AN EMPIRICALLY BASED INVESTIGATION OF JOB-SHOP SEQUENCING

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Summary

An empirically-derived job-shop simulation model is the heart of the study. This provides the opportunity to explore some techniques not normally applicable in hypothetical job-shop simulation models. First, the model is designed to include the essential characteristics of an actual sequencing environment. Second, internal consistency and representativeness are checked by comparing simulated with actual performance. Third, a "protocol" of a manager's decision process is used in the development of a general priority function in contrast to "piece-meal" rules. Fourth, sequencing rules are screened initially for practicability as defined by a shop manager. Fifth, a total relevant cost function is developed based upon actual shop costs. Finally, computer simulation results are reported concerning the nature of practicable rules and "best" rules.

Introduction

Research on sequencing has taken three primary thrusts. First, a great bulk of the reported work has concerned attempts to apply analytical and enumeration techniques to very limited versions of the sequencing problem. Most of this work has dealt with simultaneous-arrival, declining-load situations. For these cases, a fixed number of orders is released to an empty shop at time zero. No more arrivals are allowed, and the shop is run until all orders are released from the system. Conceptually, many versions of this simplified sequencing problem have been solved, although computational infeasibility is found in most situations of interesting size and complexity. Conway, Maxwell, and Miller[6] have an excellent expository book on analytical approaches to this type of problem and Day and Hottenstein[7] have just recently reviewed achievements in this area.

The second major thrust of research has involved the use of computer simulation techniques to explore more realistic and general versions of the sequencing problem. Most simulation models concern the intermittent-arrival, continuing-load case. Orders arrive randomly throughout time, and the shop is loaded to some varying fraction of capacity continuously and indefinitely. However, most of the research has been with hypothetical models with <u>many</u> simplifying assumptions.

The third major thrust has been in the application of simulation techniques in actual scheduling situations. Most of the reports concerning such applications praise improved performance achieved with the installation of a set of computerized procedures. The primary problems with such application reports have been (1) a lack of determination of what actually caused the change; (2) a realization that usually only successes are reported; and (3) the fact that research techniques are generally not coupled with the real situations.

An Empirically-based Research Model

Motivation for an Empirically-derived Model

This study is an application of simulation research methodology based upon an actual job shop, and thus is an attempt to integrate the three separate research thrusts concerning sequencing. Building an empirically-derived simulation model provides some unique opportunities not available for hypothetical models. For hypothetical models, verification has been practicably ignored. An empirically-based model provides the opportunity to test the representativeness of the model. The relevant characteristics of a jobbing-to-order shop may be identified and checked. Properties such as machine and labor limitation of capacity, changes in capacity and load, and sequence-dependent service times must be explicitly considered. In addition, an actual situation allows one to identify relevant cost factors and values.

The Firm and Problem Definition

An actual firm with its records of orders and order movements has been used as the basis for this study. The firm is a commercial printing firm that uses offset lithography. The production system may be classified as jobbing-to-order with a flow-shop type movement of orders. Queues of orders develop at the work stations. The sequencing problem is thus a major decision-making problem. Many firms were considered, but this one was selected because of (1) completeness of available records; (2) the relative simplicity of the scheduling problem (flow-shop orientation); and thus (3) an opportunity to abstract the essence of a major type of scheduling problem.

For the printing shop, production is entirely to order with comparatively low volume per order. Each order has unique specifications, and therefore no stock of standard items can be held as finished inventory. As occurs in most jobbing-to-order shops, order characteristics are highly varied. Total processing time for orders may range from six minutes to two hundred and fifty hours, the number of separate operations from one to thirty, and the order value from zero to five thousand dollars.

The operations required on an order might be art layout, composition, proofreading, finished art, camera shots, stripping, brownprinting, platemaking, press setup and run, paper cutting, handwork, folding, stitching, and/or packing. The shop is both labor-limited and machine-limited. Furthermore, there is limited flexibility in the labor force.

The primary short-run decisions of importance are those concerning sequencing. Meeting of due dates, value of work-in-process inventory, and even idle time are determined largely by the sequencing decisions made. The shop is a fast-growing shop and thus the load on the shop is maintained at near capacity. Sequencing decisions are essentially the day-to-day control decisions for the shop.

The Computer Simulation Model

The model is a simulation model based upon numerical manipulation to achieve order flow through the shop. Because of the magnitude of the problem, the simulation model has been developed for use on a high-speed computer. A CDC 3400-3600 computer system has been used. The program for the model has been written in FORTRAN because of this researcher's knowledge of the language and the flexibility of the language. Although these were the primary reasons for selecting FORTRAN, this author did not find the computer program to be so extremely complex and difficult to modify as is suggested by most authors* who compare it to special languages such as SIMSCRIPT. The computer program is in modular form to enhance flexibility, ability to change the model, detection of errors, and clarity of the program. The program is thus composed of a main program and several subroutines. Variables and arrays are held in common to maintain efficiency of the program. A run of one hundred and twenty work days takes sixty to ninety seconds of computer run time and about 30K of storage.

The model has been written to represent the actual physical flow of orders through the shop. It has not only been developed to represent the actual shop, but actual order data have been used to generate arrivals, due dates, processing times, routings, and so forth. The model incorporates the factors described in the previous section.

The model is a fixed-time-increment model. The basic clock time is kept in shop time units. One time unit represents six minutes. This unit of time is used by the actual shop to record processing times. Another clock is incremented by days. The day clock controls delays, arrivals, and daily shop statistics. Run length is given in terms of days. Processing time, order flow, idle time accumulation, order dismissals, and so forth are controlled by the time unit clock.

Run conditions specify (1) whether the priority rule is time dependent or independent, (2) the length of the run in days, (3) the number of orders in the start load, (4) the priority rule being used, (5) the order set being used, and (6) the specific start load being used. A priority rule is considered time dependent if the priority value for an order may change while the order is in any one waiting line. Run length is specified in number of working days. There are five working days per week.

Order characteristics that are required by the model include: (1) customer class, (2) arrival day, (3) due day, (4) order value, (5) paper cost, (6) ink cost, (7) plate cost, (8) negative cost, (9) number of operations, (10) total processing time, (11) routing, and (12) processing or service times. Additional data maintained after an order arrives are (1) order position along its routing, (2) work-in-process value for the order (material and labor costs are included), (3) operations remaining for the order, (4) processing time remaining for the order, and (5) priority value for the order. These data are used to maintain proper order flow, to accumulate shop and order statistics, and to determine priority values.

Orders have been drawn from an empirical distribution of orders. Using job cards, daily time sheets, and interviews with the plant manager, information was gathered for orders that arrived over sixty-one actual work days. Two hundred and thirty-four orders have been included in this set. The plant manager identified this set of orders as representative of all order arrivals. The plant manager also determined paper costs for each order and classified customers as primary, secondary, or common according to the importance of each.

Start loads and other order sets have been generated by drawing randomly from this basic set of orders to determine the characteristics of a new order. The plant manager specified a representative starting condition based upon actual shop loads. Given the number of orders in each waiting line, the specific orders may be generated randomly to produce the initial starting conditions. Orders in the starting load have been assumed to be on time relative to meeting due dates. Arrival dates have been made to agree with this assumption. Thus a starting load is representative, but it is also neutral in terms of meeting the due dates for the orders. Starting a shop in the empty and idle condition is the standard approach taken; however, this technique introduces a serious startup problem which must be reduced by discarding performance results over a fairly lengthy period of time. The approach that has been taken here cannot be considered a panacea for solving the startup problem, but it is an attractive approach when the model is empirically derived.

To generate order sets for a period of time, an empirical distribution of the number of arrivals per day has been used. One of the sixty-one days has been chosen randomly and uniformly. The number of order arrivals for that day has been used to determine the number of arrivals for the new order set for a particular day. The specific orders to arrive have been chosen randomly from the base set.

The priority rule or queue discipline may be varied by changing the priority subroutine. The priority subroutine has available all relevant order information, and, in general, the condition of the shop. The priority value is calculated for each order whenever it enters a new queue. The orders at each queue are kept in an ordered file. Higher positive priority values place orders at the first of the queue. For the time-dependent rules, the priority values and ranking are revised when an order is to be loaded for processing.

The model uses fixed processing times. The service times are the actual service times taken from job records. Actual processing times are used as predicted service times by the priority rules that use processing time in deriving priority values. In actual practice, such complete information would seldom be available before the operation has been completed. Conway, Maxwell, and Miller[6] (pp. 228-229) reported tests of the effect of errors in processing time estimates. Errors uniformly distributed from plus to minus ten percent showed no degradation in performance from having perfect knowledge. Errors uniformly distributed from plus to minus one hundred percent yielded very little change in performance of the rule. For the printing shop and the plant manager in question, estimates of service times within plus or minus ten percent are very reasonable.

To avoid having more operating capacity than is actually available, one must allow for worker absences. For planned vacation time plus unplanned absences due to sickness, workers are absent five percent of able time. For this shop, most vacation time is taken in one-or two-day blocks somewhat randomly throughout the year. Therefore, absences for the model have been assumed to be completely random. The probability of a worker being absent for any one day is five one-hundredths.

The model is thus a representation of actual order flows and processing in a commerical printing shop. The model is empirically-derived, and data used in running the model are empirically-based. It is a fixed-time-increment model that relies on a high-speed computer to perform the numerical manipulations that represent shop performance. The computer program for the model is written in FORTRAN and in modular fashion. Order flows are generated by a conjoining of the assumptions and definitions of the model and a given queue discipline.

Model Validation

Does performance generated by the programmed model flow logically from the assumptions? That is, is there agreement between performance and the assumptions and definitions? If agreement does exist, do the generated results and order flows represent performance in the actual shop from which the model has been developed? These are the difficult questions of internal consis-

*For example, see a comparison be O'Leary[14] in the Proceedings of the Fourth Conference.

tency and representativeness.

Internal Consistency

The procedure used to check the internal consistency of the model has been to examine both detailed and aggregate performance under a variety of conditions. Most importantly, the flow and assignment of orders and the availability and assignment of workers has been examined in detail. Hand-calculated statistics have been compared with computer-generated totals for accuracy of data gathered.

Daily shop status may be printed. The shop status report includes a listing of the orders presently being processed, service times remaining, and the codes for the operations. A listing of the orders in waiting lines is also made. This includes queue lengths, order numbers, priority values, and operation codes. The queues are given in ranked order. The orders delayed before bindery work are listed. Both the orders and days remaining for the delay are listed for brownprint approval delays. The results section includes a listing of all accumulated values. Much of this data is reported by customer class.

For the initial check, three small orders were loaded at time zero. The shop was run for one hundred time units using a random sequencing rule. Printed computer performance was matched to hand calculation of order flow, cumulative values, and priority rankings. Two similar checks were made with thirteen and twenty-five orders. The next major check was a complete checking of order flow, statistics gathered, and priority rankings for eighty-three orders for a one-day period. Some general checks were made by running eighty-three order start loads until all orders were completed. Next, several runs were made using a start load and intermittent arrivals over time. General and specific checks were made.

A final analysis of detailed order flow and totals was made using a shortest-processing-time rule. A starting load composed of eighty-three orders was run for two days. Accumulated values and order flows were also determined through hand calculations. Several different rules, including both time-dependent and time-independent rules, were tested to explore the model's ability to handle any situation encountered.

It has been suggested by Conway, Maxwell, and Miller [6] (pp. 15-19) that mean flow-time for any jobbing-to-order shop <u>in steady state</u> should equal the ratio of the mean number of orders in the shop to the mean arrival rate. This was proven for a few simple cases and then generalized to all cases. The performance of this model has approximately agreed with this assertion. For any rule tested under a one hundred and twenty day run, the actual flow-time achieved has been within ten percent of the flow-time calculated from the above ratio.

Representativeness

Given that the internal consistency of the abstracted model has been accepted as satisfactory, one must question the realism of the abstracted model. Building a model from an actual shop should tend to yield a more representative model. It also provides an opportunity to make more direct evaluations of model realism.

Does the model realistically abstract and present the sequencing decision problem? Ideally, one could implement actual decisions within the model and compare simulated with actual performance. This has proven to be infeasible for the current study. Records were not available in the proper form. However, it has still been possible to make several checks of model representativeness, albeit somewhat subjective. These have been made in addition to comparisons of individual assumptions with the actual shop. Given the handling of the details of the model, one should determine if the resultant model is representative of the actual shop in total. The technique has been to compare several known characteristics of the actual shop with measures generated from the model. But most importantly, the plant manager's opinion of the model has been used to evaluate the realism of the abstracted model.

To gain familiarity with the model, the manager made decisions within the constraints of the model. The manager made priority value decisions, the shop was run for a period of time, shop status was printed, and the manager evaluated the status of the shop. This process was repeated several times.

After an initial period of explanation, the manager expressed comfort with making sequencing decisions by assigning priority values. After this initial familiarization, four decision-making sessions of approximately one hour each were recorded on tape. A "protocol" was obtained. A "protocol" is a record of the verbalization of the thought processes while making decisions. This particular protocol has been useful for determining factors considered and procedures used by the manager when he makes sequencing decisions. Also, the protocol provided an opportunity to obtain the manager's opinion of model representativeness.

Overall, the shop manager seemed very satisfied with the performance and realism of the model. He felt that the conditions he encountered in making decisions for the model were very similar to situations actually found in the shop. For instance, he noted that a heavy load that was encountered in the art department was typical of shop conditions. The plant manager seemed comfortable with the constraints on the sequencing decisions. Most of the suggestions that he made may be handled through the priority function.

The manager appears to base sequencing decisions primarily on due date and customer class. Some consideration is also given to keeping the entire shop loaded. Using a sequencing rule based upon these factors, feasible performance* was obtained for a fifty-seven day run. The shop was also run for this rule using one hundred and twenty day order set. Simulated performance results were compared to actual values for the shop. The manager estimated the mean flow time to be approximately fifteen days. He estimated the average number of orders in the shop to be approximately seventy, with considerable variation, and average inventory value to be about thirty thousand dollars. Using a rule of the form discussed above, the following values were obtained: (1) a mean flow time of 16.2 days, (2) an average of 66.4 orders in the shop with a standard deviation of 12.1, and (3) an average inventory value of $29,285. Performance results with other similar rules closely approximated the manager's estimated values.

Queue Disciplines

After building and validating the model, one may incorporate a decision rule into the model and generate the resultant shop performance. Researchers have generally reported the approach of determining new rules based upon insight gained from exploration with a model. The procedures followed in this study have been: (1) to use standard rules reported by other researchers, (2) to develop other rules through insight gained or random curiosity, (3) to develop rules that incorporate relevant factors not previously considered, and finally (4) to identify possible relevant factors and incorporate them in a general priority function.

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* Feasible performance refers to the number and type of extremely late orders allowable in the shop.

Standard-type Rules

A number of rules were taken from the literature and others were generated from insight gained through experimentation. Rather than a list of all 34 rules tested under this category, a general discussion of the types and sources of rules follows. Random sequencing and first-in, first-out sequencing were used to provide base points for comparison.

The shortest-processing-time rule and job-slack rule that Conway[4, 5] and most other researchers have found to yield "good" performance have been used. The job-slack rule includes an adjustment for processing time remaining. The shortest-processing-time rule has also been truncated as suggested by Conway, Maxwell, and Miller.[6] The "COVERT" rule developed by Carroll[1] and the modified "COVERT" rule reported by Montagne[12] have been considered in developing rules relevant to the present model.

The use of job value in making sequencing decisions was suggested by Colley.[2,3] Interviews with managers of six different firms also resulted in the identification of customer value as a major factor. Hottenstein[10] examined the effects of superimposing expediting techniques. Truncation of simple rules has been developed to expedite late orders or other orders that may have special characteristics. Expediting has been based on an order: (1) being tardy, (2) having negative slack, (3) being in the shop over a certain length of time, and (4) having many operations and/or much processing time.

Look-ahead heuristics as suggested by Carroll[1] and Gere[9] have also been superimposed on a number of "simple" rules. An idle time look-ahead involves giving high priority to any order which goes to an empty queue next. If more than one order under consideration may be given high priority, then the order with the shortest imminent processing time is loaded next. A sequence dependency heuristic involves giving high priority to those orders that would reduce setup or washup time. These heuristics have been superimposed upon a number of rules to test their general effects.

A few other rules were tested because of the researcher's curiosity or because of implications from the other rules. For instance, one such rule is a multiplicative combination of the basic shortest-processing-time and job-slack rules. There is, of course, no limit to the number of rules that might be developed and tested. Hopefully some of the basic and most important rules have been included.

A Manager's Procedures

A protocol of the manager's decision-making processes was obtained. From this the factors considered by the manager and the procedures used for making sequencing decisions were identified. The primary factor that was always considered was the order due date. Secondly, customer class was the reason for the sequence chosen when due dates were nearly the same. Orders from the more important customers were given higher priority. On the shop level, idle time on the presses is very costly. The manager expedited orders in the camera department if they were to be routed to a press that was not very busy. The above three factors appeared to determine most of the manager's decisions and were thus combined into a rule.

Other factors were considered by the manager for making some of the decisions. For instance, one order was given high priority because it has a short imminent processing time and a considerable amount of work in the press and bindery departments. The purpose of this decision was to move the order out into the shop and keep total shop load balanced. Some orders were given low values because their total processing time was low, and other orders were given high priority for the same reason. This contradiction in decisions seemed to arise because of nearness of the due date. If orders had similar due dates and were the same class, then processing time was considered. Order value was considered a few times in terms of identifying a large order. Although other information was also available, the above factors were the only ones verbally identified by the manager.

A Priority Function

An analysis of the manager's protocol and the researcher's experience with the actual shop led to the conclusion that an inclusive priority function was needed. In making sequencing decisions, the manager considered many factors. Much information about order characteristics is readily available for the model as well as the actual shop, such as processing times, order value, operations yet to be performed for the order, total processing time, due date, and so forth. A critical review of sequencing rules recently developed by researchers also led to the conclusion that many of these new rules involved consideration of relevant factors previously ignored. This revealed that the determination of what variables affect the sequencing process has been partially ignored. This led to the question: Why should not all relevant factors be considered when making sequencing decisions? It would be illogical not to consider all available information that may be relevant.

Using the order information available and shop factors identified as relevant for this model, the additive priority function given in Figure 1 has been developed. For this function the relevant factors have been combined in a linear additive function. An additive function was selected because of the simplicity of this combination of factors.

One may search for a "best" combination of factors by varying the coefficients in the equation. The constants have been applied to each factor so that they will be of equal magnitude for this model. Thus the coefficients considered may be of similar magnitude. Factors may be eliminated from consideration by giving them a zero coefficient. Variations of the function were generated by changing some of the coefficients. Fourteen rules in addition to the standard-type rules were examined.

FIGURE 1: ADDITIVE PRIORITY FUNCTION

If waiting line for this queue is greater than 35, priority value = Inverse of imminent processing time; otherwise,

Priority value = Inverse of customer class x A
+ (current day + time remaining/65) - due day) x B
+ (0.05 x (current day - due day + 1)) x C
+ (order value/5000) x D
+ (order work-in-process value/6000) x E
+ (0.025 x (current day - order arrival day)) x F
+ (operations remaining / 25) x G
+ (processing time remaining / 2200) x H
+ (total number of operations / 25) x I
+ (total processing time / 2200) x J
+ (1 x K) if sequence dependency factor relevant
+ (1 x L) if idle time factor relevant
+ (Inverse of imminent processing time) x M.

Performance Evaluation Methods

Standard Measures

Mean flow time, job tardiness or lateness, and work-in-process inventory value are the statistics used most often in evaluating performance in an intermittent-arrival, continuing-load situation. For this model, the following measures may be gathered for each sequencing rule tested: (1) mean and variance of flow time, (2) mean and variance of work-in-process inventory value, (3) number of tardy orders, (4) number of tardy days, (5) total of the squared values of tardy days, (6) mean and variance of number of orders in the shop, (7) mean and variance of total workload in the shop, (8) mean and variance of total processing time remaining in the shop, (9) mean and variance of work completed in the shop, (10) number of orders completed on time, (11) number of orders completed early, (12) number of early days, and (13) number of arrivals per day. Additionally, the measures may be gathered by customer class where such a breakdown is meaningful.

Practicality of Rules

Using a model based upon an actual firm provides the opportunity to test the practicality of the sequencing rules. Does the sequencing rule yield order flows and shop conditions that are reasonable in the actual shop? Factors specified by the manager include: (1) length of waiting lines, (2) length of stay in the shop for any order, and (3) number and types of orders in the shop for an "extremely long" period of time. Information about practicality was gathered through an interview with the shop manager.

For any jobbing-to-order shop there is a limit to the length of waiting lines that can be allowed to form. The manager has indicated that queues longer than thirty-five orders are unreasonably long for this shop but not improbable. They should not occur often however, and they should be reduced to a lower level quickly. Queue lengths greater than fifty are unworkable. If such queue lengths occur, the rule may be considered impractical.

Without considering some special cases that are not incorporated in the shop model, the manager considers it impractical for an order to be in the shop over sixty days. A longer stay in the shop would cause either cancellation of the order or extremely high ill will. Either result is prohibitive. Even a stay of over thirty-five days in the shop is rare and very costly. Only large orders with many operations and a high total processing time requirement are allowed to stay in the shop over thirty-five days. The manager feels that long stays for small orders would irreparably damage the shop's desired image.

Even though it is practicable to have large orders stay in the shop over thirty-five days, the manager has stated that the number of orders that have been in the shop for such a long stay should not exceed five orders and may not exceed eight orders. If the number is between five and eight, then the individual orders must be carefully scrutinized concerning size, length of stay to date, and amount of work remaining.

The fifty sequencing rules that were developed have been evaluated for practicability. Eighteen of the rules yielded practicable performance.

Total Cost Criterion

The pitfalls of judging the efficacy of sequencing rules considering only one kind of performance statistic are many. The only satisfactory technique for evaluating performance of sequencing rules is to develop an overall performance measure. All relevant performance factors must be included in such a criterion. Given the availability of cost information from the actual firm, a total cost function has been derived for this model.

The following factors may affect costs and may be considered: (1) idle time, (2) work-in-process inventory value, (3) total value of tardy orders, (4) number of tardy orders, (5) total sum of tardy days squared, (6) sequence-dependent press cleanup time, (7) sequence-dependent bindery setup time, (8) number of early orders, and (9) number of early days. For the actual shop, early orders do not incur any additional cost. Therefore, one may assign number of early orders and number of early days cost coefficients of zero in the cost function and ignore them. The remaining factors have been combined into a total relevant cost criterion as shown in Figure 2. Tardiness cost is divided into three components. A tardy order cost and a cost per tardy day have generally been identified in other studies. The manager for the printing firm specified tardiness cost as a function of order value. Thus it was decided to include all three factors. Discussions with the manager also led to the conclusion that the cost for tardy days should be a function of the squared values of tardy days.

FIGURE 2: TOTAL RELEVANT COST FORMULATION

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\begin{aligned}
TRC = &\sum_{i=1}^{18} IDT(i) \times C(i) && \text{(Idle time cost)} \\
&+ \sum_{i=1}^{3} KSUT(i) \times CS(i) && \text{(Bindery setup cost)} \\
&+ \sum_{i=1}^{3} KUP(i) \times CP(i) && \text{(Press cleanup cost)} \\
&+ ATWIPV \times CIP(I) && \text{(Work-in-process inventory cost)} \\
&+ \sum_{i=1}^{3} TVOL(i) \times VLC(i,J) && \text{(Tardy order value cost)} \\
&+ \sum_{i=1}^{3} NOL(i) \times FLC(i,K) && \text{(Tardy order cost)} \\
&+ \sum_{i=1}^{3} ITLDS(i) \times DLC(i,L) && \text{(Tardy day cost)}
\end{aligned}
$$

where TRC = total relevant cost
IDT(i) = idle time accumulated by worker group
C(i) = cost of idle time at each worker group (idle, setup, and cleanup times are charged at the rate normally incurred by the worker group)
KSUT(i) = bindery setup time accumulated by machine
CS(i) = cost of setup for each machine
KUP(i) = press cleanup time accumulated for each worker group
CP(i) = charge for cleanup for each worker group
ATWIPV = average daily work-in-process value
CIP(I) = charge for carrying inventory value (may be varied)
TVOL(i) = total value of orders tardy by customer class
VLC(i,J) = charge for value of tardy orders by customer class (may be varied)
NOL(i) = numbers of tardy orders by customer class
FLC(i,K) = charge for a tardy order by customer class (may be varied)
ITLDS(i) = total square of tardy days by customer class
DLC(i,L) = charge for tardy days squared by customer class (may be varied)

Where indicated, charges may be varied to perform a sensitivity analysis.

Idle time charges, setup charges, and washup charges are held constant in this study. These charges depend on labor rates and machinery costs which are common throughout the commerical printing industry. Tardiness costs and inventory charges may vary considerably among firms within the trade, however. Determination of these costs must be much more subjective and may depend on each firm's special policies. Therefore, ranges of values have been explored.

Thirty-six different combinations of cost coefficients have been generated. The cost coefficients identified by the manager for the actual shop were used as the basis for determining other values to test. A representative sampling of situations with major differences between them was sought. Only those combinations of the values that would have meaning for an actual shop were tested.

The eighteen practical rules have been run for a period of time, and statistics have been gathered. Standard performance measures have been gathered and calculated. In addition, total relevant costs have been calculated for each rule using combinations of cost coefficients.

Results and Findings

For fifty sequencing rules developed, an evaluation of the practicability of each rule was made. After discarding the rules that were found to be impractical, the remaining rules were conjoined with the model to simulate six months of shop performance. Results from these runs have been evaluated by examining shop statistics gathered and by comparison of cost performance.

Furthermore, an examination of the factors included in practical versus impractical rules has been made to determine if any identifiable patterns exist. The detailed performance data gathered for the practical rules have been examined in total and by customer class to establish any major factors common to either "good" or "poor" performance rules. A sensitivity analysis of the total relevant cost function was made by varying inventory and tardiness costs.

Finally the rules have been divided into groups according to performance across all cost combinations explored. An attempt has been made to order the groups based on cost performance under the cost coefficients identified for the actual shop.

Determination of Practicability

Each rule was used to generate fifty-seven days* of shop performance based upon the same starting load and order set. The order set used was comprised of the actual arrival pattern of the orders for which information was gathered. This order set provides a good basis for judging practicality. A practical order should handle any situation encountered, including an actual one. The shop status after the fifty-seven day run was examined for each rule. Rules were classified as impractical if the final shop status violated the conditions for length of stay in the shop, number of extremely tardy orders, and mix of extremely tardy orders.

Since the determination of practicality was based on one starting load and the actual order set, the generalization of the results to other conditions was questionable. Another starting load and two additional order sets were generated randomly. This produces five additional possible combinations of starting load and order set. Several rules were tested under the additional sets of conditions and were found to yield consistent results over each additional situation.

Judging the practicality of sequencing rules as defined by the shop manager proved to be a selective criterion. Thirty-two of fifty rules were eliminated from consideration. Reasonableness of detailed performance has been largely ignored by previous researchers. Such a practice allows many extremely tardy orders to remain in the shop incompleted and forces some orders to remain in the shop indefinitely. This would be impractical for actual shops. Many of the standard rules, such as shortest-processing-time, job-slack, and first-in, first-out, were thus found to be impractical and would require some modification to obtain practicality. The conclusion reached from applying the practicality criterion was that a rule must consider due date and be time-dependent before it is likely to be practical.

Standard Measure Results

Each rule that was found to be practical was then used to generate six months or one hundred and twenty days of shop performance. Data were gathered concerning performance using the same start load and a newly generated one hundred and twenty day order set. Although this represents six months of shop performance with a randomly generated order set, one may still question the general implications of any results. During this time period approximately five hundred orders may be completed. This represents more than twice as many orders as the manager has specified to be representative. It also represents a turnover of about eight shop loads.

Evaluating detailed performance results for the eighteen rules found to be practical yielded some interesting results. For instance, mean total workload in the shop and mean total processing time remaining in the shop were found to be relatively independent of the sequencing method. Mean work completed and remaining in the shop was found to be strictly a function of shop capacity. It was also found that the various sequencing rules have different effects on each particular customer class.

The inconsistency of rule rankings based upon standard measures such as mean flow-time and tardy orders was noted. That is, a rule would be ranked near the top for one measure and near the bottom on another measure. To cope with this problem, an overall performance measure was developed. Again, the fact that the model was empirically-derived provided the opportunity for the development of a total relevant cost function. One would not consider evaluating an inventory policy unless a total relevant cost function could be specified, nor should one evaluate sequencing rules without a total cost function.

Total Cost Performance

Rule orderings were found to be fairly insensitive to changes in cost coefficients when a sensitivity analysis was conducted. This was even more true across groupings of the rules. Significant differences among rules would be very difficult to find without taking several samples under many varying conditions. However, finding "the optimal" rule is probably not important for most situations. By grouping rules and finding significant differences among groups, one may be able to find those rules that yield "satisfactory" performance. But more importantly, there may be certain common features of the "best" group of rules.

The eighteen practical rules were grouped into three groups of six based upon consistence of ordering across all cost combinations explored. The means of total cost performance for the groups were compared using Tukey's method[15] of post hoc analysis to contrast the means of the three groups. Means for each group are calculated using the actual cost situation. Tukey's method is designed for studying simple differences between means. All groups must have the same number of observations and all comparisons must be contrasts. The method relies on the assumption of independently normally distributed populations with constant variance. Tests are based on the Studentized Range distribution. Results of tests are shown in Table 1. Null hypotheses are used. Since this method has a low degree of power, any differences found may be considered highly signifi-

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* Fifty-seven days was chosen somewhat arbitrarily. It represents over two hundred order arrivals and was adequate for determining practicality.

cant.

The overall test of significance shows that some contrast may be significant beyond the 0.01 level. The other two tests show that the null hypotheses may be rejected. It may be concluded that the mean of group A is less than the mean of group B and that the combined mean of groups A and B is less than the mean of Group C. The rules in group A may thus be considered "superior" rules as a group. It should be noted that the findings are for the groupings and not the individual rules.

The six rules in the best group included two truncated shortest-processing-time rules and four additive-priority-function rules. Truncation of rules involved expediting some orders based on tardiness, stay in the shop, total operations, and/or total processing time. The latter four rules used a high

TABLE 1

COMPARISON OF GROUP MEANS

$\bar{X}_A$ = \$41,217 $\bar{X}_B$ = \$42,750 $\bar{X}_C$ = \$44,350 based on 6 months of simulated results

Overall test of significance

H_o: $\mu_C - \mu_A = 0$ $t'(3,15) = 11.68$
Significant beyond the .01 level

Comparison of Means

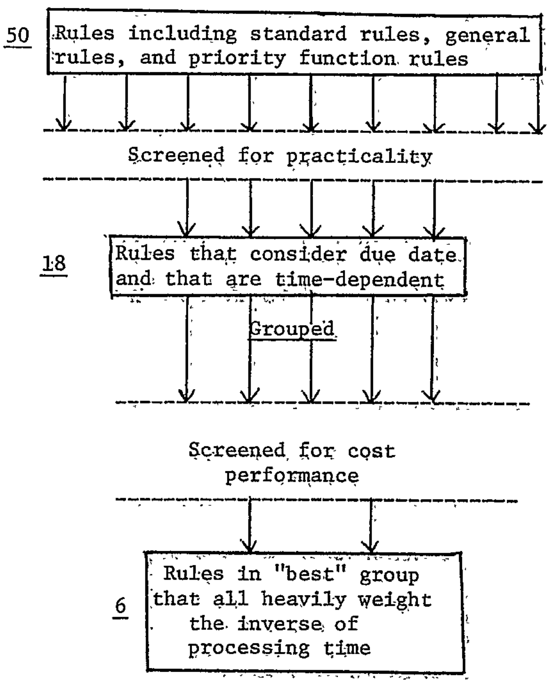
$H_o(1)$: $\mu_B - \mu_A = 0$ $t'(3,15) = 5.72$
Significant beyond the .01 level

$H_o(2)$: $2\mu_C - \mu_B - \mu_A = 0$ $t'(3,15) = 8.82$
Significant beyond the .01 level

value for the weighting of shortest imminent processing time. Thus it appears that shortest processing time should be heavily weighted to obtain "good" cost performance. However, this factor alone produces an impractical rule. Other shop and order factors must be considered, particularly due date, idle time, and customer class.

Results are summarized in Figure 3.

FIGURE 3: SUMMARY OF RESULTS



(cost savings of 7 - 10% over current methods)

Generalization of Model

The results and conclusions presented were based on the abstracted model. They may be generalized to the actual shop, other commercial printing firms, other models of jobbing-to-order shops, and general jobbing-to-order environments to the extent that the model represents these other situations. Definitive statements may be made only for the empirically-derived model and order environment; however, implications to the other situations should be possible, since the model abstracts many characteristics common to all jobbing-to-order shops.

Uniformity of commercial printing shops allows one to generalize to the job printing industry, even if one questions further generalization. There are approximately 20,000 job printing shops with over 300,000 employees in the United States. Annual dollar volume for the trade exceeds thirteen billion* Thus the utility of such a model in the commercial printing trade alone could be great.

For the simulated shop, production is entirely to order with comparatively low volume per order. Each order has unique specifications and therefore no stock of standard items may be held as finished inventory. Layout is of the flow-shop type, but similar sequencing problems arise with either flow-shop or job-shop layout. The commercial printing shop also possesses other characteristic properties of jobbing-to-order shops. To the extent that the primary jobbing-to-order factors exist in the model, results may be meaningful for the entire sequencing area.

The following directions are suggested for future research in the sequencing area:

1. Research should be more closely associated with actual situations to facilitate identification of relevant costs.

2. There should be more concern for the question of validation. Experience with actual shops enhances the possibilities.

3. Evaluation of rules should include consideration of practicality. This includes a real questioning of assumptions made and factors considered for hypothetical models. Have the proper characteristics of a jobbing-to-order shop been abstracted?

4. Information requirements and costs should be identified and considered. For the firm from which the model was built, all information requirements added no marginal costs. The information was currently available to the manager because of normal shop records and the small size of the shop.

5. More directed search for an "optimal" rule should be used. The use of an overall priority function should guide efforts. Emery[8] reported some preliminary work with screening (a psuedo-expediting to maintain practicability) and "simple sectioning search" at the third conference.

6. Performance should be evaluated in terms of a total relevant cost function. This will require more research into what costs are relevant and what their relative magnitudes may be.

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* See any recent copy of Printing and Production, which is published by the U. S. Department of Commerce.

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