REVIEW OF OPERATOR/MACHINE INTERFERENCE MODELS

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ABSTRACT

A practical problem of significant importance for many manufacturing systems is machine interference. Interference is undesirable and unnecessary machine idleness that is caused by allowing one (or more) operator(s) to tend several machines. When the service demands of machines are not synchronized, both operators and machines can experience interference. Interference obviously decreases the productivity of a manufacturing system. Most interference models are designed to attempt to minimize the cost of interference, or simply the interference itself.

In this paper, we survey the literature and classify various interference problems, models and associated assumptions, and solution techniques. Theoretical results are given. Industrial applications of the models that have been reported in the literature are also described. Finally, future applications of such interference models to robotics and flexible manufacturing systems are outlined.

1. INTRODUCTION

One of the oldest industrial engineering problems is due to a phenomenon known as machine interference, which can be described as follows: suppose that one operator or repairperson is responsible for the operation of several machines. Periodically a machine stops and will not resume production until it is fixed (attended) by the repairperson (operator). Since only one machine can be serviced at a time, if two or more machines happen to be stopped (down) at the same time, the remaining down machines have to wait to be repaired. This waiting time is what is referred to as interference time (i.e., the down machines are "interfering" with one another) (Stecke [1982]).

An example of a traditional industry in which interference problems have been studied is the textile industry, where one operator tends several looms that are weaving cloth. The operator's duties include changing the supply cone holding the yarn when it is empty, and tying together strands of yarn that break. Occasionally, many looms may be stopped simultaneously because an operator can tend only one at a time, and interference results. Interference also exists in modern job shops, especially automated manufacturing systems with computer numerically controlled (CNC) equipment. The determination of both the number of robots required to tend a system of machine tools, as well as the number of required maintenance people, are also machine interference problems. As another example, in tire molding industries, the operator time that is required by a machine is 1 or 2 minutes, while the automatic processing time may exceed 30 minutes. If service demands cannot be synchronized, both operators and machines can experience interference (Aronson [1984]). Additional examples are described in Stecke [1982].

Knowledge of the mean amount of interference idleness that results from a particular assignment of machines is a useful factor in developing reasonable

work standards and an equitable incentive plan. The amount of interference affects machine efficiencies, production rates, and hence profits.

Production is lost because of both service and interference time. The amount of interference, as well as the output from a system, are functions of three types of factors: (1) the distributions of time between failures, repair times, and the time it takes a repairperson to walk between machines; (2) the queue discipline (the rule by which the repairperson selects which machine to tend to next); and (3) the number of machines assigned to the operator.

The basic machine interference problem is to decide (on the basis of economic, production, or other considerations) the appropriate number of machines to assign to an operator. Some typical, desirable objectives are to maximize production (or, similarly, to minimize lost production due to idle machines and/or idle labor) or to minimize costs. Constraints might include: obtaining a higher (or lower) level of production; meeting a specified demand; keeping within a budget; and conforming with any union requirements that might specify which operators are allowed to tend (or are capable of tending) which types of machines.

Assigning the correct number of machines to an operator is an important and nontrivial decision. There are trade-offs and consequences to assigning either too many or too few machines. Stecke [1982] notes that some effects of assigning too many machines are that: an overworked operator with a large number of down machines can become fatigued, which may slow the work pace and further aggravate the problem; an operator might try to speed up his or her required tasks, possibly resulting in quality problems and defective output; the output expected by management is not attained; if there is an incentive plan to induce higher work rates, but standards are set too high, the bonus could rarely be achieved, causing motivated workers to be frustrated; as machines and production go down, so does the operator.

On the other hand, assigning too few machines results in unnecessary labor costs (or equipment costs, in the case of robots tending machines) and minimal effort required to keep the machines running, perhaps resulting in idleness, boredom, and inattention on the part of the operator. Work standards could also decrease. Even a monetary incentive to achieve a higher production rate might be resisted, since a continuously high output has been known to cause management to increase standards.

Interference models can be classified in several ways. One suggested classification is according to the types of machine breakdowns and service. In particular, if the time between breakdowns and service times is assumed to be constant, the model and problems are deterministic. Automatic screw machines, plastic molding presses, and NC or CNC machine tools are assumed to have deterministic patterns. If, however, the breakdown or service times are undetermined, or random, which is the more usual situation, then the interference problem can be termed probabilistic. For example, if the probability that a running machine will stop in the next instant is independent of the length of time that it has been running, then the time between breakdowns can be assumed to be exponential. However, if the time between breakdowns depends on the quality of the operator's previous repair, or on the age of the machine, then the breakdown distribution might more accurately be portrayed as hyperexponential.

Another potential classification is in terms of the number of machines and operators. Problems that are concerned with how many machines to assign to an operator may be termed multiple machine-single operator problems. Problems that concern the number of operators to assign to a given number of machines can be called multiple machine-multiple operator problems.

This paper will classify different types of interference problems and solution methods according to the first classification. Probabilistic problems

are further subclassified according to the type of mathematical approach taken to solve the interference problem. We survey various models, theoretical results, and solution methods for several types of machine interference problems, without presenting details of the theoretical development of the models. Industrial applications are also described. An extensive reference list gives the reader the opportunity to investigate in further detail any models of particular interest. The applicability, required assumptions and input, and output obtained through the use of each of the models are provided in a summary table.

One of the authors has recently written a book chapter (Stecke [1982]) that describes interference problems, models, and applications, and contains an extensive bibliography. Of necessity, much of this paper is a condensation of the chapter, although many topics are discussed in greater depth here. New models and applications are described and many additional literature references are also provided.

This paper is organized as follows. Various machine interference issues are raised in §2, and the relevant operator queue disciplines as well as required terminology are outlined. §3 surveys deterministic models and applications. Many probabilistic methods and models are presented and classified in §4. §5 contains examples of future applications of interference models that will result from the development and extensive use of newer technologies utilizing robots (for materials handling, refixturing, retooling, assembly, and part loading and unloading) and NC and CNC machine tools. A summary is contained in §6.

2. INTERFERENCE PROBLEMS

The basic interference problems are concerned with assigning a correct number of machines to operators to satisfy desired objectives and system

constraints. Some related questions associated with interference problems

include:

1. How should an operator decide which task or repair (if several are
   waiting) to perform next?

2. How is the interference time of a machine calculated or measured?

3. How are the cycle time (or average time to produce a workpiece), and
   hence the expected production rate, calculated?

4. How are equitable operator work standards determined?

The last three questions are addressed under varying circumstances and in dif-

ferent situations in sections 3 and 4. Work measurement aspects of these ques-

tions are treated further in both Neibel [1976] and Stecke [1982]. We discuss

the first question now.

If several machines are down, how does an operator choose which machine to

service next? There are several possible service rules that an operator can

follow. Those that have been assumed or examined in the machine interference

literature are summarized in Table 1. These are discussed further in the fol-

lowing sections, in the context of particular solution techniques. Other pos-

sible queue disciplines can be found in Jaiswal [1968].

We now survey the many methods, graphs, equations, charts, and tables that

have been developed to analyze and solve various aspects of interference

problems. Some of these approaches calculate an average amount of machine

interference. Others relate machine efficiency (actual production time as a

percentage of average cycle time) to average service time, average interference

time, number of machines assigned to one (or more) operator(s), or other fac-

tors. Some classical methods are generalized to take into consideration

patrolling time, personal time, maintenance time, ancillary time, as well as

other quantities.

Many methods attempt to determine the amount of interference by use of a

mathematical relationship involving the number of machines assigned to one or

TABLE 1

OPERATOR QUEUE DISCIPLINES

DISCIPLINE	DESCRIPTION
First-Come, First-Served	The down machines are serviced in chronological order of their breakdowns.
Random Tending	Each down machine has the same probability of being fixed next.
Cyclic Patrol	An operator stops to check each machine along the way of a particular path (cycle), even if the machine is not down. A cyclic patrol can be termed:
(1) Closed	The operator walks to each machine along a fixed path, going from the last machine back to the first, to repeat the cycle; or
(2) Alternating	The operator walks along a fixed path, and when the last machine is visited, reverses direction to patrol the same machines, but now in reverse order.
Distance Priority	The nearest down machine is serviced.
Nonpreemptive Priority	An operator services N different groups of machines, where the N_i machines in group i have a higher priority than the N_{i+1} machines in group i + 1; the operator chooses randomly within each group.
Preemptive Priority	The only difference from the nonpreemptive priority discipline is that if a machine that has a higher priority than the one being serviced breaks, current service is preempted. Future service on the preempted machine either resumes where it is left off or begins again, depending on the nature of service.
Shortest Service Time Priority	The machine that can be repaired fastest is serviced.

more operators and the service, production, and other times. Some techniques treat the problem deterministically and derive empirical relationships between variables of interest; others develop heuristic algorithms. Many approaches account for the variability in breakdown or service times by utilizing queueing theory or binomial expansions.

The notation that is used to describe the various interference models, techniques, and their performance is given in Table 2. Deterministic techniques are presented in the following section, while probabilistic models are surveyed in §4.

3. DETERMINISTIC MODELS

Virtually all of the deterministic models specify how many machines that a single operator should tend, based on the minimum sum of the costs of idle labor and idle machines. Machine running (processing), walking, and service times are assumed to be known and constant. Some techniques analyze systems that can have nonidentical machines; the run times may be different for different types of machines, but they will still be constant. Finally, it is assumed that random breakdowns do not occur. Operator service can consist of internal (ancillary) and external (maintenance) duties.

In a deterministic situation, it is easy to calculate such useful quantities as the cycle time (maximum of total operator time to service all machines $((S + W + A + M)N)$ and total machine time $(P + S + I + M)$, assuming that all N machines are identical), and the production rate per machine and per time unit. This information can be used to determine the cost of assigning N identical machines to a single operator (see Aronson [1981] and Stecke [1982]).

The trade-off between the cost of an idle machine (loss of production, say) and labor cost is often analyzed by comparing the workload of an operator with each machine's cycle time. This trade-off of operator versus machine time utilizations, and resultant interference time incurred by either, can be

TABLE 2

NOTATION

N = number of machines assigned to an operator

S = average service (repair) time per machine

μ = average service rate = $1/S$

P = average production (running) time per machine

   = average time between breakdowns

λ = average breakdown rate = $1/P$

ρ = ratio of the (average) service time to the (average) production time

   = servicing factor

   = $S/P = \lambda/\mu$

X = $1/\rho = P/S$

I = average interference time

      (I_M = interference time on a machine; I_R = interference time of an operator or repairperson)

W = average time to walk from machine to machine

A = average ancillary time per machine

   = operator time for duties that can be done internally (while the machine is running)

M = average maintenance time per machine

   = operator time for external duties (those that must be performed while the machine is stopped)

C = cycle time = max $\{P + S + I_M + W + M, (S + I_R + W + A + M)N\}$

M_e = machine efficiency

   = P/C

O_e = operator efficiency

   = $(S + W + A + M)/C$

E = efficiency loss

   = amount of production lost because of service and interference times

   = $(S + I)/C$

graphically displayed in a person-machine chart (Eilon [1970], Aronson [1980], Stecke [1982]). Unfortunately, these graphical methods, although easy to apply, become unwieldy for medium- or large-sized problems. More seriously, they can not guarantee good solutions.

Having nonidentical machines and different jobs complicates the deterministic problem because it involves scheduling aspects in addition to loading. Tanenbaum [1970] algebraically analyzes the problem of assigning N nonidentical machines to a single operator to minimize operator idle time (imposed by interference). He develops equations that, in effect, quantify the information provided by person-machine charts. He claims that as a result, the common trial and error approach of drawing many charts, from which the best assignment may be chosen, is avoided. However, his method is essentially the same as charting. Tanenbaum begins by choosing a candidate N and then calculates the quantities of interest; a person-machine chart provides the same information. Both procedures then iterate over several candidate N. However, Tanenbaum's method is less unwieldy than charting. Some obvious extensions of his procedure could include

1. computerization;

2. the addition of an optimization scheme to implicitly, rather than explicitly, enumerate the quantities of interest.

Miller [1972] and Miller and Berry [1977] provide a branch and bound approach to solve a nonlinear integer formulation of the deterministic interference problem of determining the optimal number and assignment of machines to a single operator to minimize the combined costs of idle labor and machines. This procedure can solve problems involving up to 15 machines (in 23.18 seconds of CPU time on a CDC 6500). On the other hand, a 20-machine problem could not be solved in 3000 seconds of CPU time. It is unlikely that the branch and bound approach could be used on large problems.

They use their optimum-producing procedure to evaluate solutions generated by two heuristics that they have also developed (Miller and Berry [1974]). In addition, their branch and bound code uses one of the heuristics to find an initial solution. The heuristics were tested on a CDC 6500 only on problems with up to 15 machines (in particular, for 5, 7, 9, 10, and 15 machines). The heuristic times ranged from about .03 to 4 CPU seconds. The required assumptions are that service and running times are deterministic and that the queue discipline is a closed cyclic patrol. An application of one of the heuristics is described in Bakshi [1974], which reports on satisfactory results.

Dube and Elsayed [1979] provide an algorithm that is based on one of the Miller and Berry heuristics to solve a slightly more general problem that allows due date considerations and operator walking distance restrictions. They claim to allow variable (normally distributed) operator service times. However, they merely use the mean and variance of service times on each machine in algebraic equations. Otherwise, the assumptions are identical to those of Miller and Berry. They report brief computational experience on problems with up to 20 machines. In particular, a 15-machine problem required 1.25 CPU seconds and a 20-machine problem took 2.3 seconds and about 42K core storage on an IBM 370/168.

Aronson offers two heuristics [1984] and two graphical methods based on the heuristics [1981] for a more general problem that allows several of the nonidentical machines to be tended more than once in every cycle. A 50-machine problem with up to 10 runs per cycle was solved to within 10% of optimality in about 10 CPU seconds on a CDC 6600.

There are situations in which the deterministic models are useful, in particular, those systems which display a periodic need for attention and are otherwise reliable. However, most of the literature and applications have focused on the more usual situation of random breakdowns and service requirements.

4. PROBABILISTIC MODELS

All of the remaining models assume some measure of uncertainty in either the time between breakdowns (the production or running time), service time, and/or walking time. The realm of applicability and required assumptions of each model are provided. The probabilistic models and techniques can be sub-classified according to the following five categories, entitled: expected workload analysis; interference formulas; binomial probability analysis; queueing theory approaches; and simulation. The queueing theoretic approaches are subclassified even further (within § 4.4) according to increasing generality and added extensions of the basic model.

4.1 Expected Workload Analysis

An operator's expected workload per machine can be estimated, given the average service, walking, and ancillary times. This early interference analysis method determines the number of machines to assign by taking the average production time of a part (average running plus service plus interference times), weighted by the machine efficiency (see Table 2), and dividing by the expected workload of the operator.

However, interference time must be known to determine the machine efficiency; also, N must be known to determine interference. This circular problem is solved by iterating back and forth, using candidate values for I and N, to hopefully converge to acceptable values of N and I. This problem spurred subsequent research resulting in many of the following methods for calculating interference, given N. In addition, performance and interference charts have been developed from time-study data to help analyze the above problem (see Niebel [1976]).

One application of the workload analysis techniques in the textile industry is provided by Berry [1968]. Following a cyclic patrol queue

discipline and using time studies and MTM (Methods Time Measurement) techniques, the aim was to utilize the operator totally while minimizing machine interference.

4.2 Machine Interference Formulas

One of the earliest formulas for determining interference was developed by Wright [1936]. Interference, as a percentage of average service time, was defined as a function of X and N (see Table 2). Production and service times are random, and machines are randomly tended. Wright's formula,

$$\frac{I}{S} \cdot 100 = 50 \ \{[(1 + X - N)^2 + 2N]^{1/2} - (1 + X - N)\},$$

has been empirically proven applicable to production systems containing more than six machines; for smaller systems, empirical curves were developed to use to determine interference. Examples can be found in Carson, Bolz, and Young [1972], Niebel [1976], and Stecke [1982].

At the same time, Duvall [1936] developed another formula,

$$I = 100 \ (N - 1) \ \exp \ (-1.4N^{-.946} \ X),$$

that was used at Western Electric Company. Production and service times are again assumed random, and machines are randomly tended. Both Wright and Duvall provide an economic evaluation for deciding N, based on the amount of resulting interference.

Smith [1965] modified Wright's formula to obtain

$$\frac{I}{S} \cdot 100 = 50 \ \{[(N - 1.5 - X)^2 + 2(N - 1)]^{1/2} + (N - 1.5 - X)\}.$$

A comparison of solutions obtained using this formula with those obtained using other methods (Wright [1936], Ashcroft [1950] (see § 4.4), Palm [1958] (see §4.4), and others) indicated that Smith's formula provided results that were most similar to Ashcroft's and Palm's. Smith developed his formula to provide

results that would be bounded by the results obtained by using Wright's and Palm's formulas. He hoped that his formula would then be more generally applicable.

Killingback [1964] developed a formula that determines interference on two machines that perform different operations, tended by one operator.

4.3 Binomial Probability Analysis

Several methods consider interference time variability through the use of the binomial distribution. These techniques assume that: machines are randomly tended; service times are randomly distributed, with a mean common to all machines; machine failures are independent. Expected interference time calculation is straightforward from probability theory (see Stecke [1982]).

Probably the earliest industrial demonstration of this approach was by Bernstein [1941]. Weir [1944] approximated Bernstein's calculation by expressing expected interference as a simple linear function of the number of machines assigned. Through a graphical transformation, his straight lines determine the most economical number of machines for an operator to tend. His graph is applicable for considering an assignment in the range of 1 to 15 machines.

Jones [1946] derived formulas for calculating average interference per machine as well as operator idle time as percentages of elapsed time, assuming that machines are similar (with respect to having the same service time requirements) and assuming a binomial distribution. From his formulas, for ease of use, he constructed a table that can be applied to assignments ranging from 2 to 100 machines.

The assumption of similar machines was subsequently relaxed (Jones [1949]). Using a simulation of systems of 2 to 10 machines, Jones showed that as the degree of difference in the machines' mean service time requirements decreased,

mean interference per machine also decreased. To adjust his table so that correct interference estimates could be obtained, linear factors for dissimilar machines were derived. Examples and tables can be found in Jones [1971] and Stecke [1982]. Formulas similar to those of Jones are given in O'Connor [1952a].

An interesting application in the tobacco industry that uses the formulas of Jones and O'Connor is described by Gillespie and Wysowski [1974]. They compare single-operator assignments to assignments to a group of operators, with the objective of minimizing total cost per unit. The results of this application will be summarized in §4.4.

Ackermann [1977] describes another application of Jones' interference tables. He uses them to help determine time standards for one operator tending several machines, and to determine the correct number of machines to assign to the operator.

4.4 Queueing Theory Approaches

The most common methodology for solving interference problems involves queueing theory. Interference is waiting, or queueing time. In this section we present models of queueing theory and applications that were developed with the solution of machine interference problems in mind. However, many other general queueing theory results might also be applicable to interference problems.

We begin by presenting the simple models in §4.4.1. As the models are complicated, more realistic systems can be analyzed. The model extensions include consideration of different breakdown and service disciplines (§4.4.2), patrolling considerations, alternative queue disciplines, and queueing network applications (§4.4.3). The presentation will be in order of increasing complexity as well as chronological.

4.4.1 Single and Multiple Server Models

The early models either ignore patrolling time or include it with average service time. The basic models with N machines and R operators all assume Poisson input, exponential service times, and first-come, first-served queue discipline (i.e., the machines are randomly tended). We refer to this as an M/M/R model. Many mean performance measures, such as machine efficiency, operator utilization, number of idle operators, waiting (interference) time, and number of waiting machines, are obtained from these models.

One of the earliest mathematical treatments of interference is by Khintchine [1933]. He uses an M/M/1 model to analyze the basic interference problem. Another early queueing analysis is by Kronig and Mondria [1943], but their mathematical expressions were not easily reduced to usable form. The best-known classical queueing-theoretic development is that of Palm [1943, 1947, translated from Swedish into English in 1958]. Formulas that give the interference time, machine efficiency, and operator utilization are provided for the M/M/1 and M/M/R queues, and Palm gives useful tables of these quantities for the M/M/1 case for $\rho \in [.01, .4]$ and N ranging from 1 to 144 machines (see Table 2).

Ashcroft [1950] derives a general solution for determining interference and machine efficiency as functions of ρ and N. He is credited with solving the M/G/1 model, which assumes exponentially distributed production times, constant service times, and random tending. However, by assuming an exponential service time distribution (i.e., an M/M/1 queue), Ashcroft's general solution becomes equivalent to Palm's. Takács [1951] provides similar formulas that one can use for the M/M/1 queueing situation. Khintchine and Ashcroft develop, in effect, the same formula for the M/M/1 situation, while Ashcroft also provides useful tables.

Benson and Cox [1951] solve an M/M/R problem, for a system where each operator specializes in one of R types of breakdown. Because of the computational difficulties associated with these models, Benson and Cox conclude that a valid approximation is to pool the various service calls and service times into one type of breakdown. They also tabulate Palm's M/M/R results. Benson, Miller, and Townsend [1953] consider the effect of ancillary work on interference.

Fetter [1955] compares the interference results obtained from the methods of Ashcroft, Duvall, Khintchine, Palm, and Wright for $\rho = .1$. He concludes that the decision concerning which model to use in a given situation should be partly based on the coefficient of variation (CV) of service time distributions (Ashcroft: CV = 0; Palm: CV = 1; Khintchine: CV = .5). Malcolm [1955] reports on an industrial application of an M/M/R model to economically design the organization of a production department that tests engines. The problem was to determine the number of inspectors required, to decrease interference time.

Peck and Hazelwood [1958] offer a book of tables based on the M/M/R case. For various parameters, these tables provide many useful performance measures that can be used to help solve various interference problems. Fetter and Galliher [1958] apply the M/M/R interference model to the problem of determining the minimum-cost number and type of material-handling facilities for transporting parts between production centers in a factory.

An industrial application of Palm's equations to develop production standards for new operations prior to installation for the Lukens Steel Company was reported by Haines and Rose [1962]. In determining the number of machines that an operator should tend, the advantages that they claimed from their approach were quick installation of an effective pay incentive plan and much quicker implementation of the new operating procedures.

4.4.2 Patrolling and Other Extensions

Benson [1957] considers the $E_k/M/1$ model, to show that the solution is identical to that of the M/M/1 model, which is a useful generalization. Another extension is by Mack, Murphy, and Webb [1957], who consider constant walking time in addition to random breakdowns and constant service times for a single operator. Machines are similar, and the queue discipline is a closed cyclic patrol.

Howie and Shenton [1959] investigate machine efficiency under a closed cyclic patrol queue discipline with constant walking time. In a particular textile application, Lawing [1959] determines the optimum number of machines (quill winders) to assign to a single operator, also assuming a closed cyclic patrol. In addition, times between breakdowns and service times are exponentially distributed. Ben-Israel and Naor [1960] also analyze interference problems while considering a closed cyclic patrol. Grant [1960] compares the random tending and cyclic patrol queueing disciplines for a group of several operators tending N machines. A good summary of some of the above is given in Cox and Smith [1961].

Morse [1962] contains a graph to help optimize operator crew size by balancing the cost of the crew with production costs, assuming exponential breakdown and service times. Morse also considers a hyperexponential breakdown distribution.

Jaiswal [1961] treats the interference problem where service is dictated by a preemptive resume priority queue discipline. Jaiswal and Thiruvengadam [1963] investigate systems of machines that are liable to two major types of random breakdowns (i.e., older versus newer machines) to determine which type should have a higher priority. They use an M/G/1 model with a nonpreemptive priority queue discipline. Their model could be adapted to consider limited

operator availability. Thiruvengadam [1966] provides some standard queueing results and useful performance measures for an M/G/R model with a preemptive priority queue discipline. The problem of Hodgson and Hebble [1967] considers one operator tending N groups of machines with N_i machines in group i. Each group is assigned a different priority. The model is M/G/1 with a nonpreemptive priority queue discipline. Mack and Stoodley [1968] analyze the M/D/2 machine interference model, for systems with deterministic service times and a pair of repairpersons.

Reynolds [1969, 1975] analyzes both M/M/R and M/M/R/N models with the shortest distance priority queue discipline, which then takes walking time into consideration. He compares the following four M/M/R models: Palm's [1947/ 1958] first-come, first-served model with patrolling, Palm's [1947/1958] model that ignores patrolling time, Lawing's [1959] patrolling model, and Reynold's [1969] distance priority model. Reynolds concludes that use of the shortest distance priority results in the largest effective number of working machines. Another useful generalization is that of King [1970], which extends Palm's methodology to find the optimum size of a service crew for a given number of identical machines.

Further extensions of the basic interference problem include the following. Bunday and Mack [1973] assume exponential breakdowns, constant service times, and constant walking times for the case of one repairperson to investigate an alternating cyclic patrol queue discipline. Carpenito and White [1976] formulate the problem of allocating nonidentical machines to nonidentical operators using a queueing model with random input and exponential service times. After finding the steady state solution to the queueing problem, a pattern-search technique is used to minimize expected cost subject to constraints. Maritas and Xirokostas [1977] treat the $M/E_k/R$ case numerically, providing useful tables of machine efficiency. Bunday and Scraton [1980] show

that the solution (steady state probabilities that n of N machines are down) of their G/M/R model is identical to that of the M/M/R case. Hence the operator utilization and machine efficiency are also the same in both cases. Therefore the breakdown time distribution can be arbitrary. In another industrial application, H. B. Maynard and Co., Inc. [1979] reports a straightforward application of Palm's results and Peck and Hazelwood's tables to calculate the amount of interference and to find the optimum number of bridge cranes to service work stations in one of KONE Oy's (Finland) shops.

Elsayed [1981] considers two repair policies for a problem similar to that of Jaiswal and Thiruvengadam [1963] with two types of breakdowns. Elsayed numerically obtains the optimal number of machines to assign to a single repair crew to demonstrate the superiority of one policy over the other according to crew efficiency and machine availability. He studies problems that have up to 10 machines.

In the interference literature, Fetter [1955], Fetter and Galliher [1958], Feller [1968], Bhat [1972], Gillespie and Wysowski [1974], Kleinrock [1976], Stecke and Solberg [1977, 1982], Allen [1978], and Stecke [1982] all provide examples of the economic advantages of pooling all operators into one repair group that is capable of servicing all down machines. Most of these observations are demonstrated through queueing theory, although Gillespie and Wysowski use binomial probabilities, and Stecke and Solberg [1977] use simulation. In particular, pooling workers increases their rate of efficiency. For example, a pool of two workers is more efficient than each operator working on his or her own individual, nonoverlapping assignment.

There are some additional considerations—perhaps sometimes disadvantages—associated with the larger assignments of more machines to groups of operators. The walking time from one down machine to another might

increase appreciably. Personality conflicts could develop between operators. If one operator consistently works harder or has a heavier workload than another, dissatisfaction might result. Hiring and training policies would have to be well-defined. New operators would most likely be slower at the beginning. It might be bad to include new hires in the pool of workers initially.

4.4.3 Queueing Network Models

Queueing network models can be used to study more realistic interference problems. Quantities of interest can be obtained that are similar to those (such as operator utilization and machine efficiency) provided by the simple queueing models, while allowing much more general assumptions on the breakdown and service distributions.

For example, the system of N machines under the care of one operator can be viewed as a cyclic network of two queues, with one queue (call it queue 0) containing the down machines and the other queue (1) containing the running machines. Suppose that the queue discipline is random (or FCFS). Since both queues 0 and 1 are quasi-reversible (see Kelly [1976]), they behave in isolation as an M/M/1 and M/G/∞ queue, respectively. The main result that is relevant to machine interference problems, is that the breakdown time distribution can be arbitrary; in this case, the results are identical to those of Palm, but the assumptions required are more general. For further model generality, by exploiting the use of different customer types and different customer routes (allowed through various queueing network models), a machine's present running time can depend on any number of its previous running times, and Palm's results still hold (see Kelly [1979]). An obvious application of this result is the consideration of machine aging, or wear and tear through constant use.

As another example, one can view a system of N nonidentical machines tended by one operator as a closed network of N + 1 queues. Machine i remains in queue i while it is running and moves to queue 0 when it stops. After it has been repaired it moves back to queue i. Because of the symmetry of queues 1 to N, Kelly [1976] shows that the running time of each machine i can be arbitrarily distributed and that the distribution may vary from machine to machine. In addition, a machine's running time may depend on its previous running times. Finally, if the mean running times of all N machines are equal, then the results are again identical to Palm's although the assumptions are more general.

As a final example (due to Kelly [1976]), consider N identical machines with two possible reasons for breakdown. Suppose there are two operators, each repairing a different type of breakdown. This system can be viewed as a closed network of three queues, the first two containing machines waiting for service from operators 1 and 2, respectively, and queue 3 containing the running machines. Then, as before, the running time for a machine can be arbitrarily distributed and may depend on previous running times and previous reasons for that machine's breakdown. In addition, the reason for a machine's breakdown may depend upon the current and previous running times and previous reasons for that machine's breakdown.

Gross and Ince [1981] analyze the interference problem of a system containing two classes of machines, each with different mean breakdown and repair times, all exponentially distributed, within the framework of a two-stage cyclic queue. The queue discipline is FCFS, and there is an arbitrary number of operators (O_i) at each stage and an arbitrary number (N_i) of identical machines of each type (class) in the system. Because of the large number of states that are generated by their solution method, they present results for 6

machines partitioned in various ways among the two classes. They also define two approximate models, which are more efficiently analyzed, that they conjecture bound the results of the exact model. They note that, theoretically, the model could be extended to several stages with several classes, state-dependent repair times, blocking, and priority queue disciplines (both preemptive and nonpreemptive). However, the computer storage and execution time would be exhorbitant.

Allen [1978] presents the steady state formulas for many of the simple queues and queueing networks that have been discussed in this section. Recall that from these formulas one can calculate many useful quantities of interest, such as operator utilization, machine efficiency, and interference. In addition, Hillier and Yu [1981] provide tables and graphs that determine interference (and other quantities) for many types of queueing systems.

These newer theoretical results are useful for extending the scope and applicability of the previous classical results that were obtained using queueing models. The more elaborate queueing network models have generalized the classical queueing theory results. Queueing network models should be pursued to expand the applicability of analytic solution techniques to machine interference problems.

4.5 Simulation

Beginning in the 1960s, simulation was used to analyze particular interference problems in greater detail than the queueing models would allow. One of the earliest reported interference applications is in setting production standards. This could be done much faster using simulation (which takes an estimated 2 person-weeks to develop and use) than by classical methods such as time studies (estimated 32 person-weeks to gather the data and subsequently analyze it) or work sampling (estimated 11 person-weeks) (Johnson and Smith

[1961]). Operator work loads and machine interference are calculated to determine wage incentives for one or more operators tending two to six machines. Burgess [1962] questions Johnson and Smith's procedure, and suggests alternative standard approaches to determine standards and equitable operator workloads, with perhaps more reasonable problem assumptions. Conway, Maxwell, and Sampson [1962] suggest the use of simulation to solve a stochastic interference problem with a cycle tending queue discipline that does not take walking time into consideration. In the context of a particular industrial application, Elicano [1967] describes a simulation that determines the number of operators to pool so as to minimize both operator idle time and machine interference in a large Midwest heavy manufacturing firm, Lear Siegler, Inc. Skeith, Curry, and Hairston [1969] apply simulation to study and solve a standard interference problem at Sun Oil Company.

In the 1970s, the simulation programs became more ambitious. Haagensen's [1970] model for the Phoenix Cable Plant allows different numbers, mixes, and speeds of machines, each having up to seven different types of breakdowns. Freeman, Hoover, and Satia [1973] develop a very general, flexible program that allows different types of operators with various skill levels. The many options available have their cost, however. The largest reported problem has six machines and 25 different tasks, storage requirements are 25,000 integer words, and the computational time is 5 to 10 minutes per run on a CDC 3300. Another versatile simulation program was developed at Western Electric to study some particular interference problem (Bredenbeck, Ogden, and Tyler [1975]).

Wiersma [1976] reported on a simple simulation used to determine the optimum utilization of fork trucks that service several production workers. Some potential problems with this approach are noted by Giffin [1976], who suggests that an M/D/1 or even an M/M/1 queueing model might be more appropriate. Elsayed and Proctor [1979] numerically examine two repair policies for two

types of breakdowns. Each policy places higher priority on one of the failure types. The optimal number of machines to assign to a repair crew, while minimizing repair cost, is provided for each policy.

Deakin [1980] uses a simple, calculator simulation to determine a regression model for deciding the number of machines to assign to an operator. The two queue disiciplines examined are the closed and alternating cyclic patrols. A relief operator is allowed during two 10-minute breaks and a 20-minute lunch period. It is assumed that service and patrolling times are constant, and the run time is exponential. Because of his particular experimental designs, the results are extremely limited. However, a similar procedure can be easily developed to use for other applications (Stecke [1982]).

Garcia-Diaz, Hogg, and Tari [1981] interface a simulation with several direct-search optimization techniques to determine strategies for assigning operators of different skill levels to multiple classes of machines under constraints of operator availability, with the overall objective of maximizing profit. The simulation considers operator cost, machine service cost, machine interference cost, and machine revenue for a particular allocation of operators to machines.

Most of the recent industrial approaches to solving interference problems have been based on simulation for several reasons:

1. Simulation has been easier to understand, use, and explain to both management and line personnel than queueing theory;

2. Simulation allows many more details to be considered, and hence, more realistic models that are effective in capturing the structure of the problem at hand.

3. General-purpose simulation languages have been developed, such as GASP IV, SLAM II, GPSS, and SIMSCRIPT, which make model development easier.

Unfortunately, simulation is also much more expensive to use and is always problem specific.

5. FUTURE APPLICATIONS

With the increasing growth in the use of new technologies such as robotics and flexible manufacturing systems, and their applications in batch manufacturing of discrete parts, the importance of explicitly considering and reducing machine interference will increase. These technologies are more expensive to acquire and run and more versatile than conventional systems. Attaining a high utilization (which can mean minimum interference) becomes an important major objective.

As a result of such technological developments and increased use of automation, new situations that breed interference problems are already occurring. Examples describing one robot tending the several machine tools that surround it are provided by Engelberger [1980]. When machining cycles are particularly long, a robot can be mounted on a track to travel among more machines than can be positioned around a stationary robot. Travel time considerations are then analogous to an operator's patrolling time in the classical machine interference literature. Engelberger describes a Japanese system with a track-mounted robot tending eleven different machine tools. Fanuc has a Kawasaki Unimate which travels overhead to tend eight NC lathes, all under direct numerical control. The computer directs the robot's movements along the 200-foot line to minimize lathe downtime (interference). Xerox Corporation has a high-volume transfer line consisting of: two CNC lathes; brazing, grinding, broaching, and turning machines; three robots; and a conveyor system. The robots tend several machines and transfer parts between the machine tools and the conveyor.

Additional interference problems will develop as robots are successfully integrated into flexible manufacturing systems (FMSs) (see Buzacott [1982] and

Stecke and Solberg [1981, 1982]). At present, the operations of most FMSs that are still manual include refixturing operations, the input and output (loading and unloading) of parts, and the delivery of tools to each machine tool's tool magazine. These are perfect applications for robots that will require consideration of machine interference.

Outside of Japan, there are very few flexible manufacturing systems that use robots for transfering workpieces. In most systems, palletized and fixtured parts are transported via wire-guided or robo-carts and positioned on the machine tools via pallet changers. Most often, the workpieces are too large and heavy to be moved by a robot.

One of the few flexible systems that do integrate robots on the line is the 9-machine, 8-robot SCAMP system, developed by the 600 Group for the Colchester Lathe Co., Ltd. in Colchester, U.K. Consisting of a mixture of CNC lathes and conventional, special-purpose machinery such as broaching and hobbing machines, each machine is tended by a 600 FANUC M1 robot, which picks and places each part off (and back on) the conveyor to (and from) the machine tool. The design decision was that usually, one robot would be dedicated to service only one particular machine tool. In addition, there is one robot tending two machines. This design decision results in the machines not having to wait for a robot to become available. However, the robots have low utilizations.

A similar potential application of machine interference solution methods is the situation in which one robot tends several others! All of these future interference problems will be somewhat different than previous ones, and there will be other factors to consider, also. For example, if a robot breaks down on a transfer line, often the system does also. However, the classical machine interference techniques could be adapted to use in these newer situations.

In a different type of application, Buzacott's [1982] study of transfer lines and FMSs investigates the problem of which machine a repairperson should tend if both machines of a two-stage transfer line have failed. Buzacott provides the solution to this problem under varying situations. He notes that although the solution is well defined, it would be difficult to implement in practice unless the repairs were automated.

6. SUMMARY

The current international concern with increasing productivity, in conjunction with the many theoretical studies and applications reported here, indicate the importance of minimizing machine interference. This paper provides a concise summary of the many models, methods, and approaches that have been taken to handle various aspects of machine interference problems. For ease of reference, the methods that are readily applicable to real interference problems are summarized in Table 3. In addition, the assumptions of each model and the range of applicability in terms of the number of machines are provided. Table 4 lists the applied and theoretical interference studies according to queue disciplines.

The categorization provided here will aid the search to find the most suitable method for a particular application. An overview of the many existing tools, and a brief description of each, has been given. The complete reference list is here for those interested in further model details.

New applications of interference-controlling methods have also been presented, such as flexible manufacturing systems, robotics, and computer-scheduling. As more automated tools, having greater individual reliability but requiring greater system reliability become available, minimizing interference will be even more important to obtain the most efficient, effective use of the potentially more productive systems.

TABLE 3

SUMMARY OF METHODS, ASSUMPTIONS, RANGES OF APPLICABILITY, AND REQUIRED INPUT/OUTPUT

Author [Year]	Service Time/Breakdown Time Distributions	Queue Discipline	Model/Formula	Range of Applicability (Number of Machines)	Output as Function of Input
Wright [1936]	Random service; one operator	Random tending	$I=50\{[(1+X-N)^2+2N]^{1/2} -(1+X-N)\}$	6 to 200	I (% of S) as a function of P/S=1/ρ and N
Wright [1936]	Random service; one operator	Random tending	Table	2 to 70	N as a function of P/S = 1/ρ and \$(mac)/\$(labor)
Wright [1936]	Random service; one operator	Random tending	Table	1 to 6	I (% of S) as a function of P/S = 1/ρ and N
Duvall [1936]	Random service; one operator	Random tending	$I=100(N-1)\cdot EXP(-1.4N^{-.946}X)$	1 to 200	I (% of S) as a function of P/S = 1/ρ and N
Weir [1944]	Random service; one operator	Random tending	Graph	1 to 15	I as a function of N, S, and P
Jones [1946]	Negative exponential service; one operator; similar machines	Random tending	Table	2 to 100 (formulas otherwise)	I and 1 - Oe as functions of N and S
Ashcroft [1950]	Constant service; negative exponential breakdown distribution; one operator	Random tending	Tables and Formulas	1 to 20	I and (Me) as a function of S/P = ρ and N
Palm [1947, 1958]	Negative exponential service and breakdown; one operator	Random tending	Tables and Formulas	1 to 144	I, P, and Oe as functions of S/P = ρ and N
Benson and Cox [1951]	Negative exponential service and breakdown; one operator	Random tending	Tables	1 to 15	Oe as a function of S/P = ρ and N
Peck and Hazelwood [1958]	Negative exponential service and breakdown; several operators	Random tending	Book of Tables	4 to 250	Me and I as a function of S/(S + P), O, and N

TABLE 3 (continued)

SUMMARY OF METHODS, ASSUMPTIONS, RANGES OF APPLICABILITY, AND REQUIRED INPUT/OUTPUT

Author [Year]	Service Time/Breakdown Time Distributions	Queue Discipline	Model/Formula	Range of Applicability (Number of Machines)	Output as Function of Input
Smith [1965]	General service; negative exponential breakdown; one operator	Cyclic patrol or distance	$I=50[\{(N-3/2-X)^2 +2(N-1)\}^{1/2} +(N-3/2-X)]$	Any number of machines	I as a function of $1/\rho$ and N
Miller [1972]	Constant service and breakdown; one operator	Closed cyclic patrol	Branch and Bound	1 to 15	N as a function of S and P
Miller and Berry [1974]	Constant service and breakdown; one operator	Closed cyclic patrol	Heuristics	1 to 15	N as a function of S and P
Deakin [1980]	Constant service; negative exponential breakdown; constant walking times; one operator	Cyclic patrol (both closed alternating) with and without relief	Equations	2 4 to 30	N as a function of S, E, and W
Dube and Elsayed [1979]	Constant service and breakdown; one operator	Closed cyclic patrol	Heuristics	1 to 10	N as a function of S and P
Aronson [1981, 1984]	Constant service and breakdown; one operator	Closed cyclic patrol	Heuristics Graphs	1 to 50	N as a function of S and P

TABLE 4

QUEUEING DISCIPLINES

Random Tending	Cyclic Patrol	Nonpreemptive Resume	Preemptive Resume	Distance Priority	General (Any)
Khintchine [1933]	Mack, Murphy and Webb [1957]	Jaiswal and Thiruvengadam [1963]	Thiruvengadam [1966]	Smith [1965] Reynolds [1969, 1975]	Haagensen [1970]
Wright [1936]	Howie and Shenton [1959]	Hodgson and Hebble [1967]	Jaiswal [1968]		Freeman, Hoover, and Satia [1973]
Duvall [1936]	Lawing [1959]				
Kronig and Mondria [1943]	Ben-Israel and Naor [1960]	Elsayed [1981]			
Palm [1943, 1947, 1958]	Grant [1960]				Bredenbeck, Ogden, and Tyler [1975]
Weir [1944]	Conway, Maxwell, and Sampson [1962]				Carpenito and White [1976]
Jones [1946, 1949]	Smith [1965]				Garcia-Diaz, Hogg, and Tari [1981]
	Miller [1972]				
Ashcroft [1950]	Bunday and Mack [1973]				
Benson and Cox [1951]					
Fetter [1955]	Miller and Berry [1974, 1977]				
Peck and Hazel-wood [1958]	Dube and Elsayed [1979]				
Grant [1960]	Deakin [1980]				
Kelly [1976]	Aronson [1980, 1981]				
Maritas and Xirokostas [1977]					
Allen [1978]					
Kelly [1979]					
Gross and Ince [1981]					

REFERENCES

1. ACKERMANN, W., "Development of Time Standards for Multi-Machine Assignments with Random Interference," Internal Publication, H. B. Maynard and Co., Inc. (June 1977).

2. ALLEN, ARNOLD O., Probability, Statistics and Queueing Theory with Computer Science Applications, Academic Press, New York, N.Y. (1978).

3. ARONSON, JAY E., "Two Graphical Methods for Determining a Cyclic Schedule for the Single Operator, Multiple Machine, Multiple Run Problem," Technical Report OREM 81007, Department of Operations Research and Engineering Management, Southern Methodist University, Dallas, Texas 75275 (November 1981).

4. ARONSON, JAY E., "Two Heuristics for the Deterministic, Single Operator, Multiple Machine, Multiple Run Scheduling Problem," Journal of Operations Management, forthcoming (1984).

5. ASHCROFT, H., "The Productivity of Several Machines under the Care of One Operator," Journal of the Royal Statistical Society B, Vol. 12, No. 1 (1950) pp. 145-151.

6. BAKSHI, M. S., "Development of an On-Line Dynamic Production Scheduling System for Efficient Multi-Machine Assignments in a Job Shop," Presented at the Joint ORSA/TIMS Conference, San Juan, Puerto Rico (November 1974).

7. BEN-ISRAEL, A. and NAOR, P., "A Problem of Delayed Service, I, II," Journal of the Royal Statistical Society B, Vol. 22 (1960) pp. 245-276.

8. BENSON, F., "Machine Interference-A Mathematical Study of Some Congestion Problems in Industry," unpublished Ph.D. Thesis, University of Birmingham, England (1957).

9. BENSON, F. and COX, D. R., "The Productivity of Machines Requiring Attention at Random Intervals," Journal of the Royal Statistical Society B, Vol. 13 (1951) pp. 65-82.

10. BENSON, F., MILLER, J. G. and TOWNSEND, M. W. H., "Machine Interference," Journal of the Textile Institute, Vol. 44 (1953) pp. 619-644.

11. BERRY, K. R., "Work Measurement in Multiple Machine Assignments," Journal of Industrial Engineering, Vol. 19, No. 8 (August 1968) pp. 17-19.

12. BERNSTEIN, PHILIP, "How Many Automatics Should a Man Run," Factory Management and Maintenance, Vol. 99, No. 3 (March 1941).

13. BHAT, U. NARAYAN, Elements of Applied Stochastic Processes, John Wiley and Sons, New York, N.Y. (1972).

14. BLOM, G., "Some Contributions to the Theory of Machine Interference," Biometrika, Vol. 50 (1963) pp. 135-143.

15. BREDENBECK, J. E., OGDEN, M. G., III and TYLER, M. W., "'Optimum' Systems Allocation: Applications of Simulation in an Industrial Environment," *Proceedings of the Midwest AIDS Conference* (1975) pp. 28-32.

16. BUNDAY, B. D. and MACK, C., "The Efficiency of Bi-Directionally Traversed Machines," *Journal of the Royal Statistical Society C*, Vol. 22 (1973) pp. 74-81.

17. BUNDAY, B. D. and SCRATON, R. E., "The G/M/r Machine Interference Model," *European Journal of Operational Research*, Vol. 4, No. 6 (June 1980) pp. 399-402.

18. BURGESS, A. R., "Comments on Simulation in the Application of Wage Incentives to Multiple Machines," *Journal of Industrial Engineering*, Vol. 13, No. 4 (1962) pp. 264-267.

19. BUZACOTT, JOHN ALLEN, "'Optimal' Operating Rules for Automated Manufacturing Systems," *IEEE Transactions on Automatic Control*, Vol. 27, No. 1 (February 1982).

20. CARPENITO, T. A. and WHITE, J. A., "The Allocation of Non-Indentical Machines among Non-Identical Servers," *International Journal of Production Research*, Vol. 4, No. 14 (1976) pp. 429-436.

21. CARSON, G. B., BOLZ, H. A. and YOUNG, H. H. (eds.), *Production Handbook*, 3rd edition, The Ronald Press Co., New York, N.Y. (1972) pp. 1277-1285.

22. CONWAY, R. W., MAXWELL, WILLIAM L. and SAMPSON, H. W., "On the Cyclic Service of Semi-Automatic Machines," *Journal of Industrial Engineering*, Vol. 13, No. 2 (March-April 1962) pp. 105-107.

23. COX, D. R. and SMITH, WALTER L., *Queues*, John Wiley & Sons, Inc., New York, N.Y. (1961).

24. DEAKIN, GEORGE R., "Simulation/Regression Approach to Machine Interference," Unpublished Report, Chemical & Industrial Engineering Management Services, Chester, Virginia (1980).

25. DUBE, RAJESH and ELSAYED, E. A., "A Multi-Machine Labor Assignment for Variable Operator Service Times," *Computers and Operations Research*, Vol. 6, No. 3 (1979) pp. 147-154.

26. DUVALL, WILLIAM G., "Machine Interference, Part II," *Mechanical Engineering*, Vol. 58, No. 8 (August 1936) pp. 510-514.

27. EILON, SAMUEL, *Elements of Production Planning and Control*, The Macmillan Company, New York, N.Y. (1970).

28. ELICANO, R. V., "How Many Helpers in a Pool?," *American Machinist* (February 1967).

29. ELSAYED, E. A., "An Optimum Repair Policy for the Machine Interference Problem," *Journal of the Operational Research Society*, Vol. 32, No. 9 (1981) pp. 793-801.

30. ELSAYED, E. A. and PROCTOR, C. L., "Two Repair Policies for a Machine Interference Problem with Two Types of Failures," Proceedings of the 10th Annual Modeling and Simulation Conference, Pittsburgh PA, Vol. 10 (April 1979) pp. 535-539.

31. ENGELBERGER, JOSEPH F., Robotics in Practice, Amacom, New York, N.Y. (1980).

32. FELLER, WILLIAM, An Introduction to Probability Theory and Its Applications, Vol. I, Third ed., John Wiley and Sons, New York, N.Y. (1968) pp. 462-468.

33. FETTER, ROBERT B., "The Assignment of Operators to Service Automatic Machines," Journal of Industrial Engineering, Vol. 6, No. 5 (September-October 1955) pp. 22-30.

34. FETTER, ROBERT B. and GALLIHER, HERBERT P., "Waiting-Line Models in Materials Handling," Journal of Industrial Engineering, Vol. 9, No. 3 (May-June 1958) pp. 202-208.

35. FREEMAN, DAVID R., HOOVER, S. V. and SATIA, J., "Solving Machine Interference by Simulation," Journal of Industrial Engineering, Vol. 5, No. 7 (July 1973) pp. 32-38.

36. GARCIA-DIAZ, ALBERTO, HOGG, GARY L. and TARI, FARHAD G., "Combining Simulation and Optimization to Solve the Multimachine Interference Problem," Simulation (June 1981) pp. 193-201.

37. GIFFIN, WALTER C., "Fork Truck Utilization: Another Approach," Industrial Engineering (July 1976) pp. 26-29.

38. GILLESPIE, W. PURYEAR and WYSOWSKI, C. H., "Teamwork Maintenance," Industrial Engineering, Vol. 6, No. 8 (August 1974) pp. 26-29.

39. GRANT, R. O., Jr., "A Comparison between the Random and the Patrolled Walk in the Assignment of Operators to Automatic Machines," M. S. Thesis, North Carolina State University, Raleigh, North Carolina (1960).

40. GROSS, DONALD and INCE, JOHN F., "The Machine Repair Problem with Heterogeneous Populations," Operations Research, Vol. 29, No. 3 (May-June 1981) pp. 532-549.

41. HAAGENSEN, GUNNAR E., "The Determination of Machine Interference Time through Simulation," The Western Electric Engineer, Vol. 14, No. 2 (April 1970) pp. 35-40.

42. HAINES, I. LANDIS and ROSE, CHARLES F., "Use of Queueing Theory in Setting Production Standards," Journal of Industrial Engineering, Vol. 13, No. 6 (November-December 1962) pp. 456-459.

43. HILLIER, FREDERICK S. and YU, OLIVER S., Queueing Tables and Graphs, North Holland, New York, N.Y. (1981).

44. HODGSON, VINCENT and HEBBLE, THOMAS L., "Nonpreemptive Priorities in Machine Interference," Operations Research, Vol. 15, No. 2 (March-April 1967) pp. 245-254.

45. HOWIE, A. J. and SHENTON, L. R., "The Efficiency of Automatic Winding Machines with Constant Patrolling Time," Journal of the Royal Statistical Society B, Vol. 21 (1959) pp. 381-395.

46. JAISWAL, N. K., "Preemptive Resume Priority Queue," Operations Research, Vol. 9 (1961) pp. 732-742.

47. JAISWAL, N. K., Priority Queues, Academic Press, New York, N.Y. (1968).

48. JAISWAL, N. K. and THIRUVENGADAM, K., "Simple Machine Interference with Two Types of Failure," Operations Research, Vol. 11 (1963) pp. 624-636.

49. JOHNSON, M. J. and SMITH, S. S., "Simulation in the Application of Wage Incentives to Multiple Machines," Journal of Industrial Engineering, Vol. 12, No. 6 (November-December 1961) pp. 428-430.

50. JONES, DALE W., "A Simple Way to Figure Machine Downtime," Factory Management and Maintenance, Vol. 104, No. 10 (October 1946) pp. 118-121.

51. JONES, DALE W., "Mathematical and Experimental Calculation of Machine Interference Time," The Research Engineer, Georgia Institute of Technology (January 1949).

52. JONES, DALE W., "Work Measurement of Multimachine Assignments," 3.92-3.112 of Maynard, H. B., ed., Industrial Engineering Handbook, McGraw-Hill, New York, N.Y. (1971).

53. KELLY, FRANK P., "Networks of Queues," Advanced Applied Probability, Vol. 8 (1976) pp. 416-432.

54. KELLY, FRANK P., Reversibility and Stochastic Networks, John Wiley & Sons, New York, N.Y. (1979).

55. KHINTCHINE, A. Ja., "Über der Mittiere Dauer des Stillstandes von Maschinen," or "On Mean Time of Stoppage of Machines," Mathematiceski Sbornic, Vol. 40, No. 2 (1933) pp. 119-123.

56. KILLINGBACK, J., "Cyclic Interference between Two Machines on Different Work," International Journal of Production Research, Vol. 3 (1964) pp. 115-120.

57. KING, J. R., "On the Optimal Size of Workforce Engaged in the Servicing of Automatic Machines," International Journal of Production Research, Vol. 8, No. 3 (1970) pp. 207-220.

58. KLEINROCK, LEONARD, Queueing Systems, Vol. I and II, John Wiley & Sons, New York, N.Y. (1976).

59. KRONIG, R. and MONDRIA, M., "On Time Losses in Machinery Undergoing Interruption," Part II, Physica, Vol. 10 (1943) pp. 331-333.

60. LAWING, W. D., "A Mathematical Method for Determining the Optimum Assignment of Quill Winders to a Patrolling Tender," M. S. Thesis, North Carolina State University, Raleigh, North Carolina (1959).

61. MACK, C., MURPHY, T. and WEBB, N. L., "The Efficiency of N Machines Unidirectionally Patrolled by One Operator when Walking Times and Repair Times Are Constants," Journal of the Royal Statistical Society B, Vol. 19 (1957) pp. 166-172.

62. MACK, C. and STOODLEY, K. D. C., "Machine Interference with Two Repairmen When Repair Time Is Constant," New Journal of Statistics and Operations Research, Vol. 4, No. 2 (1968) pp. 1-7.

63. MALCOLM, D. G., "Queueing Theory in Organization Design," Journal of Industrial Engineering, Vol. 6 (November-December 1955) pp. 19-26.

64. MARITAS, D. G. and XIROKOSTAS, D. A., "The $M/E_k/r$ Machine Interference Model," European Journal of Operations Research, Vol. 1 (1977) pp. 112-123.

65. MAYNARD, H. B. and Co., Inc., "Optimizing of Bridge Crane Use by the Interference Method," Internal Report prepared for KONE Oy, Hyvinge, Finland (April 1979).

66. MILLER, JEFFREY G., "The Multiple Machine Labor Assignment: A Combinatorial Analysis," unpublished Ph.D dissertation, Krannert Graduate School of Industrial Administration, Purdue University, West Lafayette, IN 47907 (1972).

67. MILLER, JEFFREY G. and BERRY, WILLIAM L., "Heuristic Methods for Assigning Men to Machines: An Experimental Analysis," AIIE Transactions, Vol. 6, No. 2 (1974) pp. 97-104.

68. MILLER, JEFFREY G. and BERRY, WILLIAM L., "The Assignment of Men to Machines: An Application of Branch and Bound," Decision Sciences, Vol. 8, No. 1 (1977) pp. 56-72.

69. MORSE, PHILIP M., Queues, Inventories and Maintenance, John Wiley & Sons, New York, N.Y. (1962) pp. 167-174.

70. NAOR, P., "On Machine Interference," Journal of the Royal Statistical Society B, Vol. 18 (1956) pp. 280-287.

71. NAOR, P., "Normal Approximation to Machine Interference with Many Repair Men," Journal of the Royal Statistical Society B, Vol. 19 (1957) pp. 334-341.

72. NAOR, P., "Some Problems of Machine Interference," Proceedings, First International Conference, Operations Research, English University Press, Oxford, England (1957).

73. NIEBEL, BENJAMIN W., Motion and Time Study, 6th edition, Richard D. Irwin, Inc., Homewood, IL (1976) pp. 382-385.

74. O'CONNOR, T. F., Productivity and Probability, Emmott and Co., Ltd., Manchester, England (1952a).

75. O'CONNOR, T. F., "An Easy Way to Allow for Machine Interference," Textile World (December 1952b).

76. PALM, DOCENT CONNY, "Intensitatschwankungen in Fernsprechverkehr," or "Analysis of the Erlang Traffic Formula for Busy-Signal Arrangements," Ericsson Technics, Vol. 6, No. 3 (1943).

77. PALM, DOCENT CONNY, "Arbetskraftens Fordelning Vid Betjaning av Automatmaskiner," or "The Distribution of Repairmen in Servicing Automatic Machines," Industritidningen Norden, Vol. 75 (1947) pp. 75-80, 90-94, and 119-125.

78. PALM, DOCENT CONNY, "The Assignment of Workers in Servicing Automatic Machines," Journal of Industrial Engineering, Vol. 9, No. 1 (January-February 1958) pp. 28-42.

79. PECK, L. G. and HAZELWOOD, R. N., Finite Queueing Tables, John Wiley and Sons, New York, N.Y. (1958).

80. REYNOLDS, GARY H., "An M/M/c Queue for the Distance Priority Machine Interference Problem," Operations Research Center Report 69-35, University of California, Berkeley (November 1969).

81. REYNOLDS, GARY H., "An M/M/m/n Queue for the Shortest Distance Priority Machine Interference Problem," Operations Research, Vol. 23, No. 2 (March-April 1975) pp. 325-341.

82. SKEITH, R., CURRY, G. and HAIRSTON, D., "Simulation Checks Problem of Machine Interference," Industrial Engineering (May 1969) pp. 22-26.

83. SMITH, J. TENNANT, "Machine Interference and Related Problems," Work Study, Vol. 14, Nos. 6-10 (June-October 1965) pp. 9-16, 21-28, 28-36, 25-34, and 25-32, respectively.

84. STECKE, KATHRYN E., "Machine Interference: The Assignment of Machines to Operators," in the Handbook of Industrial Engineering, edited by Gavriel Salvendy, John Wiley and Sons, New York, N.Y. (1982).

85. STECKE, KATHRYN E. and SOLBERG, JAMES J., "Scheduling of Operations in a Computerized Manufacturing System," Report No. 10, NSF Grant No. APR74 15256, School of Industrial Engineering, Purdue University, West Lafayette, IN 47907 (December 1977).

86. STECKE, KATHRYN E. and SOLBERG, JAMES J., "Loading and Control Policies for a Flexible Manufacturing System," International Journal of Production Research, Vol. 19, No. 5 (September-October 1981), pp. 481-490.

87. STECKE, KATHRYN E. and SOLBERG, JAMES J., "The Optimality of Unbalanced Workloads and Machine Group Sizes for Flexible Manufacturing Systems," Working Paper No. 290, Division of Research, Graduate School of Business Administration, The University of Michigan, Ann Arbor MI 48109 (January 1982).

88. TAKÁCS, L., "Probabilistic Treatment of the Simultaneous Stoppage of Machines with Consideration of the Waiting Times," Magyar Tud. Akad. Mat. Fiz. Ost. Kozl., Vol. 1 (1951) pp. 228-234.

89. TANENBAUM, WALTER, "How to Balance a Machine Battery," Industrial Engineering (March 1970) pp. 46-50.

90. THIRUVENGADAM, K., "Queueing with Breakdowns," Operations Research, Vol. 11 (1963) pp. 62-71.

91. THIRUVENGADAM, K., "A Generalization of Queueing with Breakdowns," Defense Science Journal, Vol. 14 (1964a) pp. 1-16.

92. THIRUVENGADAM, K., "A Priority Assignment in Machine Interference Problems," OPSEARCH, Vol. 1 (1964b) pp. 197-216.

93. THIRUVENGADAM, K., "Machine Interference Problem with Limited Server's Availability," OPSEARCH, Vol. 2 (1965a) pp. 65-84.

94. THIRUVENGADAM, K., "Studies in Waiting Line Problems," Ph.D. thesis, University of Delhi, Delhi, India (1965b).

95. THIRUVENGADAM, K., "Machine Interference Problem with Postponeable Interruptions," Defence Science Journal, Vol. 6 (1966) pp. 57-71.

96. THIRUVENGADAM, K., and N. K. JAISWAL, "The Stochastic Law of Busy Periods for the Simple Machine Interference Problems," Defense Science Journal, Vol. 13 (1963) pp. 263-270.

97. THIRUVENGADAM, K., and N. K. JAISWAL, "Application of Discrete Transforms to a Queueing Process of Servicing Machines," OPSEARCH, Vol. 1 (1964) pp. 87-105.

98. WEIR, WILLIAM F., "Figuring Most Economical Machine Assignment," Factory Management and Maintenance, Vol. 102, No. 12 (December 1944) pp. 100-102.

99. WIERSMA, CHARLES H., "Economic Utilization of Fork Trucks," Industrial Engineering, Vol. 8, No. 4 (April 1976) pp. 32-35.

100. WRIGHT, WILMER R., "Machine Interference," Part I, Mechanical Engineering, Vol. 58, No. 8 (August 1936) pp. 510-514.