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PRODUCTION CONTROL AND SCHEDULING

by

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B.S., Yale University
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ABSTRACT

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Robert J. Osterhus

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This thesis reports the analysis of a computer scheduling system which failed to accomplish its objectives. The primary reason for its failure was that the assumptions which it was based on were generally invalid for the job shop for which it was designed to schedule. In addition, the computer generated priorities for use in the dispatching of parts to available work stations. Use of the priorities in the Shop's sequential scheduling did not reasonably guarantee that parts would be manufactured in time to meet the Shop's delivery commitments.

A systematic analysis was made of one factor influencing the length of the manufacturing cycle for the Shop's parts. This analysis focused on describing the average efficiency of the workers and the variation which the Shop can expect to encounter in the average labor efficiency. Both the level and the variation of labor efficiency have a direct effect on the length of the "lead" time or manufacturing cycle time. The importance of the efficiency of the labor input to any scheduling system is that it is relatively beyond management's control. Other factors influencing the length of the manufacturing cycle can be controlled by management. One major factor of this type is the length of time a part spends waiting for assignment to machine capacity. The results of this analysis can provide management with an estimate of the effect of labor efficiency and its variation on the length of the manufacturing cycle in a quality-oriented job shop.

Thesis Advisor: Donald C. Carroll
Assistant Professor of Industrial Management

Professor Philip Franklin
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Franklin:

In accordance with the requirements for graduation, I herewith submit a thesis entitled "Production Control and Scheduling."

Throughout the duration of this thesis, Professor Donald C. Carroll has been exceptionally helpful in offering constructive criticisms and valuable advice. His effort has been appreciated immensely. I would also like to thank Professor James Emery who so helpfully served as Committee Member.

Sincerely yours,

Robert J. Osterhus

Robert J. Osterhus

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CHAPTER I

INTRODUCTION

Purposes and Methods

The basic purpose of this thesis is to study the circumstances leading to the phasing out of an elaborate application of the IBM 704 Computer to scheduling a medium-sized job shop. The secondary purpose is to analyze in depth the importance of more accurate estimates of labor efficiency on manufacturing cycle times. The methods of analysis used in arriving at conclusions with regard to the first purposes were interviewing company personnel in the job shop and analyzing the output of the scheduling routine used by the job shop.

The methods used to arrive at conclusions on the manufacturing cycle times are of an entirely different nature. This second set of methods involves the use of an IBM 1620 computer to classify and summarize records containing information on labor efficiency and the IBM 7090 computer to generate the costs of operating the job shop and the manufacturing cycle times of the shop's parts under different assumptions of labor efficiency and usage of different order quantity rules. Whereas the first set of methods used in the study of the basic purpose rests heavily on judgement, the second set of methods does not. Judgement enters into the second set of methods only in determining the classifications of labor efficiency and the selection of the order quantity rules.

Description of Problem Area

Many companies have recently taken the step toward using the computer for non-accounting purposes. Increasingly, computers have been used to assist management in making better and faster decisions. The company studied, the identity of which will remain unspecified, was one of the first to explore the use of a computer for scheduling. The production area, with its associated Production Control Department, will be referred to as the "Shop." The men who designed and programmed the computer for this scheduling application will be called the Systems and Procedures Department. And, finally, the computer-based scheduling system will be called the Computer Scheduling System (CSS).

The scope of the CSS when studied covered about 250 machine groups with a total of 300 machines or work centers in these groups. There were fewer than 300 employees on each shift. In the two areas which the CSS used for scheduling there were only approximately 150 parts manufactured within the Shop. These parts had about 6000 operations (including setups) in their manufacturing sequences. The delivery demand placed on the Shop was essentially a steady, constant requirement for approximately 50 capital goods-type assemblies per week composed of two product groups. The reason why there was virtually no uncertainty in the level of demand by customers for at least a year was the result of customer contract agreements. In effect, there was no problem of leveling production and/or work force. Thus, several of the difficult scheduling problems did not exist at all in the Shop's environment.

Other problems, which are minor in most job shops, were major in this one. A central problem was that one could never be sure he would be able to finish a sequence of operations with the original order quantity intact. The causes for this problem seemed to be primarily the breakdown of dies, reworking of parts which failed inspection, and "bumping" by other parts having a higher priority. The first two reasons were relatively uncontrollable by management. The last one was completely controlled by management.

Because of the highly technical nature of the final assemblies, production plans were subject to frequent changes. The CSS did an effective job of updating this Planning File as well as producing the paperwork required to implement the engineering changes. This was a strong feature of the CSS. But there were cheaper ways to perform the same function.

Essentially, the CSS was intended to inform the Shop as to when a part would have to be started through the Shop. During the course of manufacturing a part the Shop was supposed to use specially-designed dispatching rules which involved the utilization of CSS-generated priorities.[1] The Shop did not start parts when the CSS

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[1] J. C. Emery, "An Approach to Job Shop Scheduling Using a Large-Scale Computer,"(Cambridge: M.I.T. Industrial Management Review, 1961).

R. W. Conway, B. M. Johnson, and W.L. Maxwell, "An Experimental Investigation of Priority Dispatching," (Journal of Industrial Engineering., May-June, 1960).

indicated they should be started. In fact, in a sample of approximately five months, in only three cases out of 137 was a part started on the date scheduled. Most starts were from one week to two months late. Yet, the Shop's deliveries were not significantly overdue during the later stages of the use of the CSS. Thus, it is apparent that only to a limited extent did the Shop use the priorities to make assignments of work to employees. An informal dispatch system with a different set of priorities was employed, at least, to a certain extent. The order quantities generated by the CSS were not determined by cost considerations nor by level of inventory. These factors were intermittently brought into the scheduling function only by manual intervention. The CSS-generated order quantities were determined almost exclusively by the usage for two weeks demand.

In trying to treat all areas uniformly, especially in regard to using a universal order quantity rule, the CSS attempted to order batch quantities to be produced on a production line setup for continuous processing. When the Systems and Procedures Department set out to mechanize the Shop's scheduling function, they strove to treat separate areas of the Shop uniformly. Thus, the same order quantity rules were used universally. The variable costs which are a function of the scheduling rules were not thoroughly explored when the CSS was introduced. There seemed to be no reason for such an examination.

In addition to presenting the findings of the case study, this thesis explores the accuracy of the estimate of one factor affecting delivery time which is beyond the control of management. That factor is the average labor efficiency and its variation.

Depending upon the scheduling technique used, its importance can be either large or small. Hypothesizing the effect on the Shop's capacity or service rate of changes in the efficiency of the workers in the Shop was not the concern here. The sole concern was the accuracy of management's estimate of the true efficiency. It was found from the study that the accuracy of estimating the average efficiency was important, but knowing its variation was not important unless management was trying to rush a job through the Shop. Since the Shop was under little pressure to justify inventory levels, the scheduling environment was very flexible. Under a tighter control of inventory level and pressure to reduce the length of the manufacturing cycle, the importance, in terms of meeting delivery commitments, of this type of analysis would increase for the Shop.

Summaries of Succeeding Chapters

Chapter II describes the basic components of the CSS. It enumerates the various sources of input information and the nature of the output. A brief description is given of the underlying philosophy of the scheduling routine. The method used in the CSS to determine the priorities is outlined. Following this is a discussion of the function of dispatching in the operation of the CSS.

Chapter III presents a detailed analysis of the validity of several assumptions about the Shop which the CSS made. It describes how certain invalid assumptions contributed to the failure of the CSS. The chapter includes a description of some operating failures which also contributed to the failure of the CSS.

Chapter IV fully describes the second purpose of this thesis and the approach used in studying the predicted length of the manufacturing cycle for a part as a function of the estimated labor efficiency and the order quantity rule used. The first section of this chapter presents the method of classifying and summarizing the information on labor efficiency. The second section of this chapter presents alternative order quantity rules to the rule used by the Shop in the OSS.

Chapter V describes the results of the Manufacturing Time Analysis described in Chapter IV.

Chapter VI concludes the over-all study of the scheduling operation of the Shop.

CHAPTER II

GENERAL DESCRIPTION OF SHOP AND CSS

During the period 1957 to 1960 the production rate of the Shop increased by a factor of 100%. This rapid increase in output required the development of a systematic procedure for updating the planning sheets, scheduling instructions, and dispatching the work to the shop personnel. In 1959, three or four members of the Systems and Procedures Department began to develop a system for scheduling the work in the Shop. Introduction of the system was attempted in 1960 by this group by being made a dual scheduling system with the systems which were used by the various departments. It seemed desirable at the time to use the computer to schedule the Shop's operations. The Systems and Procedures Department sought to mechanize the scheduling procedure, but without any close study of the feasibility of so scheduling from the Shop's point of view. Since the CSS failed to accomplish its objective, it seems reasonable to assume that the failure might have been predicted from such a feasibility study. However, it is felt that the Shop was not in a position to know the nature of the details of the CSS which would create the conditions for its failure. An intensive study by the Systems and Procedures Department of the peculiar conditions of this Shop might have vividly revealed ahead of time some of the problems which the CSS would encounter.

The CSS was patterned after the IBM Job Shop Simulator.[2] However, in the operation of the CSS there is no simulation.

The CSS uses primary orders and their due dates as a base point. A new primary order is exploded into the required number and type of secondary parts and assemblies. The Hierarchy File contains a coded list of all possible parts. Figure A shows a graphical example

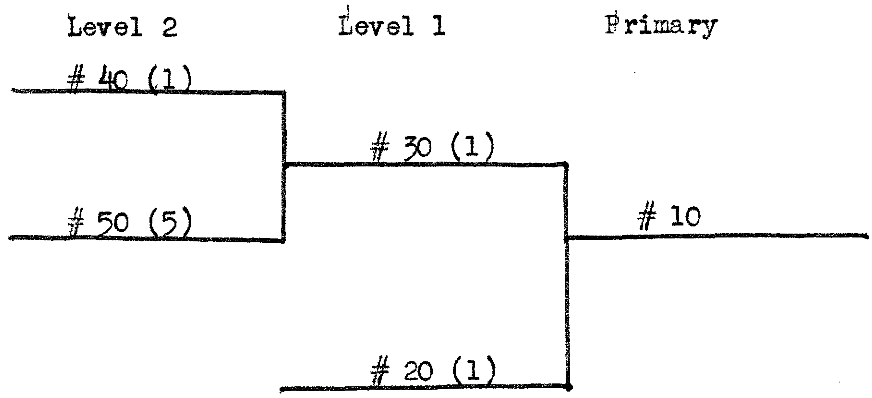

Figure A

of the contents of the Hierarchy File. Part #10 is the primary assembly. Parts #20 and #30 are level one parts which are assembled to make Part #10. Parts #40 and #50 are level two parts which are assembled to make Part #30. The numbers in parentheses indicate the number of parts needed to make one assembly at a higher level.

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[2] IBM, General Information Manual: Improved Job Shop Management Through Data Processing, (New York: Applications Library, 1960).

IBM, The Job Shop Simulator, (New York: Mathematics and Applications Library, 1959).

For the theoretical basis of the Job Shop Simulator, see Alan Jay Rowe, Sequential Decision Rules in Production Scheduling, (U. of California PhD Thesis, 1952).

For example, Part #30 uses in its assembly one of Part #40 and five of Part #50. In general, it can be said that each part being scheduled by the CSS is unique and is used on only one level in the hierarchy of only one primary assembly.

Planning File

The Planning File contains all the information used by the Production Control Department for scheduling and dispatching the parts in the Shop. This file contains the planned time for each operation of every drawing number that the Shop may do work on. The Planning Department has set up a planned time for just about every operation involved in the manufacture of all parts in the Shop. All setup operations are considered separate from their associated run operations. The Planning File can be printed to produce a planning control sheet at any time. This Planning File can be updated by submitting to the Computer Department an updating sheet which includes the old planned time and the new planned time. It may also be updated by adding new operations and is very flexible in establishing a new planning record for any planned change which is needed. The Planning File and the exploded orders for individual parts and assemblies are combined to form one tape which is fed into the scheduling routine. This routine has two or three tapes which contain the status of all parts in the Shop at any one time. The status of these parts can be changed as a result of changing the planning tape or changing the primary orders and the explosion to arrive at secondary orders.

The Scheduling Routine

The scheduling routine assigns start dates to each operation for those parts which must be manufactured by the Shop. The method used for establishing the start dates is presented in the next section entitled, "The CSS Method of Determining the Start Dates."

The output of this scheduling routine is several-fold in number. The first is a status list which indicates the status of every part in the Shop, no matter how large or how small. Secondly, an expedite list is printed which indicates those parts which need to be expedited. Thirdly, it dumps out a shortage list of those parts necessary to the completion of parts in process, but which are not available to the Shop at the present time. Fourthly, it dumps out a machine utilization report which establishes the work load on any one machine as of any one particular week in any future time period for the parts already scheduled within the Shop. Fifth, it dumps out a labor utilization report by labor class, i.e., across the board any one particular class of labor is categorized as the same and is in a pool of labor of the same class. This is not by work station or foreman number or any arrangement of this kind, but rather across the board for all several thousand employees. And, finally, it develops and generates the start cards for each of the operations to be performed in the manufacturing sequence.

The computer develops a plan, or a dispatching load, which is designed to be carried out by a human dispatcher between computer runs by assigning work to work stations using, as a guide, the start dates on the start cards. Once the operation is completed, the start card is put into the completed file, or box, near the dispatcher's desk and is carried to the IBM computation room for key punching each day and the status file of the scheduling routine is then updated in the interim between one run of the scheduling system and the succeeding run of the scheduling system.

The philosophy behind this computer system is to establish the point in time when a set of parts, or a group of parts, should be started at its first operation in order to allow the parts to be completed on time to meet a desired shipping date. The start date serves as a priority index which automatically reflects deviations from the planned cycle.[3] When a part is delayed for some reason, its start date will tend to be the earliest date in the file of jobs waiting for work. The part would then be placed first in the waiting line so as to be assigned to a machine as soon as it is available. Since the sequence of jobs to be operated on by a particular machine is not fixed ahead of time, feedback from actual performance is used for assigning relative priorities between jobs waiting for service at a single machine center. In this way the Shop is reasonably assured that they will meet their promised delivery dates for each part.

Because of the complexity of the scheduling problem of the Shop as seen by the Systems and Procedures Department, it was felt that this scheduling problem could be best solved by using a very high-powered

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[3] See Rowe op. cit., Introduction.

computer program. This program was therefore written to handle the dispatching of these large numbers of parts by an automated system. It was felt that the design changes by the Engineering Department could be relatively easily incorporated in the computer system, whereas these design changes caused a certain amount of difficulty in the manual system. In effect, the argument was stated that the computer system could adapt to changes in planning, in design, and in machine operations far more readily than could a manual system.

Part of the stimulus for the introduction of such a computer scheduling program was to allow the Shop to expand its operations by a measurable degree, both in complexity and in volume, and still maintain a reasonable amount of control over the operations in the Shop. The influx of new orders into the Shop put certain excessive stresses and strains upon the ability of the organization to adapt itself to operational changes, operation and planning changes, design changes, etc. Before the computer system was established, the various departments within the Shop operated independently in their dispatching routines. It was felt that a computer system with an integrated routine and the uniform nature with which it treated parts could accomplish an integrated operation of the Shop which would far exceed the efficiency that was achieved prior to the potential introduction of the computer scheduling system.

One problem of this system is that it is based on the philosophy of establishing a start date and scheduling parts through the Shop on the basis of this start date. An opposing view, or way of scheduling parts through a shop, is by machine loading, i.e., making sure that the machines are loaded as much as possible but never overloading a machine. The computer scheduling system assumes a capacity large enough to process any number of parts through any one work station that has a start date as of that given day allowing for an average expected queue time at that work station. No work load leveling is considered a part of this system except for the leveling of the primary demand on the level one assemblies that are shipped out the door. However, the parts and components that go into this assembly are not considered to be leveled and the demands that they make on any one work station, or group of work stations, for a certain limited period of time may be exceptionally large and may, in effect, exceed the capacity of that work station. Evidently, during the operation of this computer scheduling system certain work stations were loaded up very heavily while other work stations had not been assigned, or could not be dispatched, enough work to keep them busy. In other words, some employees were overworked and others were underworked, depending upon the nature of the demands placed upon these work stations and employees by the computer scheduling system.

The CSS Method of Determining the Start Dates

For the various secondary parts each link of which has a final due date and a beginning point or starting date, the end point or completion date for the one operation is the start date for the succeeding operation. The elapsed time between the start date and the completion date is the time assigned for transit, queue, and operation time plus a variance from this planned operation time. For a particular work station or machine group the queue and the transit times are both constant no matter what the operation is, whether it be a setup or a run operation. The queue time is considered to be eight hours, or one shift in most , but not all, cases, and the transit time is considered to be two hours within the Shop and eight hours between various buildings within the company. The transit time to outside vendors is considered to be 32 hours. The operation time, as stated before, is determined by the Planning Department and varies with the nature of the operation to be completed. The setup time is for one setup and not for more than one, and only one setup is considered to take place for any one particular run operation. In other words, a machine is set up and all parts of the whole production order for that particular part are processed through that machine center under that one setup. An average efficiency factor is applied to the planning time for any particular operation. This factor is usually 80%. The following formula is used to determine the actual time allowed for the machine operation.

$$\text{Actual Hours} = \text{Planned Hours/each} \div \text{Efficiency} \times N$$

where the N equals one for a setup and equals the batch quantity for run operations.

Each of these operations in the production cycle sequence is connected with the adjoining operations. Successively earlier start dates are determined by the computer using as the interval the length of time necessary to process each succeeding operation. This means that the planned starting date for one operation is the completion date for the preceding operation.

The Dispatching Function

For scheduling operations the computer scheduling system generates cards which have various pieces of information punched into them including the start date for the operation. These cards are placed on a dispatching board in an area next to a slot for that operation. As soon as a part reaches that particular operation in the manufacturing cycle, the start card associated with that operation of that part is placed in a queue file containing all those parts for a given work center which will perform this operation in question. When the employee in question has no work, or, the work of the preceding part has been completed, he comes up to the dispatching board and requests another job. The job assigned to this man is determined by the dispatcher according to the following rule.

Since any particular man can only perform work on certain work stations, and not others, the dispatcher looks at all those work stations which the man is capable of performing work on. He then selects that job on any one of these work stations which is free and has the earliest start date card in the queue file for all the work stations for which this man is capable of performing work. The first consideration, therefore, is what work stations can this man work on? The second consideration is which of these work stations is available, i.e., which does not have any work on it at the present time? The third consideration is: consider those work stations which are free and for which this man can work on, and then select that work station which has at the front of the queue file a part having the earliest start date of all parts for all possible work stations. Theoretically, then, the man would be assigned to do an operation on a part which is furthest behind in schedule, according to plan.

CHAPTER III

CRITIQUE OF THE SCHEDULING FUNCTION

This chapter describes some of the more important causes for the failure of the CSS. The first section is directed toward an analysis of the validity of some of the assumptions about the scheduling environment of the Shop which were used in the CSS. The second section discusses some of the operating failures of the management of the Shop in carrying out the actual dispatching on the floor.

Validity of the Assumptions

The construction of the actual computer program used in the CSS was closely patterned after the IBM Job Shop Simulator. The basic exception was that there was no simulation in the CSS. However, it was with the Job Shop Simulator that the Systems and Procedures Department studied the scheduling function of the Shop. The CSS embodied, in addition to the basic program of the Simulator, computer routines to update the Shop's manufacturing Planning File and a computer routine to generate the start cards for use in the dispatch area of the Shop. Since the Shop produces a high quality product subject to rigid quality control inspection, some of the characteristics of this Shop will not be generally found. However, it is felt that a scheduling procedure should be adapted to the Shop rather than vice versa.

The first assumption of the CSS which is invalid is that it treats each order independently from all others. The Shop is actually producing two basic product groups. All of the parts are assembled successively to form a single final product. Yet, the CSS has no way of treating the interrelationships of the various parts. When a secondary part is late in being produced, the next higher assembly, into which that part goes, cannot be started unless a buffer inventory is carried between the two.[4] In general, the Shop did not consciously try to maintain such a buffer inventory between all parts and the successive assemblies. If such a buffer existed, it was not necessarily known to management unless those parts were sent to the central "in-process" storage area. Even then, a "special study" to learn the exact quantity in storage would be necessary since the inventory records were neither adequate nor accurate enough to show this basic information in a routine manner. The decision rules of the CSS establish start dates for each part independently of all other parts. However, the final output of the Shop is an assembly of several unique parts. An assembly operation cannot be performed unless all of the parts going into that assembly have been manufactured and are available. The importance of assuring simultaneous delivery of parts is therefore increased.

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[4] See J.M. Magee, Production Planning and Inventory Control, (New York: McGraw-Hill, 1958), p. 288, for a discussion of buffer inventories in a job shop.

A second assumption of the CSS which holds true of most job shops, but which fails to hold true of this Shop, is the integrity of the quantity scheduled. By this is meant that the quantity scheduled is normally started and carried through each successive operation intact. Once assigned to a work center the whole lot is completed before the next part is set up and run. The order cannot be "bumped." Each part of the order quantity must wait until all parts have been processed before further work can take place on the next operation. In the Shop no pretense was made that this was representative of their past conditions, or, for that matter, of their current conditions.

Approximately 23 percent of the parts going through the Shop are split for some reason or other during the course of their manufacturing cycle. The source of data for this conclusion was a sample of Production Control Sheets for approximately five months. Each sheet contains a list of the days on which the quantity passes through each operation. Split lots are listed separately and can be easily recognized.

One reason why this assumption of lot integrity is not valid in the Shop studied is that uncontrollable factors could prevent continuation of the manufacturing sequence. The personnel in the Production Control Department would issue an order to produce a certain quantity of a specific part but, once issued, they did not have control over how many items of that quantity would be processed together at each operation in the manufacturing cycle. The result of this lot splitting was, of course, a reduction in the effective order quantity.

There are three reasons for splitting lots. One is that on occasion a die would break and the operation would no longer continue. If the parts were needed at the next assembly point the completed parts would then be separated from the incomplete parts and sent on. This separation effectively reduces the order quantity. One can argue that the incomplete parts can wait for the next order quantity of that part to arrive at that operation at which time these incomplete parts could merge with the new order quantity. If the part waits, then the full order quantity was not really needed to meet an assembly requirement. By waiting for the next lot to come through the incomplete parts increase the magnitude of in-process inventory and also clutter up the aisle. The advantage, on the other hand, of waiting is to be able to process a larger quantity under the same setup.

In the case of the Shop, when two lots joined each other, the results were interesting. It was the practice for the operator (and his foreman) to insist on receiving two prepunched setup labor vouchers as well as two prepunched run labor vouchers. The operator had no intent of making two setups. The "real" cost of running the two lots together did not change just because the operator had two preprinted setup vouchers. But his reported efficiency did change, since an extra prepunched labor voucher meant that he had an extra amount of planned time. Since the Shop's efficiency was measured weekly by comparing the ratio of Planned Time to Actual Time, the operator's weekly efficiency would thereby be boosted. This practice was discontinued after management found out about it.

A second reason for the splitting of a lot is that rework might be required of those parts which failed to pass inspection after that operation. Neither this reason nor the first could be adequately altered by management direction. They are, in the scheduling sense, unavoidable.

A third reason for lot splitting, bumping, is avoidable. Quite frequently, the management of the Production Control Department would authorize a setup to be torn down before the operation was completed in order to process a second part. The motive for doing this was primarily to shorten the manufacturing time of the second part in order to meet a delivery commitment. The results of this practice are a higher total variable cost of manufacturing and widely-varying manufacturing cycle times for any one part.

Thus, the lot integrity assumptions of the CSS are invalid for use in scheduling the Shop. One way to avoid this problem would have been to run the CSS frequently and to feed back the information on the split lot so that the original lot could be treated as two separate lots with two separate schedules. The practice of running the CSS every four to six weeks prevented any feedback on the status of jobs in process, since most of these jobs were completed in this period of time. No effective control could therefore be exercised over split lots.

The cycle times calculated during the running of the CSS did not reflect the actual average cycle times experienced in the history of the Shop. The generation of start dates in the CSS failed to take into account several conditions of the Shop which were not assumed to exist.

Calculation of the start dates is affected by the queue factor for the work station on which the work is to be performed, the duration of the machining time, and the average labor efficiency for the production area. None of these factors was systematically changed to reflect actual experience. In 1962 the critical work stations' average queue times were checked but no significant modifications were made.

The original estimate of the length of time required in completing an operation may be in error. Although the Simulator allows the analyst to change all estimates by a constant percentage plus an absolute amount if the cycle times do not reflect the real environment, this modification was not possible in the CSS. The Systems and Procedures Department did not isolate and remove the cause for any discrepancies that existed between the CSS-generated cycle times and the Shop's actual cycle times. The differences existed and were known by all concerned. However, interviews with the responsible personnel did not detect any systematic attempts to rectify the problem until November, 1962, when it was discovered that to both the setup time and run time the queue and transit time was added in order to calculate the CSS-generated start dates. There is of course no waiting between setup and run. In the Shop's Planning File the setup is a separate operation from the associated run operation. Prior to November 1962 a queue time was assumed to exist between the setup and run operation. There was no justification for this and it was then removed. However only two computer runs were made after this change before the CSS was abandoned. This would appear to be a significant technical error on the part of the Systems and Procedures Department. But, in a larger sense, this error points up the general lack of feedback to improve the system, make it more adaptable, more reflective of the actual environment it tried to schedule.

Operating Failures

One of the failures in the operation of the CSS was in not using the start dates as valid priorities in the dispatching function. The management in the Production Control Department circumvented the use of these start dates for parts behind schedule. They did not allow the CSS generated priorities to deliver the output for them. A key reason for the need for excessive expediting during the later stages of the manufacture was that parts were not started on time. Management then tried to modify the length of the manufacturing cycle.

Three factors influence the length of time taken in the manufacturing cycle. One is technological difficulties which are completely unpredictable but occur only on rare occasions. The second is the labor efficiency. The labor efficiency is again not subject to control by management, at least in the short-run. A detailed discussion of labor efficiency is present in the next chapter on manufacturing cycle time analysis. The third factor determining the length of the manufacturing cycle is the expected waiting time or queue factor.

Whereas it is difficult to control the labor efficiency, management can control at least the expected value of the waiting time. For example, the highest priority part can always be assigned next to a machine to minimize its waiting. Highest priority can even mean bumping off the part now on the machine and thus zero waiting time would be incurred. Beyond this, management can even have the next machine already set up and waiting for the first part to be completed on the preceding operation in the sequence. This technique can considerably reduce the normal cycle time for that part. Other parts and cost suffer but such "lap phasing" or telescoping can turn out the needed part or two in a relatively short period of time. The Shop management did this sort of manipulation of the schedule at least once or twice a week for parts which were "in trouble." This type of variation was predictable and well-controlled. There is no question that this lap phasing was an expedient short-term solution to the problem. The unfortunate consequence was that it led to a situation where nearly all parts had to be expedited through the Shop. The solution to this lies in starting the production lot through the Shop with the proper lead time so that it will be finished when desired. Until recently, management did not engage in this practice. The CSS was supposed to do it. Actually, the CSS generated the paperwork, the start dates for the various operations in the parts, and so forth; but the dispatcher could not rely on these dates as reflecting when the part should actually be started. In the first place, the whole complexion of the Shop had usually changed since the last computer run. Many parts took less than twenty working days to complete, yet the intervals between computer runs commonly was four to six weeks. The intervals were not regular. In the second place, the start dates usually had no relation to inventory level. This created the concern as to whether the part was needed at all. In the third place, assume that the part was needed on the due date specified. Since the CSS cycle time was felt to be out of line with the Shop's normal processing time, missing the start date would not usually mean they would miss the delivery date under normal conditions.

The management of the Shop was supposed to assign work according to the earliest start date as described in Chapter II. And, to a certain extent, this was the rule used in the Shop when a member of the Systems and Procedures Department was around the dispatching area to survey the situation and "help out" in the dispatching. However, the dispatching by earliest start date did not explicitly account for the need to have all parts together for a higher assembly. If a given number of these assemblies were to be shipped out that week, there was a very strong pressure to get all the parts ready so that the required amount of assemblies could be shipped that week. Heavy expediting was far too frequently found to exist. It appeared that there was very little emphasis on reduction of inventory. This would seem the natural cause of heavy expediting. It seemed that the Shop would not allow their jobs to be placed in jeopardy by explicitly following the CSS schedule. For various reasons the CSS start dates were relied upon when there was no more work or when there were no expediting instructions available for the dispatcher.

A general conclusion is that the value of the information contained in the start dates was in a large number of cases less than the value of the information available informally to the dispatcher. It is the case that the Shop's Production Control Management thought their information was more valuable when it came to dispatching than was the information generated by the CSS.

The second operating failure is that the Production Control Department made little attempt to produce economic batch quantities. The order quantities generated are on the basis of a week's production of the final assembly, and the explosion of this primary final assembly order into the various parts and components generates an automatic "E.O.Q." Whether or not this order quantity is produced as a production order is determined by manual review of the various parts and assemblies. The review consists of a determination to either schedule the parts as the computer has listed them or to do one of the following three things: one, if there is too much inventory on hand already, then no order is processed; two, if the schedule for a primary assembly is stretched out, then the economic order quantity generated by the computer would not be used at all, or else would be reduced in the quantity that was going to be produced by the Shop; three, if in the judgement of the person reviewing these computer-generated order quantities it were felt that the economic lot size should be significantly larger or smaller, then the order quantity from the computer would be increased or decreased. The order quantities would not be touched if there were not enough time on the part of the person doing the manual review or, if there were no better knowledge available to modify these order quantities.

Lack of accurate inventory records prevented the Shop's management from knowing the level of in-process and finished parts inventory on a routine basis. It was obvious throughout the case study that there was little concern on the part of management with the size and nature of their inventory. In a pure job shop one does not need to worry about buffer inventories. Each part is independent of any other part. In the Shop there was a continual production of the same parts and assembly of them at three and four levels before they were shipped.

Although their output was continuous, the volume was not large enough to warrant continuous production of each part. Hence, parts were produced in batch quantities for the most part. This type of production requires a buffer inventory at each assembly point unless all parts comprising this assembly are produced in the same quantities and arrive at the assembly point at the same time. It was the intent of the CSS to do just that. But there was no way of handling the situation where the order quantity of one part was split. Just as soon as the order quantity was split a buffer inventory was created. The information on the split lots was not regularly fed back into the CSS in time for it to generate schedule changes. Such difficulties were common to the Shop, but the design of the CSS was unable to cope with them. Had the CSS been able to control the movement of the split lot systematically, many of the Shop's problems with the CSS would have been avoided.

CHAPTER IV

MANUFACTURING CYCLE TIME ANALYSIS

The case study described above was focused on the implementation of the Computer Scheduling System. It explored the scheduling environment into which the CSS was introduced in order to find the significant reasons for its failure. Its primary emphasis was on those characteristics of the Shop which did not reasonably approximate the conditions which the CSS assumed to exist. As the case study progressed, it became apparent that the design of the CSS did not recognize the existence of several important environmental features of the Shop or the cost of scheduling. For these reasons a deeper study was made of the variable costs of operating the job shop and the manufacturing cycle time of the Shop's parts using different methods of estimating the actual labor efficiency of the Shop studied and different order quantity rules. It should be understood that using different estimates of the "true" labor efficiency does not imply changing the speed of the workers, i.e., their service rate. The different estimates of labor efficiency are arrived at by reclassifying a basic set of data into different categories and using the average labor efficiency of each category. In effect, changes in labor efficiency affect only the estimates of the processing time for that operation since the average queue time or waiting time was independently estimated and is assumed constant for each work station throughout this study.

To test the effect of certain conditions in the Shop on the scheduling decision rules an experiment was devised. The experiment was to answer two questions. What level and how much variation can one expect to find in the manufacturing cycle time due to the level and variation in labor efficiency? Secondly, what were the costs of scheduling under the CSS versus what they might have been using a simple economic order quantity rule?

Factors Influencing the Length of the Manufacturing Cycle Time

The importance of answering the first question is that uncertainty about the labor input to the processing time leads to uncertainty about the total length of time which a part requires for its manufacture. Knowing the length of the manufacturing cycle time is important for setting lead times and the level of safety stock required as well as for scheduling purposes. In the OSS the length of time required for each operation was critical to the establishing of start dates for each operation on the part. The start dates were supposed to be used as an index of the priority which should be placed on the part by the dispatcher. Therefore, if the start dates were used by the dispatcher, significant errors in those start dates would automatically mean significant errors in meeting delivery commitments or incurrence of overtime and expediting costs.

Several factors directly influence the length of the manufacturing cycle time. The first is the time it takes to perform the various machining operations for a given order quantity. For an order quantity of one part the processing time, then, would be the sum of the successive setups plus the machining time for one part at each run operation. Since the Shop normally processed its parts in batches to take advantage of spreading the cost of the setup over several parts, the cycle time was directly affected. Increasing the quantity to two parts, for example, would double the machining time for the run operations, but the setup time, of course, would remain constant. Thus, one can readily see the direct relationship between the size of the order quantities and length of the manufacturing cycle time.

A second factor which directly influences the manufacturing cycle of a part is the "slack" time between the first and the last operations on the part. The slack time is defined by the difference between the total time a part is in the manufacturing stage less the time for actual machining operations to be performed. If there is no slack time, then the total cycle time is just the machining time. Such a condition holds true when the machining time is precisely known and Gantt Chart-type scheduling is performed. However, this type of scheduling cannot be economically performed when the machining time is not precisely known and/or when there are a large number of parts with a high number of operations to be performed on each part.

When it is impossible or impractical to predict and control the start and finish of each operation, there must be some slack built into the schedule. Since the manufacturing cycle time is thereby increased, the value or magnitude of in-process inventory is also increased. This increased inventory value, with its associated interest cost, represents the cost of lengthening the manufacturing cycle time. However, with a large number of parts and a relative lack of control of their progression through the planned sequence of operations, it is inevitable that two parts will demand service from a single machine at the same time.

The implicit assumption of the preceding paragraph is that the Shop does not have an unlimited number of manned machines in each machine group. The Shop, therefore, was usually faced with at least two parts requiring service simultaneously at the same machine. Regardless of what dispatching rule is being used, one part will be given priority over the other. The other part must wait for access to that machine. When several parts are waiting, a queue is built up. The Systems and Procedures Department, in 1960, analyzed the average waiting time for each machine group and established an average queue time factor for each machine group. The queue time factor is expressed in terms of the expected number of hours which a part will spend in the waiting line for that particular work station. These hours are divided by the available machine hours per day to get the expected number of days which a part will have to wait for service at that work station or machine group. Although some changes have been made in these queue factors since that time, no attempt has been made to update them regularly.

Appendix A contains a list of the total days spent in queue for each part. The queue factor for the relevant machine group is cumulated for each setup operation and for each run operation not preceded by a setup operation. No specific objective study was made in the Shop to verify the validity of these queue factors.

Factors Influencing the Cost of Scheduling

The primary factors considered here in determining the cost of scheduling are the setup costs for each order quantity and the interest cost[5] during the manufacturing cycle (in-process inventory cost) and

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[5] See some of the excellent articles in Ezra Solomon (ed.), The Management of Corporate Capital, (Chicago: Free Press, 1959).

during the storage of finished parts. The two interest costs are kept separate because an increase in the manufacturing cycle time will increase the first inventory cost but will not affect the second inventory cost. The finished parts inventory cost is equal to $\frac{1}{2} \cdot Q \cdot C \cdot I$, where Q equals Order Quantity, C equals marginal cost of each part, and I equals interest and storage rate per year. The in-process inventory cost is arrived at by cumulating the value of $\frac{D}{Q} \cdot C \cdot Q \cdot T \cdot i$ at each run operation where D equals yearly demand, Q equals the order quantity being processed, C equals the average value of the part at that point in the cycle, T equals the time in days to complete the operation for all parts in the order quantity, and i equals the daily interest rate.

The setup costs used in the cost of scheduling include both the machine setup time and the additional cost of processing the paperwork for each extra order quantity. The procedure employed for calculating the cost of scheduling included the first factor but excluded the latter. The second factor cannot be obtained by merely dividing the yearly cost of all of the order clerks, computer time, analyst's time, and so forth, by the number of lot quantities processed during the year. A large share of these costs would not be changed unless there were a significant increase or decrease in the number of lots processed during a year. Therefore, no incremental cost of processing the paperwork was included in the cost of scheduling.

Analysis of Labor Efficiencies

The efficiency of the direct labor performing the various operations is not controllable by management in the short-run. An analysis was made of the level of labor efficiency and the range of variation one can expect from the mean efficiency. By itself, this analysis has limited merit. However, when used in conjunction with the scheduling of this job shop, its importance increases. The source of data was a set of labor vouchers of the company for all personnel in the two areas studied. These data covered a period of thirteen weeks. The company uses these vouchers to determine its manufacturing costs and to prepare a weekly statement of average labor efficiency by foreman. The purpose of analyzing labor efficiencies is to establish a more accurate estimate of its level so as to provide a scheduling system with an accurate efficiency input. Knowing the expected range of variation of the labor efficiency will provide an estimate of its effect on variations in the length of the manufacturing cycle time. Management cannot control this variation but should know its contribution to the total cycle time variations. Unless stated otherwise, the term, "variation," will be synonymous with dispersion.

Although the efficiency of labor is uncontrollable, the expected length of a particular part's total queue time during its entire manufacturing cycle time is not. There is a relatively wide range in the production of parts in a job shop in which management can change the actual manufacturing cycle time of certain parts at the expense of others by effectively changing the priorities' rules used for dispatching jobs. An exhaustive probing of the production control records unveiled some interesting things. Examples existed where management was able to send parts through the Shop in less than a third of the time generated by the CSS. The queue time factor accounts for 50 to 85 percent of the cycle time as shown in Appendix A. The queue time for any one part can be reduced to zero at the expense of increasing the cycle time for others when management is willing to incur the costs of heavy expediting.

The cost of doing this is very elusive and is hard to pin down. For example, if no setups are broken into and there are no late deliveries, then the cost would be only for the increased attention which must be paid to this part plus the inventory cost of storing the other a little extra time. The cost of not accelerating the one part may mean that a final assembly line would have to shut down. When meeting delivery dates is considered so important, it seems imperative that the scheduling decision rules incorporate a strategy for meeting these delivery dates.

The fact that the management of the Shop was able to accelerate the flow of specific parts as described above indicates that the total expected queue time for any one part can be under the control of management.

The labor vouchers contain the planned time, the actual time and whether or not it is a setup or a run labor voucher, as well as the operation number and the drawing number, and the account number, the foreman number, an operator number, and the week number. The information derived from the labor vouchers has been of the nature of the average efficiency in comparison to the planned standard for each work station and for each operation of each part. In addition, analysis had been made of the standard deviation of this labor efficiency for each of the above classifications. It seems that one group of parts within the company, in general, is processed a great deal faster and more efficiently by the employees than is a second category of parts. The second category of parts is newer to the Shop and, therefore, the Shop personnel may be less experienced in producing and manufacturing these parts. In general, no reason was found for the deviations of the labor time efficiency from the mean average labor efficiency.

The different levels of efficiency between the product groups were not recognized in the CSS. Nor were differences in the average efficiencies of work stations recognized by the CSS. Finally, if one classifies all of the labor vouchers by operation number within each part, an estimate can be made of the efficiency with which each operation is performed. By level of efficiency or mean efficiency is meant the ratio of the planned time to the average actual time for the particular classification in question. When the data are classified by work stations, the efficiencies will be called work station efficiencies. When the data are classified by operations within parts, the efficiencies will be called operation efficiencies. Both sets of efficiencies are used in determining the effect of using different assumptions for labor efficiency in the generation of start dates. Their effect on the manufacturing cycle times of the parts studied is described in the next chapter on results. Appendix A summarizes the data on which these results depend.

About 50,000 vouchers were analyzed, checked for accuracy, sorted into their proper category, and summarized to generate mean efficiency, standard deviation, and frequency distributions for each work station and for each operation. Incidently, all frequency distributions were visually inspected for normality. All work station frequency distributions had a single mode and appeared to be normally distributed around their means. Two operations had frequency distributions which had two modes. These two were rejected and replaced by the work station averages. All other operations had a single mode and could be said to be reasonably the shape of a normal distribution. However, for some operations the sparsity of the data prevented a good judgement. For these few operations all that can be said is that the efficiencies were in a cluster. The average order quantity was derived from a synthesis of the information from actual Production Control Sheets used by the dispatcher. These were tabulated and analyzed for a sample period of approximately five months.

Order Quantities

Several alternative sets of order quantities were used in the Manufacturing Time Analysis (MTA). The first set of order quantities is called the Historical Average Quantity, which was the set used in the CSS. Where several order quantities were used in the Shop for one part, the average size order quantity was used. Since the determination of these order quantities did not consider the costs of scheduling a second set was derived from a simple formula to illustrate the minimal savings which might have been realized by the CSS.

The second set of order quantities used was generated in the

MTA from the standard lot size formula for inventory recording decisions[6] to indicate the minimal savings of using an Economic Order Quantity.

$$Q^* = \sqrt{\frac{2DS}{IC}}$$

where Q^* = optimal order quantity
D = demand per year
S = setup cost
C = marginal value per part
I = interest and storage rate.

Recognition is not made in this formula for the value of in-process inventory. This set of order quantities will be referred to as the standard E.O.Q.'s.

The third set of order quantities recognizes the interest cost of carrying in-process inventory during the manufacturing cycle time. The standard production model available in the literature assumes only

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[6] See: E.H. Bowman and R.B. Fetter, Analysis for Production Management, (Homewood, Ill.: Irwin, 1957), p. 278.

R.B. Fetter and W.C.Dalleck, Decision Models for Inventory Management, (Homewood, Ill.: Irwin, 1961), p. 9.

G. Hadley and T.M. Whitin, Analysis of Inventory Systems, (Englewood Cliffs: Prentice, 1963), p. 29.

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T.M. Whitin, The Theory of Inventory Management, (Princeton: Princeton U. Press, 1957, 2nd ed.), p. 30.

one setup and then continuous flow-type production. For a job shop the continuous production assumption is invalid. None of the parts is available for final use until the last of several setups has been completed. The model used in the third set of order quantities is based on the following total cost function.

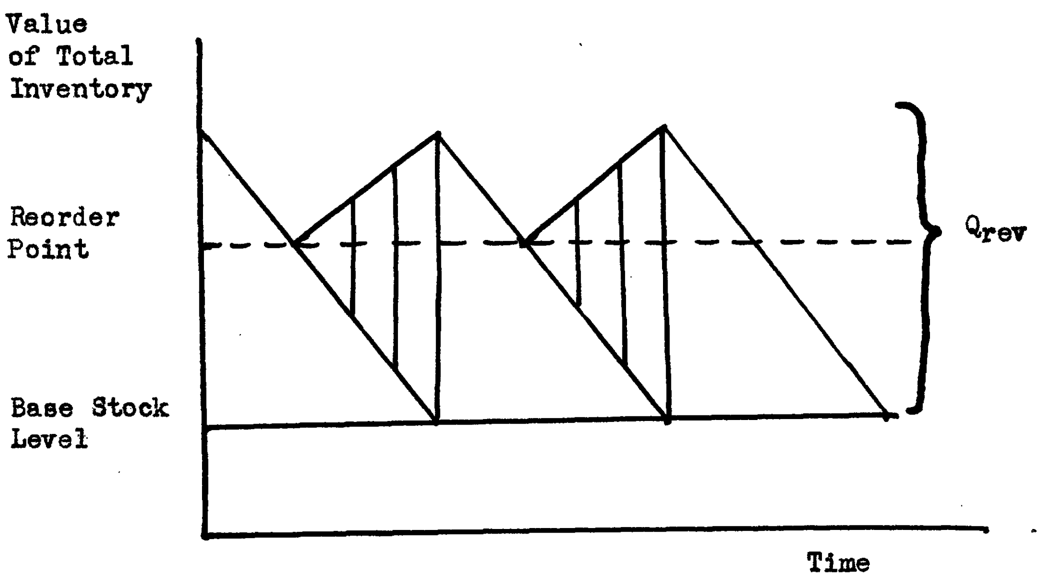
$$TC = CD + \frac{D}{Q}S + \frac{1}{2}QIC + \left(\frac{D}{Q}\right)\left(\frac{1}{2}ICQ\right)\left(\frac{Q}{P}\right)$$

where TC = Total Cost
P = Production rate per year
and D, C, S, and I are the same as before.

Setting the derivative equal to zero and solving for Q gives

$$Q_{rev} = \sqrt{\frac{2DS}{IC}\ \frac{P}{P+D}}$$

Graphically, the last combination of variables summarizes the inventory carrying costs incurred in the cross-hatched area of time and value of total inventory. This third set of order quantities will be referred to as the Revised E. O. Q.'s.



Although the revised E.O.Q. assumes a straight-line increase in work-in-process, the bookkeeping procedure used in the computer program simulates the actual increase in work-in-process inventory. For example, when a batch of parts are waiting for service, there is no increase in inventory value. A test was made on five parts to determine the affect on the Revised E.O.Q. of this inconsistency. It was found that using the bookkeeping method caused the optimal quantity to be slightly larger than when the straight-line increase in work-in-process was used. For this reason the production rate P was determined at the standard E.O.Q. Because of the fixed-time components of the manufacturing cycle the P decreases with the size of the order quantity. If the P were replaced by a factor which was independent of Q_{rev}, such as $250\left(\frac{Q}{s+MQ}\right)$, where there are 250 working days in the year, s equals the total setup and queue time in days for one batch, and M equals the total machining time in days per each part, then Q_{rev} would be lower and the cost of scheduling would be higher due to the non-straight-line nature of the increase in work-in-process.

Computer Program

A computer program was designed to perform the bookkeeping in totaling the various categories of the cost of scheduling, manufacturing cycle times, and to calculate economic order quantities, efficiencies and their variations, and queue times. The program was flexible enough to allow for experimenting with different combinations of each factor. The basic input data came from the Shop in one form or another.

These data were for, close to, 100 parts having a total of 3600 operations. For each operation of each part the input information included identification numbers for the parts, operation number, the Shop's estimate of mean efficiency, the work station number, the planned time for the operation, the yearly demand for the part (constant), the queue time factor according to the work station, the material cost, the average work station labor efficiency and its standard deviation, the average labor efficiency on that particular operation and its standard deviation, and the average order quantity which the Shop used. The first pieces of information came from the Shop's Planning File from which I took off the pertinent information. All planning information was the same as used in the CSS. The queue time factors were taken directly from the input to the CSS. The material cost came from the Accounting Department's records of material costs at the successive stages in the manufacturing sequence. The data used for the work stations and operations came from a group of labor vouchers for thirteen weeks.

CHAPTER V

RESULTS

The results of the Manufacturing Time Analysis are summarized in Appendices A,B,C, and D. Appendix D shows the comparison of the manufacturing cycle times (MCT) which would be generated by the CSS, and the MCTs which would have been generated had the CSS used a more accurate estimate of labor efficiency. The quantities used are the Historical Average Quantity, i.e., those described in Chapter IV as "set one." Only the expected value of labor efficiency is different between the two columns of Appendix D. Using the planned standard efficiency of the CSS results in cycle times which are, on the average, eight percent longer than they would have been using a more accurate estimate of labor efficiency. The bias of the CSS in using lower than average labor efficiency resulted in longer cycle times.

Appendix A uses the order quantities generated by the standard lot size formula for inventory reordering decisions. It compares the manufacturing cycle times which would have been generated had different sets of labor efficiencies been used to adjust the processing times. The use of separate efficiencies for each operation in each part produces only a small difference in total MCT from the MCTs using work station average efficiencies. However, the efficiencies used by the CSS produced a significant bias in the total MCT due to a grossly inadequate estimate of the actual labor efficiency. The conclusion can, therefore, be made that knowing the operation efficiencies does not significantly improve the MCT estimate over using expected work station labor efficiencies, but either work station efficiency estimates or operation efficiency estimates eliminate the unintentional bias of the CSS efficiency estimates.

The standard deviations of the MCTs are not significantly affected by using the operation efficiencies over the work station efficiencies. Although the expected dispersion in the MCT for each part may be increased or decreased by the additional information of the expected efficiency on each operation, the overall average standard deviation of the MCTs remains basically the same. The conclusion which can be reached is that there is only a small potential increase in the information content available under the knowledge of operation efficiencies. For most job shops this added information from knowledge of operation efficiencies on the length and variation of the MCT for each part would not alter management decisions in the scheduling function.

The last two columns of Appendix A illustrate the importance of the variation in labor efficiency on the MCT. When the machining time is used as the base then one can expect the actual machining time to fall within 95% confidence interval of ± 20% of the expected machining time. This means that if all of the machine operations take five days on the average, then there is a 95% chance that the true actual time would be between four and six days. However, when the expected time spent in queue is added to the machining time, the expected confidence interval due to the labor efficiency input is only ± 5.5%. The general conclusion which can be drawn from these data is that the fluctuations of labor efficiency account for only small changes in the MCT. This conclusion was predicted in advance. However, the precise effect of the fluctuations of the labor efficiency on the MCTs has now been determined.

Appendix B contains the Data on the Comparative Cost of Scheduling. The cost of scheduling is defined as before as the sum of the variable costs as affected by the schedule. In this case they represent the sum of the interest cost on both work-in-process and finished goods inventory plus the yearly setup costs measured in direct labor dollars. Two sets or order quantities are used. The first set, denoted by "E.O.Q.", is derived from the standard E.O.Q. formula while the second set represents the Historical Average Quantity for that part. Thus, for the two categories of quantities there are two sets of costs.

The MCT for the E.O.Q. is calculated using the operation efficiencies. The second column contains the calculation of the MCT using the Historical Average Quantity and operation efficiencies. The third column lists the average actual processing time of the respective parts when being manufactured in the Shop.

Naturally, since the average order quantity used by the Shop is lower than under the E.O.Q., the Calculated Actual Time is less than the manufacturing cycle time with the E.O.Q. Prior to December, 1962 the average of the cycle times generated(See col. 1 of Appendix D) by the CSS was about the same as the sample of actual cycle times shown in Appendix B. Any large difference between the Historical Average Time and the CSS generated time must be due to some other cause than labor efficiency. One hypothesis to explain this difference is that management may unconsciously reduce the MCT for high value parts. By plotting the variable cost of scheduling versus the ratio of actual over calculated time, it was discovered, however, that this hypothesis was not generally valid. One conclusion which can be made is that the fluctuations in the MCT are very large and unexplained in terms of the variables used in the OSS. The fact that the overall average historical time is longer than the calculated value may be partially fictitious. It was the practice at times to complete the first operation on a part long before it was intended to continue through the manufacturing sequence. This practice prevented other areas from "stealing" their raw material. Secondly, management sometimes discovered that a part already started was not needed until much later than was initially expected. They would therefore delay further processing until it was needed. This practice was confirmed in the analysis of the Production Sheets by the occurrence of gaps in production of several weeks.

Appendix B indicates that there is a 13 percent reduction in the variable costs of setup and inventory carrying charges when the Standard E.O.Q. is used rather than the OSS order quantity. Using the Revised E.O.Q. results in another 3 percent reduction in variable costs. The Revised E.O.Q. can be easily calculated once the production rate is known in the range of the economic order quantity. The advisability of using the Revised E.O.Q. would depend upon the cost of obtaining the production rate. The cost of scheduling includes total yearly setup cost, work-in-process inventory cost and finished parts' inventory cost. A detailed description of these costs begins on page 34.

CHAPTER VI

CONCLUSIONS

There would be little to gain for the Shop to go through the sometimes tortuous analysis performed for this thesis on a continuing basis. For the job shop studied, accurate knowledge of labor efficiency would have helped to establish a closer estimate of the manufacturing cycle time. Lack of accurate knowledge of queue time factors was the biggest source of difference between actual processing times and the manufacturing cycle time generated by the CSS. Unless the actual MCTs of a job shop closely correspond to the expected MCTs, it would not be valuable for most job shops to continually perform the detailed analysis of the variation in labor efficiencies. Such an analysis certainly does not need to be performed on individual parts unless it is suspected that significant differences between parts will result. When this condition exists, it may prove economical to generate an estimate of variation for each part. Updating this variance could be accomplished through the use of the mean absolute deviation which is proportional to the variance σ^2.[7]

In the Shop under study management pressure was primarily on quality output. There was no strong pressure to justify inventory levels. Since the schedule could not account for unexpected changes, management could not rely upon the CSS directives to get the parts out. Thus, informal dispatching rules circumvented those upon which the CSS was based. After a period of time, the Shop never bothered to page through

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[7] Robert G. Brown, Smoothing, Forecasting and Prediction of Discrete Time Series, (Englewood: Prentice, 1963), p. 282.

the voluminous output reports. This task was relegated to an analyst who soon found out that no one was interested in them. The key to success of the CSS was not to be found in its beautiful, well-organized output reports. Success lay in its ability to keep all the workers busy and shipments made on time. On both counts it failed.

The Production Control management continued to operate as they always had and were reasonably successful. As Appendix B shows, their average processing time was sometimes longer, sometimes shorter than what the CSS would calculate (in its final version). The important point to remember is that there was a considerable degree of variation in the length of time it took them to manufacture a part. Nearly all of this variation can be attributed to the management's dispatching rules and to uncontrollable technological factors in the production sequence. Relatively little of this fluctuation in manufacturing time was due to variation in the labor efficiency. And, except for a very few operations, none of it was due to technological difficulties. As was described in detail above, management can maintain reasonable control over the cycle time of individual parts if it wants to and needs to.

The precise estimates of processing times in Appendix B and the knowledge of their variation found in Appendix A are unusable to the Shop so long as it does not know when parts are needed and does not start the parts when they should be started. This basic knowledge was virtually unavailable in the Shop under the CSS. Until the Shop discovers the essential importance of knowing the level of finished parts inventory and in-process inventory of good parts, they will have a difficult time in determining start dates for their parts. Their present philosophy is to schedule a fixed amount at fixed intervals. Since their demand is constant and of the same mix, no serious problems would arise with this philosophy if all the parts of an order quantity made it to the end in one batch in the time allowed. The first two conditions do not hold for the Shop. The present study has not uncovered enough information to conclude that the Shop cannot live with the cycle times of Appendix B or of Appendix A, if they go to more economic order quantities.

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APPENDIX A

COMPARISON OF MANUFACTURING CYCLE TIMES AND THEIR VARIATION

using an economic order quantity rule with I = 25%

Part Number	$Q = \sqrt{\frac{2DS}{IC}}$ Order Quantity	Total Queue Time	CSS Std Eff	Average Work Station Eff.	Average Opr. Eff.	Range of Variation Machining Time	Range of Variation Tot. Cycle Time
550900	95	9.6	14.09	13.59(.35)	13.80(.44)	42	13
550901	59	5.6	14.68	17.66(1.16)	same	38	26
550903	97	14.9	19.12	18.90(.22)	18.89(.20)	20	4
550912	796	4.0	10.65	10.60(.72)	10.53(.65)	40	25
550936	54	8.0	8.83	8.76(.06)	8.78(.04)	25	2
550937	60	11.2	8.41	12.13(.08)	12.17(.08)	28	3
550940	49	5.8	7.60	7.40(.19)	7.37(.18)	44	10
550941	614	4.4	5.52	5.31(.09)	5.31(.09)	38	7
550942	2412	8.3	33.54	28.16(1.23)	28.81(1.41)	28	18
550943	219	13.7	22.90	22.62(.68)	same	27	11
550944	116	11.1	20.02	18.28(.57)	18.42(.40)	21	8
550945	170	11.2	18.52	17.08(.33)	17.47(.31)	20	7
550946	281	13.9	25.95	25.17(.87)	25.10(.87)	31	14
550948	224	17.7	44.54	40.09(1.24)	39.86(1.02)	18	10
550960	138	8.1	23.05	20.03(1.36)	19.70(1.11)	40	22
550962	138	3.8	5.00	4.64(.10)	4.70(.06)	29	6
556001	256	15.7	34.24	29.81(.90)	30.58(.72)	19	9
556002	58	10.7	15.98	14.69(.19)	14.75(.16)	15	4
556004	88	13.1	17.95	16.77(.18)	18.04(.61)	48	13
556005	136	8.5	15.75	14.30(.62)	14.27(.67)	46	16
556006	58	9.1	13.23	11.82(.27)	11.84(.21)	30	6
556007	199	5.9	26.37	19.04(1.47)	18.67(1.44)	45	31
556009	59	6.7	14.15	11.46(.45)	11.57(.48)	39	17
556010	87	8.0	12.25	11.25(.27)	11.46(.47)	54	16
556011	249	4.8	6.06	6.02(.11)	same	35	7
556017	105	8.0	49.45	35.22(3.71)	39.53(3.46)	41	33
556018	6	8.2	8.48	9.20(.44)	8.59(.05)	57	2
556019	25	5.7	6.17	6.12(.05)	6.20(.06)	58	4
556049	69	11.4	15.63	14.21(.18)	14.96(.14)	15	3
556051	25	5.5	5.83	5.68(.05)	6.05(.24)	163	15
556052	22	17.7	19.03	19.05(.11)	18.80(.08)	30	1
556076	253	22.8	50.53	44.07(.87)	44.59(.76)	14	6
556080	63	10.4	14.47	12.21(.10)	same	21	4
556081	440	7.6	14.11	13.46(.25)	same	17	8
Average		9.7	19.64	16.61(.573)	16.80(.566)	39	11

Note: All of the above manufacturing cycle times are in working days. The numbers in parentheses are the standard deviations of the respective cycle times. The Range of Variation represents the 95% confidence interval of ± 2.0 standard deviations.

APPENDIX B

DATA ON THE COMPARITIVE COST OF SCHEDULING

Part	Total Queue Time	Manufacturing Cycle Time: E.O.Q. I=25% Time	Calc. Actual Time	Hist. Avg. Time	Order Quantity: E.O.Q. I=25% Quan.	Hist. Avg. Quan.	Cost of Scheduling: E.O.Q. I=25% Cost	Hist. Avg. Cost
401272	14.7		18	28		65		3629
549002	12.4	38	19	40	418	100	2664	3848
549004	4.0	6	4	6	1498	160	209	696
550900	9.6	14	11	7	95	30	5273	8310
550903	14.9	19	19	20	97	100	2445	2440
550912	4.0	11	5	15	796	60	912	5303
550936	11.2	9	12	35	54	61	2298	2776
550937	11.7	12	13	17	60	62	1734	1730
550940	5.8	7	8	5	49	60	1956	2018
550942	8.3	29	34	20	2412	3000	3569	3938
550943	13.7	23	21	33	219	160	2585	2519
550944	11.1	18	20	40	116	145	5824	6127
550945	11.2	17	17	42	170	145	3709	3694
550946	13.9	25	21	23	281	186	2141	2039
550948	17.3	40	24	60	224	60	10088	11731
556001	15.6	20	20	33	138	70	2362	3941
556002	10.7	15	14	30	58	50	5936	5945
556004	13.1	18	16	15	88	50	1705	1899
556005	8.5	14	12	15	136	100	565	595
556006	9.1	12	12	50	58	70	2631	2663
556007	5.9	19	10	60	199	60	3932	3910
556049	11.4	15	15	15	69	80	4874	4890
556051	5.5	6	6	5	25	44	1936	2144
556052	17.7	19	19	14	22	30	9640	9684
556076	22.8	45	29	60	253	60	7049	11319
556080	10.4	12	12	15	63	70	8139	8195
556084	11.2	17	14	10	40	20	6100	5910
556085	11.2	18	15	27	52	28	3997	3897
556161	17.8	25	22	32	98	50	8633	9150
556162	12.9	17	15	15	81	50	3863	4158
Average	11.6	18.6	15.9	26.2	271	174	$4026	$4637

Note: The figures under the heading of Cost of Scheduling have a direct relationship to the true costs, but are not equal to true costs in order that proprietary interests may be protected.

APPENDIX C

REVISED ECONOMIC ORDER QUANTITIES

Part	Actual Quantity $	E.O.Q. $\sqrt{\frac{2RS}{I\ C}}$ $	Revised E.O.Q. $\sqrt{\frac{2RS}{I\ C}\ \frac{P}{P+D}}$ $	Revised E.O.Q. Quantity
550900	8310	5273	5292	86
550903	2440	2445	2454	73
550912	5303	913	909	719
550936	2776	2298	2353	42
550937	1730	1734	1672	71
550940	2018	1956	1961	37
550941	1482	825	426	1933
550942	3938	3569	3251	1384
550943	2519	2585	2523	156
550944	6127	5824	5753	85
550945	3694	3709	3704	138
550946	2039	2141	2039	185
550948	11731	10088	9543	157
556001	3941	2362	2371	218
556002	5945	5936	5965	48
556004	1899	1705	1711	76
556005	595	565	566	131
556006	2663	2631	2646	52
Average	$3841	$3142	$3063	

APPENDIX D

COMPARISON OF CYCLE TIMES

FOR HISTORICAL ACTUAL ORDER QUANTITIES

Part	Computer Scheduling System using overall Shop Efficiency: Prior to Dec., 1962 (days)	Computer Scheduling System using overall Shop Efficiency: After Dec. Correction (days)	Cycle Times when labor vouchers are classified by operation (days)
401272	24	19	18
549002	30	23	19
549004	6	5	4
550900	19	12	11
550903	26	19	19
550912	6	5	5
550936	22	12	12
550937	17	13	13
550940	9	8	8
550942	43	39	34
550943	29	21	21
550944	28	22	20
550945	26	18	17
550946	30	22	21
550948	33	27	24
556001	31	21	20
556002	22	15	14
556004	25	16	16
556005	19	14	12
556006	19	14	12
556007	16	13	10
556049	24	16	15
556051	8	6	6
556052	31	19	19
556076	51	33	29
556080	21	15	12
556084	20	14	14
556085	21	15	15
556161	37	23	22
556162	26	17	15
Average	23.6 days	17.2 days	15.8 days