Design of a Naval Tender Job Shop

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The project described in this chapter deals with the determination of the optimal man/machine configuration of a naval tender job shop. The approach illustrates how to complement the strengths of two important modeling techniques: mathematical programming and simulation. The problem can be characterized as one of capacity planning, where a great deal of uncertainty exists as to the demands on the system.

The approach taken is hierarchical in the sense that an aggregate planning model first suggests a man/machine configuration for the job shop and then a detailed model evaluates the performance of this configuration in a simulated environment. The aggregate model extends over a six-month planning horizon and has a mixed-integer programming structure. Once a proposed configuration for the job shop is generated by the aggregate planning model, the detailed model addresses the uncertainties and the precedence relations that affect the job-shop environment on an hour-by-hour basis. If the detailed evaluation of the configuration is unacceptable, constraints are modified in the aggregate model and the procedure is repeated.

This hierarchical approach, which combines optimization and simulation, provides a viable way of eliminating the weaknesses inherent in the two modeling approaches. The mixed-integer programming model cannot incorporate the detailed precedence relationships among jobs or include uncertainties explicitly, without becoming so large that it would be impossible to solve. On the other hand, the simulation model does not generate alternative man/machine configurations, but merely evaluates those presented to it. By using the two approaches jointly, it is possible both to generate a reasonable set of alternative configurations and to evaluate each one against a set of scheduling environments.

The hierarchical approach also facilitates the decision-maker's interaction with the models, and allows for comprehensive testing of a wide variety of options that can result in robust and efficient solutions.

10.1 THE PROBLEM DESCRIPTION

In order to support its fleet of ships, the U.S. Navy maintains a number of special-purpose ships, called naval tenders, which are dedicated to performing maintenance functions for the fleet. The purpose of this project is to develop an analytic approach for determining the machine configuration and manpower allocation for a naval-tender machine shop. Although this objective might be regarded as quite specific, the naval-tender machine shop can be considered a typical example of an intermittent-production, open job shop wherein general-purpose equipment and trained mechanics are held ready to meet a widely fluctuating demand for repair and manufacturing work. In this specific case, the work is generated by the fleet of ships for which the tender is responsible. The suggested design approach can be extended easily to other job-shop configurations.

The principal functions of the naval-tender machine shop are to repair pumps, valves, and similar mechanical equipment; to manufacture machinery replacement items; to perform grinding and engraving work; and to assist other tender shops. The typical modern naval-tender machine shop contains milling machines, drill presses, grinders, engine lathes, a furnace, a dip tank, bandsaws, shapers, turret lathes, boring mills, a disintegrator, an arbor press, and various other equipment. The shop normally is supervised by three chief petty officers, and the operations personnel include several petty officers (first-, second-, and third-class) as well as a large number of "non-rated" machinery repairmen.

In order to reduce the scope of the study to a more manageable size, we have excluded from our analysis the engraving and grinding sections, since there is virtually no cross-training between these sections and the remaining part of the tender, and their use does not overlap with the remaining activities of the naval tender. It would be straightforward to extend our suggested approach to cover grinding and engraving operations if proper data were available.

The Use of Numerically-Controlled Machines

A primary concern of our study is to examine the applicability of numerically-controlled machine technology to naval tenders. Numerical control provides for the automatic operation of machinery, using as input discrete numerical data and instructions stored on an appropriate medium such as punched or magnetized tape. The motions and operations of numerically-controlled machine tools are controlled primarily, not by an operator, but by an electronic director, which interprets coded instructions and directs a corresponding series of motions on the machine. Numerically-controlled machine tools combine the operations of several conventional machines, such as those used in milling, drilling, boring, and cutting operations.

To evaluate the decision-making problem properly, it is important to examine some of the advantages that numerically-controlled machines offer over conventional machine tools.

First, the combination of many machining activities into one machine may decrease setup losses, transportation times between machine groups, and waiting times in queues. Jobs then tend to spend less time in the shop, and so generally there will be less work-in-process and less need for finished-good inventories.

Second, the programmed instructions provided to the numerically-controlled machines can be transmitted, by conventional data lines or via a satellite system, to tenders in any of the seas and oceans. This creates an opportunity to develop centralized design, engineering, parts-programming, and quality-control organization, which can offer many economical, tactical, and manufacturing advantages.

Third, because numerically-controlled machines can be programmed to perform repetitive tasks very effectively, the jobs that they complete may require less rework and can be expected to result in less scrap. Also, superior quality control can be gained without relying on an operator to obtain close tolerances, and significant savings in inspection time can be realized.

Fourth, numerical control can have major impacts on tooling considerations. Tool wear can be accounted for, at given speed and feed rates, by automatically modifying the tooling operation to compensate for the changes in tool shape. With this compensation, numerous stops to adjust tools are avoided, and the tool is changed only when dull.

Finally, skills that are placed onto tape can be retained even though there are numerous transfers and changes in shop personnel. Despite this characteristic, inferences regarding individual skills and capabilities of operating personnel cannot be drawn so readily. Some advocates of numerical control would say that the personnel skill level could be lower in a numerical-control machine shop. On the other hand, several users of numerical control (e.g., the Naval Air Rework Facility in Quonset Point, R.I.) have indicated no change in overall skill levels when numerically-controlled machines are used, since experienced machinists are needed to ascertain whether the machine is producing the desired part or not.

All of these considerations suggest investigating the possibility of placing numerically-controlled machines on board naval tenders. The justification, or lack of justification, for the replacement of conventional machinery by numerically-controlled machinery is one of the important questions addressed in this study.

The Hierarchical Approach

There are two distinct levels of decision in the design of a naval-tender machine shop. The first level, which involves resource acquisition, encompasses the broad allocation of manpower and equipment for the tender, including the capital investment required for purchasing numerically-controlled machinery. The second level, dealing with the utilization of these resources, is concerned with the detailed scheduling of jobs, equipment, and workmen. Although it is theoretically possible to develop a single model to support these two levels of decisions, that approach seems unacceptable for the following reasons:

First, present computer and methodological capabilities do not permit solution of such a large integrated/detailed production model.

Second, and far more important, a single mathematical model does not provide sufficient cognizance of the distinct characteristics of time horizons, scopes, and information content of the various decisions.

Third, a partitioned, hierarchical model facilitates management interaction at the various levels.

Therefore we approach our problem by means of a hierarchical system in which the two decision levels are represented by two interactive models:

The aggregate model. Utilizing forecast demand as input, it makes decisions regarding machinery purchases and work-force size; and

The detailed model. Utilizing the machinery configuration and work-force schedule derived in the aggregate model as inputs, it simulates scheduling and assignment decisions, and determines shop performance as well as manpower and machinery utilization.

The time horizon of the aggregate model is at least as long as the tender deployment period, typically six months, whereas the detailed model addresses decisions on a daily or hourly basis. The two models are coupled and highly interactive. The aggregate model is oblivious to daily or weekly changes in the demand patterns, and does not consider bottlenecks or queue formations in front of machine groups; the machine configuration and work-force output of the aggregate model does, however, bound the daily and hourly operation of the tender machine shop. On the other hand, in its scheduling of jobs and assignment of machines and work force, the detailed model determines the utilization of manpower (undertime or overtime) and recognizes how demand uncertainties affect measures of shop performance (such as number of tardy jobs, or mean tardiness of jobs). This information can alter the machinery configuration and/or work-force allocations by labor class as determined by the aggregate model. It is proposed that the two models be solved sequentially, the aggregate model first, with iterations between the two models as necessary to address the interactions.

10.2 THE AGGREGATE MODEL

Model Objective and Assumptions

The primary objective of the aggregate model is to provide a preliminary allocation of manpower requirements by skill classes, and to propose a mix of conventional and numerically-controlled machines. These allocations are made by attempting to minimize the relevant costs associated with the recommended manpower and machine configuration, while observing several aggregate constraints on workload requirements, shop-space availability, weight limits, machine substitutability, existing conventional machine configuration, and machine and manpower productivities.

Several assumptions have been made to simplify the model structure, while maintaining an acceptable degree of realism in the problem representation.

First, demand requirements are assumed to be known deterministically. This assumption is relaxed in the detailed model where the impact of uncertainties in workload estimates are evaluated.

The work force (whose size and composition is to be determined by the model) is assumed to be fixed throughout the planning horizon. Hiring and firing options, which are available in *industrial* job-shop operations, are precluded in this application. Moreover, we have not allowed for overtime to be used as a method for absorbing demand fluctuations in the aggregate model; rather, overtime is reserved as an operational device to deal with uncertainties in the detailed model.

Rework due to operator error or machine malfunction is not considered explicitly. Rather, the productivity figures that are used include allocations for a normal amount of rework. Similarly, no provision is made for machine breakdown or preventive maintenance. Field studies indicated that a conventional machine is rarely "down" completely for more than one day; preventive maintenance time can be considered explicitly by the addition of "jobs" requiring manpower and machine time but no throughput material.

Finally, we assume that required raw materials always are available in necessary quantities in inventory on board the tender.

The Aggregation of Information

One of the basic issues to be resolved when designing an aggregate model is the consolidation of the pertinent information to be processed by the model in a meaningful way. Workload requirements are aggregated in terms of labor skill classes, machine types, and time periods. At the detailed level, these requirements are broken down into specific jobs, with precedence relationships, uncertainties in task-performance times, and due dates properly specified.

Now, we will review the major categories of information proposed in this model.

Timing

The planning horizon of the models has a six-month duration, which corresponds to a typical naval-tender deployment period. This planning horizon is divided into six equal time periods of one month each, because much of the data is gathered on a monthly basis and the current planning practices are based on monthly reports. The time periods are designated by t, for $t = 1, 2, \ldots, 6$.

Machines

The machines in the naval tender are grouped into two sections: heavy and light. Due to the nature of the operations performed, the logical candidates for substitution by numerically-controlled machines are the standard lathes in the light section and the universal/plain milling machines in the heavy section. Each of these two classes of machines, then, should be examined as separate machine groups. The remaining machines of the light section can be grouped into one large group, since the tender machine shop is labor-limited in this area; similarly, the remaining machines of the heavy section are grouped together. The machine groups are denoted by i, for $i = 1, 2, 3$, and 4.

Workforce

The workforce is divided into four groups corresponding to the current classes of skill/pay rates. Furthermore, the number of chief petty officers required for shop administration and supervision is assumed to be constant for all machinery configurations; since these costs are fixed, they do not enter into our analysis. The workforce classes are denoted by ℓ, for $\ell = 1, 2, 3$, and 4.

Model Formulation

Prior to presenting the mathematical formulation of the aggregate model, it is useful to introduce the symbolic notation used to describe the decision variables and the parameters of the model.

Decision Variables

Essentially, the decision variables are the number of conventional and numerically-controlled machines, the number of workers of various skill classes needed on the tender, and the allocation of the workers to the machines.

The following list describes each of the decision variables included in the aggregate model, in terms of conventional machines:

$X_{\ell it}$ Number of hours of conventional machine time used by workers of skill-class ℓ on machine group i in time period t;

N_i Number of conventional machines required in machine group i;

$\underline{N}_{it}$ Number of conventional machines in machine group i required to satisfy the workload demand for that machine group in time period t;

$N_{\ell t}$ Number of skill-class ℓ workers required to meet the workload demand on conventional machinery in time period t;

R_i Number of conventional machines removed from machine group i;

M_ℓ Number of skill-class ℓ workers; and

$M_{\ell t}$ Number of skill-class ℓ workers required to meet the workload demand on *both* conventional and numerically-controlled machinery in time period t;

$X^*_{\ell it}$, $\underline{N}^*_{it}$, N^*_i, $N^*_{\ell t}$ Decision variables corresponding to $X_{\ell it}$, $\underline{N}_{it}$, N_i, $N_{\ell t}$, respectively, for the numerically-controlled machines.

Parameters

The parameters of the model reflect cost, productivity, demand, and weight and space limitations. The following list describes each of the parameters included in the aggregate model in terms of conventional machinery:

$C_{\ell t}$ Composite standard military pay rate (salary and benefits equivalent) charged for a worker of skill-class ℓ in time period t;

f_i Productivity factor reflecting an increased throughput rate for jobs that are completed on a numerically-controlled machine rather than on a conventional machine, for a particular machine group i—for example, if in the aggregate a set of jobs requires 100 hours of numerically-controlled lathe time or 300 hours of conventional lathe time, then the productivity factor for a numerically-controlled machine in the lathe-machine group would be 3;

$d_{\ell it}$ Number of hours of conventional machine time to be performed by workers of skill-class ℓ on machine group i in time period t;

h_{it} Number of hours that a conventional machine in machine group i can be productive in time period t;

k_i Constant ($0 \leqq k_i \leqq 1$), reflecting the fact that a certain amount of the demand workload cannot be performed on a numerically-controlled machine. In the context of constraint (6), if $k_i = 0$, then *all* of the demand can be accomplished on numerically-controlled machinery, whereas if $k_i = 1.0$, then all of the demand must be met by work on *conventional* machinery;

b_i Original number of conventional machines in machine group i, prior to any substitution by numerically-controlled machinery;

a_i Deck area required for a machine in machine group i;

k' Constant that can be utilized to introduce more (or less) free deck space in the tender machine shop: k' is the ratio of the areas of removed machines to the areas of numerically-controlled machines brought aboard and, as such, reflects the limited deck area available for the mounting of machinery; if $k' = 1$, then the amount of space devoted to machinery *cannot* be altered;

w_i Weight of a conventional machine to be removed from machine group i;

m Maximum permissible machinery weight, reflecting naval architecture (weight-constrained design) or other design constraints on the bringing aboard of *additional* weight;

$h_{\ell t}$ Number of manhours that a worker of skill-class ℓ will be available for productive work on conventional machinery during time period t;

k'' Constant used in smoothing manpower requirements on second and later iterations through the aggregate model; $k'' = 1$ for the first iteration; use of k'' will become clear when constraint (13) is discussed later in this section.

h^*_{it}, a^*_i, w^*_i, $h^*_{\ell t}$ Parameters corresponding to h_{it}, a_i, w_i, $h_{\ell t}$, respectively, for the numerically-controlled machines.

In addition,

C^*_{it} Share of the acquisition, installation and incremental operation, maintenance, and overhead costs attendant to bringing aboard a numerically-controlled machine into machine group i, attributable to time period t.

Mathematical Formulation

The mathematical formulation of the aggregate model is as follows:

$$\text{Minimize} \sum_t \sum_\ell C_{\ell t} M_\ell + \sum_t \sum_i C^*_{it} N_i + \sum_i (1) R_i,$$

subject to:

$$
\begin{array}{llllr}
X_{\ell it} & + f_i X^*_{\ell it} & = d_{\ell it}, & \text{all } \ell, i, t & (1) \\
\sum_\ell X_{\ell it} & - h_{it} \underline{N}_{it} & = 0, & \text{all } i, t & (2) \\
\sum_\ell X^*_{\ell it} & - h^*_{it} \underline{N}^*_{it} & = 0, & \text{all } i, t & (3) \\
\underline{N}_{it} & - N_i & \leqq 0, & \text{all } i, t & (4) \\
\underline{N}^*_{it} & - N^*_i & \leqq 0, & \text{all } i, t & (5) \\
\sum_\ell X_{\ell it} & & \geqq k_i \sum_\ell d_{\ell it}, & \text{all } i, t & (6) \\
R_i & + N_i & \leqq b_i, & \text{all } i & (7) \\
a_i R_i & - k' a^*_i N^*_i & \geqq 0, & \text{all } i & (8) \\
\sum_i w^*_i N^*_i & - \sum_i w_i R_i & \leqq m, & & (9) \\
\sum_i X_{\ell it} & - h_{\ell t} N_{\ell t} & = 0, & \text{all } \ell, t & (10) \\
\sum_i X^*_{\ell it} & - h^*_{\ell t} N^*_{\ell t} & = 0, & \text{all } \ell, t & (11) \\
N_{\ell t} & + N^*_{\ell t} - M_{\ell t} & = 0, & \text{all } \ell, t & (12) \\
k'' M_{\ell t} & - M_\ell & \leqq 0, & \text{all } \ell, t & (13) \\
\multicolumn{3}{l}{X_{\ell it},\ X^*_{\ell it},\ N_{it},\ N^*_{it},\ R_i,\ N_{\ell t},\ N^*_{\ell t},\ M_{\ell t},} & \text{all nonnegative,} & (14) \\
\multicolumn{3}{l}{N_i,\ N^*_i,\ R_i,\ M_\ell,} & \text{all nonnegative integers.} & (15)
\end{array}
$$

The resulting model is a mixed-integer program. We will now briefly comment on the model structure.

The objective function attempts to minimize the manpower costs and the acquisition, installation, and incremental costs introduced by the numerically-controlled machines. The third cost component in the objective function discourages the removal of more conventional machines than necessary by assigning a fictitious penalty of one dollar for the removal of one conventional machine. This gives some extra capacity to the naval tender and allows for more flexibility in its operation.

Constraint (1) requires that the demand be satisfied by a proper combination of conventional and numerically-controlled machines. Note that f_i is a factor that represents the increase in throughput for jobs processed in a numerically-controlled machine rather than a conventional machine.

Constraints (2) and (3) convert hours of conventional and numerically-controlled machines required each month to number of machines. Constraints (4) and (5) specify that the numbers of each type of machine required at *any* time cannot exceed the number carried aboard throughout the time horizon.

Constraint (6) requires that a given fraction of the demand must be met by conventional machinery, since *numerical control is not universally applicable.*

Constraint (7) states that the number of machines to be removed from a machine group, R_i, plus the actual number required N_i, *cannot exceed the initial number* b_i of machines in the group. Restrictions (8) and (9) represent constraints on deck area availability, and weight limits.

Constraints (10) and (11) determine the required manpower for conventional and numerically-controlled machinery during each month. Constraint (12) simply computes the sum of the two manpower needs. Finally, constraint (13), when $k'' = 1.0$, requires that a man of skill-class ℓ needed at any time during the planning horizon be ordered aboard at the *start* of the time horizon and kept aboard until the end of the planning horizon (in our case, a six-month deployment). The factor k'' is provided for use on subsequent runs in an iterative process: For example, if the overtime utilization of skill-class ℓ exceeds the desires of the decision-maker, k'' can be set greater than 1.0, thereby requiring additional personnel aboard.

10.3 THE DETAILED MODEL

Model Objective and Assumptions

The objective of the detailed model is to test the preliminary recommendations obtained from the aggregate model regarding machine and manpower mix, against a more realistic environment, which includes the uncertainties present in the daily operation of the job shop, the precedence relationships that exist in scheduling production through the various work centers, and the congestion generated by executing the production tasks.

Demand requirements are being specified in terms of individual jobs. Each job has a given duration, which is defined by means of a probability distribution. Alternative paths through the machine shop, e.g., from a numerically-controlled lathe to a conventional drill press, or from a conventional lathe to a conventional drill press, are specified. Each alternative path includes certain precedence relationships that must be observed; e.g., a shaft must be turned on a lathe and then a keyway has to be cut on a boring mill; the keyway *cannot be cut before* the shaft is turned.

Most machine-shop personnel coming aboard work first in the light section and then move to the heavy section of the tender. Therefore, we will assume that workers in the heavy section can perform work in both sections, whereas those in the light section are not assignable to the heavy section. We also assume that workers of a higher skill class can accomplish work normally assigned to a lower skill class; in other words, there is *downward substitutability* among worker skill classes. Further, a job can be worked on by only one worker of one skill class at a time; this assumption ignores the fact that large bulky items may require more than one man to set up a machine, but the amount of time required for this setup is generally quite small compared to the overall time on one machine with one worker.

It is assumed that each job is broken down into its smallest components. In order to satisfy the constraint stating one man and one machine for each operation, as well as the precedence relationships, we shall permit no overlapping of operations. A job which has two or more parts that can be worked in parallel is decomposed into two or more new jobs, with the appropriate due dates.

No preemption of jobs is allowed. This is not to say that a job leaving its first operation and entering a queue for its second operation cannot be delayed by a higher-priority job, but only that, once a machine and a man *have been committed* to performing an operation on a specific job, that operation on that job will be completed without interruption, irrespective of the higher-priority arrivals at the queue for that machine.

As before, we assumed that required raw materials, or satisfactory substitute materials, are always in inventory on board the tender in necessary quantities.

The Simulation Approach

In Chapter 1 we discussed the basic characteristics of simulation models. The essence of simulation is to provide a realistic and detailed representation of the problem under study, which allows the decision-maker to test various alternatives he might want to consider. The simulation model evaluates each alternative by calculating its corresponding measure of performance. It is important to emphasize that simulation models do not generate an optimum solution, but simply permit the evaluation of alternative solutions supplied externally by the decision-maker.

A simulation model was chosen to represent the detailed characteristics of the job-shop activities. Simulation has proved to be a very effective and flexible modeling tool for dealing with queueing networks such as a job-shop scheduling problem. Basically, the simulation model identifies each machine that is part of the machine shop and each job that has to be processed in the job shop. The dispatching rules that govern the order in which jobs are processed and their sequencing through the shop, the characteristics of the jobs themselves, and the availability of machine and manpower capabilities determine how fast the jobs can be processed and what overall measures of performance will be obtained from the job-shop operation. Common measures of performance are: percentage of jobs to be processed on time; total tardiness in job execution; utilization of manpower and machines, and so forth. The simulation models allow us to incorporate a number of characteristics of the job-shop performance that have not been taken into account in the aggregate model. The most important of these characteristics are uncertainties in job completion times, priority rules associated with job execution (since some jobs are more important than others), precedence relationships associated with the various activities or tasks that are part of an individual job, alternative ways of executing these activities (i.e., using either a conventional or a numerically-controlled machine), and so on.

More specifically, the basic elements of the simulation model are:

Jobs, which flow through a network of machines that perform a variety of operations; where the sequence, machine groups, worker skill levels, and service times at each step are a function of and specified by the job itself.

A job is composed of various activities:

Activities are the basic elements of a job. They utilize multiple resources (machines, manpower, and material), and require time to be performed;

Flow lines connecting a network of activities, defining a sequence of operations, and denoting a direction of flow; and

Boundary elements, that is, points of job origination (sources) and job termination (sinks).

These elements provide the network configuration. In addition, the following input data should be provided by the user:

Service times to perform the various activities; these are random variables specified by their probability distributions, which depend on the individual characteristics of each job;

Job routing through alternative paths within the network;

Queue disciplines, that regulate the order in which jobs waiting at a station are processed. Common queue disciplines to be used are FCFS (first come, first served), shortest processing time (the activity with shortest processing time goes first), due dates (the job with closer due date is processed first), and so on;

Operating schedules for the system, whereby standard workdays can be established, and the system closed or open to arriving jobs according to some predetermined role. The operating schedules keep track of the passage of time, and thus simulate the time dimensions of the problem.

Figures 10.1 and 10.2 present flow charts describing how these elements are integrated into a job-shop simulator model. A job arriving in the shop is characterized by its priority, the minimum skill-class worker required, its preferred and acceptable alternative paths through the shop (where applicable), and the service times needed at each node on the respective paths. For example, consider a job specified by $P/L/R\text{-}ab/S\text{-}cd$: The first digit P refers to priority (1 through 9), which is determined exogenous to the simulator by combining the requesting ship's assigned priority (1, 2, 3, 4) and the initial slack (due date minus arrival date minus expected operating time); the second digit L refers to the minimum skill-class worker (1 through 4) required to accomplish the job; the next group $R\text{-}ab$ refers to the preferred path

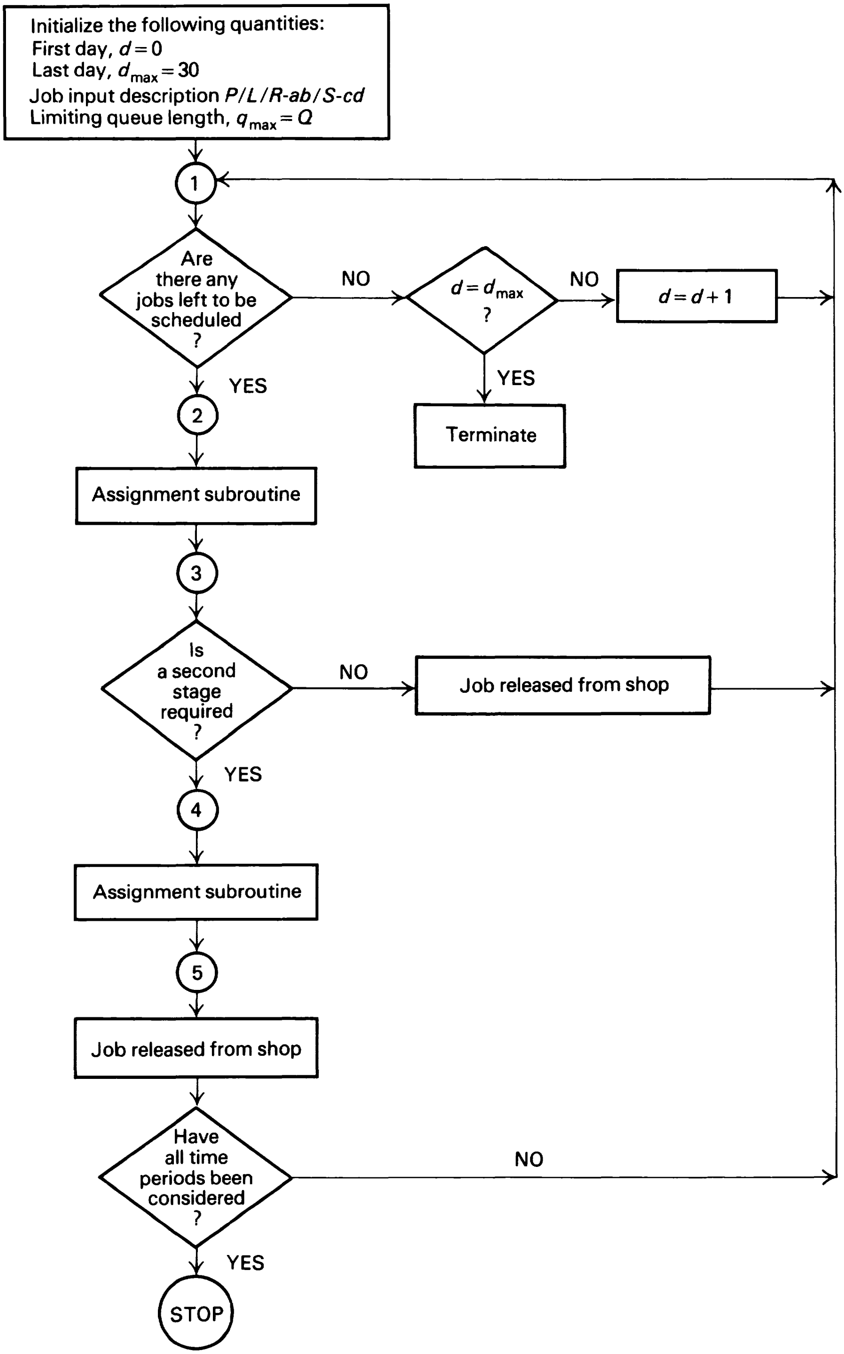

Fig. 10.1 Simulation-model flow chart for a two-stage job-shop problem.

(in this case R) and the probability distribution characterizing the duration of the two-stage production activities (i.e., we are assuming that each job is composed of at most two activities, with processing times a and b, which have to be executed one after the other); the last group S-cd refers to an acceptable alternative path (in this case S) and the operating-time distributions at each stage on the path.

A specific example that provides detailed characterization of the input data is given in Section 10.6. Figure 10.1 provides an overall representation of the simulation model for a two-stage job-shop problem. It is simple, conceptually, to expand the simulation to cover more complex job-shop situations, where jobs are allowed to have any number of activities in parallel and in series.

The assignment subroutine is described in Fig. 10.2. This subroutine assigns each individual job to a specific machine in accordance with the job specification, the machine availabilities, and the queue discipline adopted (in our example, we use FCFS = first come, first served). The flow-chart description is presented in very broad terms, explaining the major transactions that take place in the simulation, but avoiding unnecessary detailed information.

10.4 INTERACTION BETWEEN THE AGGREGATE AND DETAILED MODELS

We have indicated in the previous two sections how the resource acquisition and resource utilization decisions associated with the job-shop tender problem have been partitioned into two manageable models. We now analyze the way in which the two models are linked and the iterative nature of their interaction. Figure 10.3 illustrates this integrative scheme.

First, the aggregate model is solved, obtaining an initial recommendation for machine and manpower requirements. Then, these requirements are examined by the decision-maker to check their consistency with existing managerial policies that have not been included explicitly in the initial model formulation. New constraints or changes in the cost structure might be used to eliminate potential inconsistencies.

For example, the manpower requirements might have violated a desired pyramid-like manning organization, which can be preserved by adding the following constraints:

$$M_1 \leqq M_2, \qquad M_2 \leqq M_3, \qquad \text{and} \qquad M_3 \leqq M_4.$$

These constraints might not be included initially, to give an idea of an optimum manpower composition without these additional requirements.

In order to prevent excessive undertime, the following constraint might be used:

$$\sum_{t=1}^{T} M_{\ell t} - T(0.75)M_\ell \geqq 0,$$

on appropriate labor-class ℓ over T aggregate time periods. This constraint would require the average utilization of the workers of class ℓ to be at least 75 percent over the T time periods.

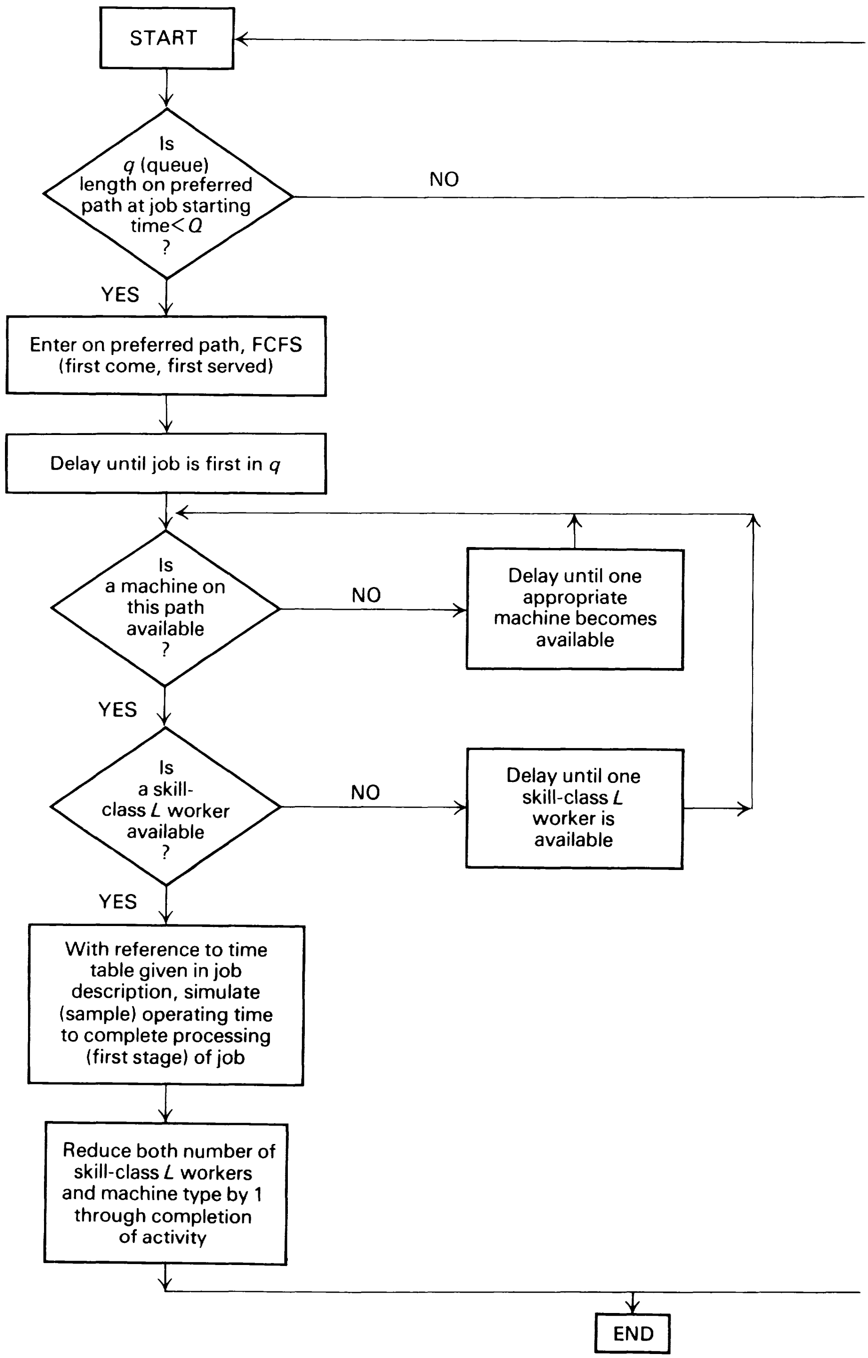

Fig. 10.2 Assignment subroutines.

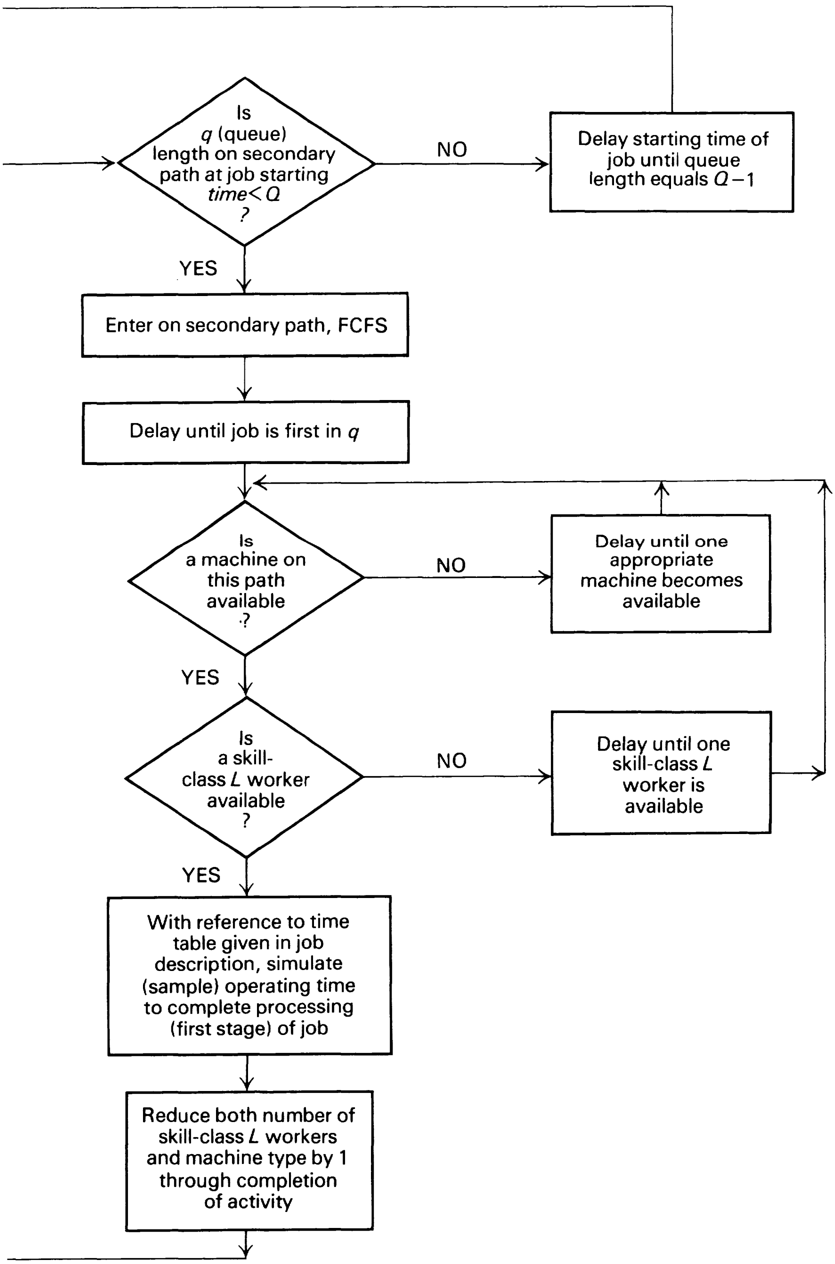

Fig. 10.2 *(contined)*

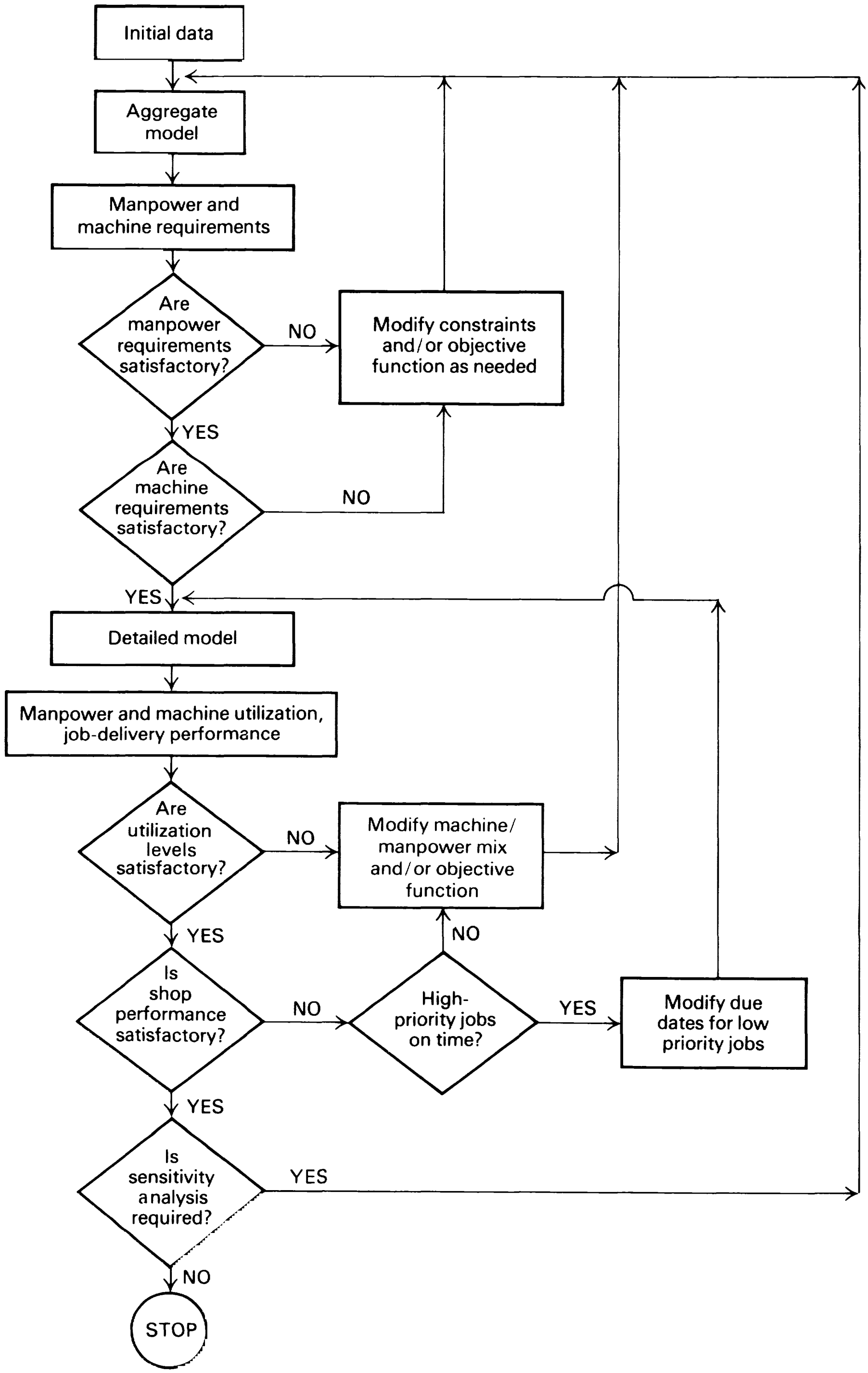

Fig. 10.3 Aggregate-detailed model interaction flow chart.

Alternatively, if the manpower utilization rate seems to be excessive at the aggregate level, leaving little or no room for absorbing demand uncertainties, the following constraint could be added for the appropriate skill class ℓ:

$$\sum_{t=1}^{T} M_{\ell t} - T(0.90)M_{\ell} \leqq 0,$$

forcing the average utilization of workers belonging to skill-class ℓ to be less than 90 percent over T time periods.

Similar types of constraints may be utilized for the machinery mix. For example, if the decision-maker desires to impose an upper bound on the ratio of numerically-controlled lathes to conventional lathes, the following constraint could be introduced:

$$N_1^* - 3N_1 \leqq 0,$$

which would require the machinery mix to provide at least three conventional lathes for each numerically-controlled lathe. Direct upper bounds also can be imposed on the number of machines to be used (for example, $N_1^* \leqq 2$), thus permitting better machine utilization

Adding new constraints to the problem will allow the decision-maker to explore the cost sensitivity to the proposed changes. In a linear-programming model, most of this information is provided directly by the shadow prices associated with the original model constraints. Our aggregate model, however, is of a mixed-integer programming type, which does not generate similar shadow-price information. This is the reason for the more elaborate sensitivity analysis.

Changes also can be performed in the cost structure of the initial model, by including hiring and firing costs (although this is not applicable in the naval-tender case), overtime penalties, backordering costs, and so forth.

Once a satisfactory combination of manpower and machinery requirements have been obtained, a simulation is conducted with these data as input parameters to the detailed model. The manpower and machine utilization levels obtained from the simulation then are examined. If these levels are not considered acceptable, new changes in the manpower and machine composition and/or in the cost structure may be indicated. These changes then will modify the aggregate model formulation, which will force a new iteration to take place. If the utilization levels are satisfactory, the shop performance (in terms of delivery dates versus due dates) can be checked. In the actual tender environment, jobs with lower priorities could be "slipped" for completion at a later time. Once both acceptable utilization and shop performance levels are obtained, a sensitivity analysis can be conducted to test how robust the performed manpower and machine configurations are to changes in the problem parameters. The results of the sensitivity analysis may indicate that some of the parameters, constraints, or demand characteristics should be modified, and the problem is run again starting with the aggregate model.

The proposed hierarchical approach provides the decision-maker with an effective tool to test the performance of the job-shop operations under a wide range of anticipated conditions, and thus permits a satisfactory solution to the tender design problem, which performs well against a wide collection of possible job characteristics.

10.5 IMPLEMENTING THE MODEL

The Experimental Environment

The naval-tender machine-shop configuration used is similar to that found on the latest generation of destroyer tenders, exemplified by USS PUGET SOUND (AD–38). A field study was conducted, in which the historical workload over several months was examined, and the month of May 1973 was chosen as typical. Several days were spent with the leading petty officers of both the light and heavy sections. Each job was analyzed in detail regarding work accomplished and problems encountered, and the following data were collected for each job: description; skill class required; machine(s) required; prescribed sequence of operations; time distributions of each node in the sequence (to determine favorable, most likely, and pessimistic estimates); setup times; job release date to shop; job due date from shop; lot-size or number of items to be manufactured; and job priority as assigned by the customer ship. These jobs (approximately 178) comprised the workload for the first month ($t = 1$). For the other five months, various perturbations about this benchmark month were permitted; changes also were made in terms of both skill-class and machine-group requirements for each month.

Once these data were determined, a field study was continued at the Naval Air Rework Facility, Quonset Point, Rhode Island. Each job from the month of May 1973 was explained in detail by a leading petty officer from USS PUGET SOUND to one or more numerically-controlled machine specialists. For those jobs (or portions of jobs) that could be accomplished readily on numerically-controlled lathes or machining centers, data was gathered similar to that specified above for the conventional machinery. We assumed that the same skill-class worker could perform the job on either conventional or numerically-controlled machinery. It was found that numerically-controlled machinery could be utilized for approximately half of the jobs (representing approximately half of the required conventional man-hours).

A description of the data input for the aggregate and detailed models is provided in Section 10.6.

Results of the Model Experimentation

Several tests were conducted with the aggregate model in order to assess the sensitivity of the results to varying conditions of demand and productivity improvements introduced by the numerically-controlled machines. Three different demand levels were analyzed, corresponding to 100, 110, and 120 percent of the May 1973 demand; and two productivity factors ($f_i = 3$ and 5) were tried. A summary of the sensitivity analysis results is provided in Fig. 10.4.

	$f_i = 3.0$						$f_i = 5.0$					
	$1.00d_{\ell it}$		$1.10d_{\ell it}$		$1.20d_{\ell it}$		$1.00d_{\ell it}$		$1.10d_{\ell it}$		$1.20d_{\ell it}$	
	Integer solution	*Overall utilization*	*Integer solution*	*Overall utilization*	*Integer solution*	*Overall utilization*	*Integer solution*	*Overall utilization*	*Integer solution*	*Overall utilization*	*Integer solution*	*Overall utilization*
N_1	6	0.81	6	0.88	7	0.80	6	0.83	8	0.70	8	0.78
N_2	4	0.65	4	0.72	2	0.83	4	0.67	4	0.72	4	0.50
N_1^*	2	0.81	2	0.89	2	0.92	1	0.93	1	0.91	1	0.97
N_2^*	0	—	0	—	1	0.59	0	—	0	—	1	0.44
M_1	3	0.93	3	0.90	3	0.92	3	0.74	3	0.75	3	0.91
M_2	3	0.58	3	0.63	2	0.52	2	0.80	3	0.61	2	0.77
M_3	4	0.95	4	0.97	4	0.91	3	0.87	4	0.77	3	0.96
M_4	8	0.86	9	0.86	10	0.84	9	0.84	9	0.90	11	0.83
Cost	\$78,838		\$81,966		\$90,416		\$68,276		\$75,972		\$83,981	

Fig. 10.4 Summary of sensitivity-analysis results with the aggregate model.

Detailed model results for the base case ($1.00d_{\ell it}$ and $f_i = 3$) are given in Fig. 10.5. These results were obtained by using the IBM Mathematical Programming System Expanded (MPSX), which provides a mixed-integer programming capability. It is interesting to note that, in the trial cases, when the productivity factors are 3.0 and 5.0, for the $1.00d_{\ell it}$ (i.e., original demand data) and $1.10d_{\ell it}$ (i.e., 10 percent increase in the original demand data) cases, the purchase of numerically-controlled machining centers was not recommended; purchase of a numerically-controlled machining center was recommended only when the demand was increased by twenty percent of the base case. Additionally, it is worth observing the results regarding numerically-controlled lathes: in the $f_i = 3.0$ case, utilization of two numerically-controlled lathes was recommended, whereas for the $f_i = 5.0$ case, only one such lathe was recommended. Upon first examination, the latter result may appear counterintuitive—if the machines were more efficient, it may be reasoned, more of them should have been introduced. Alternatively, however, since the machines were more efficient ($f_i = 5.0$ versus $f_i = 3.0$), and since the fractions of the total work that could be performed on them was constrained, only one numerically-controlled lathe was required to accomplish its share of the workload.

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	*Integer solution*	*Overall utilization*
N_1	4.464	6.00	4.571	4.850	4.164	5.164	6	0.811
N_2	2.457	2.750	2.471	2.371	2.578	3.064	4	0.654
N_1^*	1.843	1.048	1.526	1.617	1.886	1.828	2	0.812
N_2^*	0	0	0	0	0	0	0	—
	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	*Integer solution*	*Overall utilization*
M_1	3.00	2.625	3.00	2.083	3.00	3.00	3	0.928
M_2	1.439	1.542	1.458	2.008	1.480	2.432	3	0.575
M_3	4.00	4.00	4.00	3.450	4.00	3.402	4	0.952
M_4	5.795	7.119	6.309	7.071	6.812	7.997	8	0.856
Total cost = \$78,838								

Fig. 10.5 Aggregate-model results for the case $1.00d_{\ell it}$ and $f_i = 3.0$.

With respect to the manpower/machinery costs shown in the aggregate-model results, direct comparison was possible between $1.00d_{\ell it}$ ($f_i = 3.0$ and $f_i = 5.0$) cases and a $1.00d_{\ell it}$ ($f_i = 0$, i.e., numerically-controlled machinery not introduced) case. When $f_i = 0$, the required manpower can be obtained by dividing the total conventional workload for skill-class ℓ by the available number of hours $h_{\ell t}$ for the appropriate skill class; since no numerically-controlled machines are introduced, there is no acquisition cost, and therefore no penalty cost was incurred for removing existing machinery. Then, the required manpower would be 3 of skill-class 1, 3 of skill-class 2, 7 of skill-class 3, and 9 of skill-class 4, for a total cost of $80,675. Comparing this cost figure with the two earlier cited cases shows that, in the aggregate, the incorporation of numerically-controlled machine technology can indeed result in manpower reductions and a lower total cost. Using the manpower and machinery configuration recommended by the aggregate model, the detailed simulation tested what would actually occur on an hour-by-hour basis. The output of the detailed simulation reflects the performance of the configuration recommended by the aggregate model—measures of effectiveness presented here include the number of jobs completed, mean flow times of completed jobs, and manpower and machinery utilization. The first simulation was based on the manpower/machinery configuration determined by the aggregate model with $1.10d_{lit}$ and $f_i = 3$: 6 conventional lathes, 4 conventional milling machines, 2 numerically-controlled lathes, 0 numerically-controlled machining centers, the existing configuration of "other lights and heavies," 3 workers of skill-class 1, 3 workers of skill-class 2, 4 workers of skill-class 3, and 9 workers of skill-class 4.

The simulation run with the above configuration showed that 34 jobs (of 178 total jobs) were not completed; the average elapsed time to perform a job (including delays) was 25 hours and 55 minutes, and the average delay for a job was 9 hours and 38 minutes. The utilization data for the various manpower levels indicated that the eighth and ninth members of skill-class 4 were needed only 11.2 percent of the time; however, all four of the skill-class 3 workers were needed 88.4 percent of the time. The other manpower and machinery utilization appeared to be satisfactory.

A second simulation, with skill-class 3 augmented by one worker and skill-class 4 reduced by two workers (all other manpower and machinery pools unchanged) was carried out. For this case, 20 jobs were not performed; although the average elapsed time per job (including delays) increased slightly to 27 hours and 41 minutes, the average delay time for a job was reduced to 8 hours and 36 minutes, indicating that more jobs that required increased machining time were actually completed. The manpower utilization data shifted in such a way that all 7 members of skill-class 4 were needed 20 percent of the time, while all 5 members of skill-class 3 were needed 67.1 percent of the time.

Finally, a run was made with 6 skill-class 3 workers (the other resources unchanged). Marked improvement in the machine shop performance resulted: only 4 jobs were not completed; the average elapsed time (including delays) was relatively unchanged at 27 hours and 50 minutes, while the average delay was reduced significantly to 6 hours and 42 minutes. The utilization data for machines and manpower groups of interest are presented, for this last simulation, in Fig. 10.6. Utilization data for manpower skill-class 1 is not presented because this skill-class was assigned only 2 jobs; although 3 members of this skill-class were indicated (since $h_{lt} = 10$ hour/week), only 1 member (at 35 hours/week availability) was utilized in the simulation. Additionally, data for conventional milling machines is not reported: The aggregate model

Conventional lathes

Number	%
0	0
1	0
2	2.6
3	7.3
4	10.4
5	16.8
6	62.9

Numerically-controlled lathe

Number	%
0	0
1	61.2
2	38.8

Skill-class 2 manpower

Number	%
0	0
1	1.8
2	20.2
3	78.0

Skill-class 3 manpower

Number	%
0	0
1	0
2	4.5
3	17.2
4	19.7
5	12.9
6	45.8

Skill-class 4 manpower

Number	%
0	1.4
1	18.3
2	11.5
3	19.0
4	17.1
5	10.3
6	1.6
7	20.6

Fig. 10.6 Utilization data for selected machinery types and manpower skill classes, as determined by the detailed model.

indicated that 5 milling machines were required (since they did not need to be removed), while the maximum simultaneous usage for these machines in the simulation was 3. The six conventional lathes recommended were utilized simultaneously in the detailed simulation 62.9 percent of the time, whereas the aggregate model indicated 4.464 were needed in the first time period. The higher utilization in the simulation reflected the congestion that occurred in the machine shop, which the aggregate model was designed to ignore. This last run seemed to offer a satisfactory solution.

The manpower and machinery configurations suggested by the model are as follows:

a) Remove two conventional lathes, and replace them with two numerically-controlled lathes;

b) Do not replace any of the existing conventional milling machines with numerically-controlled machining centers; and

c) Assign three machinery repairmen first class, three machinery repairmen second class, six machinery repairmen third class, and seven machinery repairmen "strikers" (a skill-class 4 worker in the model formulation).

10.6 DESCRIPTION OF THE DATA

This section is essentially an appendix describing the data used for implementing the model.

Data Input for Aggregate Model

1. $d_{\ell it}$ = Demand in conventional hours, representing workload in May 1973 ($t = 1$):

	Machine i				
Skill-class ℓ	*1*	*2*	*3*	*4*	*Total*
1	0	0	0	70	70
2	53	116	4	35	208
3	523	118	7	98	746
4	673	110	50	173	1006
Total	1249	344	61	376	2030

Small perturbations on these data generated demand for time period $t = 2, 3, 4, 5$, and 6.

Source: Fieldwork on board of USS PUGET SOUND (AD-38)

2. $C = \sum_{t=1}^{6} C_{\ell t}$: Composite standard military pay rate (salary and benefits) for worker in skill-class ℓ, for a six-month period:

$$C_1 = \$5060, \qquad C_2 = \$4130, \qquad C_3 = \$3566, \qquad C_4 = \$3127.$$

Source: Navy Composite Standard Military Rate Table

3. C_i^* = Discounted acquisition, installation, and incremental operation, maintenance and overhead costs for numerically-controlled machine i, attributable to a six-month period:

$$C_1^* = \$5994 \qquad \text{(NC lathe)}$$

$$C_2^* = \$9450 \qquad \text{(NC machining center).}$$

Source: Naval Ship Research and Development Center, Carderock, Md.

Assumption: Incremental expense of \$1000 per machine. Economic life of 4 years, with salvage value assumed to be one-half of initial acquisition cost. Discount rate of 10 percent.

4. f_i = Factor that reflects the increase in productivity for numerically-controlled machine i with respect to corresponding conventional machine.

In the first set of runs $f_1 = f_2 = 3$. A second set of runs was conducted with $f_1 = f_2 = 5$. These values represent reasonable expected performance.

The remaining factors f_3 and f_4 have been set at $f_3 = f_4 = 0$, since machine groups 3 and 4 are not candidates for numerically-controlled replacement.

5. $h_{it}, h_{it}^* =$ Number of hours during month t a machine must be available for the accomplishment of productive work. Set at:

$$\left(4\frac{\text{week}}{\text{month}}\right) \times \left(35\frac{\text{hours}}{\text{week}}\right) = 140\frac{\text{hours}}{\text{month}} \qquad \text{for all groups.}$$

6. $k_i =$ Proportionality constant relating the minimum fraction of work that must be accomplished on conventional machinery:

$$k_1 = 0.5, \qquad k_2 = 0.5, \qquad k_3 = 1.0, \qquad k_4 = 1.0.$$

7. $b_i =$ Original number of conventional machines aboard of USS PUGET SOUND:

$$b_1 = 9, \qquad b_2 = 5, \qquad b_3 = 12, \qquad b_4 = 15.$$

8. $a_i, a_i^* =$ Deck area required for conventional and numerically-controlled machines, respectively:

$$\begin{aligned} a_1 &= 96 \text{ sq ft}, & a_2 &= 225 \text{ sq ft},\\ a_1^* &= 105 \text{ sq ft}, & a_2^* &= 225 \text{ sq ft}. \end{aligned}$$

Since there is no substitution allowed for machine groups 3 and 4, a_3, a_4, a_3^* and a_4^* were set to zero.

The factor k', used to introduce more (or less) free deck space, was set at unity.

Source: Naval Ship Research and Development Center, Carderock, Md.

9. $h_{\ell t} = h_{\ell t}^* =$ Number of man-hours that a worker of skill-class ℓ must be available for productive work. Set at the following values:

$$\begin{aligned} h_{1t} &= \left(10\frac{\text{hours}}{\text{week}}\right) \times \left(4\frac{\text{weeks}}{\text{month}}\right) = 40\frac{\text{hours}}{\text{month}},\\ h_{2t} &= \left(30\frac{\text{hours}}{\text{week}}\right) \times \left(4\frac{\text{weeks}}{\text{month}}\right) = 120\frac{\text{hours}}{\text{month}},\\ h_{3t} = h_{4t} &= \left(35\frac{\text{hours}}{\text{week}}\right) \times \left(4\frac{\text{weeks}}{\text{month}}\right) = 140\frac{\text{hours}}{\text{month}}. \end{aligned}$$

Assumption: The figures of allowable productive hours worked per week by the first- and second-class petty officers ($\ell = 1$, $\ell = 2$) were chosen arbitrarily to permit their participation in various shop administration, supervision, and training functions. Since the basic shop work-week for planning purposes is 35 hours, this figure was chosen for the lower rated personnel.

Data Input for Detailed Model

1. Partial listing of jobs input to the detailed model:

Arrival date	*Priority*	*Labor class*	*Preferred path*	*Timetables*		*Alternative path*	*Timetables*	
				1	*2*		*1*	*2*
0	4	4	C	F	A	K	H	H
	5	3	B	L	H			
	5	3	B	L	H			
	5	3	B	L	H			
	9	4	D	A	—	A	H	—
	3	3	B	F	G			
	4	4	A	K	—			
	4	2	A	G	—			
	7	2	C	A	C	B	G	E
	8	4	A	I	—			
	4	4	D	G	—	A	M	—
	2	4	D	A	—	B	G	B
	4	4	T	H	B			
	2	3	D	C	—	A	A	—
	4	4	A	G	—			
	4	4	N	E	—			
	5	3	A	J	—			
	4	4	A	B	—			
1	3	4	A	C	—			
	6	3	H	J	C			
	5	4	A	D	—			
	5	4	A	C	—			
	1	4	X	K	—			
	1	4	A	E	—			
	8	2	M	D	I			
	5	4	Y	F	—	U	A	S
	7	4	A	G	—			
2	9	4	A	D	—			
	6	3	I	A	E	H	D	E
	5	2	B	K	K			
	1	3	A	G	—			
	7	4	A	K	—			
3	9	3	E	F	A	B	M	I
	9	4	C	A	A	B	E	B
	9	3	Y	H	—	B	P	E
	9	3	D	F	—	A	F	—
	4	3	D	A	—	A	D	—
	9	4	F	B	C	B	N	C
	7	2	C	A	C	B	G	E
	7	2	B	A	M			

Note. The complete listing included 30 days. Descriptions of machine paths and timetables used are given in the following pages.

2. Paths in simulation network:

Path	*Node 1*	*Node 2*	*Node 3*	*Node 4*
A	QA1	Conv. Lathe		
B	QB1	Conv. Lathe	QB2	Conv. Mill
C	QC1	NC Mill	QC2	NC Lathe
D	QD1	NC Lathe		
E	QE1	NC Lathe	QE2	NC Mill
F	QF1	NC Lathe	QF2	Conv. Mill
G	QG1	Vertical Mill		
H	QH1	Conv. Lathe	QH2	Cleerman Drill
I	QI1	NC Lathe	QI2	Cleerman Drill
J	QJ1	Band Saw	QJ2	Conv. Lathe
K	QK1	Cleerman Drill	QK2	Conv. Lathe
L	QL1	Gap Lathe	QL2	Conv. Mill
M	QM1	Monarch Lathe	QM2	Conv. Mill
N	QN1	Horiz. Bar Mill		
P	QP1	Band Saw		
Q	QQ1	Horiz. Tur. Lathe		
R	QR1	Radial Drill		
T	QT1	Conv. Mill	QT2	Cleerman Drill
U	QU1	Conv. Lathe	QU2	Wells Index
V	QV1	Vert. Tur. Lathe		
W	QW1	Conv. Mill	QW2	Vertical Mill
X	QX1	Drill Press		
Y	QY1	NC Mill		
Z	QZ1	Bullard		

3. Processing timetables utilized in detailed model:

Table	*Cum. prob.*	*Time*	*Cum. prob.*	*Time*	*Cum. prob.*	*Time*	*Cum. prob.*	*Time*	*Cum. prob.*	*Time*
A	0.0	0.25	0.25	0.33	0.5	0.5	0.75	0.75	1.0	1.0
B	0.0	0.5	0.25	0.6	0.5	1.0	0.75	1.3	1.0	1.5
C	0.0	1.5	0.25	1.6	0.5	2.0	0.75	2.3	1.0	2.5
D	0.0	2.5	0.25	2.6	0.5	3.0	0.75	3.3	1.0	3.5
E	0.0	3.5	0.25	3.6	0.5	4.0	0.75	4.3	1.0	4.5
F	0.0	4.5	0.25	4.6	0.5	5.0	0.75	5.3	1.0	5.5
G	0.0	5.0	0.25	5.4	0.5	7.0	0.75	8.6	1.0	9.0
H	0.0	6.0	0.25	6.4	0.5	8.0	0.75	9.6	1.0	10.0
I	0.0	7.5	0.25	8.0	0.5	10.0	0.75	12.5	1.0	13.0
J	0.0	9.0	0.25	9.5	0.5	12.0	0.75	15.0	1.0	15.5
K	0.0	11.0	0.25	11.5	0.5	14.0	0.75	17.0	1.0	17.5
L	0.0	13.0	0.25	13.5	0.5	16.0	0.75	19.0	1.0	20.0

Table	Cum. prob.	Time	Cum. prob.	Time	Cum. prob.	Time	Cum. prob.	Time	Cum. prob.	Time
M	0.0	18.0	0.25	14.0	0.5	21.0	0.75	23.0	1.0	25.0
N	0.0	23.0	0.25	23.7	0.5	25.0	0.75	26.5	1.0	27.0
P	0.0	26.0	0.25	26.7	0.5	28.0	0.75	30.0	1.0	31.0
Q	0.0	28.2	0.25	28.7	0.5	30.0	0.75	33.5	1.0	35.0
R	0.0	30.0	0.25	31.5	0.5	35.0	0.75	40.0	1.0	42.0
S	0.0	35.0	0.25	36.0	0.5	40.0	0.75	45.0	1.0	49.0
T	0.0	55.0	0.25	56.0	0.5	60.0	0.75	64.0	1.0	65.0

EXERCISES

Problem Description

1. Try to structure the overall nature of the naval-tender job-shop design problem. What is the relevant planning horizon for the manpower and machine configuration decisions? What are the appropriate decision variables, parameters, constraints, and objective function? Are the uncertainties of the problem very significant? Can the problem be formulated as a single model? What are the difficulties in approaching the problem via a single model? What is the essence of the proposed hierarchical approach? What are the advantages and disadvantages of the hierarchical approach versus a single-model approach?

The Aggregate Model

2. Discuss the stages of model formulation with respect to the aggregate model. In particular, interpret the objective function and constraints given by expressions (1) to (15). How many decision variables and constraints are there? How many of those decision variables are required to assume only integer values? Discuss the interpretation of the shadow prices associated with every constraint type. What important elements of the problem have been left out of this model formulation? Why?

The Detailed Model

3. Contrast the characteristics of optimization models and simulation models. Why has a simulation model been suggested as the detailed model of the naval-tender job-shop design problem? Would it have been possible to formulate the detailed model as an optimization model? Review and discuss the model description provided in the test. How would you change the flow chart of Figs. 10.1 and 10.2 if every job consisted of several activities in series and/or in parallel? What measures of performance do you propose to use to evaluate the job-shop efficiency? What alternative can be evaluated by means of the simulation model? How are these alternatives generated?

Interaction between the Aggregate and Detailed Models

4. Discuss the nature of the proposed interaction between the aggregate and detailed models represented in Fig. 10.3. What outputs of the aggregate model become inputs to the detailed model? How does the detailed model modify the aggregate-model recommendations? What mechanisms would you propose to enhance the interaction of the models?

Implementation of the Models

5. Discuss the implementation approach and the results of the model experimentation. Analyze the summaries provided in Figs. 10.4 and 10.5. What kind of experimental design would you have suggested? What conclusions can you draw from the existing results?

ACKNOWLEDGMENTS

The material in this chapter is based on the paper by Robert J. Armstrong and Arnoldo C. Hax, "A Hierarchical Approach for a Naval Tender Job-Shop Design," M.I.T. Operations Research Center, *Technical Report No. 101*, August 1974.