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ABSTRACT

The feasibility of using a particular simulation as (1) an aid in management, (2) a management training device, (3) a tool for management research is reported. Corresponding interfaces for the simulation are described and discussed in terms of the way they represent the activity for the user. Estimated costs are reported for alternative implementations of the simulation through the use of several costing categories. (Author)

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SIMULATION OF RESEARCH AND DEVELOPMENT ACTIVITY: A FEASIBILITY STUDY

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Simulation of Research and Development Activity: A Feasibility Study

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This paper examines the feasibility of four possible applications of a mathematical model originally designed to study manpower utilization and task scheduling in an advanced academic program operating concurrently with a related service program in a university setting. The academic program recruits students with various academic backgrounds and work experience in order to encourage an interdisciplinary point of view. The academic training is designed to give equal emphasis to research, engineering and quality control so that each student develops skills in all three areas. The related service program provides internship experience for students who work part-time giving professional service commensurate with their current state of academic training. The intership offers to the student the opportunity to apply principles learned in the academic program and at the same time serves as a vehicle for conducting theory-based research related to the professional practice. An example is the advanced academic program in engineering wherein students serve part-time internships in an outside engineering organization. The program has been described here in general terms in order to emphasize the relevance

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of the model to other situations.

The model applies to a situation wherein a moderate number of people are engaged in a moderate number of projects. Each project is composed of tasks which are relatively large in number when accumulated across projects. Tasks require numerous special skills. People's skills vary from person to person so that there are few relevant skills which are possessed by all people and few people possess all relevant skills. The relatively small number of people available makes necessary sequencing work on tasks so that people work first on some tasks and then on others until all tasks currently planned are completed.

The simulation model incorporates features of job-shop scheduling models and task assignment models reported in management science literature by Pritsker, et al. (1969), Davis in Heidorn (1971) Schrage (1972) and Charmes et al. (1969). Since formulations and algorithms are reported in detail by these authors, details will not be repeated here. However, relevant properties of the formulations will be described. The model described in this paper incorporates some features from each one cited in order to better account for the complexities of the situations to be represented.

Job-Shop Scheduling Models

The job-shop scheduling problem concerns scheduling resources to accomplish tasks so that a given objective function is maximized subject to stipulated constraints on tasks and resources. The job-shop scheduling models are important to the formulation of the model reported in this paper because they provide a representation for the people (resources), tasks and projects found in the situation to be simulated.

Authors formulate the problem in different ways by making use of different possible objective functions and different ways of representing tasks, resources and their interrelationships. Some major features of the various formulations are (1) resource classes, (2) (time-variant) resource constraints, (3) resource substitutability, (4) job splitting, (5) job constraints and (6) relations defined on the set of jobs.

Resource classes provide a means of segregating different kinds of resources according to their various characteristics. For example in a particular instance people could be segregated into three classes corresponding to professionals, students and skilled workers. In another instance, people could be classified into three classes corresponding to supervisors, operators, and maintenance technicians. Using the resource class feature in a representation makes it possible to ignore individuality of resources within each class. The representation is more efficient as a result. The feature is also convenient for representing customary class dinstinctions such as those used in the example above. The notion of resource classes is general since ordinary alternatives (where individual resources are accounted for and where all individual resources are identical) can be realized as extreme cases (where there is exactly one individual resource per resource class and the case where there is only one resource class).

Resource constraints represent the relative scarcity of resources in the situation being simulated. Constraints generally take the form of a specified number of resource classes and specified numbers of resource classes and specified number or resources in each class. In some situations sacrcity of resources varies with time. This can be represented, once the basis for representing time has been determined, by specifying the resource constraints for each time period. In a given model, numbers of different resources available during a specific time period can be made to depend on conditions occurring during the previous period.

Resource substitutability in a model makes it possible to replace one individual resource with another in a specific task assignment, in a type of task assignments or in any task assignment depending on the definition. Consequently, resource substitutability provides an alternative to classifying resources insofar as assignment to tasks is concerned. That is, resources that can be substituted for one another constitute a class of equivalent resources for the purpose of substitution.

Job splitting is a feature used in models to represent jobs which can be repeatedly discontinued and then taken up at a later time without much prior preparation. Although most jobs usually require some advance preparation to resume, job splitting does serve a specific purpose for some jobs besides providing an example of a more general notion of job classification.

Job constraints pertain to such job-related information as the resource requirements and time constraints for jobs. Appropriate aasignment of people to tasks depends on having knowledge not only about the people but also about the tasks. For example, resources cannot be assigned to perform task X until it is known that task X requires a plumber and a wrench, and until it is known that resources A and B are a plumber and a wrench, respectively.

Other job constraints relate to the time frame determined for the job by contextual aspects not represented in the model. When resources not represented in the model are needed to perform a task, then the scheduled use of that resource must be specified as a time constraint for the task. For example, if the task constitutes administering a test at a particular school, the scheduled administration of the test must be entered in the model at some time prior to the simulation of the test administration.

Relations defined on the set of jobs provide a means of representing task precedence and equivalency. For example, the most common use of a relation on tasks specifies a PERT chart for the tasks telling what jobs must be performed before work on a given job can begin. Other relations tell whether two given jobs can be performed concurrently, what jobs must be performed immediately before a given job, and what job or jobs can be performed in place of a given job.

Authors report various formulations of the job-shop scheduling problem. Among those cited in this paper Pritsker et al. (1969) give the model which is most generally applicable. Their formulation incorporates time-variant multiple resource constraints, due dates, job splitting, resource substitutability, and concurrence and nonconcurrence of job performance. Incorporating a zero-one linear programming approach to the job-shop scheduling problem, their formulation is claimed to be more efficient because it uses fewer variables and fewer constraints than those reported by earlier authors.

Davis and Heidorn (1971) report a formulation similar to that of Pritsker et al. except that two task precedence relations are included. The first relation is the usual one defined as "must precede." It is used to indicate that job X must be performed before job Y is begun. The second relation is defined as "must immediately precede" and is introduced because each job is assumed to be a series of unit-duration tasks performed one immediately after another until all of the tasks making up the job are completed. (The second precedence relation can be justified on another basis besides being necessary because of job splitting. Jobs must be performed in immediate sequence whenever high setup costs, decay or other deleterious effect due to the passage of time must be avoided.)

Schrage (1972) reports a simpler formulation of the job-shops scheduling problem than those just cited. The formulation is based on a specified set of activities for each of which an activity time is specified telling how much time the assigned resource must spend in order to complete the activity. Activities are related to one another by specifying a set of predecessor activities and a set of successor activities for each one. Of a given set of resources, exactly one is required by each activity. That is, the formulation does not include the multiple-resource feature found in others cited in this paper. Schrage's formulation also lacks the job-splitting feature.

The job-shop models cited here are primarily useful for representing the mechanics of work flow in the job-shop situation. However, formulations of the job-shop scheduling problem cited in this paper oversimplify the assignment of resources to tasks. The inadequacy of the models is particularly apparent when people are the resources being represented. Traits and skills considered when tasks are assigned to people cannot be adequately represented in terms of a few resource classes. Shrage's model entirely avoids the problem of assignment by assuming that resources are assigned to tasks *a priori*. Other models assume exact equivalence of resources in any given class. Accordingly, assignment models will be considered since they represent aspects of the job-shop situation not adequately handled by job-shop scheduling models.

Assignment Models

The assignment problem is concerned with matching up resources and jobs so that some measure of total value is maximized. For example, given a project analyzed into smaller tasks, how can work most economically be assigned to individuals in a given group of people when training, skills and wages are taken into account? Charnes et al. (1969) report several mathematical formulations of the assignment problem which address problems of this type. A basic formulation is given for assignment of a number of people to the same number of tasks. Several different value functions are discussed for this basic model. Then, variations of the basic formulation are presented which take into account effects of training, experience, job preparation and development. While the authors suggest that the models should be applied to assignment of people to employment positions, the generality of the formulations makes them readily applicable on a different level to situations where people are assigned to detailed tasks. The extended models accounting for effects of training would be particularly useful where the job-shop situation is an internship program.

While assignment models fill a gap left by job-shop scheduling models, assignment models do not function in place of scheduling models. Assignment models cited above include representations of jobs and attributes of resources required for their performance. However, no feature of the assignment models represents the dependencies among jobs. Neither are job constraints taken into account in formulating the assignment models. These models principally focus on making good, one-time assignments of resources to jobs, sometimes taking into account results of similar one-time assignments made previously. Consequently, assignment models and job-shop scheduling models complement each other in representing the complexities of the job-shop situation.

Simulation Model

Features of the job-shop scheduling models and the assignment models are brought together here to form the mathematical foundation for a computer-based simulation of broad potential applicability. The simulation consists of interaction between one or more participants and a computer algorithm. Participants may operate in a real-life situation depending on the particular application. The simulation activity can be described in terms of an algorithm which defines the sequence of events concerning the participants and the computer program.

The first step in the algorithm (and the branch point for continuation) requires the participants to gather information from the external context. This step constitutes the contact between the participants and the training problem or the situation being managed, modeled or controlled. Repetitions of this step furnish new information about the real or pretended circumstances being represented.

Next the participants make decisions which structure and possibly change their perception of the external circumstances and determine specific information to be coded for input to the computer. Any number of participants can play a part in the simulation so long as there is a minimum of one to keep it going. Participants interact according to the way responsibility for tasks, projects, etc., is determined by the group or by outside organizers. Participants interact on a decision-making level. They take individual and group actions including (1) preparing and revising individual schedules of participants, (2) (re-) organizing tasks and projects, (3) choosing objective functions used in the computer algorithm, (4) assigning tasks and projects to other participants, and (5) simulating performance or non-performance of tasks. The last item may require assessing actual performance of tasks.

As decisions are made during and after group interaction, participants formalize their choices through the use of a work booklet or similar device. This medium insures that there is sufficient information to support the input requirements of the computer program. The booklet structures participation by specifying the elements of the simulation game and identifying actions that can be taken. Once completed, these booklets are readily converted to punched cards or entered on the appropriate computer file via a video or teletype terminal.

The simulation continues by executing the computer algorithm. Default options are applied to insure successful execution. The algorithm solves the network problem involved in scheduling tasks subject to the time-varient resource constraints represented by participants' schedules. Task assignments are accomplished through the assignment model incorporated into the simulation algorithm. All this is done for a pre-specified period of simulated time. Finally, reports are generated to include (1) an activity schedule for each person reflecting the combined results of individual and group decisions for the simulated period; (2) reports of tasks and projects showing work accomplished during the period, and showing impending work for the next period; (3) a one-time complete task network; (4) summary schedules of participants future activities, and (5) reference tables including a dictionary of labels corresponding to alphanumeric codes used in other reports.

Once reports are generated, participants are ready to assess performance during the period just simulated and to begin a new cycle in the simulation activity. Participants are able to review their previous activities based on individual schedules produced by the computer. Each participant is able to assess the effects of actions taken by other participants by referring to his individual schedule. Progress on tasks and projects can be assessed by referring to the report on tasks and projects. Based on this information each participant can formulate a plan of action to realize completion of projects he has planned. At this point the simulation cycle is begun again with group interaction or else it can be terminated.

Applications

The simulation described above has potential application in four problem areas (1) management research, (2) management systems, (3) management systems design and (4) management training. Each problem area will be defined or illustrated with an example and the feasibility of employing the simulation described above as a solution will be discussed.

Before discussing specific cases a few simple observations pertaining to costs and benefits are in order. Dollar costs can be divided roughly into two categories, development costs and operating costs. Development costs accrue as a result of developing the materials and programs for the simulation whereas operating costs result from use of the simulation. The simulation would have to be used for a sufficiently long period in order to realize a return that would justify development costs. Dollar benefits can result from reducing present costs or from increasing present income, for example, by cutting costs due to lateness penalty and by realizing a profit from sale of printed material to users, respectively. Costs and benefits not measureable directly in dollars can also result. The problem in assessing feasibility of any implementation is to weight the anticipated costs and benefits over the intended period of implementation.

<u>Management Research Application</u>

While on the surface it may seem circular (since the simulation is based on job-shop scheduling and assignment models from management science), implementation of the simulation as a mathematical model in management science has genuine substance. Although some models provide for time-dependent multiple resource constraints, the effects of various patterns of resource availability on job-shop production have not been investigated. Several other classes of questions are suggested by merging a job-shop scheduling model and an assignment model under suitable assumptions about abilities, potentials and on-the-job training. Knowledge about management research models would be extended by investigating these new suggested formulations.

Development of the simulations described above solely for the purposes of management research must be justified on the basis of its merits as a research tool. Although the simulation does suggest questions to be investigated and can serve to clarify situations which it is used to represent, it is difficult to demonstrate how the simulation used as a research tool would result directly in dollar benefits. Operating costs of the simulation used as a research tool are more easily justified than are development costs and operating costs together. Therefore, the most feasible way of implementing the simulation as a tool for research seems to be to do it concurrently with another application.

Management System Application

Using the project reports and resource schedules to effect management control, the simulation could be used as a management system in the job-shop situation. Project reports indicating the status of current tasks on each project would keep management and supervisors abreast of current status on projects. Schedules indicating work assignments could be used to establish work priorities and control progress toward desired objectives. Information about tasks accomplished at the end of each reporting period could be fed into the program immediately before generating the next series of reports and schedules. A special interface for the computer program may be necessary in order to satisfy requirements of a specific application. However, since the simulation is sufficiently general to accommodate a wide variety of projects and resources, tailoring would be relatively minor.

Reiter (1966) reports the results of a specially designed management system suitable for use in a large job-shop situation manufacturing gears for machinery. He indicates that the job-shop has two important services in addition to a product or service produced according to a given set of specifications. These are reliability and fast delivery, both valuable commodities to the customer. Delivery of the customer's order by a stipulated early data depends on efficient allocation of resources to jobs. As the number and variety of tasks in the job-shop increases, operations in different parts of the shop become more interdependent. To maintain an acceptable level of efficiency, management must increase coordination of shop operations as size and complexity increase. Reiter points out that there is a threshold beyond which management cannot deal with size and complexity by using ordinary methods. By using a management system similar in principle to the simulation reported here, he reports that the manufacturing firm where the system was implemented was able to shift attention from problems of managing the shop to problems of procurement and pre-shop paper work.

Feasibility of the simulation as a managment system depends on the size of operation to be simulated, on the frequency of use and on the length of time the simulation is to be used. Within this context, development and operation costs must be justified in terms of value returned either as dollar profit of other value. Reiter's implementation on the IBM 1440 with two IBM 1311 disk drives required from 14 to 18 hours (assumedly, run time) to generate one complete shop schedule for 15,000 tasks. In Reiter's application the cost of developing the program probably was equivalent to the cost of generating a relatively small number of shop schedules in view of the relatively long run time. Thus, in the large job-shop feasibility depends mainly on increased net profits covering cost of operating the management system since development costs can be recovered relatively quickly.

In the smaller shop where development costs are much greater in relation to operating costs, feasibility depends not only on being able to cover operating costs but also on operating for a longer time to cover costs of development. Keeping operating cos down is more vital to feasibility in the smaller shop. Economy of scale not enjoyed by the smaller shop could make Reiter's managment system an unnecessary luxury.

However, use of Reiter's management system in the smaller shop should not be ruled out on the basis of its performance in generating a shop schedule for 15,000 tasks. Run time for large programs such as these is often a quadratic function of the number of data points. Since such a function is dominated by its linear term for small values, it is possible that Reiter's system could generate one shop schedule for 1000 tasks in as little time as 5 minutes. For, if we assume that the linear term is neglegible, then operating time can be computed by substituting 16 hours for $\underline{t}$ and 15,000 for $\underline{n}$ in the equation $\underline{t = a n^2}$. This gives the equation $\underline{t = 4.26n^2}$ where $\underline{t}$ is run time in minutes and $\underline{n}$ is number of tasks in thousands.

In a situation where there are 1000 tasks instead of 15000 as in Reiter's case, the minimum estimated run-time would be about five minutes. This would cost on the order of twenty five dollars at this author's in-situation, a cost that could be covered on a regular basis in a small job-shop situation where operations were sufficiently complex to warrant using the simulation as a management system.

Management Systems Design Application

The simulation finds application in the job-shop situation where need for a management system exists yet where the operation is not large enough to warrant using the simulation to satisfy the need. Complexity of the operation can make management difficult yet size of the operation may not be sufficiently large to warrant using a computer-based management system like Reiter's or like the simulation described here. In this case the simulation can find limited application by helping to discover simpler management techniques. Applied as a mathematical model or as a management game, the simulation provides a logical testing ground for policies and simpler control devices potentially useful to management in a real setting. This application resembles the training application described below insofar as it helps the users learn about the real situation simulated. However, it differs because in the present case the learners are people who have direct responsibility for an actual job-shop situation whereas students in general do not have responsibility for or access to such a real situation.

In the systems design application, the simulation is employed as a tool to test various rules formulated for the specific situation in terms of job classifications skills requirements, estimated job completion time, resource skills, resource usages rates, etc. Sets of rules would be tested one against another to determine which one yielded the best results in terms of a stipulated criterion. A best set of rules would become operational policy for the shop.

Costs for this application would have to be balanced against benefits of improved shop management. Since use of the simulation as a management system design tool is necessarily short-term, the user will probably not be interested in paying development costs. However, improved management resulting from testing a variety of possible shop policies can justify costs of running one-time simulations.

Training Application

Skills learned in a training application of the job-shop scheduling model must necessarily be those skills associated with managing part or all of a job-shop situation. In the absence of an automated management system similar to the one reported by Reiter (1966), the individual people responsible for the operation must shoulder the management task.

Professional service operations can be viewed from the standpoint of a job-shop scheduling model. One or more individuals perform a wide variety of specific tasks. Often the tasks are numerous so that constraints on human resources predominate in determining limitations on production. In some operations tasks are aggregated into projects contracted by clients. In such systems short-term management problems consist of deciding what tasks to perform next and assigning work in such a way that skills and resources are used efficiently.

Training programs in professional service must aid students to integrate isolated skills into a marketable professional practice. The simulation described above provides such a device when it is applied as a training simulation. Students participating become the resources. Services demanded by clients constitute the projects and tasks. Since students do not actually perform the tasks, the experience of managing his own activities in the context of a professional service organization is compressed in time. Consequently, management training can be conducted in a short period of time or in segments ne distributed over a longer interval.

Feasibility of the training application depends on the validity of the training as well as on dollar values discussed for the foregoing applications. If the simulation can economically replace an equally valid alternative training program or device and if the savings will offset development costs within a reasonable period, then the simulation could reasonable be developed. This rules out the possibility of short-term or low-volume use of the training simulation since development costs could not be recovered sufficiently soon under these circumstances.

Conclusion

Are the applications of the simulation feasible? The answer is affirmative but must be qualified. Efficient algorithms exist as evidenced by reports cited above. Technology sufficient to implement any of the applications is readily available. Consequently, the applications are within the relm of possibility. However, success depends on being able to justify application of the simulation in preference to whatever other alternatives are available in a given situation. The four alternative applications described above outline in general terms some of the particular alternatives available in a given case. Others become clear once the particular situation is stipulated.

The potential for a successful application of the simulation can be increased by providing for multiple applications. Designing the simulation so that it can be applied in two or more ways increases the number of potential users. Distributing the one-time development costs over a larger number of users results in costs being recovered in a shorter period of time. Greater ease in covering development costs makes the investment in development more attractive.

The management system application and the training application constitute the most promising of the possible multiple applications when combinations of the four simple applications described above are considered. Demand for these two applications would be more continuous than would the demand for the management systems design application or the management research application. Each of the favored applications implemented separately has a higher likelihood of covering costs than does either of the remaining applications. If the simulation is designed to serve both as a management system and as a training simulation, then the ability to cover costs in further increased. This combined application becomes an attractive alternative in the job-shop situation where management effectiveness must be increased and where training is an intended outcome. However, whether the simulation can be implemented so that it successfully satisfies an existing need remains to be demonstrated.

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ABSTRACT

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INSTITUTION: Brigham Young University

DATE: March 13, 1974

Proposes a simulation based on a mathematical model incorporating features of job-shop scheduling models and task assignment models from management science. The simulation has single or multiple applications as (1) a management research tool, (2) a management system, (3) a management system design tool, or (4) a management training simulation. The management system application and the management training application are the two most feasible design alternatives. Multiple applications make a single simulation more feasible by increasing demand and by allowing development costs to be recovered more rapidly.