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Introduction to SIMRAND

SIMulation of Research ANd Development Project

Ralph F. Miles, Jr.

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ABSTRACT

SIMRAND: SIMulation of Research AND Development Projects is a methodology developed at the Jet Propulsion Laboratory of the California Institute of Technology to aid the engineering and management decision process in the selection of the optimal set of systems or tasks to be funded on a research and development (R&D) Project. An R&D project may have a set of systems or tasks under consideration for which the total cost exceeds the allocated budget. Other factors such as personnel and facilities may also enter as constraints. Thus the project's management must select, from among the complete set of systems or tasks under consideration, a partial set that satisfies all project constraints. The SIMRAND methodology uses analytical techniques of probability theory, decision analysis of management science, and computer simulation, in the selection of this optimal partial set.

The SIMRAND methodology is truly a management tool. It initially specifies the information that must be generated by the engineers--thus providing information for the management direction of the engineers--and it ranks the alternatives according to the preferences of the decision makers. The decision makers could be either the project's management, the funding agency, or the end users.

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INTRODUCTION

A commonly occurring engineering and management decision on research and development (R&D) projects, whether commercial or military, is that of the optimal allocation of R&D funds, given budgetary constraints in funding alternative systems for achieving the project's goals. Because of the budget constraints, not all of the proposed systems can be funded for R&D work. The engineering and management decision then is, "What set of the proposed systems should be funded?" SIMRAND: SIMulation of Research AND Development Projects is a methodology developed at the Jet Propulsion Laboratory of the California Institute of Technology to aid engineers and management in the selection of the optimal set of systems to be funded.

An R&D project must satisfy the following criteria for the SIMRAND methodology to be appropriate:

- (1) The goals of the project must be attainable by a system comprising hardware and manpower elements for which estimates of variables such as cost and performance can be made. Examples of such a system might be a logistics system or a system for producing solar-cell modules.
- (2) The systems for achieving the project goals must have a common measure of preference. Such a measure might be cost, with a preference for minimizing cost, or it might be performance, with a preference for maximizing performance.
- (3) It must be possible to relate the variables that describe a system to the measure of preference.

Although the following criteria are not mandatory, they do permit the full use of the SIMRAND methodology:

- (1) More than one system should be under consideration to satisfy the project goals. The systems may be fundamentally different, such as windmills versus solar cell modules for generating electricity, or they may be parametric variations on a system design, such as the selection of the number and type of engines for a cargo aircraft. SIMRAND can select the optimal set of systems for R&D funding.
- (2) Uncertainty should be present with respect to the variables that describe the systems. The *raison d'etre* of R&D funding is to remove or at least reduce uncertainty, and in doing so to identify the "best" system or set of systems--otherwise, the project should enter directly into the implementation phase. SIMRAND incorporates this uncertainty by treating the system variables probabilistically.
- (3) The decision makers (who could be either project management, the funding agency, or the end users) should have a preference for the degree of risk they are willing to assume in terms of the extent to which the selected systems ultimately satisfy the project goals. SIMRAND represents this risk preference through the formal incorporation of a risk analysis.

Given that these criteria are met, SIMRAND can determine the optimal set of systems for R&D funding. The inclusion of a specific system is tantamount to the funding of certain R&D tasks. SIMRAND will identify which R&D tasks are to be funded, and can also specify the level of funding required for each task.

EXAMPLE NO. 1

Consider a military R&D decision to develop a logistics system, where the measure of preference is to minimize the life-cycle cost per ton-mile of equipment moved. Assume that two systems are in contention for R&D funding--System A and System B--but that the funding level will only permit one of the two systems to be developed. Assume that System A is an upgraded version of an existing system, and therefore the preference measure is known with virtual certainty--a point estimate will suffice. Assume that System B is an advanced system, for which the preference measure can only be stated in probabilistic terms, e.g., a 50/50 chance that the cost per ton-mile for System B is less than that of System A. With no other information, and no knowledge of the risk preference of the decision makers, it is not possible to state whether System A or System B is the best system to develop.

The SIMRAND methodology can be applied to this decision. SIMRAND not only structures the problem by placing it in a decision-making context, but also specifies the required information, and processes that information so that the question "Which system is preferred?" can be answered.

The SIMRAND modeling of this decision is shown in Figure 1. There is a System Model, which is capable of analytically describing the two systems, and a Value Model, which takes the output of the System Model and determines which system is preferred. The two decision alternatives--which are to select either System A or System B--are shown as an arrow pointed into the System Model. Uncertainty as to the characteristics of System B is shown as another arrow, also pointed into the System Model. The outputs of the System Model are called Outcomes, and represent a characterization of the two systems as they would actually be realized--a characterization that can only be described probabilistically for System B. The two outcomes form the input to the Value Model. The Value Model incorporates both the preference measure of minimizing the cost per ton-mile and also the risk preference of the decision makers. The output of the Value Model is a preference ranking of the two alternatives.

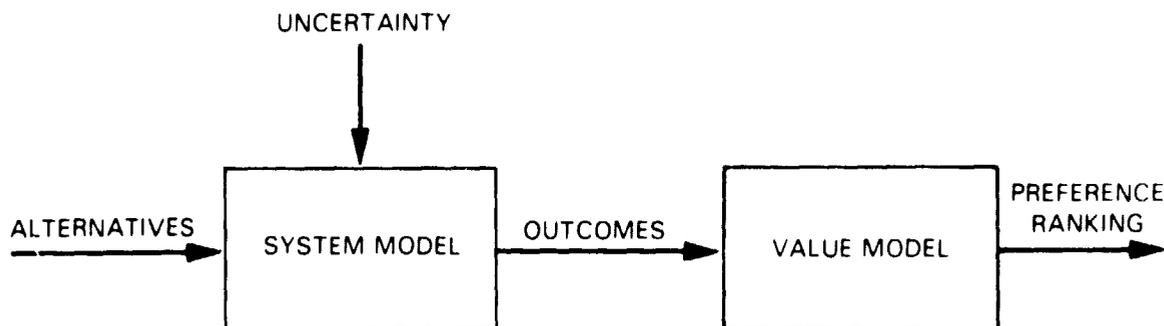


Figure 1. A Block Diagram of the SIMRAND Methodology

The information required by SIMRAND from the engineers for this logistics problem is straightforward, although the engineering effort required to develop the information may not be, depending upon the complexity of the system and the uncertainties involved. A point estimate of the cost per ton-mile is required for System A, and a probability distribution--formally called a cumulative distribution function--is required for System B. The probability distribution for System B is obtained by asking the engineers to make estimates in response to the following kinds of questions: "For what cost per ton-mile for System B does the actual cost have an x% chance of being less than or equal to it?" where x% would vary over the range from none to 100%. The cost per ton-mile for which System B would have a 50/50 chance of being less than or equal to it would be the 50% value. Other values of x% (1%, 10%, 25%, 75%, 90% and 99%) would provide enough information in most cases to draw a line through the points, thus forming the probability distribution of cost per ton-mile for System B. Figure 2 shows typical probability distribution for both System A (a point estimate) and System B, measured in units of the cost per ton-mile for System A.

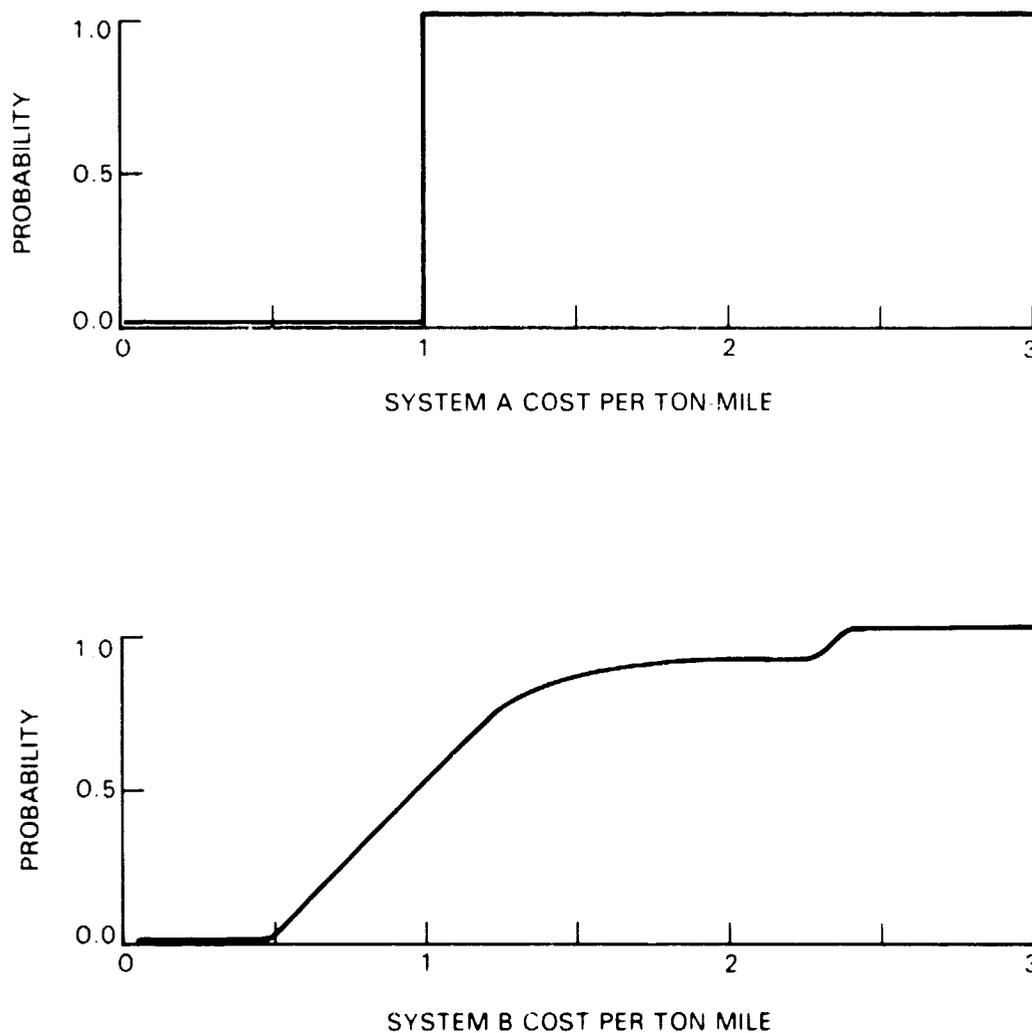


Figure 2. Probability Distributions for the Estimated Cost per Ton-Mile for Example No. 1

A risk analysis is incorporated in SIMRAND by assessing the preferences of the decision makers for different values of cost per ton-mile. The preferences are measured in such a way that both strength of preference and risk preference are assessed. These preferences are assessed by asking the decision makers such questions as "Would you rather have a system cost of 1 unit per ton-mile or a 50/50 gamble yielding a system cost of 0.5 units per ton-mile with probability 1/2 or a system cost of 2.0 units per ton-mile with probability 1/2?" From questions such as this one, a preference curve (formally called a utility function) can be constructed for each decision maker, such as that in Figure 3. Then an expected utility value can be determined for each system by integrating the utility function times the associated probability (as determined from the probability distribution) over the range of values for cost per ton-mile. This integration determines an expected utility value for each system for each decision maker. Since greater utility values imply greater preference ranking, a preference ranking is established for each decision maker.

If this risk analysis is applied to Figures 2 and 3 for Example 1, then System A receives an expected utility value of 0.50 and System B receives an expected utility value of 0.45. Therefore, for this hypothetical decision maker, the alternative of funding System A would be preferred to funding System B. In a similar manner, preference rankings could be determined for other decision makers. Group decision rules could be applied to the preference rankings for each of the decision makers to identify a group consensus, if one exists. Typically, one person has the responsibility and authority to make the system selection, but that one person may be interested in the preferences of others before making the system selection. It is in this context that "decision makers" is used in the plural form.

If the probability distributions for the cost per ton-mile of Systems A and B are sufficiently well separated and do not overlap, then the risk analysis portion of the SIMRAND methodology is not required. For example, if in Figure 2 the probability distribution for System A were to lie entirely to the left of the probability distribution for System B, then System A (with a lower cost per ton-mile) would clearly be the preferred system.

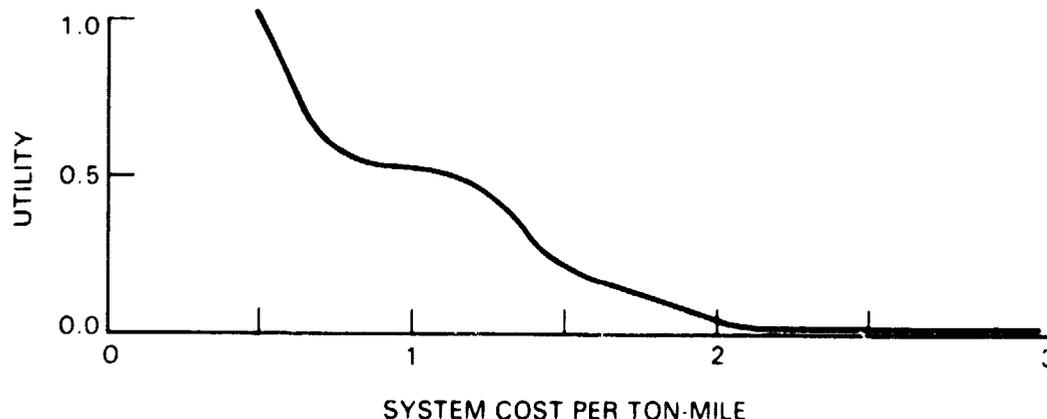


Figure 3. Typical Utility Function for a Decision Maker for Example No. 1

Even in this simple application of the SIMRAND methodology, several aspects of the methodology were used. A measure of preference for comparing the two systems was used--the cost per ton-mile of equipment moved. Probability theory was required to model the uncertainty associated with System B. Finally, risk analysis was used to measure the risk preference of the decision maker. The SIMRAND analysis of this example showed that the decision maker preferred System A. The undesirable prospect that System B might yield cost numbers significantly higher than System A outweighed the desirable prospect that System B might yield a cost number as low as one-half that of System A. For another decision maker, with a different utility function, the preference of System A over System B might be reversed.

EXAMPLE NO. 2

Example No. 2 is more complicated than Example No. 1, and demonstrates the full capability of the SIMRAND methodology. It is a simplified example of its application that has been made at the Jet Propulsion Laboratory for the Flat-Plate Solar Array Project. The objectives of the Project at the time the analysis was done were to minimize the production price of solar-cell modules, and to demonstrate their ability to perform reliably in operational environments. Attainment of these objectives was sought by funding R&D tasks that could result in different ways of producing inexpensive solar-cell modules.

Figure 4 is a simplified task network for the production of solar-cell modules. The production process is divided into five steps. Step 1 is the silicon purification step. Step 2 produces crystalline silicon, necessary for

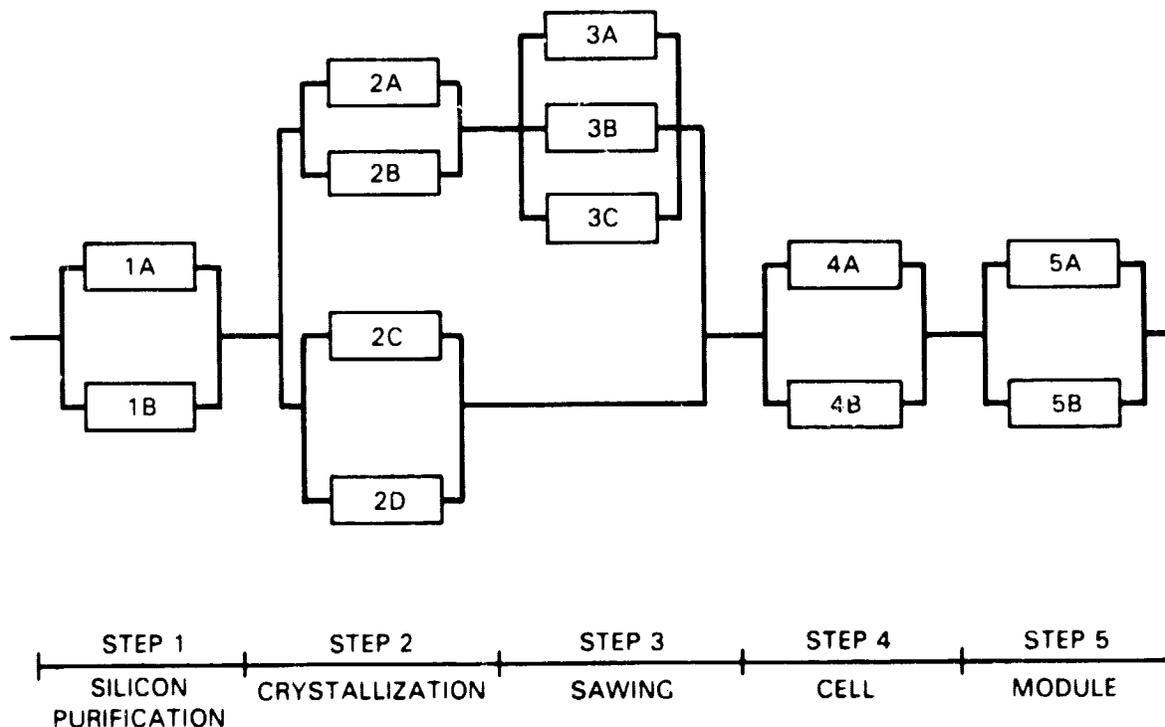


Figure 4. Task Network for Solar-Cell Module Production for Example No. 2

the photovoltaic transformation of sunlight into electricity. Step 3 is a sawing step that may or may not be necessary, depending upon whether the silicon is cast as ingots (for which sawing into sheets is necessary) or is pulled as ribbons (for which the sawing is not necessary). Step 4 takes the silicon in sheet or ribbon form and performs the necessary cleaning, doping, and conductor deposition to form a cell. Step 5 connects the cells and encapsulates them in a frame to form modules of cells. Price equations must be supplied for each step. The price equations will include known constants such as the density of silicon and the intensity of sunlight. The price equations will also include variables that can only be expressed probabilistically, such as solar cell efficiency and the prices of materials per unit quantity and the costs of processes. The price of the solar cell modules will be the sum of the value-added prices of each of the five steps.

Figure 4 shows two different tasks (1A and 1B) by which the silicon can be purified in Step 1. Either Task 1A or Task 1B can purify silicon. The reasons for funding the two tasks in parallel are that technology and economic uncertainties make it impossible to know which task will purify the silicon at the least price, and that one of the tasks may involve an advanced technology that cannot be guaranteed to work. Step 2 shows four tasks by which the silicon can be crystallized. Two of the tasks (2A and 2B) produce ingot silicon which must be sawed in Step 3, and two tasks (2C and 2D) produce ribbon silicon which requires no action in Step 3. Step 3 shows three tasks (3A, 3B, and 3C) for sawing the ingot silicon. Step 4 shows two tasks for producing the cells and Step 5 shows two tasks for producing the modules.

There are 64 paths through the task network of Figure 4. Of these 64 paths, 48 involve ingot tasks and 16 involve ribbon tasks. Several different questions may be asked of this task network. If all of these tasks are funded, then what is the price of the solar cell modules--or more correctly, what is the probability distribution of the price of solar cell modules? If the R&D cost of funding all of these tasks exceeds the Project funding level, then what set of these tasks consistent with the funding level will result in the minimum price for the solar cell modules--or, more correctly, what set of these tasks consistent with the funding level will result in the most preferred probability distribution? If the tasks can be funded at different levels, then what distribution of funding over the task network will result in the most preferred probability distribution? The SIMRAND methodology can be applied to any of these questions, given that the necessary information can be obtained.

The SIMRAND methodology proceeds in two phases, a reduction phase and a simulation phase. In the reduction phase, analytical techniques from probability theory and simulation techniques are applied to reduce the complexity of the task network. In this simple example, there are only 64 paths through the task network; a more complicated case could have hundreds, or even thousands, of paths through the network. For example, a network consisting of 10 steps and four parallel tasks for each step would have 1,048,576 paths. Clearly, any techniques that can be applied to reduce the number of paths can be extremely useful. In Figure 5, parallel tasks have been combined where possible to reduce the number of paths through the task network from 64 to two.

The simulation phase provides the capability for the probabilistic analysis of task networks not amenable to the analytical techniques of probability theory. Figure 6 expands the reduced task network of Figure 5 to form

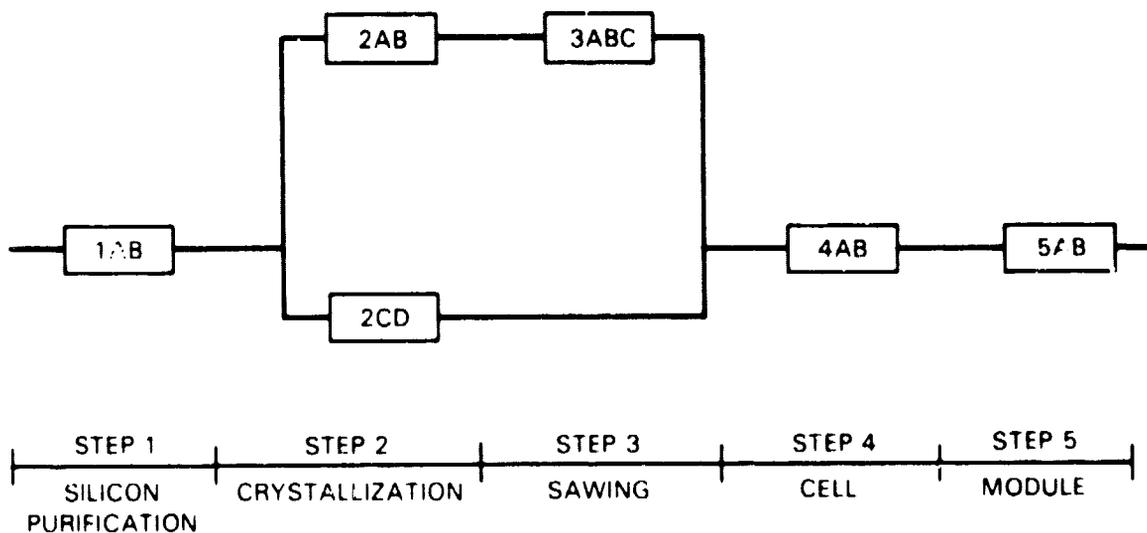


Figure 5. Reduced Task Network for Solar-Cell Module Production of Example No. 2

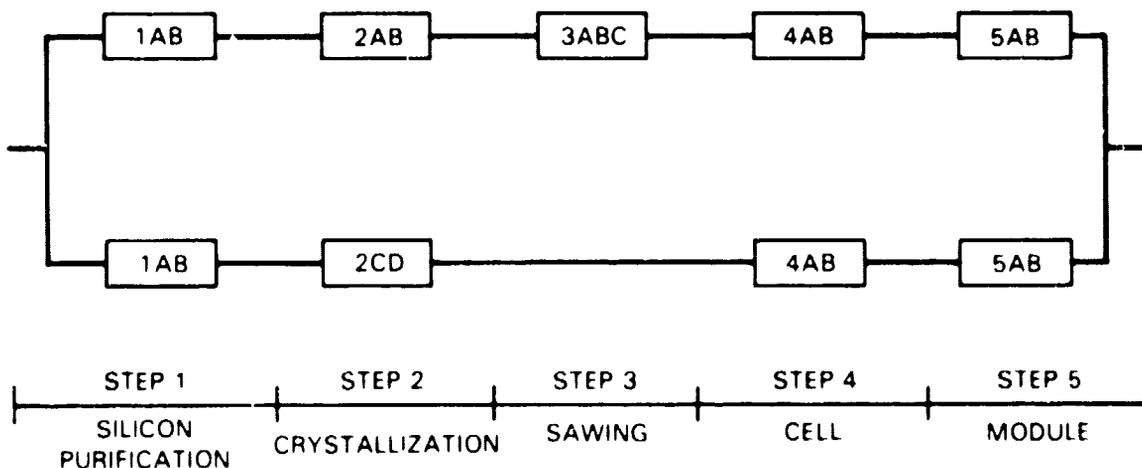


Figure 6. Simulation Task Network for Solar-Cell Module Production of Example No. 2

the simulation task network, which explicitly displays the two paths through the task network. Techniques from simulation theory are now applied to this simulation task network. The task network is simulated in a computer program. The computer program performs the simulation by carrying out a series of Monte Carlo trials, consisting of (1) assigning a different random number to each of the probabilistic variables that appear in the price equations for the tasks, (2) calculating prices for each task using the task price equations, (3) summing the task prices for each of the two paths through the simulation task

network, (4) selecting the path with the minimum total price, (5) adding this minimum total price to a total price histogram, and the associated step prices to step price histograms, and (6) incrementing the count of the number of times that the path for the minimum total price has been selected. The random numbers are selected for each of the probabilistic variables according to their frequency of occurrence as determined by their associated probability distribution.

These Monte Carlo trials are repeated many times with different sets of random numbers until histograms with sufficient precision have been constructed for the total price, the step prices, and the selected paths. Probability distributions and relevant statistics are calculated during the Monte Carlo trials or from the histograms. Probability distributions are calculated for the total price and for each of the step prices. Statistics such as mean price, variance in price, and percentiles are calculated for the total price and for each of the step prices. The number and percentage of times that each path of the network is selected as the minimum total price path are also calculated.

The computer program performs a risk analysis by combining the utility functions of the decision makers with the total price histogram, and by deriving certainty equivalents for the total price probability distributions for each decision maker and for each task network under consideration. A certainty equivalent for a task network is the price at which a decision maker would have no preference between (a) receiving the price with certainty and (b) the uncertainty of the probability distribution of total price associated with the task network. The importance of the certainty equivalent is that in the presence of uncertainty, it is the correct quantity to use in ranking the task networks according to the risk preference of the decision maker. Of the alternative task networks under consideration (and that meet all the necessary project constraints, such as funding level), the task network with the lowest certainty equivalent is most preferred by the decision maker.

As in Example No. 1, if the probability distributions of the total prices for the task networks do not overlap, then the risk analysis portion of the SIMRAND methodology is not required. An examination of the probability distributions, such as in Example No. 1, or a statistic such as the mean total price, can be used to determine the preference ranking of the task networks.

It is through this two-phased process that the SIMRAND methodology is able to efficiently model and analyze complex R&D funding decisions as multi-step, multitask networks. The reduction phase reduces the task network complexity, and in doing so reduces the simulation effort required in the simulation phase. The simulation phase provides the capability of probabilistic analysis of task networks not amenable to the analytical techniques of probability theory.

SUMMARY

Certain criteria must be met for the SIMRAND methodology to be appropriate for modeling and analyzing the optimal allocation of funds for an R&D project. These criteria include definitions of the R&D systems from which cost and performance estimates can be made. It must be possible to relate these

cost and performance estimates to a common measure of preference. The full capability of SIMRAND can be used when, in addition, more than one system is under consideration, when uncertainty exists with respect to the variables that define the systems, and when the risk preferences of the decision makers can be assessed. The decision makers may be either project management, the funding agency, or the end users.

The SIMRAND methodology can make probabilistic estimates of the measure of preference of a system. The SIMRAND methodology can be applied to complex R&D task networks, and can provide information relevant to such questions as "Which set of R&D tasks should be funded?" and "What is the optimal distribution of funding across a set of R&D tasks?"

Two examples were used to illustrate how the SIMRAND methodology could be employed. The examples illustrated the use of several systems analysis concepts, including the modeling of systems in the presence of uncertainty, risk analysis for incorporating the risk preference of decision makers into the system rankings, and the use of simulation techniques for analyzing task networks too complex for a straightforward application of probability theory.

An important point to be made is that the preference rankings of the alternative systems generated by the SIMRAND methodology are those of the decision makers, not those of either the SIMRAND analysts or the engineers that perform the tasks and make the engineering and economic estimates for the systems. Thus the SIMRAND methodology is truly a management tool. The SIMRAND methodology initially specifies the information that must be generated by the engineers--thus providing information for their management direction--and it ranks the alternatives according to the preferences of the decision makers.