Proceedings of the 1984
Winter Simulation Conference
S. Sheppard, U. Pooch, D. Pegden (eds.)

A SIMULATION/OPTIMIZATION-BASED PLANNING AND DECISION SUPPORT SYSTEM

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ABSTRACT

A decision support system (DSS) was developed for determining the number of items to purchase of a capital intensive commodity and when these items should be purchased in order to satisfy projected operational requirements. Such decisionmaking represents a major planning effort of many organizations such as airlines, trucking companies, and satellite telecommunications firms. The determination of these decisions is complicated by the length of time necessary to produce the commodity, the potential for failure, uncertain future costs and capacity requirements, multiple, conflicting, and noncommensurate objectives, and various exogenous factors. The DSS that was developed uses the simulation of a large Markov decision process (MDP) to evaluate purchase strategies generated by (1) domain experts, (2) heuristic procedures, and (3) the solution of an aggregated version of the MDP. Application of the DSS to a spacecraft purchase problem of INTELSAT is discussed and is used to motivate the developments.

BACKGROUND

The DSS described in this paper was developed under contract for the International Telecommunications Satellite Organization (INTELSAT) to assist in analyzing spacecraft procurement options. INTELSAT, headquartered in Washington, D.C., provides satellite communication services to member nations on a commercial basis. Established in 1964, this cooperative commercial venture had a membership at the end of 1983 comprised of 108 countries. The INTELSAT global communication satellite system carries approximately two-thirds of all international telephone, telex, and other message services and handles nearly all of the world's international television transmissions. To carry this vast amount of telecommunications traffic, INTELSAT operates approximately fifteen communications satellites of different designs. These satellites are linked to the domestic communications networks of individual user nations via several hundred earth stations. Further, INTELSAT must design and produce new generations of satellites, not only to replace those in-orbit reaching their end of life, but also to meet the growing demand for a variety of sophisticated new communication services by its users.

THE SPACECRAFT PROCUREMENT PROBLEM

The spacecraft procurement problem described in this paper resembles a multi-period, multi-item inventory control problem and can be modeled, as will be shown later, as a large scale Markov decision process. There are, however, several complicating factors which add to the dimensionality of the problem. We now briefly describe these factors.

Based on forecasts of future demand for various communication services, detailed operational plans are prepared which, among other things, specify the number and type of spacecraft which must be available in-orbit to satisfy the global communication needs at any given time in the planning period. The spacecraft types differ in terms of their traffic-carrying capacity (e.g., high-capacity INTELSAT VI versus relatively low-capacity INTELSAT V spacecraft) as well as in terms of specialized communication services (e.g., Business Service versus Maritime Communication Service) for which they are equipped. Obviously, there is some flexibilty in the operational plans with regard to the choice of spacecraft; for example, a high-capacity spacecraft can, in general, substitute for a lower-capacity satellite.

The operational plans provide a starting point in planning for the procurement of spacecraft since they indicate the future need for spacecraft of different types, and the time when they are required to be in orbit. In deciding the quantity and timing of spacecraft purchases, several other factors also need to be considered. First, the probable remaining lifetime in orbit of spacecraft already purchased and successfully launched must be taken into consideration. The probability distribution of the lifetime in orbit of a successfully launched spacecraft can be estimated based on its reliabilty characteristics and the supply of fuel available for maneuvering the spacecraft. Second, the procurement plan must make adequate contingency provisions for launch failures. The procurement decision must be made sufficiently in advance to allow the time necessary for the design, manufacture, and testing of spacecraft. This delivery lag time is typically on the order of 36 months for spacecraft requiring a minimum of technological development. Further, the procurement decision must take advantage of the lower unit cost that can often be realized under contractual terms when satellites are ordered early and/or in larger quantities. This price advantage must be carefully weighed against the cost of buying too many spacecraft too early. Considering that a communication satellite can cost from $30 million up to $100 million, clearly the goal should be to buy as few satellites as possible, consistent with meeting the operational plan requirements with sufficiently high probability.

The problem of when to purchase spacecraft is basically a multiattribute decision analysis problem, with the two major and obviously conflicting attributes being dollar cost and some measure of operational plan efficacy. Many spacecraft purchase policies will generate results that are nondominated, i.e., policies that are at least as good as other policies on one or more attributes. The existence of several nondominated strategies requires tradeoffs to be made between dollar cost and operational plan efficacy - tradeoffs that can be difficult, stressful, and time consuming.

SPACECRAFT PROCUREMENT MODEL

The conceptual basis of the DSS built for INTELSAT is the Markov decision process (MDP), a natural model choice considering the dynamic and stochastic nature of the spacecraft purchase problem (see Scherer, 1983, for details on the planning system; see Heyman and Sobel, vol 2, 1984 for a mathematical description of a MDP). The MDP assumes a maximum of 100 spacecraft of at most 10 types, with each spacecraft having a state space of 72 states. The planning horizon is assumed to be 10 years, and each stage or decision epoch occurs every 3 months. Therefore, the planning horizon in stages is 40. Below are the state definitions for the individual spacecraft:

State	Definition
1	nonexistent
2-29	being manufactured (lag states)
30	available for launch
31-70	operational
71	non-launch failure
72	launch failure

The state transition dynamics are as follows (see Figure 1 below). When a spacecraft is in state 1, i.e., the nonexistent state, the only action allowable is either to order the spacecraft and move to a "being manufactured" state or to do nothing. The only other state that permits action selection is state 30, the action being whether or not to launch the spacecraft. Transition dynamics for states 2 through 29 are deterministic and represent production lags. States 31 through 70 represent the up-to-40 stages of spacecraft life, and movement through these states is governed by a known reliabilty distribution. Once the decision has been made to launch a spacecraft, then that spacecraft moves to state 31 if the launch is successful or to state 72 if the launch is unsuccessful.

The dollar cost of ordering a spacecraft is a function of time, previous order quantities and order times, the current number being ordered, and whether or not manufacturers' data exist for the given spacecraft type. If ordering cost data are not available for a given spacecraft type, estimates are made using single unit costs, learning curves and inflation tables.

SIMULATION MODEL

The MDP described above has a state space of dimension 72**100 (72 raised to the 100th power), which is computationally intractable on any existing computer. Standard techniques for such large scale problems include using a census process (Haurie, 1981), approximations (Whitt, 1978), aggregation (Puterman, 1978), and decentralization (White and Schlussel, 1981). Considering the extremely large size of the MDP, we felt that the above procedures would be of questionable quality and decided to simulate the MDP in order to capture all the complexities of the actual spacecraft procurement problem. It should be noted that many computationally intractable MDP's are easily simulated. The INTELSAT spacecraft purchase problem belongs to a large class of multi-period, multi-item inventory models, many of which are computationally intractable when modeled as an MDP.

A FORTRAN V Monte Carlo simulation model of the MDP was developed, and verification and validation of the model is being conducted in coordination with the INTELSAT staff. An iterative process was used to structure the input and output features of the simulation model into a form that was best suited to INTELSAT. The simulation model serves as the benchmark for determining the "quality" of procurement policies generated by either an approximating MDP, heuristic procedures, or planning experts on the INTELSAT staff.

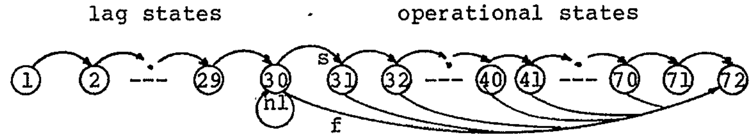

FIGURE 1:Transition Dynamics

Several heuristic procedures were developed to generate purchase policies. These procedures were based on "common sense" or "rule-of-thumb" generated through discussions with the planning staff at INTELSAT. Three procedures were developed:

1. A straightforward "look-ahead" policy that does not consider spacecraft or launch failures. This simple policy does not possess the ability to look further into the future than a preset number of quarters and therefore cannot always adjust to changes in the operational plan. The policy is concerned only with operational plan efficacy and does not make purchase decisions based on dollar cost, as is also true with the next procedure.

2. A probabilistic purchase policy that purchases spacecraft in an attempt to maintain a user-selected probability of meeting the operational plan. This heuristic procedure is also problematic when faced with operational plan requirements that have large jumps in desired quantity from one period to another period.

3. A simple simulation-optimization procedure that uses a local search procedure to improve a predetermined purchase policy of the type described in the first procedure. Two attributes are used:

   (i) a measure of operational plan efficacy that is selected by the user and

   (ii) the discounted dollar cost of the given policy.

This heuristic procedure searches in two dimensions:

   (1) the quantity ordered (a risk factor) and

   (2) how far to look ahead (a lead-time factor).

Given an initial purchase policy, the procedure searches in four directions by increasing or decreasing by 1 unit (1 spacecraft or 1 quarter) one of the two factors. Each search consists of determining, through Monte Carlo simulation, values for each of the two attributes for the modified purchase policy. If the results of one of the four directions dominates the initial policy, i.e., has an equal or lower dollar cost and an equal or higher probability of meeting the operational plan, then that policy becomes the new initial policy and the procedure is repeated. If none of the four directions produces results that dominate the results of the initial policy, the procedure terminates. The user can then stop or can select another initial purchase policy to explore. This heuristic procedure can be CPU time intensive due to the extreme number of replications that may be required.

AGGREGATED MDP MODEL

In addition to the heuristic policies and procedures described above, the original MDP was approximated by a significantly smaller MDP. The following reductions were made:

1. The number of states for an individual spacecraft was reduced from 72 to 4. This was accomplished by approximating the 28 lag states by a geometric random variable and replacing the up-to-40 state spacecraft lifetime reliability distribution with the sum of two geometric random variables. Launch failure probabilities were built into the two-state reliabilty distribution. The mean and variance of the approximating distribution were matched to the actual reliabilty distribution when possible. Also, the "available for launch" state was eliminated, and the assumption was made that spacecraft are launched as they become available.

2. An assumption was made that spacecraft types are independent, i.e., that there is no substitution of spacecraft types.

3. Numerous approximations were made regarding the cost structures.

4. The objective function of the MDP was comprised of a weighted sum of the dollar cost and a measure of operational plan efficacy. This is the only procedure that directly considered the tradeoff between the two attributes, allowing the user to select his or her own tradeoff weights.

5. A census prosess (Haurie, 1981) was used to reduce the state space of the model. This procedure "counts" the number spacecraft in each state, resulting in a loss of individual spacecraft identity.

Purchase policies generated by the approximating MDP have been evaluated by using them in the simulation model and comparing the results with the simulation results of alternative purchase policies. The heuristic procedures and the aggregated MDP described above were incorporated into the simulation model, the result being a menu-driven planning and decision support system for spacecraft procurement that represents a class IV hybrid simulation/analytic model (Shanthikumar and Sargent, 1983). The system allows the user to input his or her own purchase strategy for impact analysis. Also, the system allows the user to use various combinations of his or her own policies in conjunction with policies generated by the heuristic procedures or by the approximating MDP .

RESULTS and CONCLUSIONS

Currently available results of an ongoing evaluation and comparison with other studies done at INTELSAT indicate that the DSS is accurate and useful. More specifically:

1. The DSS makes an excellent learning tool in that it allows members of the INTELSAT staff to better understand the effects of various purchase policies on dollar cost and operational plan efficacy. Such "WHAT IF" experiments would be virtually impossible to evaluate without a computer based model.

2. Policies generated by the DSS were informative and useful. The approximating MDP model, for example, generated policies that were not dominated by policies supplied by the INTELSAT staff for evaluation.

3. The incorporation of an option that allows for heuristic purchase policies based on expert knowledge to be used in combination with optimization routines is a flexible and useful feature of the DSS. This allows the user to input purchase decisions that may be of particular interest or sensitivity and let the optimization routines determine the remaining purchase decisions.

In the actual planning process, many nondominated policies will probably be generated by this DSS. Once such nondominated policies have been generated, however, it still is necessary to select only a single policy. A second knowledge-based planning and decision aid could be useful in this selection process. Such an aid would acquire sufficient tradeoff information from the user in order to help determine the most preferred policy in the nondominated set of policies. An example of this type of aid is ARIADNE (White, et al., 1984), a primary intent of which is to reduce to the extent possible the time and cognitive stress necessary for policy selection.

We feel that an important contribution of this research project is the use of Monte Carlo simulation in the solution of computationally intractable MDP's. The simulation model, although hindered by the need for a policy and not being an optimization model, is an excellent benchmark by which to compare policies generated by other means. Currently, we are considering a procedure that combines the Markov decision model and a simulation of the Markov decision model into a single simulation/optimization model that will generate "near" optimal policies.

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This paper describes work performed under the sponsorship and technical direction of the International Telecommunications Satellite Organization, INTELSAT. Any views expressed are not necessarily those of INTELSAT.