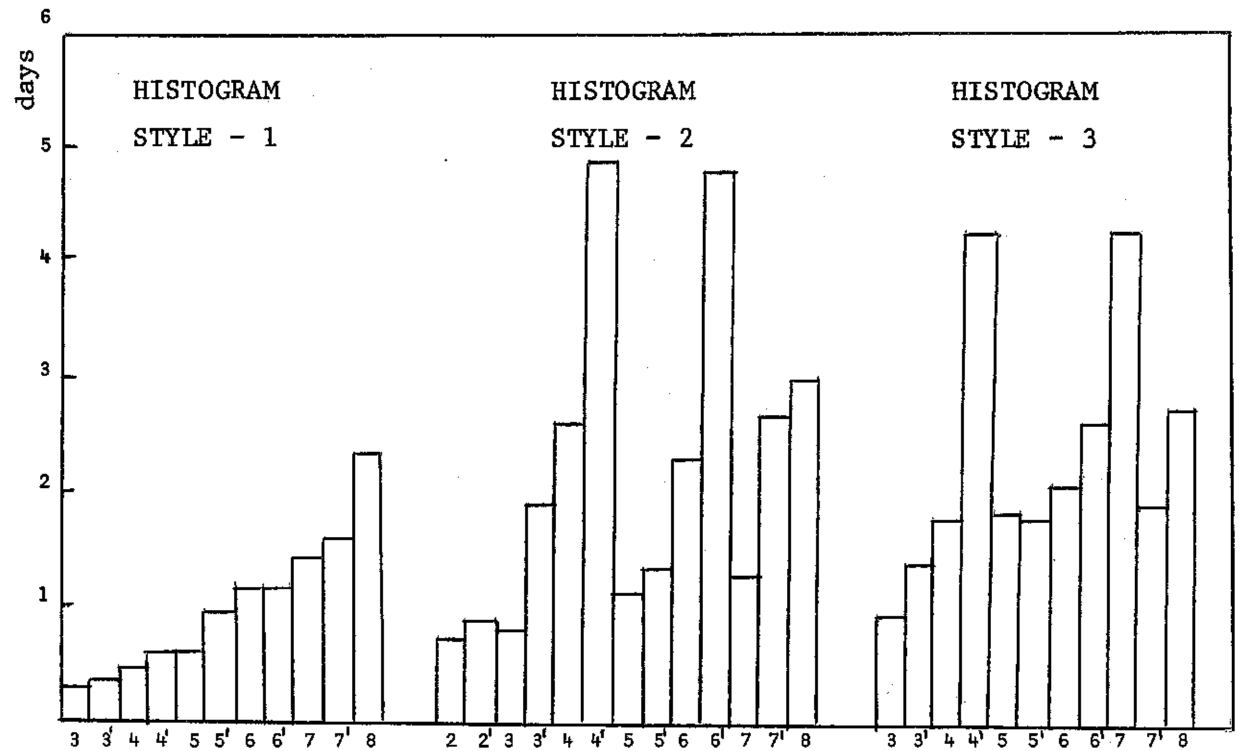


FIGURE 2

HISTOGRAMS OF MEAN WAITING TIME IN QUEUE (PRIORITY FIFO)

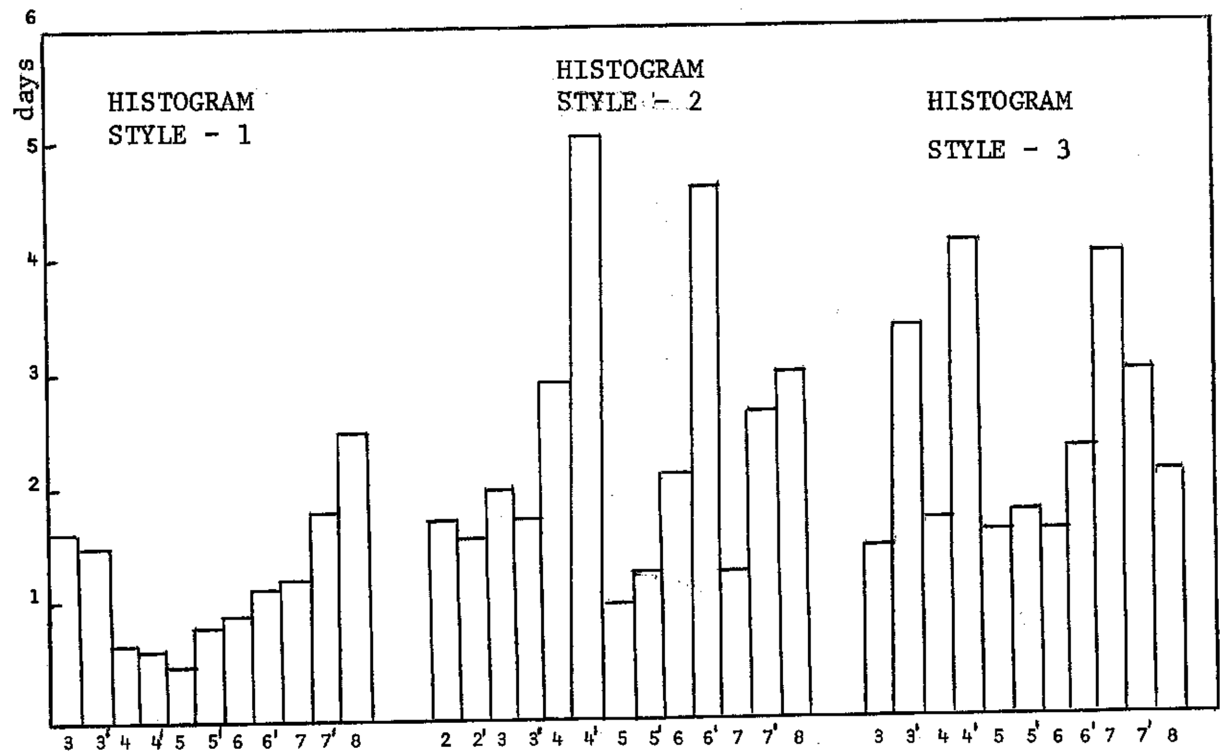


FIGURE 3

HISTOGRAMS OF AVERAGE WAITING TIME IN QUEUE FOR DIFFERENT PRODUCT SIZES

(PRIORITY FIFOB)

FIGURE 4-A

SYSTEM CONFIGURATION bdf

PERCENTAGE OF LATE ORDERS

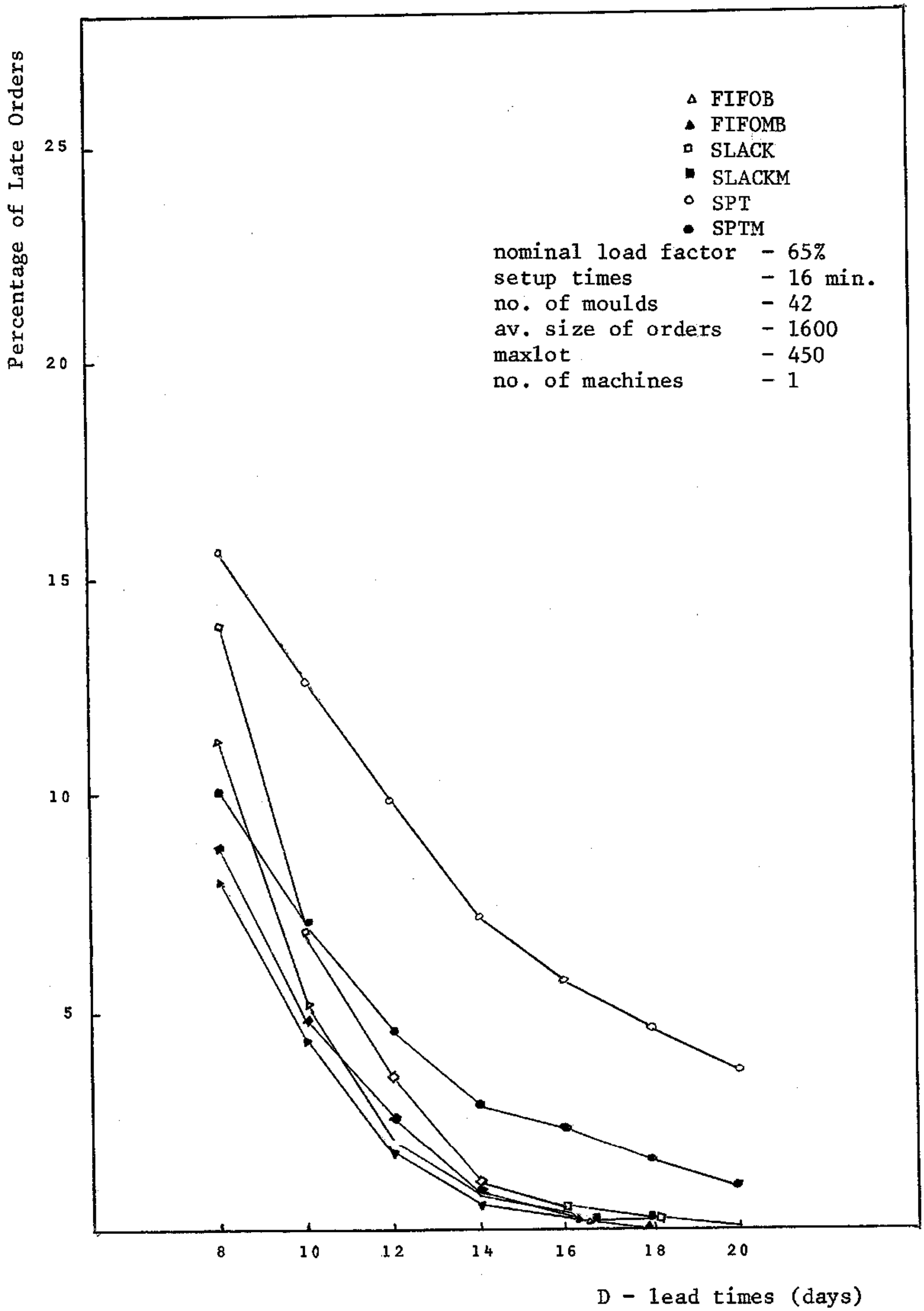


FIGURE 4-B

SYSTEM CONFIGURATION bdf

TARDINESS INDEX OF ORDERS

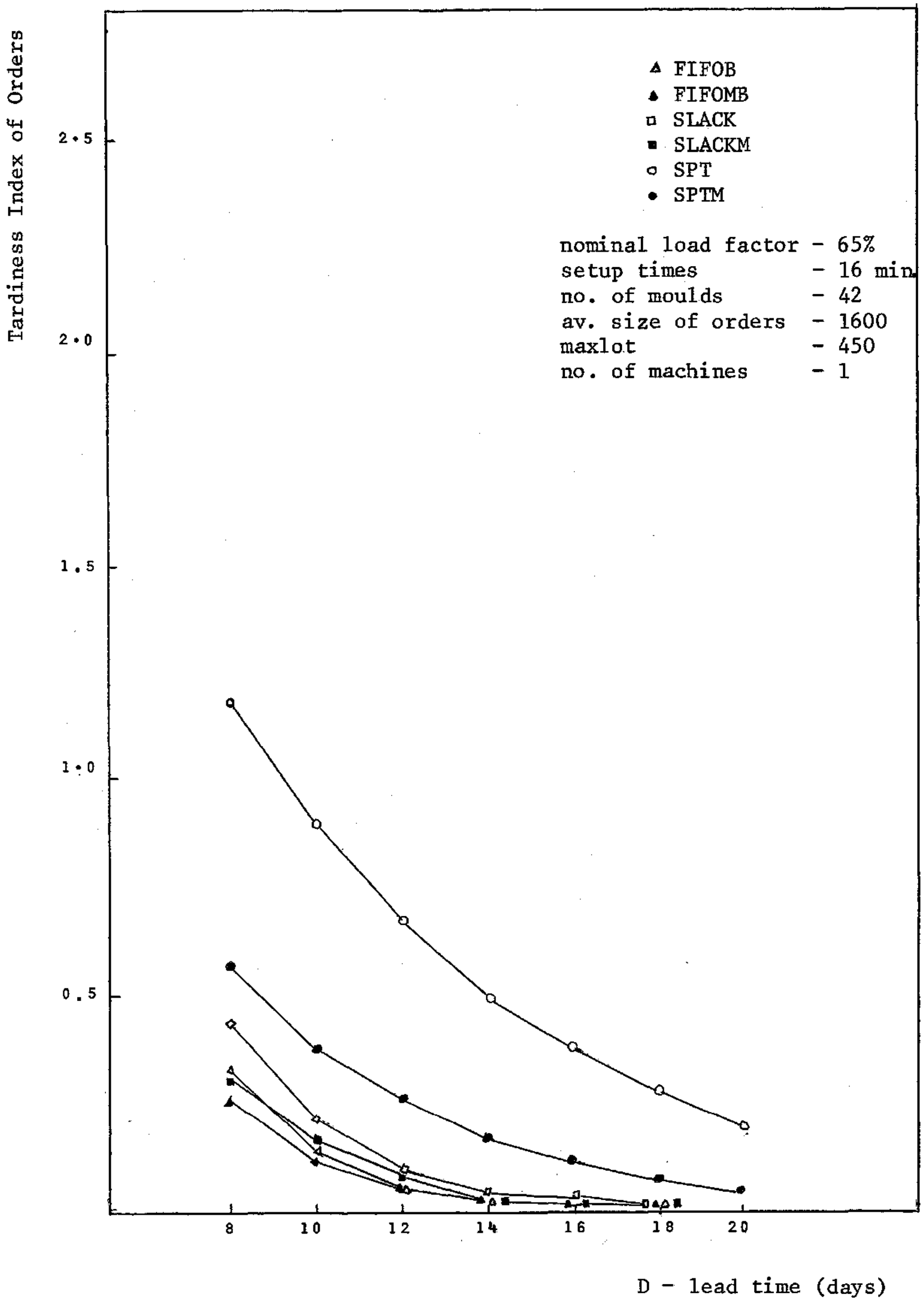


FIGURE 4-C

SYSTEM CONFIGURATION bdf

PERCENTAGE OF PRODUCTION DELIVERED LATE

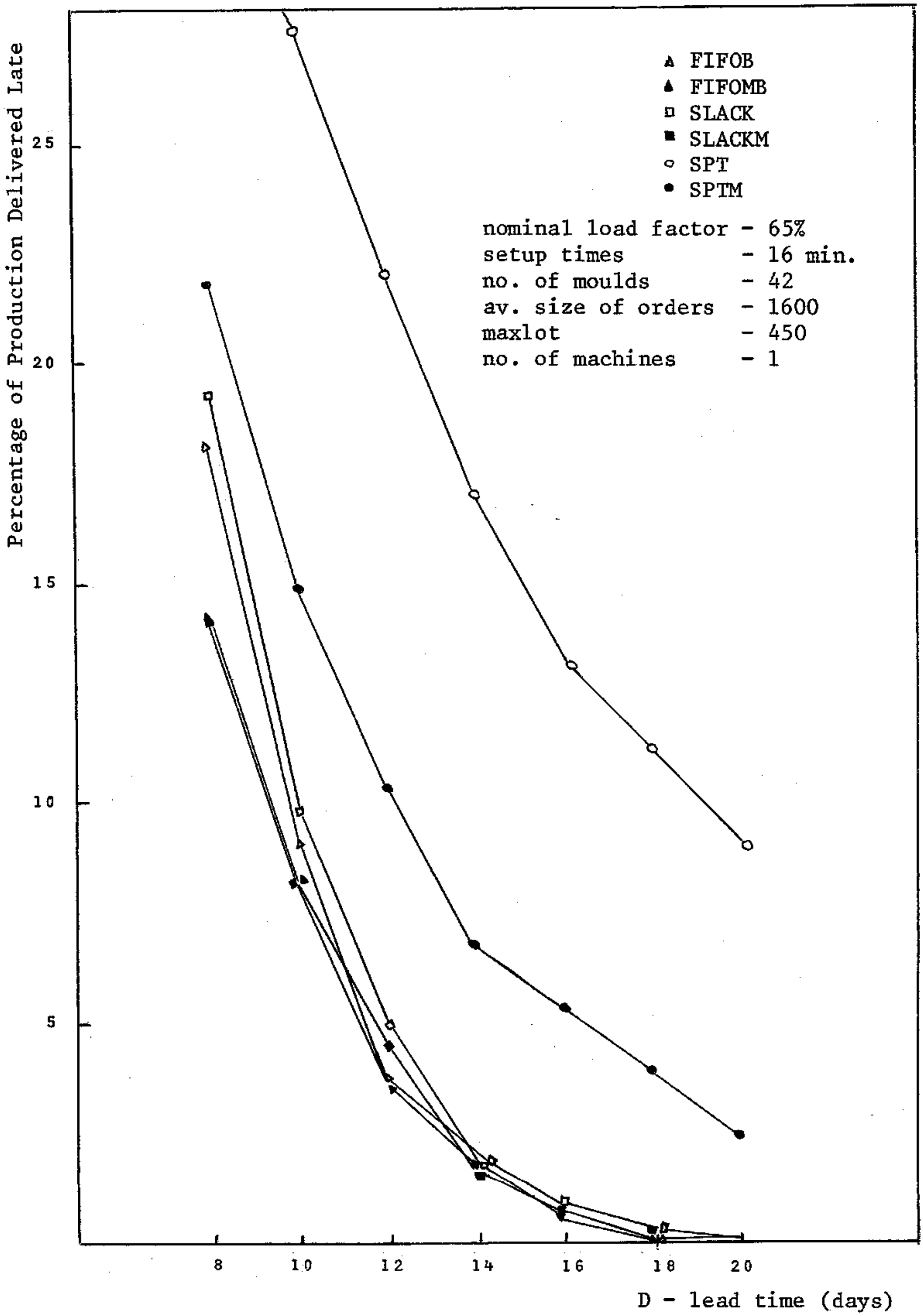
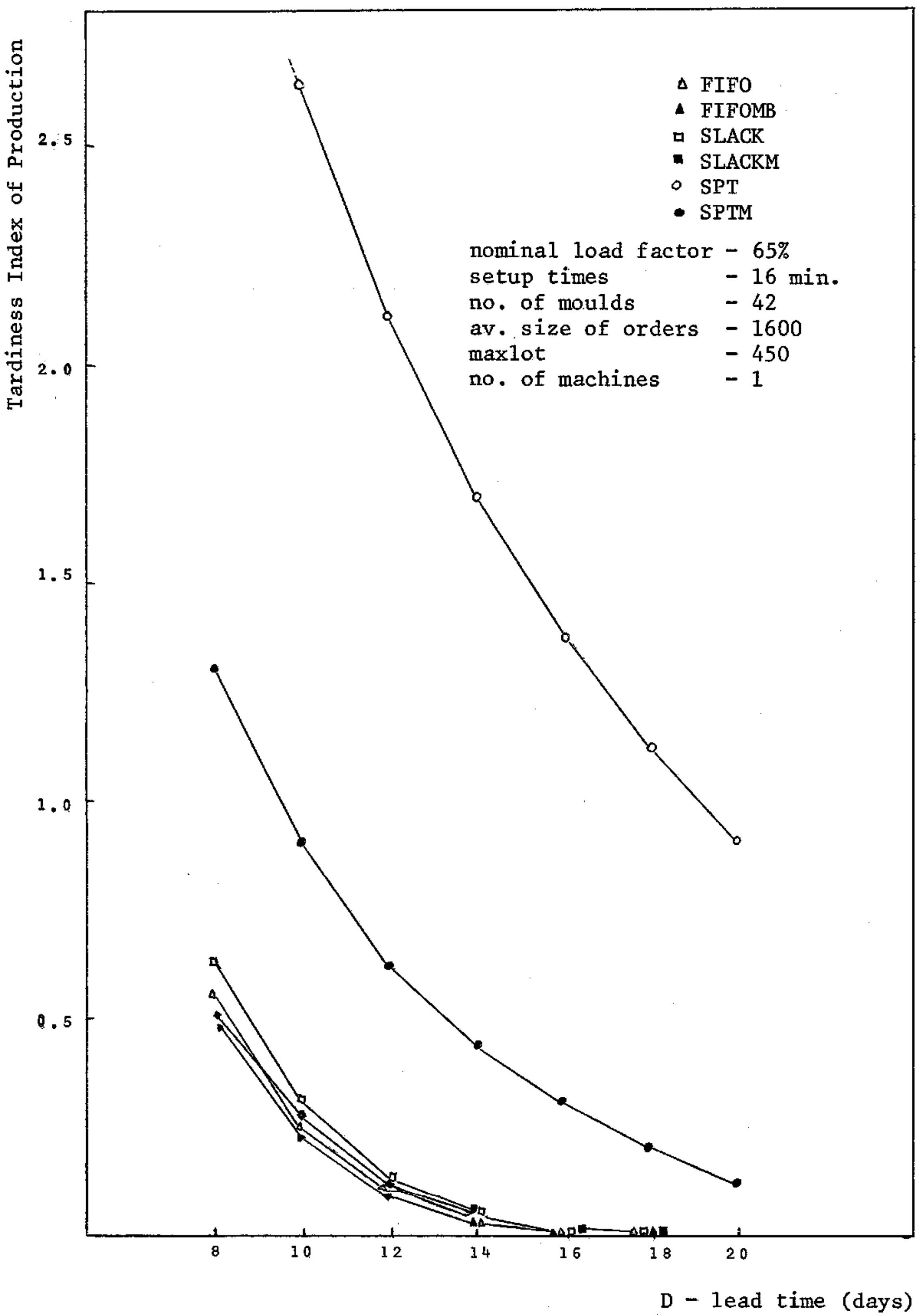


FIGURE 4-D

SYSTEM CONFIGURATION bdf

TARDINESS INDEX OF PRODUCTION



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