RISK EVALUATION IN RESOURCE ALLOCATION

VALLIAPPA ARUNACHALAM

RISK EVALUATION IN RESOURCE ALLOCATION

by

© Valliappa Arunachalam, B. Tech., M. Tech., C. C. E.

A Thesis submitted in partial fulfilment
of the requirement for the degree of
Master of Engineering

Faculty of Engineering and Applied Science
Memorial University of Newfoundland
April 1984

St. John's Newfoundland

To My Daughter
LAKSHMI

ABSTRACT

The conventional resource allocation procedures implicitly assume that availability of resources is certain. In real life situations, their availability at times is uncertain. A simple model is required to categorize and quantify the uncertainty due to resource availability and evaluate its impact on project schedule and cost. This thesis proposes a Risk Evaluation Model (REM) which takes a resource justified schedule as input, incorporates the uncertainty associated with availability of resources, and generates alternate sets of values on project completion time, cost and performance probability. It will help select a resource justified schedule which has not only the least duration or cost but also reasonable performance probability.

ACKNOWLEDGMENTS

I wish to thank Professor H. N. Ahuja, for suggesting this research problem to me, supervising the work and guiding me in the write up of this thesis. With profound gratitude and pleasure I also acknowledge the moral support of Dr. F. A. Aldrich, Dean of Graduate School. In addition, I appreciate the continued encouragement of Dr. G. R. Peters, Dean, Faculty of Engineering and Applied Science and Dr. T. R. Chari, Associate Dean, Faculty of Engineering and Applied Science. I also appreciate the help extended by all secretaries in the School of Graduate Stduies.

Last but not the least, I express my fondest thanks to my wife Shantha for her much needed encouragement and understanding.

CONTENTS

Description		Page Number
List of Tables		VII
List of Figures		VIII
Chapter 1		
1.1.0	Introduction	1
1.2.0	Deficiencies in Conventional Resource Allocation	2
1.3.0	Scope of the Study	5
1.3.1	Uncertain Resources	5
1.3.2	Availability of a Resource Type from a Single or Multiple Independent Sources	5
1.3.3	Availability of a Resource Type from Multiple Dependent Sources	7
1.3.4	Availability of Multiple Resource Types from a Single Source	7
1.4.0	State of the Art	8
1.4.1	Time-Cost Tradeoff Procedures	8
1.4.2	Resource Leveling	9
1.4.3	Constrained Resource Allocation	11
1.5.0	Risk Evaluation in Probabilistic Network Scheduling	13
1.6.0	The Need for a New Methodology	14
1.7.0	Problem Statement	16

Chapter 2

2.0.0	Rationale of the Model	17
2.1.0	Risk Evaluation Model	17
2.2.0	Resource Allocation Processor	17
2.3.0	Stage One and Stage Two Processor	19
2.3.1	Stage One Processor	19
2.3.2	Stage Two Processor	20
2.4.0	Cost Evaluation Processor	22
2.5.0	Probability Evaluation Processor	23
2.5.1	Time Estimates for Uncertain Resource Availability	23
2.5.2	Selection of Probability Distribution	24
2.5.3	Beta Distribution	25
2.5.4	Parameters of Beta Function	26
2.5.5	Reference Points for Time Estimates	27

Chapter 3

3.0.0	Risk Evaluation Model	31
3.1.0	Resource Allocation Processor	31
3.2.0	Stage One and Stage Two Processor	39
3.3.0	Cost Evaluation Processor	40
3.3.1	Resource Cost	40
3.3.2	Mobilization Cost	47
3.3.3	Other Costs	48
3.3.4	Overhead Cost	48
3.3.5	Penalty	48
3.3.6	Total Project Cost	49
3.4.0	Probability Evaluation Processor	49

3.5.0 Restricting the Number of Iterations 59

3.5.1 Selection of Time Units 60

3.5.2 Restricting the number of Computations 60

3.5.3 Restrictions in the Choice of Sources 62

3.6.0 Computer Software 63

Chapter 4

4.0.0 Illustration of Use of the Model 64

4.1.0 Solution 71

4.2.0 Discussion 85

Chapter 5

5.0.0 Summary and Conclusions 90

5.1.0 Applications of REM 90

5.2.0 Scope for Future Research 93

6.0.0 References 95

Appendix A 104

Appendix B 121

List of Tables

	Description	Page Number
3.1	Elapsed Time Estimates for Activities of Ongoing Project	54
4.1	Resource Requirement of the New Project	66
4.2	The Availability Status of Resources	67
4.3	Time Estimates for Resource Availabilities	68
4.4	Time Adjustment Factor	69
4.5	Unit Cost of Resources	70
4.6	Available Number of Resources for the First Run	73
4.7	Grouping of Resources	81
4.8	Determination of the Range of Interest	82
4.9	Output from First Run	83
4.10	Available Number of Resources for Second Run	86
4.11	Output from Second Run	87

List of Figures

	Description	Page Number
1.1	Uncertainty Associated with Availability of Resources for the New Project	3
1.2	Types of Uncertainties	6
2.1	Risk Evaluation Model	18
2.2	Computation by Substituting Uncertain Resources with Hired Resources	21
2.3	Reference Points for Time Estimates	29
3.1	Risk Evaluation Model	32
3.2	Resource Profile	42
3.3	Probability Evaluation for the Availability of Resources from more than one Independent Source	51
3.4	Probability Evaluation for the Availability of Resources from more than one Dependent Source - Case A	53
3.5	Probability Evaluation for the Availability of Resources from more than one Dependent Source - Case B	56
3.6	Availability of Multiple Resource Types from more than one Activity of a Single Project	58
3.7	Availability of Multiple Resource Types from a Single Activity of an Ongoing Project	59
3.8	Evaluation of Uncertainty Spread	61
4.1	CPM Network	65
4.2	(a) Resource Profile of R1	74
	(b) Resource Profile of R2	75
	(c) Resource Profile of R3	76

(d) Resource Profile of R4 77

(e) Resource profile of R5 78

(f) Resource profile of R6 79

A. 1 Input-Output Model 107

A. 2 Working of REM 118

CHAPTER 1

IMPACT OF UNCERTAIN RESOURCES

ON PROJECT SCHEDULE AND COST

1.0.0 IMPACT OF UNCERTAIN RESOURCES ON PROJECT SCHEDULE AND COST

1.1.0 Introduction

The use of network scheduling such as CPM/PERT in organizing the multiactivity projects have been commonly accepted in many engineering fields for several years. However, network scheduling techniques have a limitation because they are based on the assumption that the resource availability is unlimited. When resource availability levels are checked against these required levels of demand, the problems of resource allocation arise. It may be that demands exceed availability levels in some time periods. A second possibility is that the variation in resource profiles is considered excessive, and there is reason to reduce excessive peaks and smooth the profiles of usage. Yet another problem may be that the initial project duration is unsatisfactory and additional resources are required to shorten the duration. These three cases can be broadly classified as conventional resource allocation problems for solving which much work has been done in recent years.

While planning a project, there can be a different type of problem which arises when the resource availability from expected sources is not certain. Schedules obtained from the conventional resource allocation procedures with such conditions can at most be probabilistic. A methodology is needed to categorize and quantify the uncertainty associated with availability of resources and evaluate its impact on project duration and cost. It will help in selecting a resource justified schedule which has not only an acceptable duration and minimum cost but also a reasonable performance probability.

1.2.0 Deficiencies in Conventional Resource Allocation

The conventional resource allocation procedures implicitly assume that the availability of resources to schedule the project under consideration (hereinafter referred to as the new project) is certain. In real life situations the availability of resources may be uncertain at times, the reasons for which are illustrated in Figure 1.1 and discussed below.

Normally it is the objective of a contractor or whoever schedules the project, to minimize cost of the new project. Hence he uses, so far as possible, his less expensive in-house resources in preference to more expensive externally hired resources. His in-house resources are generally tied up with his other ongoing projects where the characteristics of the construction industry's environment such as weather, labour strikes and variation in productivity make it difficult to rigidly follow the original resource justified schedule to free them for the new project. For example, if the ongoing project is a tunneling job, the production rate will depend on the ground conditions. During the course of work, if it is found that the rock is harder than what was predicted through site investigation, the tunneling activity is likely to take more time than planned, resulting in delay in release of equipment. There are other similar project risks in the construction environment of ongoing projects which are part of the reasons

UNCERTAINTY ASSOCIATED WITH AVAILABILITY OF RESOURCES FOR THE NEW PROJECT

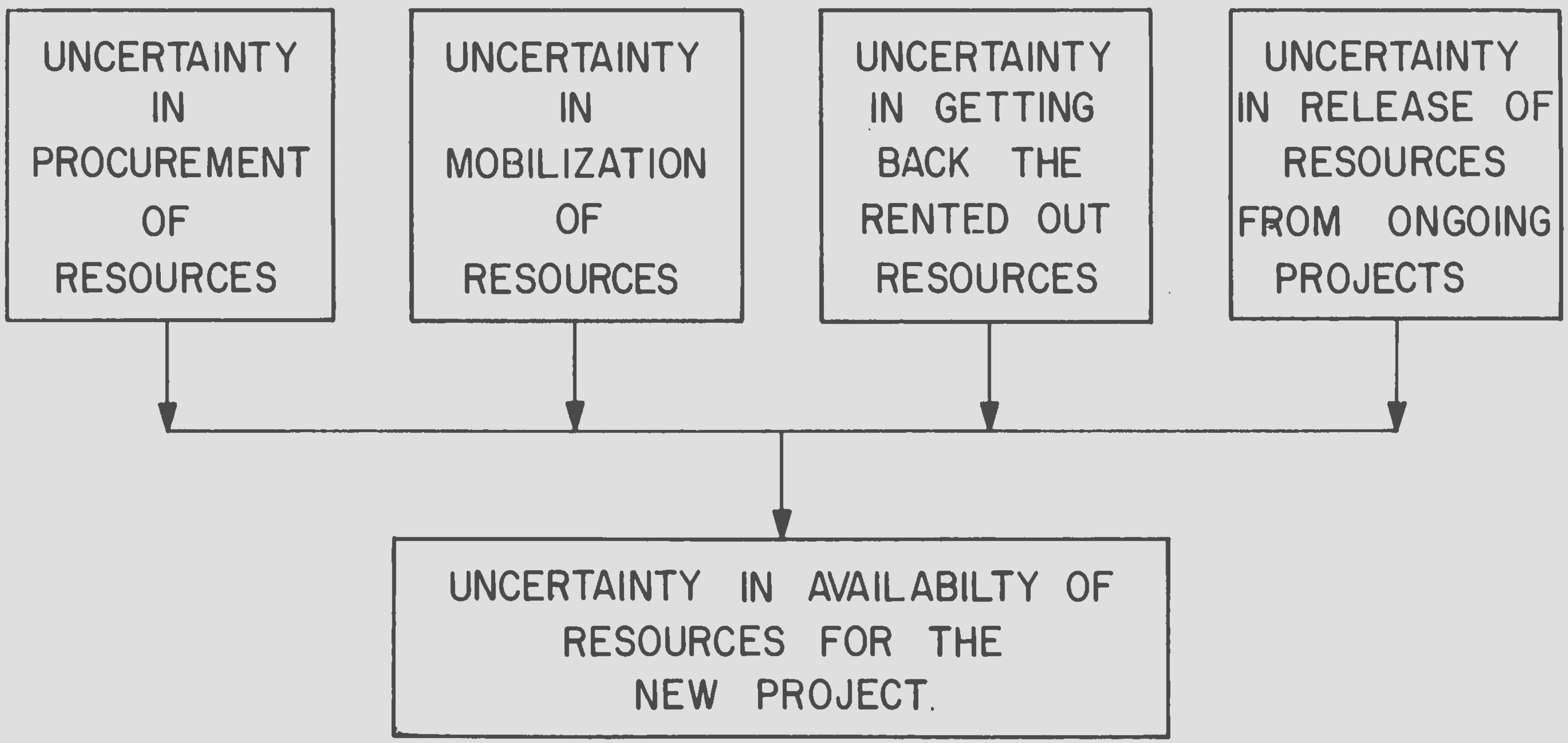


FIGURE 1.1

construction environment of ongoing projects which are part of the reasons for the uncertainty associated with resource availability for the new project. Some of the other reasons follow:

1) If the required resources are going to be purchased, the delivery of resources by vendor/manufacturer may be uncertain. If it is a human resource, the date of joining the firm may be uncertain.

2) There may be an uncertainty in mobilization of the required resources from the ongoing project site to the new project site.

3) There may be an uncertainty in getting back the required resources which have been rented out by the contractor.

Due to these uncertainties, two basic questions 1) how many and 2) when the resources will be available for use on the new project, can not be answered with certainty. Hence, the project duration obtained after resource allocation scheduling and the associated project cost could only be probabilistic. Probability may be improved either by delaying the use or varying the number of uncertain resources, of course , at the expense of project duration or cost or both. Hence, it is evident that additional processing of schedules obtained from conventional methods is necessary to study the impact of uncertain resources on project schedule and cost.

Having discussed the environment in which the present problem exists, the scope of the study and the state of the art may be further analyzed so the problem is fully defined.

1.3.0 Scope of the Study

The reasons for uncertainty associated with resource availability were outlined in section 1.2.0. In order to quantify these uncertainties, they are categorized as shown in Figure 1.2. To help define the scope of the problem a brief description of each category with its section numbers keyed to the figure, follows:

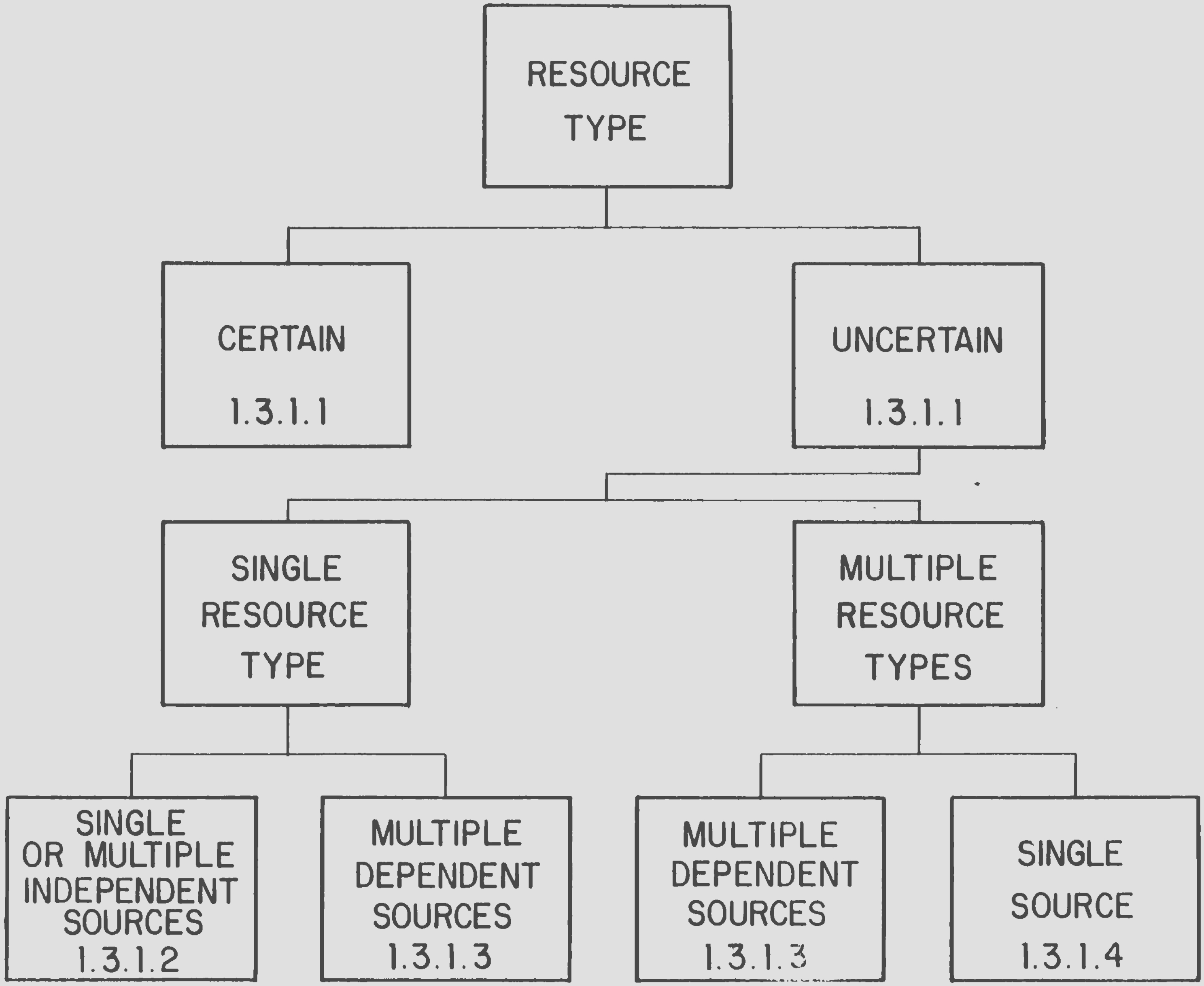
1.3.1 Uncertain Resources

A number of resources of a particular type for the new project may be available definitively when required but the availability of the remaining resources may be uncertain. Supposing ten cranes are required for a new project; the availability of a number of them may be certain and that of the rest uncertain.

The resources whose availability is uncertain will be hereinafter referred to as '**uncertain resources** ' and the resources which are available definitively will be referred to as '**certain resources** '.

1.3.2 Availability of a Resource Type From a Single or Multiple Independent Sources

If there is more than one ongoing project, it is quite possible that any type of resource required by the new project is drawn from not one but several of the ongoing projects depending upon the requirement.



TYPES OF UNCERTAINTIES

FIGURE 1-2

1.3.3 Availability of a Resource Type from Multiple Dependent Sources

A particular type of resource required by the new project may be expected from a number of dependent uncertain sources, for example from different activities of the same project which depend on each other for resources and the durations of which are probabilistic.

Similarly multiple resource types may be drawn from multiple dependent sources.

1.3.4 Availability of Multiple Resource Types from a Single Source

More than one type of resource may be expected to become available from the same source. For example, there may be an activity in an ongoing project after completion of which multiple resource types will become available for the new project.

The larger the number of uncertain sources from which the required resources are expected to become available, the higher is the associated risk. Hence, a scheduling engineer normally restricts such sources. A maximum of three sources whether dependent or independent for each type of resource seems adequate. However, there is no limit on number of sources as long as they are certain. The scope of the problem is to evaluate the risk in project schedule and cost when required resource types are available from a maximum of three uncertain sources. It could be a single source, or multiple dependent or independent sources.

1.4.0 <u>State of the Art</u>

A review of existing resource allocation methods applicable to 1) time-cost tradeoff procedures, 2) resource leveling, and 3) constrained resource allocation is given in this section which will help determine the state of the art and therefore the need for the present study.

1.4.1 <u>Time-Cost Tradeoff Procedures</u>

The first study on functional relationship between project cost and duration is due to Kelly(23),(24). He developed a parametric linear programming formulation and used Ford-Fulkerson network-flow algorithm to obtain the project cost curve. In a separate article originating slightly after the first article by Kelly, Fulkerson(15) also presents a network-flow solution of project cost curve.

Because of the restrictive assumptions imposed on the activity time-cost functions by Kelly-Fulkerson procedure, other time-cost tradeoff procedures have been devised which are intended to handle nonconvex activity functions as well as discrete time-cost points. The DOD/NASA Guide PERT/Cost(12) describes such an approach. A similar idea is proposed by Alpert and Orkand(2) and also by Moder and Phillips(30).

Other approaches developed for time–cost tradeoff function include integer linear programming technique offered by Meyer and Shaffer(28), and mathematical programming approach offered by Jewell(21). A different approach for the restricted case of continuous convex activity time–cost functions is offered by Berman(5). He assumes that cost approaches infinity as time approaches some minimum feasible value and that as time increases cost will decrease to some minimum value and then turn up.

Handa(18), Parikh and Jewell(33), and Prager(35) have offered different approaches for reducing the total amount of computer memory storage required by the network flow algorithm.

It may be concluded that there is a variety of analytical solutions available for the time–cost tradeoff problems. All these available techniques differ primarily because of their assumptions about the characteristics of the activity time–cost functions. Very little research has been conducted to analyze this problem when resource availability is uncertain.

1.4.2 Resource Leveling

The purpose of resource leveling is to smooth the resource usage as much as the problem will permit, subject to the time constraints of the various activities. A systematic approach to this problem has been offered by Burgess and Killebrew(7). They suggest a method of comparing alternate schedules obtained by sequentially moving, in time, slack activities and computing the resulting resource profile. The measure of effectiveness they propose for comparison of schedules is the sum of the squares of the resource requirements. Dewitte(11) as well as Levy, Thompson and Wiest(25) describe two different computer programs for smoothing manpower requirements. These programs are designed to minimize manpower fluctuations by adjusting the start times of project activities having slack.

A slightly different version of the Levy procedure is presented by Wilson(42), designed to produce the minimum number of resources required to achieve a given project duration. Instead of random choice step, as in the Levy Model, he incorporates a dynamic programming scheme at each iteration to determine feasible combinations of activities. However he makes a simplifing assumption that each activity requires one unit of the same type of resource.

A somewhat similar technique of splitting events into divisible unit time lengths is offered by Black(6) for the resource leveling problem. His approach is an adaptation of the Gutjahr–Nemhauser (17) line balancing algorithm. It involves generation of feasible sets of jobs in the given network, then construction of a new network using the generated sets as nodes and stated resource constraints as arc lengths. This method will produce all feasible solutions with respect to resource constraints.

It may be summarized that the techniques adopted for leveling resource demands depend on whether resource availability is limited or unlimited. In both the cases, extensive research has been done using heuristic as well as optimal procedures. However, little work has been done to extend these procedures to take into account the uncertainty due to resource availability.

1.4.3 Constrained Resource Allocation

The constrained resource allocation scheduling may be classified into two main categories namely 1) heuristic procedures and 2) optimal procedures. The heuristic procedures involve the use of some rule of thumb or "heuristic" in determining priorities among jobs competing for available resources. In contrast, the optimal procedures aim at producing the best possible or optimal schedules. Within each of these two major categories, there are further possible schemes of initial sub-categorization. Existing heuristic procedures, for example, fall into the categories of 1) serial or 2) parallel routines depending upon whether the priorities assigned to competing jobs are determined before the sequencing takes place or during the sequencing operation. A review of the existing methods for both heuristic and optimal procedures is given below.

Heuristic Procedures

A great deal of work has been done in the development of different heuristic rules as well as in the selection of heuristic rule for a network under consideration. Only few noteworthy works are mentioned here.

One early heuristic based procedure which is important from historical point of view is RAMPS program developed jointly by CEIR Inc.(now a division of Control Data Co.) and the Du Pont Company. Description of this procedure is available in Moshman, Johnson and Larsen(29) and

Wiest(38),(39). Briefly, a parallel routine is used to examine in each time period all feasible combinations of competing jobs. This program can handle up to 100 separate projects each consisting of up to 2000 activities and requiring up to 100 different resource types.

Another of the earliest program was developed by J.D. Wiest. His SPAR (Scheduling Program for Allocating Resources) I and II are described in (41) and (39). These programs have been applied to single and multiple project problems of more than 200 jobs and 20 different resource types. These two programs were followed by a series of works all of which employ one or more scheduling heuristic in a general fashion described succinctly by Wiest(40). Very general descriptions of the resource allocating features of these and other such programs are given by Phillips(34), O'brien(31), Woodgate (43), Antill and Woodhead(3), Hooper(20),and O'Rourke(32).

Optimal Procedures

In contrast to the tremendous efforts which have gone into the investigation and creation of elaborate heuristic based scheduling models, the development of optimal procedures has progressed relatively slowly. The reason for this is that no formal mathematical model can be utilized at the present time for scheduling projects under limited resources. Rather, only heuristic methods can be employed.(1), (8). Employing optimization procedures for resource allocation has been explored by Wiest(39), Elmaghraby(13), Pristker, Watters and Wolfe(36), Fisher(14), Johnson(22), Davis(10), Balas(4), Sunaga(37), Gorenstein(16),and

Hastings(19). However, till today, there is no optimal procedure available which can be applied to commercial projects with large number of activities and resource types.

It may be concluded that much research has been done in the selection of proper heuristic rules as well in the development of optimal procedures for solving resource constrained problems. Only the heuristic approach is applied for large networks while further research is being conducted to improve the applicability of the optimal approach. However, both these approaches do not consider the uncertainty associated with resource availability.

1.5.0 <u>Risk Evaluation in Probabilistic Network Scheduling</u>

From the state of the art in resource allocation, it is clear that uncertainty due to availability of resources has not been taken into account. It is now necessary to see how far it is incorporated in probabilistic network scheduling. A technique for exposing uncertainties during network scheduling stage was first presented by D.G. Malcom, J.H.Roseboom, and C.E.Clark (27) in their paper which describes the development of a technique for measuring and controlling development progress for the Polaris Fleet Ballistic Missile program, Special Projects Office, Bureau of Ordinance , U.S. Navy. The uncertainty of each activity is expressed in the form of three elapsed time estimates namely the optimistic, most likely and pessimistic time estimates. For further evaluation of mean duration and the associated variance, a beta distribution is formed out of these three time estimates. This technique is commonly known as PERT (Program Evaluation Review Technique).

As per the definition PERT, in estimating the optimistic time, better than normal conditions are assumed to prevail during the execution of an activity. The pessimistic time is the maximum possible time required to complete the activity, if everything went wrong and abnormal situation prevailed. The most likely time assumes that things go in normal way with few setbacks.

Now the question arises, what uncertainties are covered by these three time estimates and whether or not the uncertainties associated with the availability of resources is included. While evaluating the start and finish times from network scheduling, the question of resource availability is not considered. Matching the resource availability with demand is done exclusively at the second stage i.e. in resource allocation scheduling. Moreover, the uncertainty due to resource availability can not be evaluated while estimating durations of individual activities of the new project because the time when each activity requires these resources is not known. It is known only after allocating resources. Hence it can be concluded that the activity elapsed time estimates do not reflect the uncertainty due to resource availability and this uncertainty should be treated as part of the resource allocation problems. The literature survey, as referenced in this and preceding sections indicates that there is no existing procedure available for risk evaluation in resource allocation when resource availabilities are uncertain.

1.6.0 The Need for a New Methodology

When uncertain resources are used for planning and scheduling a new project, both the completion time and cost of the new project become probabilistic. A scheduling engineer needs to know the extent of risk involved in using resources with varying level of uncertainty. This information will aid him in planning and scheduling the new project with confidence. As discussed in the preceding sections, neither the probabilistic network nor the conventional resource allocation scheduling takes this uncertainty into account. Hence, there is a need for a new methodology to determine the impact of uncertain resources on project schedule and cost so management can evaluate the risk associated with each alternative schedule and select the one which meets its needs.

1.7.0 Problem Statement

Having defined the scope of the problem, reviewed the existing procedures and having discussed the need for a new methodology, the problem can be precisely stated. The uncertainty associated with availability of resources is a major factor to be considered for resource allocation because the best schedule must not only have the least duration and minimum overall cost but also a reasonable level of probability to accomplish the project on time and within cost. A simple model is required to quantify this uncertainty and evaluate its impact on project duration and cost.

CHAPTER 2

RATIONALE OF THE MODEL

2.0.0 RATIONALE OF THE MODEL

This thesis proposes a Risk Evaluation Model (REM) which takes a resource justified schedule as input, incorporates uncertainty associated with availability of resources and generates alternate schedules with different cost and performance probability. The rationale of REM is presented in this chapter while its working is described in Chapter 3.

2.1.0 Risk Evaluation Model

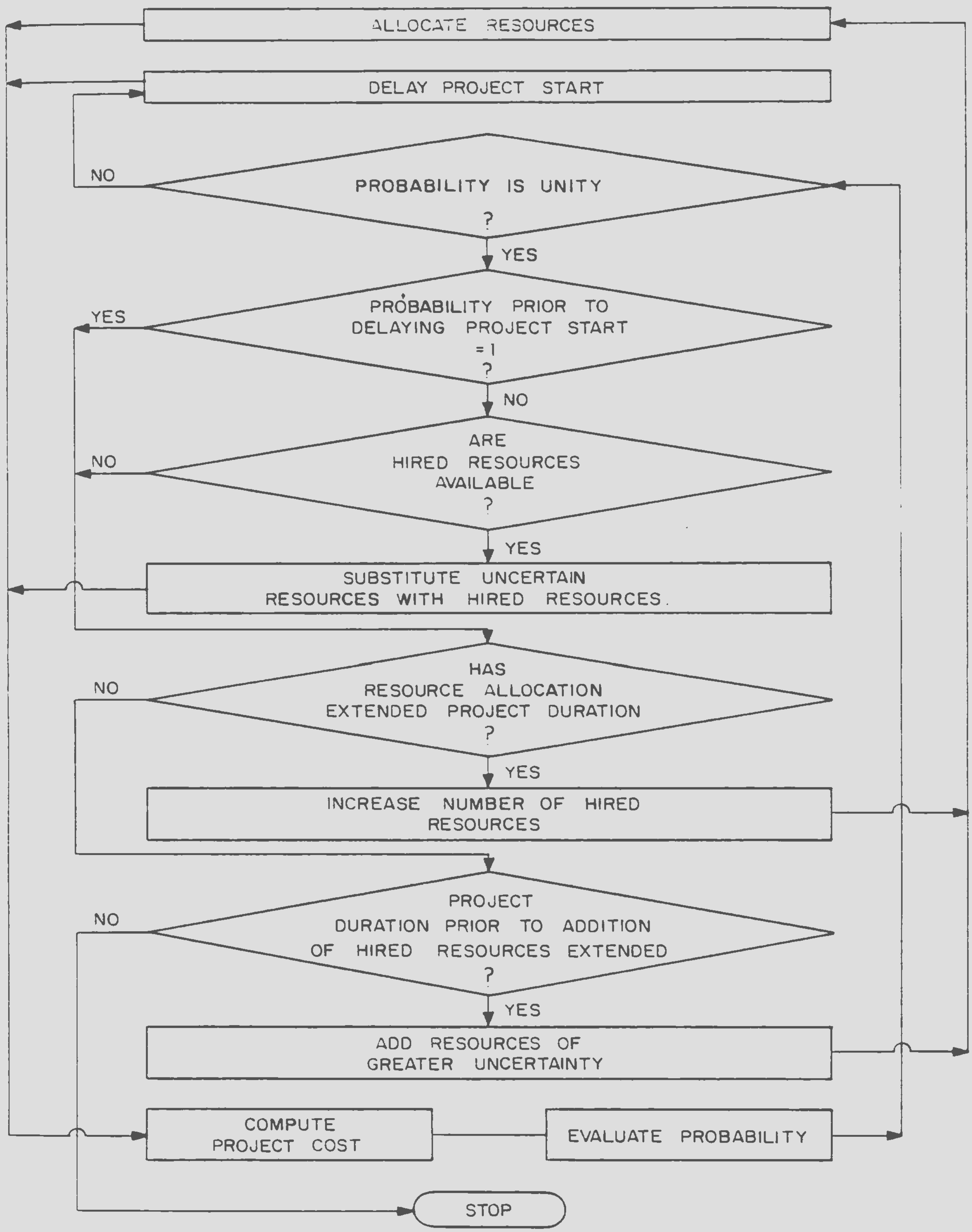
REM is illustrated by the schematic chart in Figure 2.1. It consists of the following four major processors.

1) Resource Allocation Processor,
2) Stage One and Stage Two Processor,
3) Cost Evaluation Processor, and
4) Probability Evaluation Processor

The principle behind each one of these processors, keyed by section numbers to relevant parts of the flow chart, follows:

2.2.0 Resource Allocation Processor

To evaluate risk due to uncertainty in resource availability, it is necessary to know when the uncertain resources will be required for the first time and subsequent times on the new project. A CPM network followed by resource allocation scheduling can provide the answer. REM considers for allocation 1) in-house resources, either certain or uncertain and 2) hired resources i.e. the resources which are hired specifically for



RISK EVALUATION MODEL

FIGURE 2-1

the use on the new project. Of course, the hired resources are expensive in comparison to the in-house resources but are definitely available. Only in-house resources from the least uncertain source are considered for allocation in the first instance and a resource justified schedule is obtained using standard resource allocation procedure.

This schedule is further processed by the Stage One and Stage Two Processor, Cost Evaluation Processor, and Probability Evaluation Processor and different sets of data on project completion time, cost and performance probability are obtained. The same procedure is repeated by considering various combinations of hired resources and in-house resources from different uncertain sources. This step is illustrated in Figure 2.1 and the methodology is discussed in detail in Chapter 3.

2.3.0 Stage One and Stage Two Processor

The uncertainty level of each resource justified schedule is improved in two ways 1) by delaying the start of the new project (This will be referred to as Stage One Processor) and 2) by substituting the uncertain resources with hired resources (This will be referred to as Stage Two Processor). The description of the two stages of processors follows:

2.3.1 Stage One Processor

The Stage One Processor is achieved by shifting forward the start date of the new project without altering the resource profile. For example, if the start date is pushed forward by a week, the first day when all uncertain resources will be required is correspondingly moved forward.

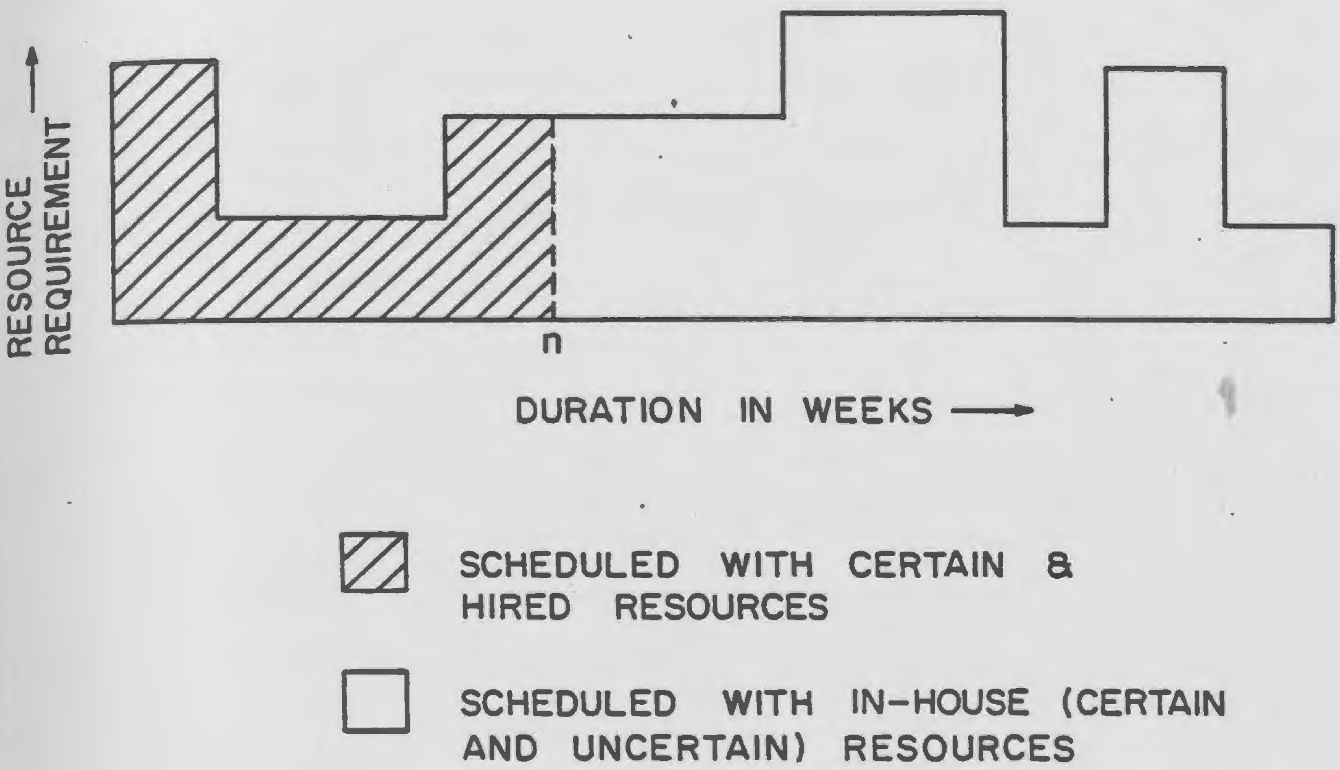
This enhances the certainty of their availability. However, since the project completion time is delayed, the project cost may go up due to penalty.

2.3.2 Stage Two Processor

When the penalty for delay is heavy, the performance probability can be improved by replacing uncertain in-house resources with hired resources. When the uncertainty of in-house resources reaches the acceptable level, they can be substituted back for hired resources. In doing so the project cost increases neither by penalty nor by overheads. However, it goes up because more resources are hired at a cost comparatively higher than the in-house resources. This procedure is discussed with the help of Figure 2.2.

The profile of resource type R1 required by the new project is shown in the figure. First 'n' weeks are completely scheduled with certain, in-house and hired resources. At the end of the nth week, the hired resources are replaced by uncertain resources. This procedure delays the requirement of uncertain resources at least by 'n' weeks and hence improves the performance probability. By varying the value of 'n', alternate project schedules are generated which have the same project duration but different resource usage patterns.

If the new project requires more than one type of resource, the substitution of uncertain by hired resources can be done for each resource type as well as different combinations among them. These procedures result in a large number of alternate schedules with different cost and probability. Moreover, for each alternative obtained by such substitutions,



COMPUTATION BY SUBSTITUTING UNCERTAIN RESOURCES WITH HIRED RESOURCES

FIGURE 2-2

additional combinations are obtained by delaying the project start. Heuristic methods, developed to keep the number of alternatives within a reasonable limit, are discussed in detail in Chapter 3.

2.4.0 Cost Evaluation Processor

The Stage One and Stage Two processing of resource justified schedule is followed by project cost analysis, the purpose of which is to compute the cost of each alternative. In addition, it also indicates to Probability Evaluation Processor the time when the uncertain resources are required by the new project.

The alternatives generated by Stage One and Stage Two Processor have different completion times. Hence, it would seem appropriate to compute the net present worth of each alternative by discounted cash flow technique (DCF). However, DCF technique is not adopted for the present study due to the following reasons.

1) While planning a project, highly uncertain sources are not generally considered. Hence, Stage One Processing may not generate alternatives having widely different completion times and direct cost computation may not result in appreciable error.

2) The extension of project completion time results in decrease in net present worth of the direct cost. However, it also increases penalty due to delay, overhead and escalation costs which may nullify the decrease in net present worth of direct cost to some extent.

The total cost of a project is comprised of the following:

1) Resource Cost.

2) mobilization cost.

3) other costs.

4) overhead cost and.

5) penalty. if any.

Other cost inludes the cost of nonscarce resources not considered for resource allocation. all indirect costs including contingency. provision for escalation etc. The computation of each component of project cost is dealt with in detail in Chapter 3.

2.5.0 Probability Evaluation Processor

The Cost Evaluation Processor indicates the time when the uncertain resources will be required by the new project. The probability of resource availability is evaluated for each alternative from this time and the corresponding probability distribution curve. Selection of proper probability distribution for the availability of each uncertain resource type and evaluation of its parameters are elaborated in this section.

2.5.1 Time Estimates for Uncertain Resource Availability

The first step towards selection of proper probability distribution is to define the time estimate for the availability of each uncertain resource type. The inherent difficulties and variability in the resource availability can be expressed by giving three time estimates namely the optimistic. most likely and pessimistic time estimates. These estimates are obtained from technical persons who are responsible for the release of resources for the new project. The definitions of these estimates follow:

The Optimistic Time Estimate

This is the estimate of the shortest possible time in which an uncertain resource(s) will be released for the new project under ideal conditions. In arriving at this estimate no provisions are made for delays or set backs. Better than normal conditions are assumed to prevail during the execution of the job to which the required resources are tied up.

The Most Likely Time Estimate

The most likely time estimate lies between the optimistic and the pessimistic time estimates. It assumes that things go in the normal way, with few setbacks, usual lapses in deliveries, and no dramatic break throughs.

The Pessimistic Time Estimate

This is the maximum possible time it could take to accomplish the job. If everything went wrong and abnormal situations prevailed, this would be the time estimate for the release of resources. Of course, major catastrophes like labour strikes or unrest, acts of God, etc. are excluded from this estimate.

2.5.2 Selection of Probability Distribution

The probability distribution curve is formed out of the three elapsed time estimates given for resource availability. Assuming that the distribution is continuous, unimodal and that it touches the abscissa at two nonnegative points, a number of distributions from triangular to beta distribution may be thought of. However, the beta distribution is preferred because it is flexible and offers a compromise most suited to wide range of circumstances, encountered in a regular project (1), (30). This assumption is the same as the PERT assumption (27) of beta distribution for activity duration.

In PERT while activity duration is assumed to have beta distribution, the project completion time is assumed to be normally distributed by the application of central limit theorem. The quality of this assumption improves with the number of uncertain activities in the network. In the proposed model, the availability of resources from independent uncertain sources is assumed to have beta distribution, whereas availability of resources from dependent uncertain sources such as interlinked uncertain activities of an ongoing project, is assumed to be normally distributed.

2.5.3 Beta Distribution

A probability distribution appropriate for a random variable whose values are bounded between two finite limits is the beta distribution. The finite limits for the present study are the optimistic and pessimistic times because the duration of an activity can have any value between these two extreme limits. The density function of this distribution is as follows:

$$f_x(x) = \frac{1}{B(q,r)} \frac{(x-a)^{q-1}\,(b-x)^{r-1}}{(b-a)^{q+r-1}} \qquad a < x < b \qquad \ldots.\ 2.1$$

$$= 0 \qquad \text{elsewhere}$$

Where

B(q,r) is the beta function,

a is the optimistic time,

b is the pessimistic time.

q and r are the parameters of beta function.

2.5.4 Evaluation of Parameters of Beta Function

The beta function is evaluated by the following equation.

$$B(q,r) = \int_0^1 x^{q-1} (1 - x)^{r-1}\, dx \qquad 2.2$$

The mean t_e. variance σ^2 and mode m are given by the following equations.

$$t_e = a + q.(b-a)/(q+r) \qquad ..... 2.3$$

$$\sigma^2 = qr.(b-a)^2 / [(q+r)^2.(q+r+1)] \qquad .... 2.4$$

$$m = a + (1-q).(b-a)/(2-q-r) \qquad ..... 2.5$$

Where,

m is the most likely time

The two unknown parametrs q and r must be evaluated for defining the beta function completely. There is only one normal equation (equation 2.5). Hence further assumption regarding mean or variance is necessary. Again a comparison with PERT assumption that the standard deviation is one sixth of the difference between pessimistic and optimistic time estimates is useful. The same assumption is made to evaluate the unknown parameters. It is reported in the literature(26) that the worst absolute error in this assumption is about 17%(26). This occurs for the extreme values for q and r. Solving the simultaneous equations 2.4. and 2.5. the values of r and q are obtained as follows:

$$A1.r + A2.r + A3.r + A4 = 0 \qquad \ldots 2.6$$

$$q = [r(m-a) + (b-2m+a)]/(b-m) \qquad \ldots 2.7$$

Where

$$A1 = (b-a)^3$$

$$A2 = 3(b-a)^2(b-2m+a)+(b-m)^3+(b-m)(m-a)^2-34(m-a)(b-m)^2$$

$$A3 = 3(b-2m+a)^2(b-a)+2(b-m)(m-a)(b-2m+a)-34(b-m)^2(b-2m+a)$$

$$A4 = (b-2m-a)^3+(b-m)(b-2m+a)^2$$

Now the beta distribution is completely defined. However, it requires a solution of a cubic equation. The problem is simplified in PERT by further assuming that mean time is one sixth of the optimistic and pessimistic times, and four times the most likely time. It has been concluded by several authors(26) that such an assumption may cause a worst absolute error of 33%. Since the number of uncertain activities in PERT is large, the pluses may offset the minuses and the resultant error may not be appreciable. However, since the number of uncertain resource types required by the new project may not be large, this assumption may cause an appreciable error in the present study. Hence, REM solves the cubic equation in preference to use of the approximate solution.

The assumption on variance is also provisional. If it is possible to obtain the variance for the availability of the resources, the same should be used to define the beta function.

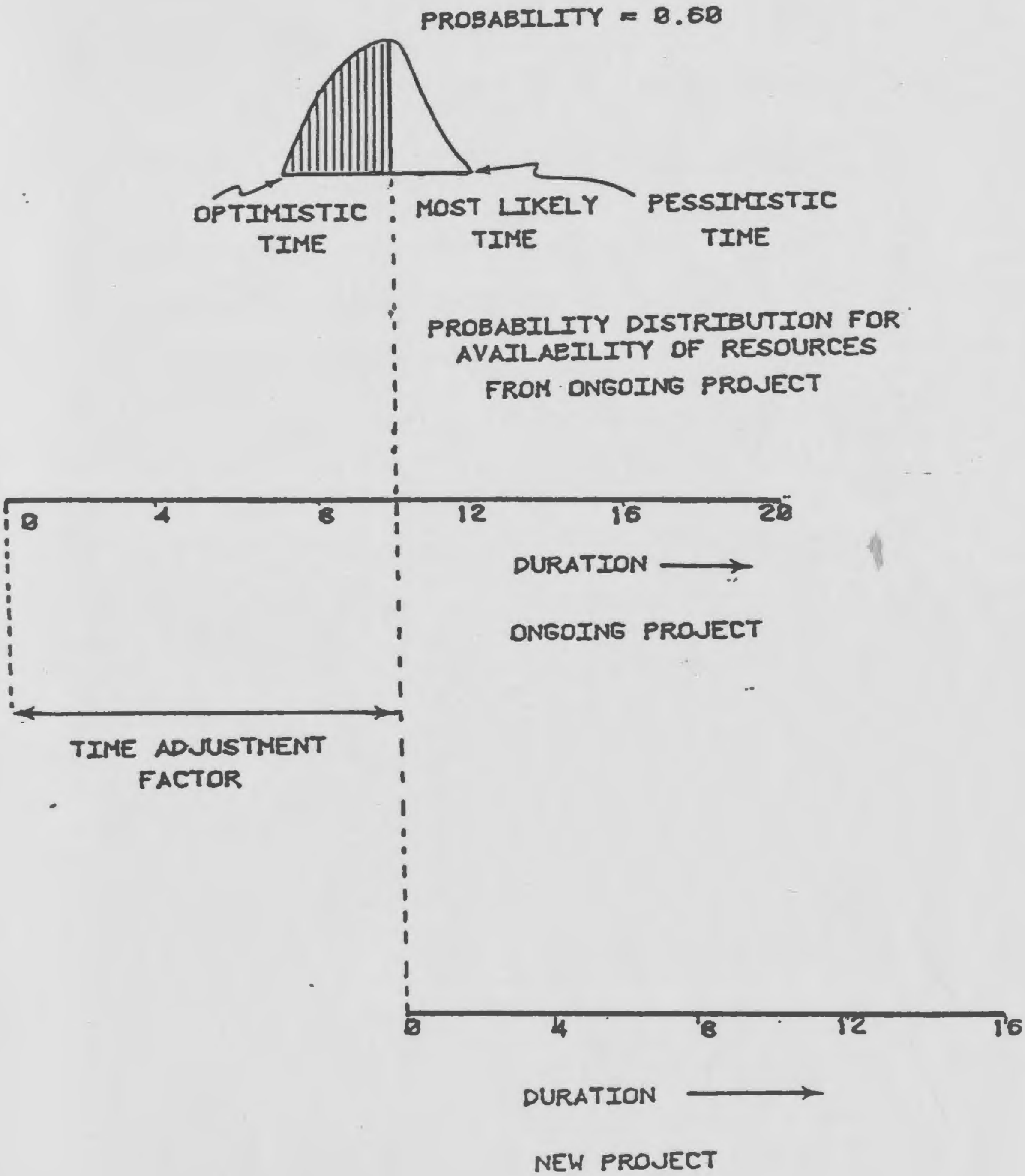
2.5.5 Reference Points for Time Estimates

If an uncertain resource is expected from an ongoing project, the three time estimates are given with reference to the scheduled start time of the ongoing project. The time estimates include the completion time of the activity from which the resources are likely to be released as well as the time required to mobilize them from ongoing to new project site. This procedure is illustrated in Figure 2.3. A resource type R1 is required by the new project from the ongoing project. The optimistic, most likely and pessimistic times for the availability of R1 are 7, 10 and 12 respectively which also include the time required to mobilize them from ongoing to new project site. The adjustment factor which is the time difference between scheduled start date of the ongoing and the new projects is 10. The new project requires these uncertain resources on the very first day i.e 11th day from the start of the ongoing project. The probability for receiving the resources on the new project on day 11 from the probability distribution curve is 0.60.

However, if the required resources are expected from dependent activities of the ongoing project, the time estimates for the availability of resources from the first activity are given with reference to the start of the ongoing project and the time estimates for the availability of resources from the following activity must refer to the completion time of first activity and so on.

If the uncertainty for the availability of resources is due to any reason other than project risk of the ongoing project, the time estimates must be given with reference to scheduled start date of the new project and the adjustment factor is zero.

As per the definition of beta distribution, all the three time estimates



REFERENCE POINTS FOR TIME ESTIMATES

FIGURE 2.3

must be nonnegative. Hence, if the optimistic time estimate is negative, then the addition of a value equal to the magnitude of the optimistic time estimate to all the three time estimates as well as to the adjustment factor makes them positive.

The principle behind the probability evaluation was presented in this chapter. The method of probability evaluation which varies with nature of uncertainty associated with availability of resources, is discussed in Chapter 3.

CHAPTER 3

RISK EVALUATION MODEL

3.0.0 RISK EVALUATION MODEL

Chapter 2 discussed the rationale of REM whose working is described elaboratedly in this chapter. REM is discussed with the help of the summary flow chart illustrated in Figure 3.1 which presents greater detail than presented in Figure 2.1. The explanation for each major step in the summary flow chart is presented here under the following headings.

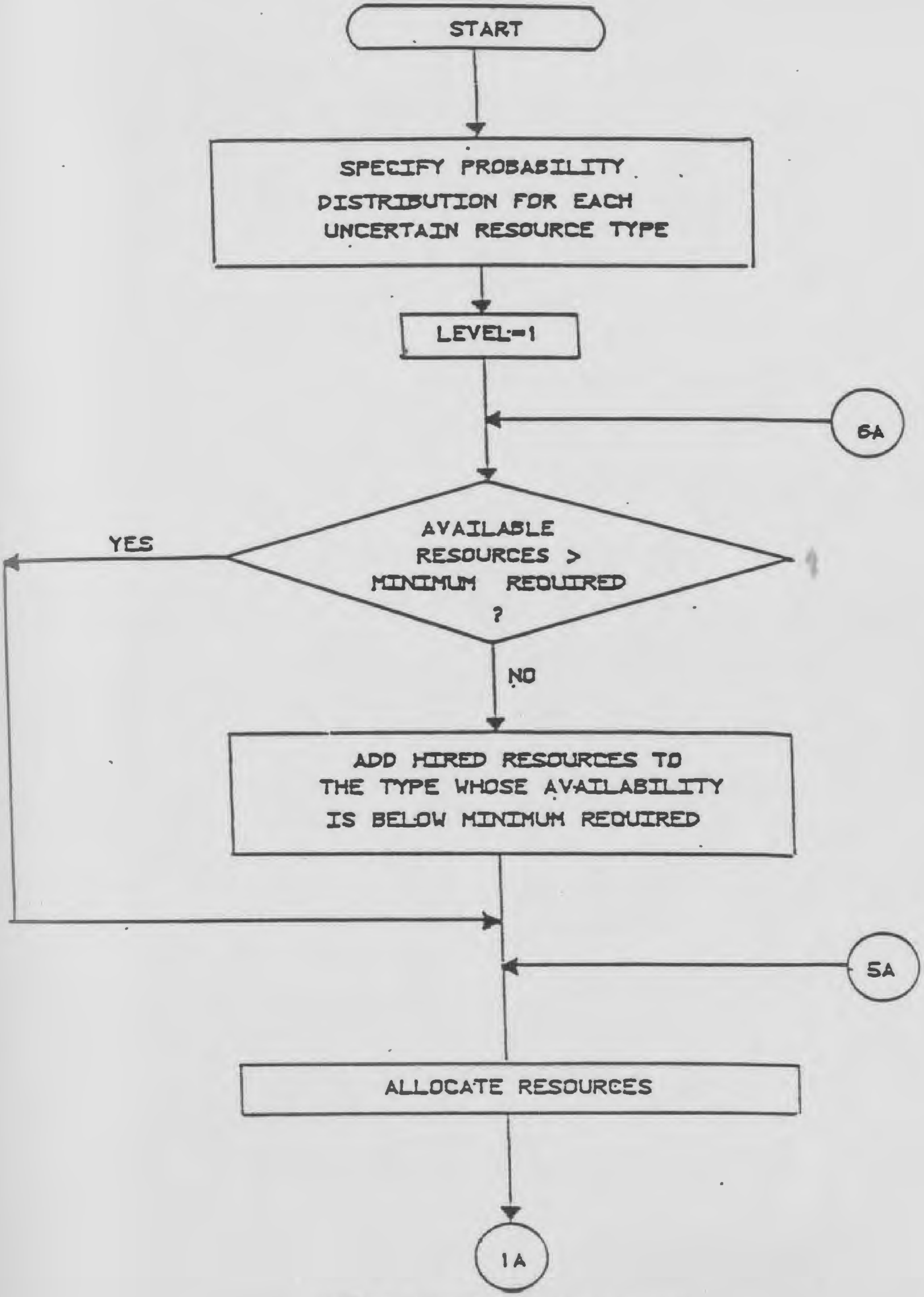
1) Resource Allocation Processor.
2) Stage One and Stage Two Processor.
3) Cost Evaluation Processor. and
4) Probability Evaluation Processor

3.1 0 Resource Allocation Processor

Allocation of resources to different activities of the new project is the first step in REM. Both certain and uncertain in-house resources and the resources which can be hired definitively are considered for resource allocation in the order mentioned. The resource allocation procedure consists of the following major steps.

Step 1

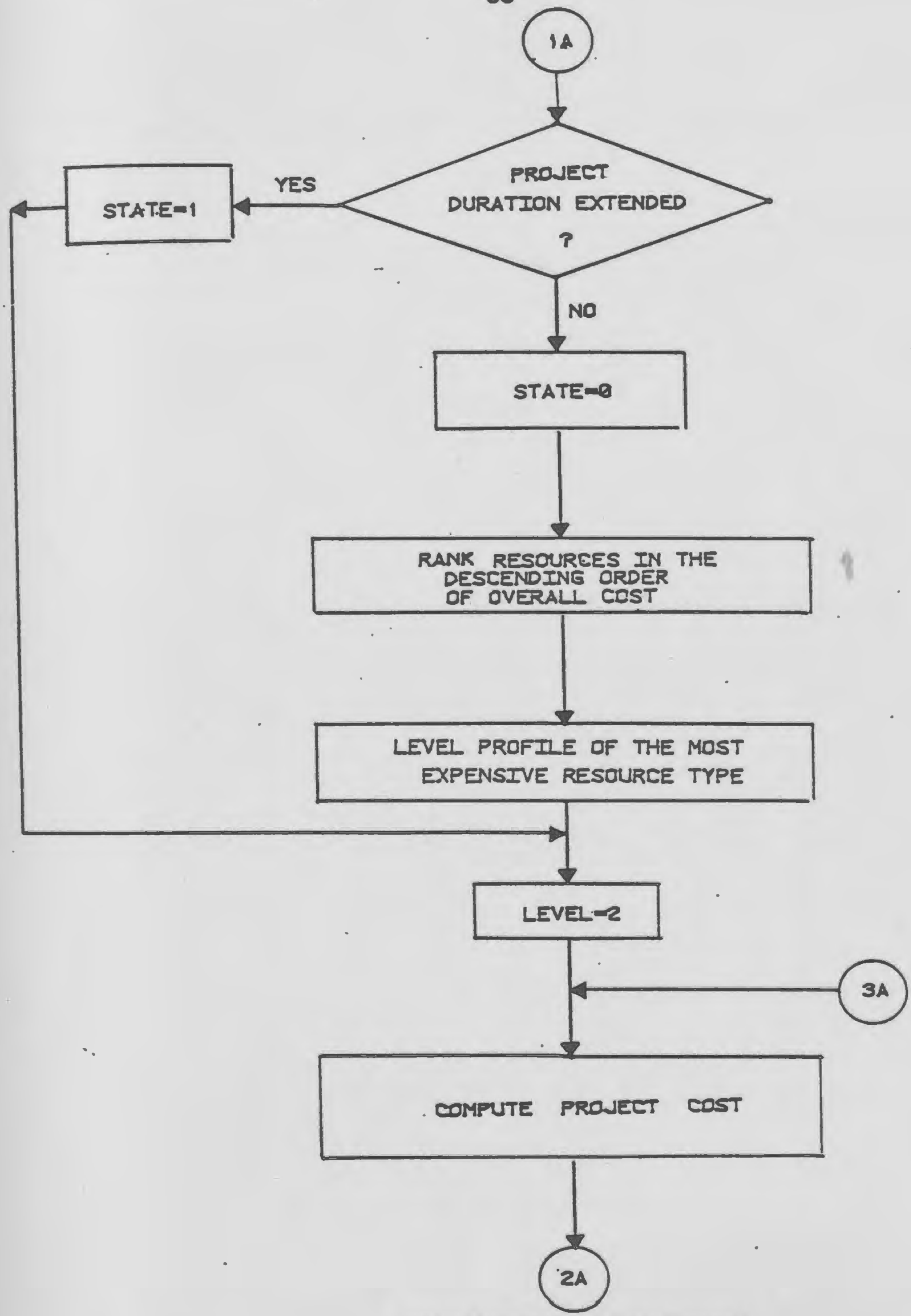
The first step is to determine whether the resource requirement of the new project can be met with in-house resources. If so. the extent of their certainty or uncertainty must be determined. If any resource type is expected from more than one independent source with unequal uncertainty. the resources from the least uncertain source are considered first.



RESOURCE ALLOCATION

STEPS 1-2

Risk Evaluation Model
Figure 3.1, Cont'd..

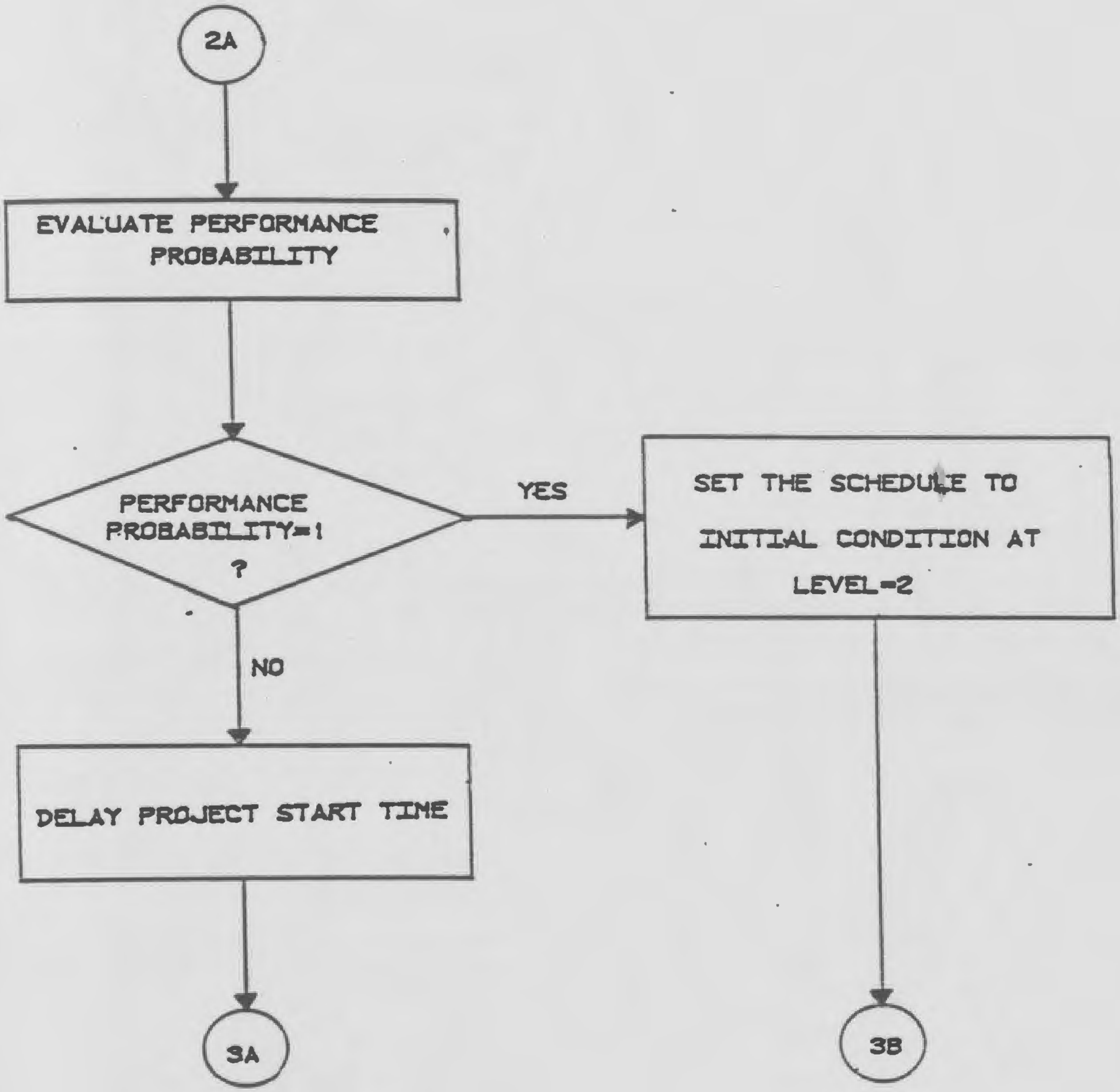


RESOURCE ALLOCATION

STEP 3

Risk Evaluation Model

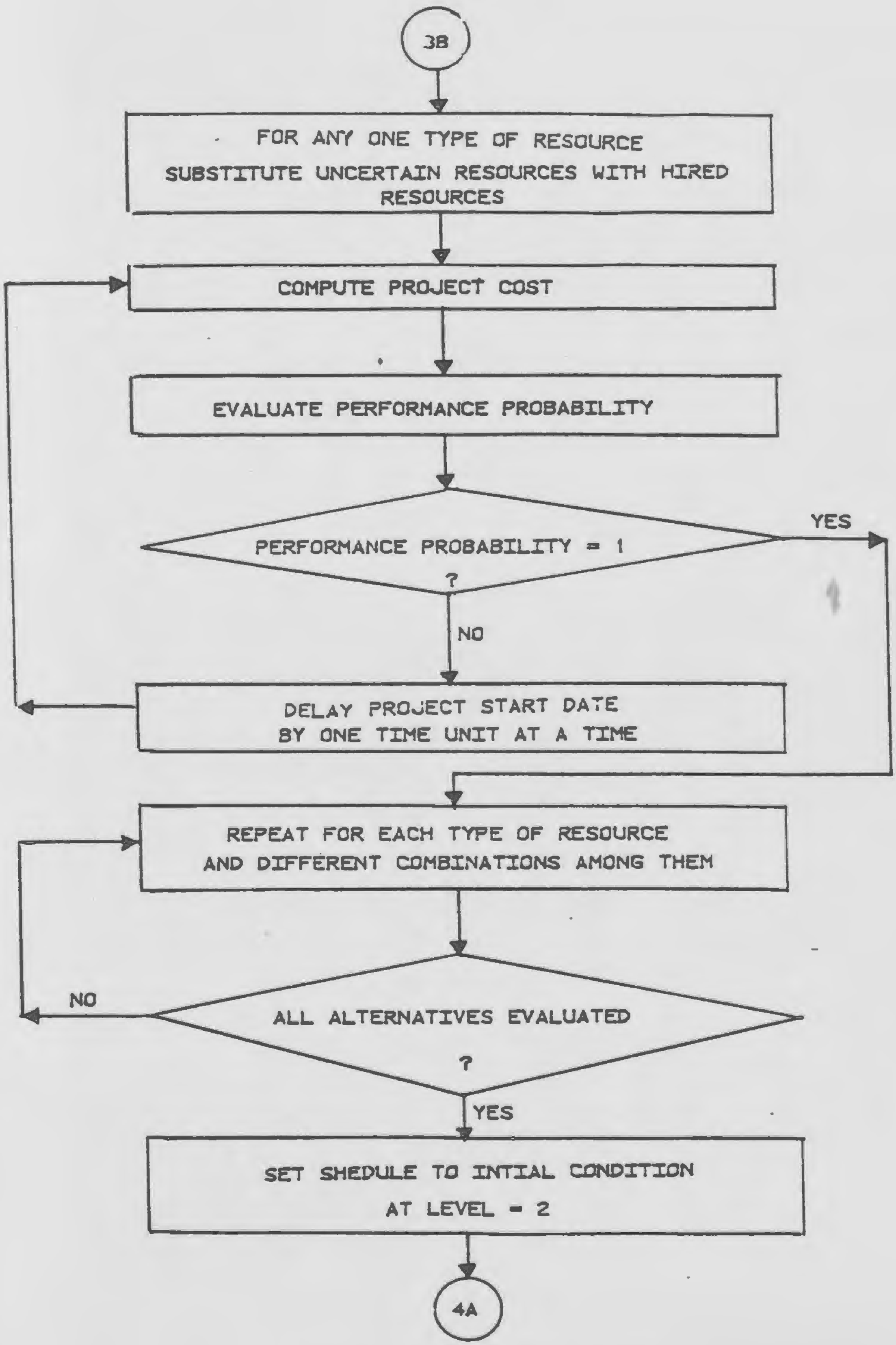
Figure 3.1. Cont'd..



STAGE ONE COMPUTATION

STEP 4

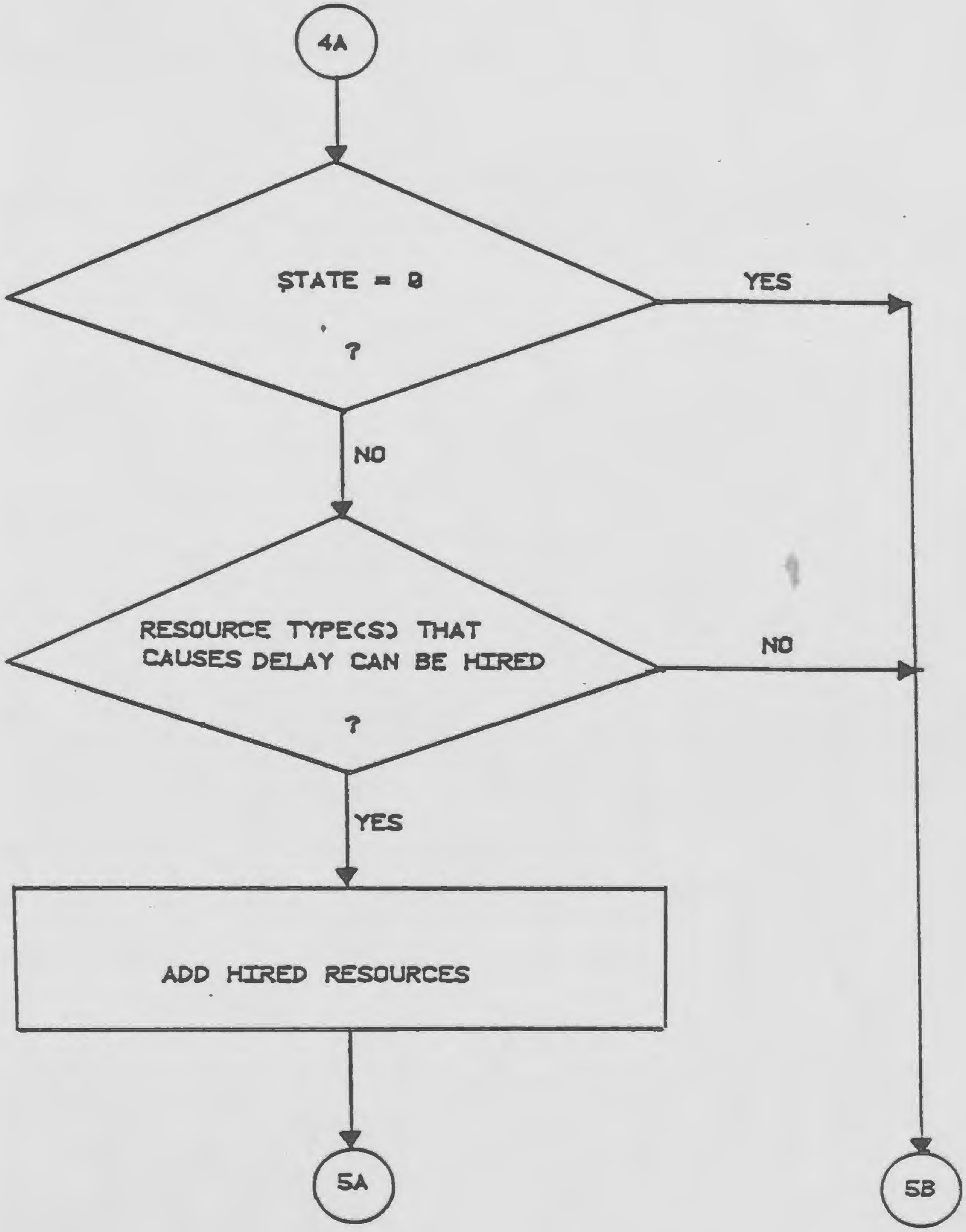
Risk Evaluation Model
Figure 3.1. Cont'd..



STAGE TWO COMPUTATION

STEP 4 (continued)

Risk Evaluation Model
Figure 3.1. Cont'd..

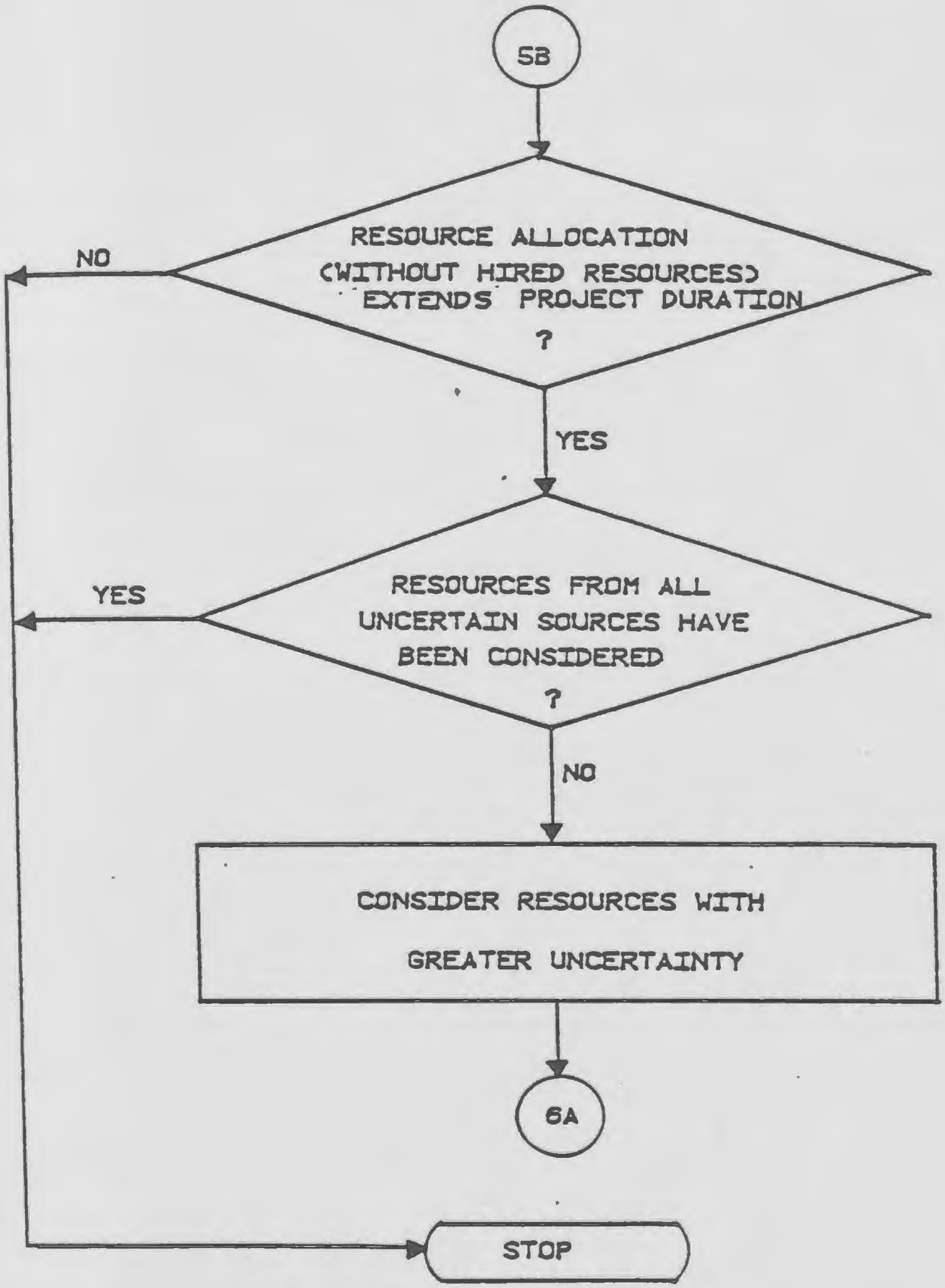


ALTERNATE RESOURCE ALLOCATION SCHEDULING

BY VARYING THE NUMBER OF HIRED RESOURCES

STEP 5

Risk Evaluation Model
Figure 3.1, Cont'd..



ALTERNATE RESOURCE ALLOCATION SCHEDULING

BY USING RESOURCES OF GREATER UNCERTAINTY

STEP 6

RISK EVALUATION MODEL

FIGURE 3.1

Step 2

The available number of each type of resource determined in this manner, is compared with the number of corresponding type required by each activity of the new project. If the available resources are less than the largest number required by any one activity of the new project and if such resources can be hired, sufficient number of hired resources are added to bring this number to the required level. If the resources of the required type can not be hired, the resources from the next higher level of uncertainty, if available, are considered.

Step 3

Resource allocation scheduling follows. Any package program may be used for allocating resources. IBM/PMS IV Resource Allocation Processor (RAP) was used in the present study. If the resource allocation scheduling does not extend the project duration, the usage profile of the most expensive resource type is leveled.

Step 4

The resource allocation is followed by evaluation of alternate sets of project completion time, cost and performance probability which is discussed in sections 3.3.0 and 3.4.0

Step 5

If the schedule is extended in step 3, additional resources of the type that caused the extension, may be hired within specified limits. Steps 3 and 4 are carried out once again after adding hired resources. This procedure is repeated until no more resources can be hired or the desired project duration is achieved whichever occurs earlier.

Step 6

If the resource allocation scheduling using only in-house resources had extended the project duration in step 3, the resources from the next least uncertain source, if any, are added to the type which caused the extension. Steps 3 to 5 are reiterated followed by step 6 until a resource justified schedule with the desired project duration is achieved or resources from all uncertain sources are exhausted, whichever occurs earlier. If the extension is due to shortage of more than one type of resource, then various combinations among them are considered in this step.

3.2.0 Stage One and Stage Two Processor

The alternative schedules with different project completion time, cost and performance probability are obtained in two stages namely 1) delaying the start of the project and 2) substituting the uncertain resources with hired resources. These two stages were discussed in section 3.3.0. The method of evaluating project cost and performance probability is elaborated in the following sections.

3.3.0 Cost Evaluation Processor

As stated in section 3.4.0, the total cost of a project is comprised of the following :

1) Resource cost,
2) mobilization cost of resources,
3) other costs,
4) overhead cost, and
5) penalty, if any.

The method of evaluation of each of the above costs follows:

3.4.0 Resource Cost

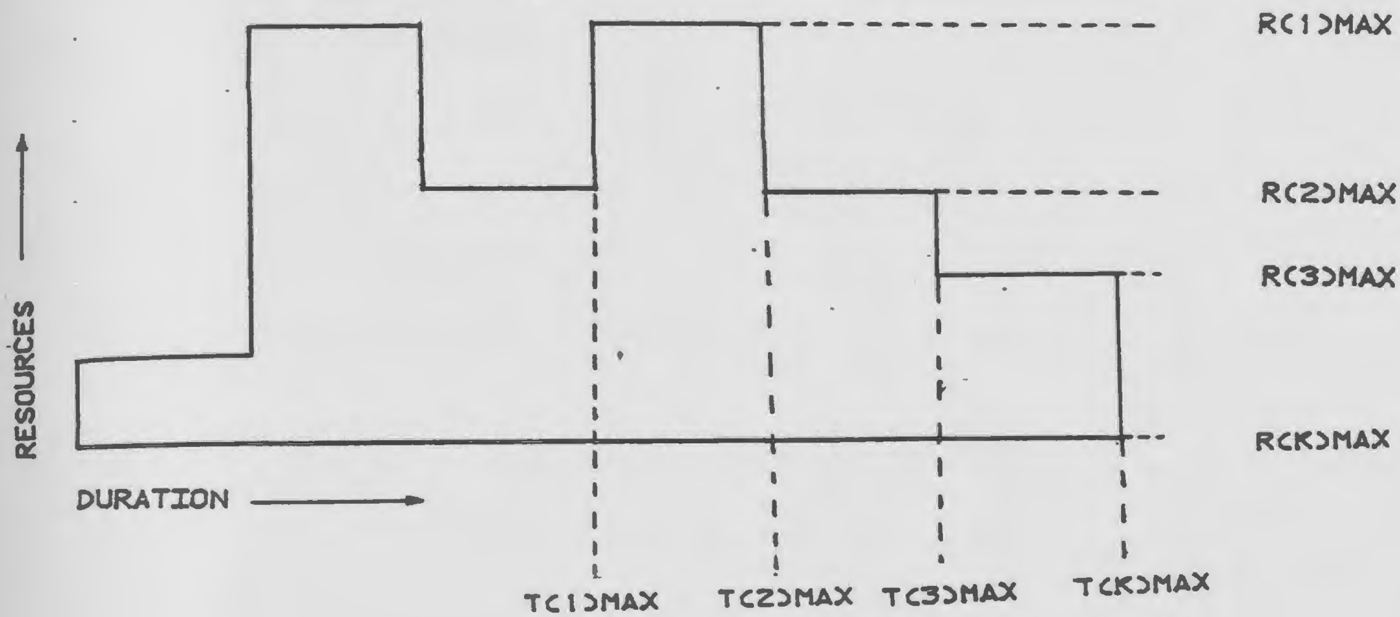
The cost of each type of resource is calculated separately from resource justified schedule. The technique adopted for calculation of cost depends on whether stage one or stage two computation is in progress.

Evaluation of Resource Cost for Stage One Processor

The resource cost is evaluated from the resource usage profile which is built up gradually from the start of the project until the peak requirement is reached whereafter the resources are retired gradually. Hence, the time when the requirement reaches the peak is determined from the resource profile and this peak is hereinafter referred to as R(1)Max. The number one in parenthesis stands for the first peak from left of the resource profile. If there are more than one R(1)Max in the same profile, the one rightmost from the start on the profile is considered as R(1)Max. Then R(2)Max which is the peak between R(1)Max and the requirement in the last time unit of the profile is evaluated. This procedure which is illustrated in Figure 3.2, is repeated until R(K)Max i.e. the requirement in the last time unit is reached. The duration corresponding to R(1)Max, R(2)Max..... and R(K)Max are T(1)Max, T(2)Max..... and T(K)Max respectively.

The objective being to keep the overall cost of the new project to a minimum, certain in-house resources are considered first. When resource requirement exceeds the available number of certain resources, the uncertain in-house resources are considered. When in-house resources are not adequate to meet the requirement of the new project, hired resources are added. The project cost is kept to a minimum by delaying the utilization of hired resources. Risk is minimized by delaying the utilization of uncertain resources.

The resource profile is gradually built up until T(1)Max is reached. No resource is retired even if some are idle for a time between the start of the project and T(1)Max. However, resources while being idle, can be rented out or used on other projects temporarily, until it is required on the new project. This aspect is discussed in detail later in this section. Once T(1)Max is reached, the quantity amounting to the difference between R(1)Max and R(2)Max is retired. This procedure is repeated until T(K)Max is reached.



RESOURCE PROFILE

FIGURE 3.2

The cost of a resource depends on whether it is an in-house resource or hired one. Again, the cost of an in-house resource depends on whether it is in use or idle. Hence, in use or idle time costs are evaluated separately as follows:

a) <u>Cost of In-House Resources in Use</u>

This refers to the cost of owning and operating equipment including depreciation, taxes, insurances, operator's wages, fuel oil, lubricants, spare parts, the cost of preventive maintenance and storage facilities. If it is a human resource, the cost includes wages and all fringe benefits. This cost is calculated by dividing the project profile into two parts (i) from start of the project until T(1)Max is reached and (ii) from T(1)Max to end of the profile.

i) The cost of in-house resources in use from start to T(1)Max, (C1), is given by the following equation.

$$C1 = \sum_{I=1}^{T(1)Max} [\,[\,R(I)*CRO,\ \text{if } X < ORC + UR\,] + [\,(R(I)-H)*CRO,\ \text{if } X > ORC + UR,\ \&\ R(I) > H\,]\,]$$

...3.1

Where,

R(I) is the resource requirement of the new project on time unit 'I'.

ORC is the number of certain resources available.

UR is the number of uncertain resources available.

the initial value of X = R(1),

If X < R(I), X = R(I)

H is the number of hired resources required,

H = X − ORC − UR, if X > ORC + UR

and CRO is the unit cost of in-house resources in operation.

ii) The cost, (C2), of in-house resources from T(1)Max to end of the profile is given by the following equation.

$$C2 = \sum_{J=2}^{K} \sum_{I = T(j-1)Max + 1}^{T(j)Max} [[R(I) * CRO, \text{ if } R(T(J)Max) < ORC + UR]$$

$$+[[R(I)-H] * CRO ,$$

$$\text{if } R(T(J)Max) > ORC + UR \ \& \ R(I) > H]] \qquad \ldots .3.2$$

Where,

H = R(T(J)Max) − ORC − UR, if R(T(J)Max) > ORC + UR

K = total number of resource peaks in the profile and

j = number of the resource peak under consideration from start of the profile

b) Cost of In-House Resources in Idle Time

During the course of scheduling, idle resources, if any, can be rented out. The feasibility of renting out option depends on how long the resources remain idle, location of the new project, availability of renters and cost of mobilization. If due to high mobilization cost, renting out turns out to be uneconomical, it will be better to retain the resources at site and bear the owning cost which includes insurance, preventive maintenance, storage facilities, interest, and depreciation.

The unit cost of idle in-house resources is given by the following equation.

$$RCI = CROWN - CROR \qquad \ldots .3.3$$

Where,

RCI is the unit cost of idle in-house resources,

CROWN is the unit cost of owning the resources,

and CROR is the unit price at which the resources are rented out.

As before, the overall cost of idle resources is calculated by dividing the profile into two parts (i) from start of the project until T(1)Max is reached and (ii) from T(1)Max to end of the profile.

i) The cost, (C3), of idle resources from start to T(1)Max is given by the following equation.

$$C3 = \sum_{I=1}^{T(1)Max} [[(X - R(I)) * RCI, \text{ if } X < ORC + UR \text{ or if } X > ORC + UR \ \& \ R(I) > H]$$

$$+ [X - H] * RCI, \text{ if } X > ORC + UR \ \& \ R(I) < H]$$

.... 3.4

ii) The cost, (C4), of idle resources from T(1)Max to end of the profile is given by the following equation.

$$C4 = \sum_{J=2}^{K} \sum_{I=T(J-1)Max+1}^{T(J)Max} [[(R(T(J)Max)-R(I))*RCI, \text{ if } R(T(J)Max) < ORC + UR,$$

$$\text{or if } R(T(J)Max) > ORC + UR \ \& \ R(I) > H]$$

$$+[(R(T(J)Max)-H)*RCI, \text{ if } R(T(J)Max) > ORC + UR, \ \& \ R(I) < H]]$$

..... 3.5

c) <u>Cost of Hired Resources</u>

This is the cost of renting resources from outside agencies.

i) The cost, (C5), of hired resources from start to T(1)Max is given by the following equation.

$$C5 = \sum_{I=1}^{T(1)Max} [H * CRB, \text{ If } X > ORC + UR] \quad \ldots\ldots \quad 3.6$$

where,

X = R(1), If X < R(I), X = R(I),

H = X - ORC - UR, if X > ORC + UR, and

CRB is the unit cost of hired resources.

ii) The cost, (C6), of hired resources from T(1)Max to end of the profile is given by the following equation.

$$C6 = \sum_{J=2}^{K} \sum_{I=T(J-1)Max+1}^{T(j)Max} [H * CRB, \text{ if } R(T(J)Max) > ORC + UR]$$

... 3.7

Where,

H = R(T(J)Max) - ORC - UR, if R(T(J)Max) > ORC + UR

Evaluation of Resource Cost for Stage Two Processor

When uncertain resources are substituted by hired resources as illustrated in Figure 2.2, the project cost is estimated in two parts :- 1) the part scheduled with certain and hired resources and 2) the part scheduled with in-house (certain and uncertain) resources. The principle behind this computation is discussed in section 3.3.0. Each part is costed separately using relevant costing equations described for Stage One Processor.

As the project progresses, more and more uncertain resources may become certain, thus reducing the requirement of hired resources. However, if sufficient hired resources are not available for replacing the uncertain resources, no further substitution of uncertain resources by hired resources for the resource type in question is carried out.

3.3.2 Mobilization Cost

Each project has widely different mobilization costs depending upon the project location, transportation mode, climatic conditions, communication facilities, logistic problems etc. This cost includes all expenditures on disassembly, assembly and mobilization of resources from their present location to the new site and upon completion of their use, similar expenditure to return the resources to their original or any other desired location.

This cost is applicable to only in-house resources and is user specified. For hired resources, the user specified cost is inclusive of the mobilization cost.

3.3.3 Other Costs

The cost of labour, materials and all nonscarce resources (not considered for resource allocation), contingency, provision for escalation etc are summed up. This sum is added to each alternative.

3.3.4 Overhead Cost

Overhead cost applies to the daily cost of all nonproductive operations on the new project. It includes the prorated portion of the head office overhead cost and is the product of the project duration (T(K)Max) and the user defined overhead cost per unit time (OH). It is added to the total project cost.

3.3.5 Penalty

The penalty for unit time delay varies with the nature of project, order of investment etc. The amount of penalty for each alternative is obtained by multiplying the penalty for the unit time delay by the extension beyond the desired completion time of the project for the alternative under consideration.

3.3.6 Total Project Cost

The total cost of the new project is obtained by summing up the cost of individual resource types used in REM analysis and adding to it mobilization cost, other costs, overhead cost, and penalty. REM determines total project cost separately for each alternative generated by Stage One and Stage Two Processor.

3.4.0 Probability Evaluation Processor

The cost evaluation step discussed in section 3.3.0, provides the information on when the uncertain resources are required for the first time and subsequent times during resource allocation scheduling. With this information and with the help of beta and normal distributions formed out of the time estimates, the probability of availability of an uncertain resource type on any particular day is found out.

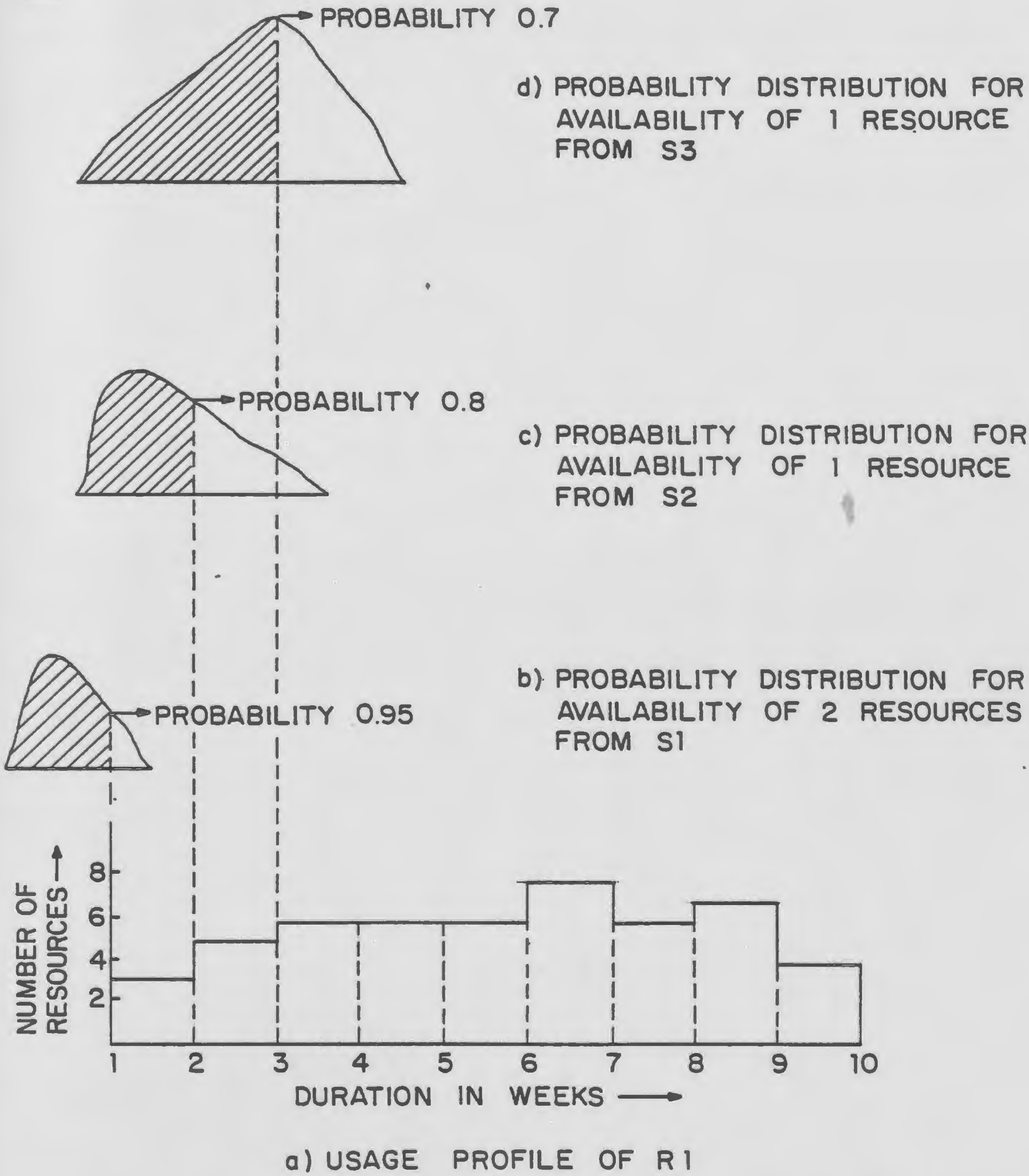
The type of uncertainty associated with an individual resource type determines the method applicable for evaluation of probability. Different types of uncertainties included in the scope of the problem were discussed in section 1.3.0. A discussion on the evaluation of probability for each type of uncertainty follows.

Availability of an Uncertain Resource Type from Multiple Independent Sources

The evaluation of probability for the availability of an uncertain resource type from multiple independent sources is illustrated in Figure 3.3. The new project requires a resource type R1 whose profile is illustrated in Figure 3.3(a). The peak requirement in the example profile is eight resources. Out of these eight resources six are in-house resources and two are to be hired. Out of the six in-house resources, the availability of four is uncertain and that of the two certain. These four uncertain resources are expected from three sources namely S1,S2 and S3. The number of resources available from S1, S2 and S3 are 2,1,and 1 respectively. The probability distributions for the availability of resources from S1,S2 and S3 are given in Figure 3.3 b,c, and d respectively. It is seen that S1 is the least uncertain source and S3 the most uncertain.

From the resource profile, the requirement in the first week is 3. There are only two certain resources and hence one uncertain resource is required. Since S1 is the least uncertain source, the resources from S1 will be considered first. The probability for the availability of resources from S1 in the first week is given by the area under the curve to the left of week one, that is 0.95.

The resource requirement in week two is 5. Hence, the resources from S1 and S2 are needed to meet the requirement. Since the availability of resources from S1 was already considered, only the uncertainty of S2 needs to be evaluated. The probability of availability of resources from S2 on 2nd week is 0.80. Similarly, the probability of resources becoming available from S3 is 0.70.



PROBABILITY EVALUATION FOR AVAILABILITY OF A RESOURCE TYPE FROM MORE THAN ONE INDEPENDENT SOURCE.

FIGURE 3-3

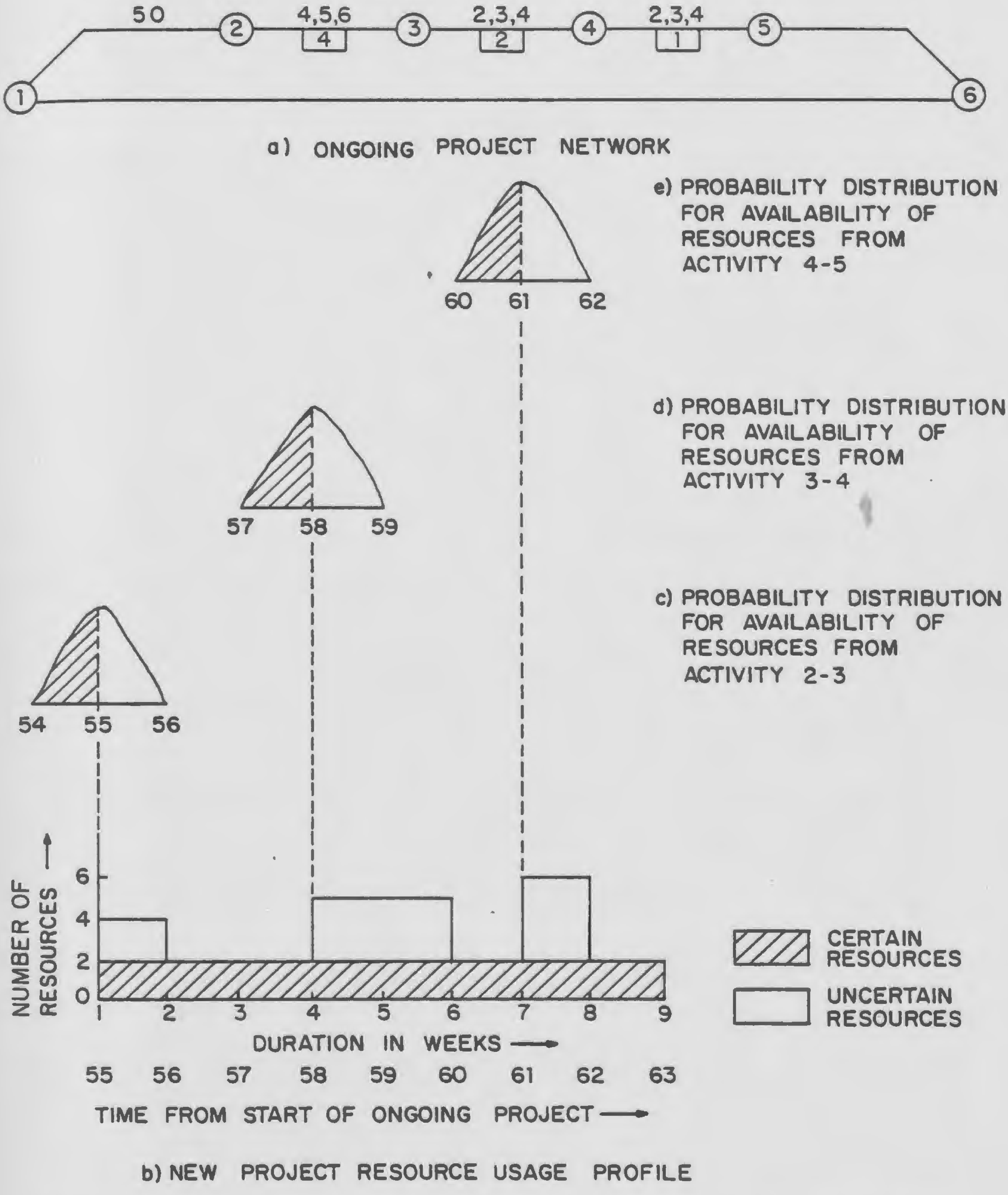
Since all three sources are independent, the overall probability for the availability of required resources from them is the product of these three individual probabilities i.e. 0.70 x 0.80 x 0.95 = 0.50.

Availability of an Uncertain Resource Type from Multiple Dependent Sources

Case A

The evaluation probability for the availability of an uncertain resource type from multiple dependent sources can be discussed with the help of Figure 3.4(a) which illustrates an ongoing project. A resource type R1 is expected to become available for the new project from three activities 2–3, 3–4, and 4–5 which have probabilistic durations as shown. The number of resources used by these activities are 4, 2, and 1 respectively. Since two resources will be required by activity 3–4, two resources can be released after completion of activity 2–3. One resource will be released after completion of activity 3–4, and one more resource after completion of activity 4–5.

The optimistic, most likely, and pessimistic time estimates for the durations of these activities are estimated by responsible scheduling engineers. The time estimates for all the three activities are given in Table 3.1



PROBABILITY EVALUATION FOR AVAILABILITY OF A RESOURCE TYPE FROM MORE THAN ONE DEPENDENT SOURCE.

FIGURE 3-4

Elapsed Time Estimates For Activities of Ongoing Project

Table 3.1

Activity	Time Estimate in Weeks		
	Optimistic	Most Likely	Pessimistic
2-3	4	5	6
3-4	2	3	4
4-5	2	3	4

The time difference between the expected start date of the new project and actual start of the ongoing project is 55 weeks and the duration of the activity 1-2 is 50 weeks. The time required to mobilize released resources to the new project site is negligible.

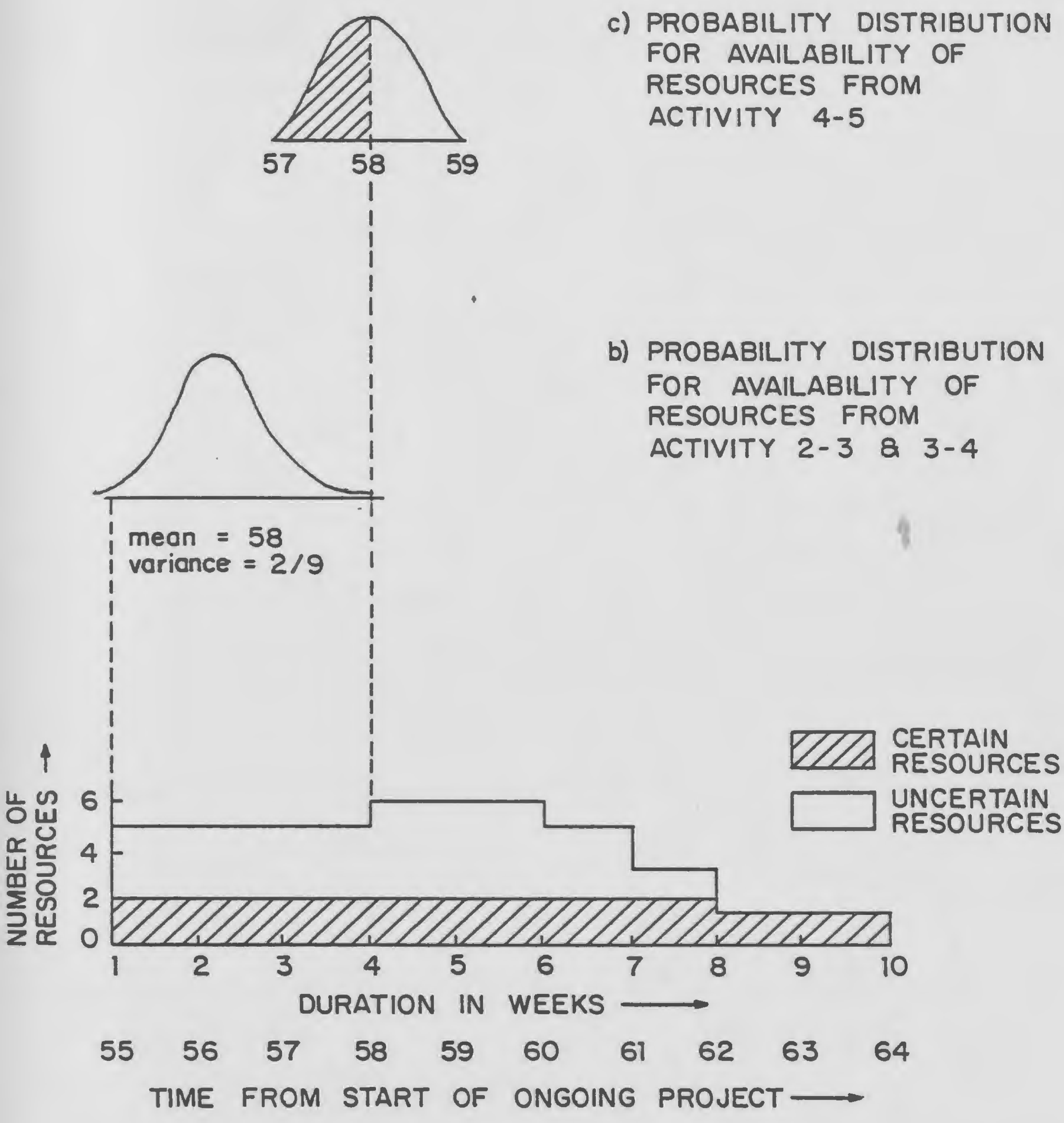
The optimistic, most likely, and pessimistic times for completing activity 2-3 are 54, 55 and 56 weeks respectively. The probability distribution for this activity is illustrated in Figure 3.4(c). The requirement of uncertain resources by the new project is two on week one, three on week four, and four on week seven. The resource profile is shown in Figure 3.4(b). The probability of getting two uncertain resources for the new project in the first week is 0.50. Since activity 2-3 has already occured on week 55 with a probability of 0.50, the optimistic, most likely and pessimistic times for completing activity 3-4 are 57, 58 and 59 weeks respectively. The probability distribution for this case is shown in Figure 3.4(d) and the probability of getting one more resource on week 59 is also 0.50. Similarly, the optimistic, most likely and pessimistic times for completing activity 4–5 are 60, 61, and 62 weeks respectively. The probability of getting one more resource for the new project on week 62 is 0.5 from Figure 3.4(e).

The overall probability of the required resources becoming available for the new project is the product of the individual probabilities i.e. 0.50 x 0.50 x 0.50 = 0.125.

Case B

It is assumed that the new project requires three uncertain resources in the very first week i.e 56th week from start of the ongoing project as shown in Figure 3.5(a). The required resources can be made available after completing activity 3–4 which includes the uncertainty of activity 2–3 and 3–4. By applying the central limit theorem, normal distribution is assumed for completion of activity 3–4. The mean duration of activities 2–3 and 3–4 are five and three weeks respectively. The variance of both the activities is 1/9. The mean time for completing activity 3–4 is 58 and its variance is 2/9. The probability distribution for completing activity 3–4 is illustrated in Figure 3.5(b). The probability of getting three resources on week 56 is 0.00. The optimistic, most likely and pessimistic times for completing activity 4–5 are 57, 58, and 59 respectively. If the new project requires four resources on week 59, the probability of obtaining the additional one resource is 0.50 as shown in Figure 3.5(c).

The overall probability of scheduling the new project with uncertain resources is the product of individual probabilities i.e 0.00 x 0.50 = 0.00.



a) NEW PROJECT RESOURCE USAGE PROFILE

PROBABILITY EVALUATION FOR AVAILABILITY OF A RESOURCE TYPE FROM MORE THAN ONE DEPENDENT SOURCE.

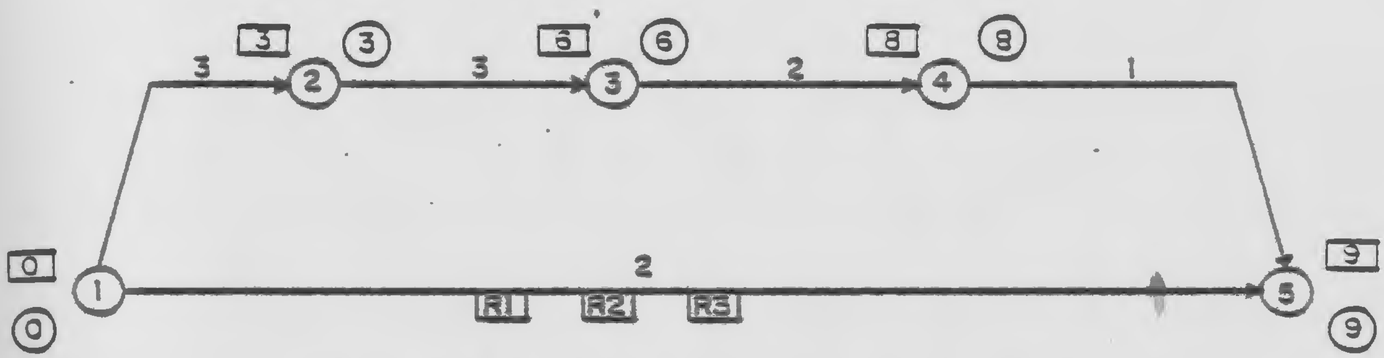
FIGURE 3-5

Availability of Multiple Resource Types from Multiple Dependent Sources

The evaluation of probability for the availability of multiple resource types from multiple sources is very similar to the one described in the foregoing section. It can be discussed with the help of Figure 3.4(a) already referred to in that section. It is assumed that the activities 2-3, 3-4, and 4-5 of the ongoing project are using resource types R1, R2, and R3 respectively. If the new project requires R1 early in the schedule, followed by R2 and then R3, the overall probability is evaluated as explained in Case A. However, if either R2 is required prior to R1 or R3 prior R2, the method described in Case B is used for evaluating the overall probability.

Availability of Multiple Resource Types from a Single Source

The evaluation of probability for the availability of multiple resource types from a single source can be discussed with the help of Figure 3.6 which illustrates an ongoing project. It is observed that the resource types R1, R2, and R3 required by the new project will become available from activity 1-5. The completion time of activity 1-5 is uncertain and hence the availability of all three resources for the new project is uncertain. However, the resource type which is required first by the new project is considered uncertain and the other two, if required later, are treated as certain. The method described for evaluating probability for the availability of single resource type from a single source is adopted to evaluate probability.



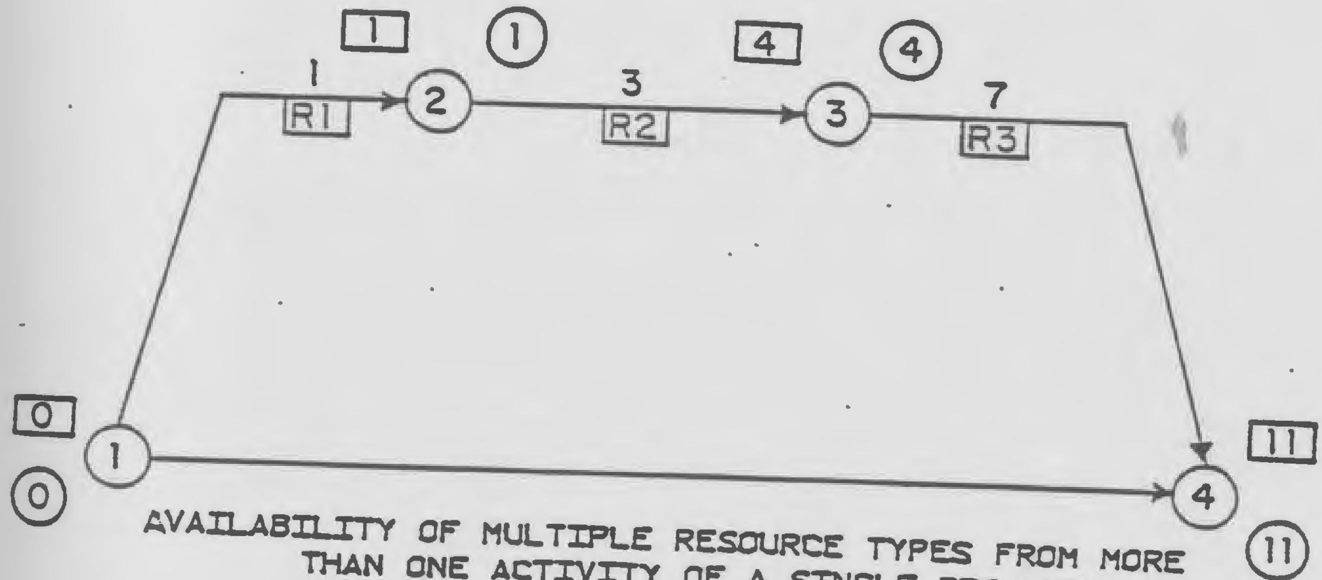
AVAILABILITY OF MULTIPLE RESOURCE TYPES FROM
A SINGLE ACTIVITY OF AN ONGOING PROJECT

FIGURE 3.6

Yet another variation, somewhat similar to the one just described, may be discused with the help of Figure 3.7. Activities 1–2, 2–3, and 3–4 of the ongoing project use resources R1, R2 and R3 respectively. The duration of activity 1–2 is probabilistic and that of 2–3 and 3–4 are deterministic. Because of dependency among activities, the availability of all three resource types for the new project is uncertain. However, applying the same logic as given in the preceding paragraph, only the resource type which is required first by the new project is considered uncertain and the remaining two certain and the probability is evaluated as before.

Performance Probability

The performance probability, which is the overall probability of achieving any combination of project completion time and the corresponding cost is obtained as the product of probabilities associated with availability of individual resource types.



AVAILABILITY OF MULTIPLE RESOURCE TYPES FROM MORE THAN ONE ACTIVITY OF A SINGLE PROJECT

FIGURE 3.7

3.5.0. Restricting the Number of Iterations

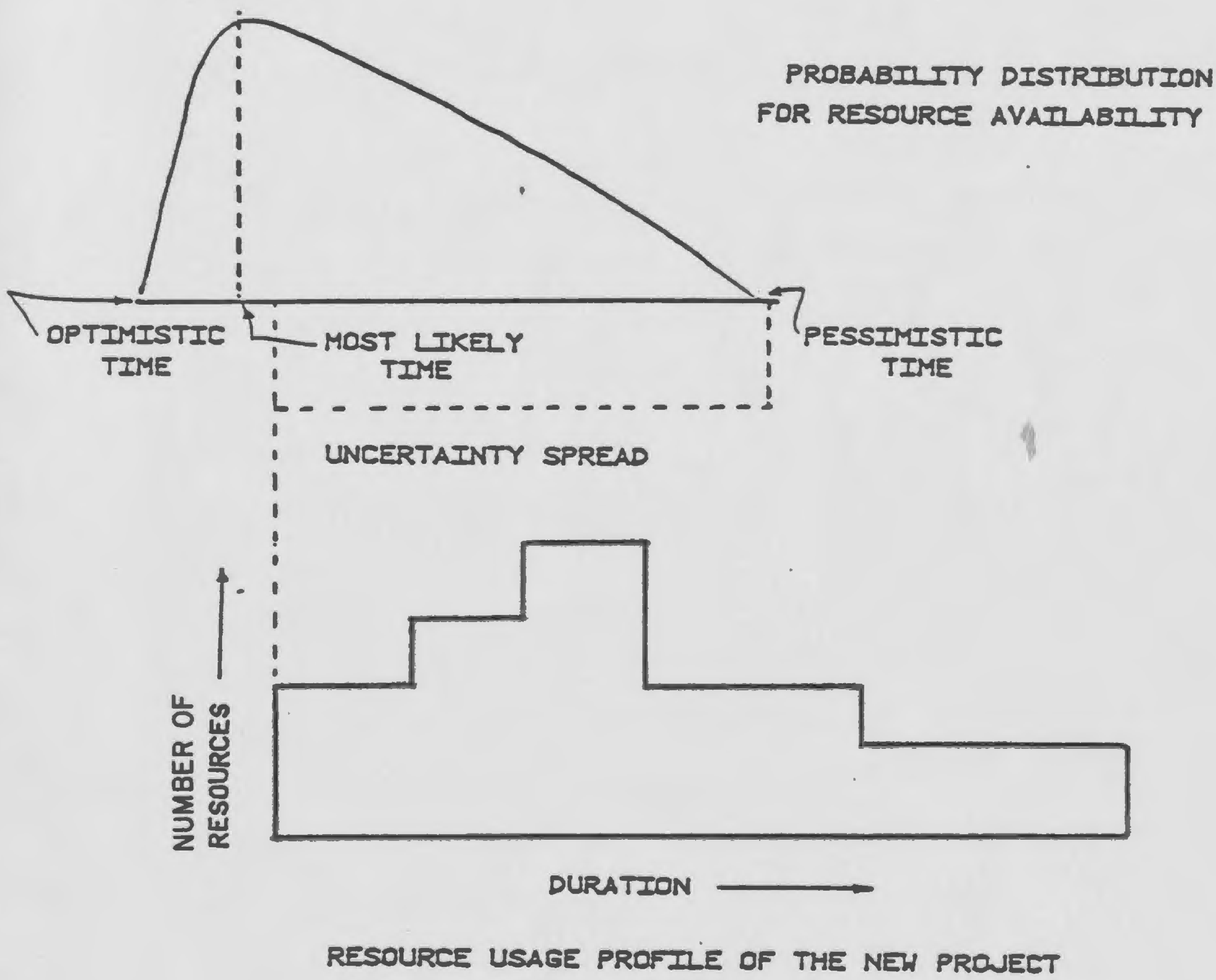
The computer time required to evaluate alternate project completion time, cost and performance probability depends on the complexity of the problem, number of uncertain resource types, nature of probability distributions, dependency among uncertain resources etc. If the number of iterations are not restricted, computing cost will outweigh the benefit to the user. In addition, if the number of alternatives is too large decision making becomes tedious. Methods are presented in the succeeding sections to minimize the number of iterations.

3.5.1 Selection of Time Units

The overlapping period between the resource usage profile of the new project and the probability distribution for resource availability is called the 'uncertainty spread'. This is illustrated in Figure 3.8. Each resource type has an uncertainty spread, the largest value of which is called the range of interest (ROI). If ROI is long, the number of computer runs will be quite large. Hence, ROI is divided into a maximum of ten to twelve time units. If the ROI is ten weeks, the value of each time unit is a week. If the ROI is six months, the value of each time unit is a fortnight. The time units may be selected by the user of the model judging from the complexity of the problem.

3.5.2 Restricting the Number of Computations

Normally one would be prepared to take small calculated risk. Hence, the probabilities in the range between 0.0 and 0.5 as well as 0.8 to 1.0 will have less significance, when compared to the range between 0.5 to 0.8. Hence, while obtaining alternate values for project completion time, cost and performance probability by stage one computation, longer delay periods may be used in the less significant range. For example, the start of the new project may be delayed by two time units when the



EVALUATION OF UNCERTAINTY SPREAD

FIGURE 3.8

probability is between 0.3 and 0.5, and 0.8 and 1.0; and one unit when it is between 0.5 and 0.8. This ensures closer performance probability evaluations in the middle range and sparse at the ends.

3.5.3 Restriction in the Choice of Sources

Earlier it was suggested that if an uncertain resource type is expected to become available from more than one independent source, the resources from the least uncertain source will be given preference in usage. If the least uncertain source has only a limited number of resources, compared to the requirement on the new project, the resources from the first two sources may be considered together, thus reducing the number of iterations appreciably.

If the probability distribution for availability of resources from a particular source is flat compared to the project duration indicating unlikelihood of availability of resources, and if the penalty for the delay on the new project is quite heavy, the resources from this source may be ignored and not considered for resource allocation. Similarly, if the cost of hiring a particular type of resource is quite high compared to that of the in-house resources, the resources from more than one source may be tried together in the first run itself. Also, if the difference between the costs of in-house and hired resources is large in comparison to penalty for the delay, stage two computation need not be carried out.

Using professional judgement one can devise similar shortcuts at resource allocation stage so that the computer processing is justifiable by the end use.

3.6.0 Computer Software

The computer program for REM in FORTRAN language has been developed to accept the resource justified schedule as input, and to generate alternate values for 1) project completion time 2) project cost and 3) performance probability. The computer program along with the description of various input variables appear in the Appendix.

CHAPTER 4

ILLUSTRATION OF USE OF THE MODEL

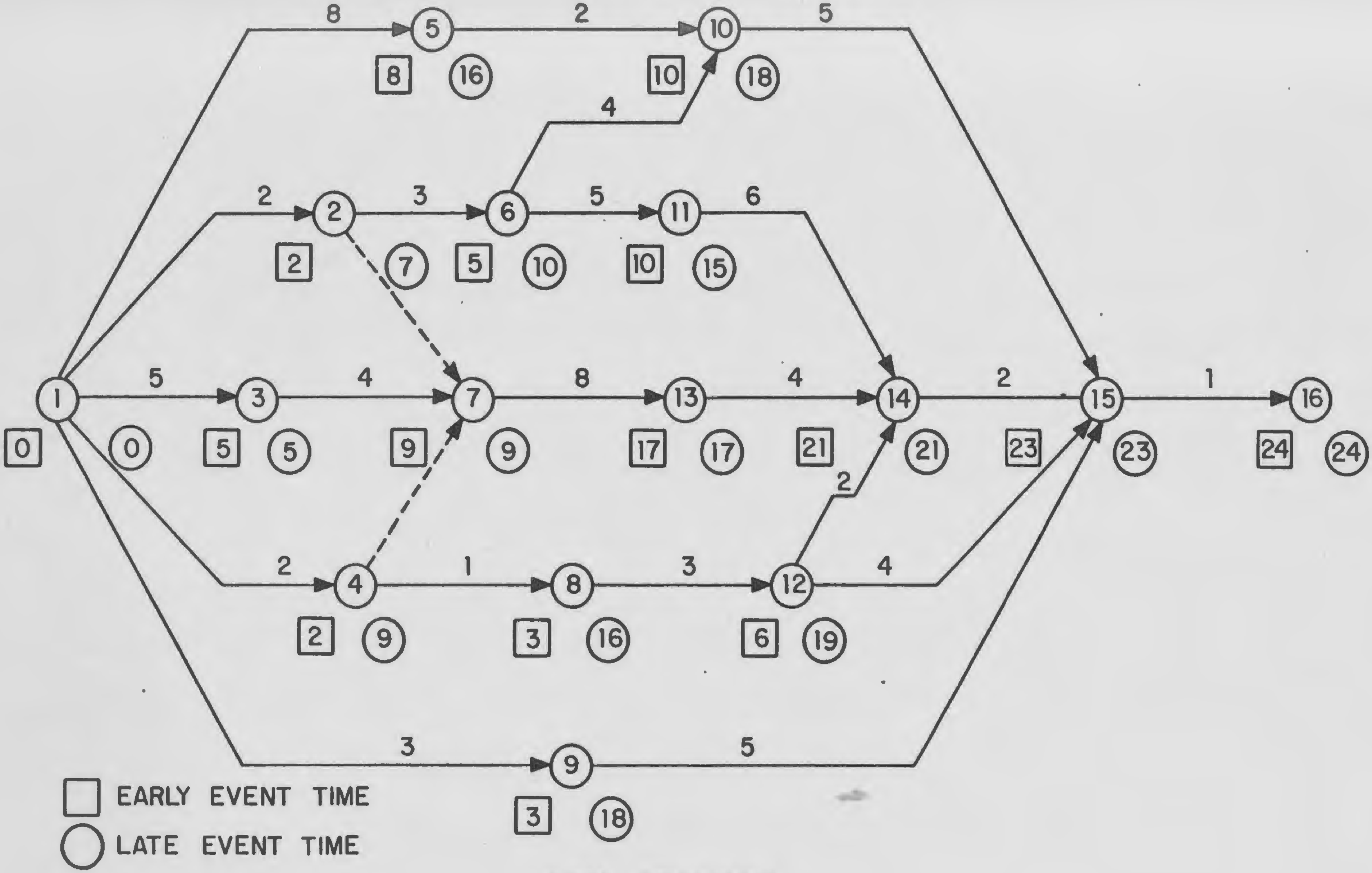
4.0.0 ILLUSTRATION OF USE OF THE MODEL

To demonstrate how REM can aid in evaluating risk on account of uncertain resources, a typical example is presented in this Chapter. Figure 4.1 illustrates a CPM network of a new project which requires six resource types namely crushers(R1), portable concrete batch plant(R2), excavators(R3), cranes(R4), skilled mechanics(R5), and senior supervisors(R6). The resource requirement of each activity is listed in Table 4.1.

It is intended to use on the new project, those resources which are expected to become available from four ongoing projects namely P1, P2, P3, and P4. The availability status of each resource type is listed in Table 4.2. The optimistic, most likely and pessimistic time estimates for uncertain resource availability are given in Table 4.3.

The scheduled start date of the new project is April 9, 1984 and the time difference between actual start dates of the ongoing projects and the scheduled start date of the new project is given in Table 4.4. The cost of hired resources, and mobilization, operating and idle time costs of in-house resources are given in Table 4.5.

The working of REM and its effectiveness in aiding the selection of best schedule will be demonstrated with the help of this example.



CPM NETWORK

FIGURE 4.1

Resource Requirement of the New project

Table 4.1

Activity	Resource Type R1	R2	R3	R4	R5	R6
1-2	3	4	4	-	-	-
1-3	2	1	2	7	-	-
1-4	1	2	3	4	-	-
1-5	1	2	-	6	-	-
1-9	4	2	4	4	-	-
2-6	-	-	4	2	-	-
2-7	-	-	-	-	-	-
3-7	5	5	2	3	-	-
4-7	-	-	-	-	-	-
4-8	3	3	-	3	4	-
5-10	-	-	5	-	5	4
6-10	-	-	7	-	7	6
6-11	-	-	2	-	6	9
7-13	-	-	3	-	3	10
8-12	-	-	6	-	2	8
9-15	-	-	3	-	1	4
10-15	-	-	5	-	-	3
11-14	-	-	4	-	-	2
12-14	-	-	-	-	-	4
12-15	-	-	1	-	-	3
13-14	-	-	2	-	-	1
14-15	-	-	1	-	-	2
15-16	-	-	-	-	-	-

The Availability Status of Resources

Table 4.2

Resource Type	In-house Resources Certain	In-house Resources Uncertain	Hired Resources	Ongoing Project	Remarks
R1	3	11	7	P1	*
R2	5	9	4	P1	*
R3	2	2	6	P2	**
		5		P3	
R4	10	-	6	--	***
R5	5	10	6	P4	****
R6	7	8	8	P4	****

* The uncertain resources of R1 and R2 are expected from two dependent activities of P1.

** The uncertain resoures of R3 are expected from two independent sources P2 and P3.

*** The availability of all resources of R4 are certain.

**** The uncertain resources of R5 and R6 are expected from single activity of P4.

Time Estimates for Uncertain Resource Availabilities

Table 4. 3

Resource		Time Estimate in Weeks for uncertain Resource Availability			
Type	Number	Optimistic Time	Most Likely Time	Pessimistic Time	Remarks
R1	6	8	12	16	*
R2	6	1	3	6	**
R3	2	12	16	18	***
	5	8	12	27	****
R5	6	7	13	20	*****
R6	8	7	13	20	*****

* These time estimates are with reference to start of P1.

** These time estimates are with reference to completion time of an activity from which R1 is likely to be released.

*** These time estimates are with reference to start of P2.

**** These time estimates are with reference to start of P3.

***** These time estimates are with reference to start of P4.

Time Adjustment Factor

Table 4.4

Project	Time Difference in Weeks between the Start Of the Ongoing Project and Scheduled Start of the New Project
P1	10
P2	13
P3	16
P4	8

Unit Cost of Resources

Table 4.5

Resource Type	Cost of In-house Resources Operation $/week	Idle Time $/week	Cost of Hired Resources $/week	Mobilization Cost $/unit
R1	1000	800	1500	200
R2	1500	1200	2250	250
R3	1500	1200	2500	100
R4	3000	3000	4500	750
R5	600	600	1100	300
R6	900	900	1700	500

Penalty = $10.000/week

Overhead = $2.500/week

4.1.0 Solution

The solution to the problem is presented in steps similar to those described in section 3.1.0.

Step 1

The first step is to assess the nature of uncertainty associated with each type of resource. As can be seen from Table 4.2, the availability of all resource types except R4 is partly certain and partly uncertain. The resource types R1 and R2, expected to become available from two dependent uncertain activities of project P1, are multiple dependent resource types. The uncertain resource type R3 will become available from two independent projects P2 and P3. The uncertain resource types R5 and R6 are expected to become available from a single activity of project P4.

For the first run, for each type of resource, only certain resources and those uncertain resources which can be released from only one independent source are considered. Only resource type R3 has two independent uncertain sources. From Table 4.3 and 4.4, it is observed that P2 is the least uncertain source for the availability of R3 and hence the resources from P2 are considered for the first run. Now 14 type R1, 14 type R2, 4 type R3, 10 type R4, 15 type R5 and 15 type R6 resources are available for allocation.

Steps 2 and 3

The second step is to compare the available number of each type of resource with the requirement of each activity of the new project, listed in Table 4.1. The available number of all resource types except R3 is more than the requirement of all activities of the new project. Activity 6-10 requires 7 type R3 resources, while only 4 are available. Hence three R3 type hired resources are added.

Resources are now allocated. It is observed that the resource justified project duration is 39 weeks, whereas the normal project duration is only 24 weeks. The penalty is 10,000 $/week. Since the penalty is heavy when compared to the cost of the hired resources, the number of iterations are brought down, as discussed in section 3.6.3.0, by increasing the number of resource types that cause the extension. As detailed in section 3.2.0.0(step 5), hired resources will be added for increasing the resource levels.

It is observed by trial and error that the availability of R3, R4 and R6 are limited. Hence, hired resources of these three types are added. Resource allocation after adding three type R3, six type R4 and three type R6 resources reduces the project duration to 27 weeks with an extension of original schedule by 3 weeks. No more hired resources of types R3 and R4 are available, and no more addition of type R6 hired resources reduces the project duration. The input data relating to the resources considered for allocation is given in Table 4.6. Since resource allocation scheduling extends the project duration, resource profiles are not leveled. The resource profiles of the first run having a duration of 27 weeks, are given in Figures 4.2(a) to (f). The resource requirement in each time unit is shown by these profiles.

Available Number of Resources for First Run

Table 4.6

Resource Type	In-house Resources Certain	Uncertain	Hired Resources
R1	3	11	-
R2	5	9	-
R3	2	2	6
R4	10	-	6
R5	5	10	-
R6	7	8	3

PERIOD RESOURCE LEVELS

SORTED BY SUBNET, R-CODE

EVERY 1.00 UNITS FROM 09OCT83 to 30NOV84 SCALED BY 56

RESOURCE CODE R1

```
Date            10         20         30         40         50         60         70         80
         ---------------------------------------------------------------------------------------
15OCT83  |XXXXXX
22OCT83  |XXXXXX
29OCT83  |XXX
05NOV83  |XXX
12NOV83  |XXX
19NOV83  |XXXXXXXXXXXXX
26NOV83  |XXXXXXXXXX
03DEC83  |XXXXXXXXXX
10DEC83  |XXXXXX
17DEC83  |X
24DEC83  |
31DEC83  |
07JAN84  |
14JAN84  |
21JAN84  |
28JAN84  |
04FEB84  |
11FEB84  |
18FEB84  |
25FEB84  |
03MAR84  |
10MAR84  |
17MAR84  |
24MAR84  |
31MAR84  |
07APR84  |
14APR84  |
21APR84  |
```

RESOURCE PROFILE OF R1
FIGURE 4.2(a)

PERIOD RESOURCE LEVELS

SORTED BY SUBNET, R-CODE

EVERY 1.00 UNITS FROM 09OCT83 to 30NOV84 SCALED BY 56

RESOURCE CODE R2

```
Date               10        20        30        40        50        60        70        80
          |------------------------------------------------------------------------------
15OCT83   |XXXXXXX
22OCT83   |XXXXXXX
29OCT83   |XXX
05NOV83   |XXX
12NOV83   |XXX
19NOV83   |XXXXXXXXXXXX
26NOV83   |XXXXXXXXX
03DEC83   |XXXXXXXXX
10DEC83   |XXXXXXX
17DEC83   |XX
24DEC83   |
31DEC83   |
07JAN84   |
14JAN84   |
21JAN84   |
28JAN84   |
04FEB84   |
11FEB84   |
18FEB84   |
25FEB84   |
03MAR84   |
10MAR84   |
17MAR84   |
24MAR84   |
31MAR84   |
07APR84   |
14APR84   |
21APR84   |
```

RESOURCE PROFILE OF R2
FIGURE 4.2(b)

PERIOD RESOURCE LEVELS

SORTED BY SUBNET, R-CODE

EVERY 1.00 UNITS FROM 09OCT83 to 30NOV84 SCALED BY 56

RESOURCE CODE R3

```
Date            10        20        30        40        50        60        70        80
        |-------------------------------------------------------------------------------
15OCT83 |XXXXXXXXX
22OCT83 |XXXXXXXXX
29OCT83 |XXXXXX
05NOV83 |XXXXXX
12NOV83 |XXXXXX
19NOV83 |XXXXXXXX
26NOV83 |XXXXXXXX
03DEC83 |XXXXXXXX
10DEC83 |XXXXXXXXXX
17DEC83 |XXXXXXXX
24DEC83 |XXXXXXXXX
31DEC83 |XXXXXXXXXX
07JAN84 |XXXXXXXXXX
14JAN84 |XXXXXXXXXX
21JAN84 |XXXXXXXXXX
28JAN84 |XXXXXXXXXX
04FEB84 |XXXXXXXXXX
11FEB84 |XXXXXXXXXX
18FEB84 |XXXXXXXXXX
25FEB84 |XXXXXXXXXX
03MAR84 |XXXXXXX
10MAR84 |XXXXXXXX
17MAR84 |XXXXXX
24MAR84 |XXXXXX
31MAR84 |XXXXX
07APR84 |XXXXX
14APR84 |XXXXX
21APR84 |XXXXX
```

RESOURCE PROFILE OF R3
FIGURE 4.2(c)

PERIOD RESOURCE LEVELS

SORTED BY SUBNET, R-CODE

EVERY 1.00 UNITS FROM 09OCT83 to 30NOV84 SCALED BY 56

RESOURCE CODE R4

```
Date            10        20        30        40        50        60        70        80
        |--------------------------------------------------------------------------------
15OCT83 |XXXXXXXXXXX
22OCT83 |XXXXXXXXXXX
29OCT83 |XXXXXXXXXXXXXXX
05NOV83 |XXXXXXXXXXXXXXX
12NOV83 |XXXXXXXXXXXXXXX
19NOV83 |XXXXXXXXXXXXXXXX
26NOV83 |XXXXXXXXXXXXX
03DEC83 |XXXXXXXXXXXXX
10DEC83 |XXXXXXXXX
17DEC83 |XXXXXX
24DEC83 |
31DEC83 |
07JAN84 |
14JAN84 |
21JAN84 |
28JAN84 |
04FEB84 |
11FEB84 |
18FEB84 |
25FEB84 |
03MAR84 |
10MAR84 |
17MAR84 |
24MAR84 |
31MAR84 |
07APR84 |
14APR84 |
21APR84 |
```

RESOURCE PROFILE OF R4
FIGURE 4.2(d)

PERIOD RESOURCE LEVELS

SORTED BY SUBNET, R-CODE

EVERY 1.00 UNITS FROM 09OCT83 to 30NOV84 SCALED BY 56

RESOURCE CODE R5

```
Date              10        20        30        40        50        60        70        80
         |--------------------------------------------------------------------------------
15OCT83  |
22OCT83  |
29OCT83  |
05NOV83  |
12NOV83  |
19NOV83  |XXXXXXXXXX
26NOV83  |XXXXXX
03DEC83  |XXXXXX
10DEC83  |XXXXXXXX
17DEC83  |XXXXXXXX
24DEC83  |XXXXX
31DEC83  |XXXXXXXXXX
07JAN84  |XXXXXXXXXX
14JAN84  |XXXXXXXXXX
21JAN84  |XXXXXXXXXX
28JAN84  |XXXX
04FEB84  |XXXX
11FEB84  |XXXX
18FEB84  |X
25FEB84  |X
03MAR84  |
10MAR84  |XXXXX
17MAR84  |XXXXX
24MAR84  |
31MAR84  |
07APR84  |
14APR84  |
21APR84  |
```

RESOURCE PROFILE OF R5
FIGURE 4.2(e)

PERIOD RESOURCE LEVELS

SORTED BY SUBNET, R-CODE

EVERY 1.00 UNITS FROM 09OCT83 to 30NOV84 SCALED BY 56

RESOURCE CODE R6

```
Date              10        20        30        40        50        60        70        80
          |------------------------------------------------------------------------------
15OCT83   |
22OCT83   |
29OCT83   |
05NOV83   |
12NOV83   |
19NOV83   |XXXXXXXXX
26NOV83   |XXXXXXXXX
03DEC83   |XXXXXXXXX
10DEC83   |XXXXXXXXXXXXXXXXX
17DEC83   |XXXXXXXXXXXXXXXXX
24DEC83   |XXXXXXXXXXXXXXXXXX
31DEC83   |XXXXXXXXXXXXXXXX
07JAN84   |XXXXXXXXXXXXXXXX
14JAN84   |XXXXXXXXXXXXXXXX
21JAN84   |XXXXXXXXXXXXXXXX
28JAN84   |XXXXXXXXXXXXXXXX
04FEB84   |XXXXXXXXXXXXXXXX
11FEB84   |XXXXXXXXXXXXXXXX
18FEB84   |XXXXXXXXXXXXXX
25FEB84   |XXXXXXXXXXXXXX
03MAR84   |XXXXXX
10MAR84   |XXXXXXXX
17MAR84   |XXXXXX
24MAR84   |XXXXX
31MAR84   |XXX
07APR84   |XXX
14APR84   |XXX
```

RESOURCE PROFILE OF R6
FIGURE 4.2(f)

Step 4

The next step is to prepare input data for REM so it can generate alternatives with varying project completion time, cost and performance probability.

The type of uncertainty associated with each group of resources is given in Table 4.7. The computation of range of interest which is the largest value of uncertainty spread (Mpath), is illustrated in Table 4.8. The information contained in Tables 4.3 to 4.8 and figures 4.2(a) to (f) is input to the computer model.

The computer output presents a large number of sets of data on project completion time , cost and performance probability. The method of generating alternate sets of data can be discussed with the help of the output presented in Table 4.9. The project duration for the first run is 27 weeks and the corresponding project cost and performance probability are $1,518,300 and 0.00 respectively (line 1). Since the performance probability is less than 0.50, the project start time is delayed by two time units, and the computation of completion time, cost and probability is carried out once again. The new values for project completion time, cost and performance probability are 29 weeks, $1,538,300 and 0.04 respectively (line 2). This procedure is repeated, by delaying the project start time by two units each time while the performance probability is less than 0.5 or greater than 0.8 and by one time unit when it is between 0.5

Grouping of Resources

Table 4.7

Resource Group	Resource Type	Classification of type of uncertainty* Code 1 (IPATH(IR))	Code 2 (KEPE(IR))	Code 3 (KITE(IR))
1	R1, R2	4	2	2
2	R3	3	0	2
3	R4	4	1	1
4	R5, R6	4	1	2

* Description of these terms is provided in the Appendix A (page 110).

Determination of the Range of Interest

Table 4.8

Resource Type	Pessimistic Time Estimate	Time Adjustment Factor	Uncertainty Spread
R1	16	10	6
R2	22	10	12
R3	18	13	5
	27	16	11
R4	--	--	0
R5	20	8	12
R6	20	8	12

Mpath = 12

Output from First Run

Project Duration = 27 Weeks

Table 4.9

Line Number	Project Completion Time in Weeks	Project Cost in $	Performance Probability
1	27	1,518,300	0.00
2	29	1,538,300	0.04
3	31	1,558,300	0.46
4	33	1,578,300	0.88
5	35	1,598,300	1.00
6	27	1,521,300	0.00
7	29	1,541,300	0.12
8	31	1,561,300	0.70
9	32	1,571,300	0.88
10	34	1,591,300	1.00
11	27	1,502,700	0.02
12	29	1,522,700	0.50
13	31	1,542,700	1.00
14	27	1,494,500	0.03
15	29	1,514,500	0.55
16	30	1,524,500	0.90
17	32	1,544,500	1.00
18	27	1,515,200	0.00
19	29	1,535,200	0.13
20	31	1,555,200	0.70
21	32	1,565,200	0.88
22	34	1,585,200	1.00
23	27	1,496,600	0.04
24	29	1,516,600	0.55
26	30	1,526,600	0.90
27	31	1,542,700	1.00
28	27	1,518,300	0.00
29	29	1,538,300	0.04
30	31	1,558,300	0.46
31	33	1,578,300	0.88
32	35	1,598,300	1.00
33	27	1,508,000	0.00
34	29	1,530,100	0.05
35	31	1,550,100	0.46
36	33	1,570,100	0.88
37	35	1,590,100	1.00

and 0.8, until the performance probability reaches unity. The final values of project completion time, cost and performance probability obtained by this procedure are 35 weeks, $1,598,300 and 1.00 respectively (line 5).

Next, uncertain resources of type R1, required in the first week of the schedule is substituted by hired resources of type R1 and the project completion time, cost and performance probability are evaluated once again, the values of which are 27 weeks, $1521300 and 0.00 respectively (line 6). As stated before, the project start time is delayed by one or two time units at a time depending on the performance probability and the additional sets of data are generated. The use of hired resources in preference to uncertain resources yields more alternatives. This procedure is carried out for each resource type namely R1, R2, R5 and R6 as well as for different combinations among them. The resource types R3 and R4 are not considered because all R3 hired resources were used up at resource allocation stage and type R4 uncertain resources are not available.

Only a few alternative sets selected from the output of the first run are presented in Table 4.9. The data presented in this table can also be sorted in ascending or descending order of project completion time or cost or performance probability, if required.

Steps 5 and 6

In order to reduce the number of iterations, step 5 was coupled with steps 2 and 3 and hence only step 6 remains to be carried out. The procedure described in steps 1 to 3 are repeated considering the resources from second least independent uncertain source. Only resource type R3 has two independent uncertain sources, P2 and P3. The resources from P2 were included in the first run and hence resources from both P2 and P3 are considered now. The data relating to number of resources considered for allocation are given in Table 4.10. Resource allocation scheduling is carried out once again. The output of resource allocation scheduling along with the information contained in Tables 4.3 through 4.5, 4.7, 4.8 and 4.10 are the input to REM for the second run. A large number of alternatives are generated as described for the first run. A portion of the output from the second run is given in Table 4.11.

The availability of R3 is found to be limited, causing the extension of project completion time. Since all R3 type resources are exhausted, no more alternate schedules can be generated.

4.2.0 <u>Discussion</u>

From Tables 4.9 and 4.11, the minimum and maximum values for project costs are $1,502,700 and $1,628,450 and the corresponding probabilities are 0.02 and 1.00 respectively. Similarly, the earliest and latest completion times are 25 and 35 weeks and the corresponding probabilities are 0.02 and 1.00. Between these two extreme values for project completion time and cost, one may choose an alternative, which has the lowest project cost although its performance probability may be low. On the other hand, one who wants to avoid too much risk, may opt for a higher probability say 0.8 or above.

<u>Available Number of Resources for Second Run</u>

Table 4.10

Resource Type	In-house Resources Certain	In-house Resources Uncertain	Hired Resources
R1	3	11	-
R2	5	9	-
R3	2	7	6
R4	10	-	6
R5	5	10	-
R6	7	8	3

Output from Second Run

Project Duration = 25 Weeks

Table 4.11

Line Number	Project Completion Time in Weeks	Project Cost in $	Performance Probability
1	25	1,514,750	0.00
2	27	1,534,750	0.03
3	29	1,554,750	0.41
4	31	1,574,750	0.88
5	33	1,594,750	1.00
6	25	1,521,250	0.00
7	27	1,541,250	0.09
8	29	1,561,250	0.63
9	30	1,571,250	0.85
10	32	1,591,250	1.00
11	25	1,523,450	0.00
12	27	1,543,450	0.17
13	29	1,563,450	0.79
14	30	1,573,450	0.93
15	32	1,593,450	1.00
16	25	1,514,600	0.01
17	27	1,534,600	0.36
18	29	1,554,600	0.90
19	31	1,574,600	1.00
20	25	1,547,250	0.00
21	27	1,567,250	0.05
22	29	1,587,250	0.46
23	31	1,607,250	0.88
24	33	1,627,250	1.00
26	25	1,521,250	0.00
27	27	1,541,250	0.09
28	29	1,561,250	0.63
29	30	1,571,250	0.85
30	32	1,591,250	1.00
31	25	1,578,450	0.00
32	27	1,598,450	0.57
33	28	1,608,450	0.90
34	30	1,628,450	1.00
35	25	1,520,800	0.02
36	27	1,540,800	0.50
37	29	1,560,800	1.00

All the three parameters, namely completion time, cost and probability are to be considered in the selection of the best schedule. To start with, one looks for a desired combination at a project completion time of 25 weeks, which is the lowest he can hope to achieve. If there is none at 25 weeks, he looks for a 26 week alternative and so on.

Suppose, one does not find a desired alternative with a completion time of 25, 26, 27, or 28 weeks and he decides to look for an alternative with completion time of 29 weeks. The lowest and highest performance probabilities at which this completion time can be achieved are 0.04 and 1.00 with corresponding lowest project costs of $1,538,300 and $1,560,800 (line 2 in Table 4.9 and line 37 in Table 4.11) respectively. However, it is noted that there is an alternative (line 15 in Table 4.9) which has a total cost of $1,514,500 and a performance probability of 0.55. This cost is much less than the cost at which the performance probability is 0.04. The explanation for the occurence of such results follows:

Resource allocation generates numerous resource justified schedules with varing project durations. In addition, Stage One and Stage Two Computations generate many alternatives for each resource justified schedule. The former improves the performance probability at the expense of penalty whereas the latter employs more hired resources to produce the same result. Since the resultant increase in total project cost as well as the degree of improvement in probability achieved by these two computations are different, there is a likelihood for the occurrence of such combinations presented in the preceding paragraph. Hence, one needs to be rather carefull in choosing the best alternative. The following are the only three combinations (with a completion time of 29 weeks) that deserve further attention.

Project Cost $	Performance Probability
1,514,500	0.55
1,554,600	0.90
1,560,800	1.00

If one selects the alternative having a project cost of $1,554,600, he should be prepared for a maximum cost overrun of $6,200 (the difference between $1,560,800 and 1,554,600). It is observed that the probability of occurrence for this overrun is 0.10.

In short, by considering various combinations of uncertain and hired resources and using them for obtaining alternate resource justified schedules, REM provides a large number alternatives with different project completion time, cost and associated probability. One may select the best schedule depending on his outlook towards risk.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.0.0 SUMMARY AND CONCLUSIONS

This thesis has presented REM to evaluate the risk emanating from resources whose availabilities are not definite. It categorizes and quantifies the uncertainty associated with availability of resources. By using resources of varying certainty, it generates numerous resource justified schedules through standard resource allocation procedures. Further, it generates a large number of alternatives for each resource justified schedule by both delaying the project start as well as employing hired resources in preference to uncertain in-house resources. Further, it uses heuristic methods to keep the number of iterations to a minimum. Each alternative generated through these iterations has a different combination of completion time, cost and performance probability.

5.1.0 Applications of REM

It helps a scheduling engineer select a resource justified schedule which has not only the shortest duration and the minimum cost but also a reasonable performance probability. In addition, there are other possible applications of REM, a brief description of which follows.

Resource Procurement Planning

With the help of various combinations of hired and uncertain in-house resources. REM generates a large number of resource justified schedules with varying project completion time, cost and performance probability. Depending on one's outlook towards risk, one can select a schedule which has reasonable project completion time, cost and performance probability. This schedule determines the number of hired resources required in each type. This information, if available in the early stages of project planning, can aid in the formulation of a sound strategy for procuring resources. from external agencies and thus reduce overall cost of the project.

Preparation of Financial Requirement Estimate

The information on number of hired resources needed to schedule the new project can aid in estimating funds required for procuring resources. This information is necessary for arranging funds from financial institutions.

Feedback Control

REM quantifies and reveals the risk associated with availability of resources from uncertain activities of ongoing projects. This information can be advantageously utilized as feedback for taking corrective action on the ongoing projects, where possible.

Investment Planning

To achieve a higher growth rate, it is normal practice to invest earned profit from existing plants either in new projects or in expansion of the existing ones. However, profit from existing plants is neither a definitive amount nor certain and is subject to variations because of factors such as market demand fluctuations, productivity changes, competitors' price, quality of product, government regulations etc. Under these circumstances, one can only make probabilistic forecast of profit and hence any planning for new project or expansion which is dependent on this profit must also be probabilistic. REM can be used in making "go – no go" decision for capital projects. Here funds from existing projects can be considered as in-house resources and funds which the entrepreneur can borrow from financial institutions at higher interest rate can be considered as hired resources. In place of resource justified schedule, the cash flow outlay of the new project shows when the uncertain profit from the existing projects is required for investment on the new project. Overhead cost and penalty are replaced by accumulated interest on the investment and the loss of profit from the new project respectively. The output of the model, the time, cost and performance probability can assist in the decision, whether or not to invest in the expansion or new project.

Corporate Planning in Consultancy Organization

Yet another application of REM is in a consultancy organization which typically employs designers and draftsmen of different disciplines at various levels. These resources are engaged in design and implementation of its various ongoing projects from which they are progressively transferred to new project(s). If there is an uncertainty in the release of resources from the ongoing projects, the organization faces the question whether or not to accept a new project. REM can be used to aid in such decisions.

5.2.0 Scope for Future Research

REM has been developed based on the assumption that the durations of all activities of the new project are deterministic as in a CPM network. The model can not be used if there is an activity in the new project with probabilistic time estimates and scheduling of this activity overlaps with the range of interest. Further research is required to develop a methodology to handle such situations.

REM considers for allocation certain and uncertain in-house resources as well as certain hired resources. However, uncertain hired resources are not considered because if the availability of hired resources from any particular source is uncertain, one can always look for an alternate source. Further work is necessary to extend the use of the model to incorporate the uncertainty of hired resources.

REM does not consider DCF technique for evaluating total cost of each alternative because the difference between the completion times of these alternatives is not generally appreciable. However, when this difference is appreciable, further research is required to incorporate DCF technique in REM.

Replacement of hired resources by uncertain resources can also affect productivity when rhythem is broken waiting for the resources to arrive. This area also needs further research to determine the extent of productivity loss. On the contrary, there could be productivity gain when hired resources are used in place of uncertain resources. The evaluation of such gain also needs researching.

The methodology developed for risk evaluation does not impose any restriction on the number of sources to be considered for the availability of each type of resource. However, the computer program has been developed to handle a maximum of three sources either dependent or independent for the availability of each resource type. This limit is fixed because the dependence of a project for any resource type on more than three uncertain sources increases the risk beyond acceptable limit. Also to ensure simplicity and practicality of the model, only one type of uncertainty is considered for the availability of each type of resource. Further work is necessary to modify the model in order to consider more than three sources and more than one type of uncertainty for the availability of each resource type.

REFERENCES

6.0.0.0 REFERENCES

1) Ahuja H.N., Project Management: Techniques in Planning and Controlling Construction Projects. John Wiley & Sons, New York, 1983.

2) Alpert Lewis, and Orkand D.S., A Time Resource Trade-off Model for Aiding Management Decisions, Operations Research Inc., Technical Paper No. 12, Silver Spring, Maryland, 1962.

3) Antill James M., and Woodhead Ronald W., Critical Path Methods in Construction Practice, Wiley-Interscience, John Wiley and Sons Inc., New York, 1970.

4) Balas Egon, Project Scheduling With Resource Constraints, Application of Mathematical Programming Techniques, Carnegie-Mellon University, 1970.

5) Berman E.B., Resource Allocations in PERT Network Under Continuous Time-Cost Functions, Management Science, July 1964.

6) Black O.J., An Algorithm for Resource Leveling in Project Networks Unpublished Paper, Department of Industrial Administration, Yale University, May 1965.

7) Burgess A.R., and Killebrew J.B., Variation in Activity Level on a Cyclic Arrow Diagram, Journal of Industrial Engineering, March-April 1962.

8) Davis E.W., A Comparison of Heuristics and Optimum Solutions in Resource Constrained Project Scheduling. Management Science. Vol 21. No 8. April 1975. pp 944-955.

9) Davis E.W., Project Scheduling under Resource Constraints - Historical Review & Categorization of Procedures. AIIE Transactions Vol 5. No 4 December 1973. pp 297-313.

10) Davis E.W., and Heidorn George E., An Algorithm for Optimal Project Scheduling Under Multiple Resource Constraints. Management Science. Vol 17. No 12. August 1971. pp 803-815.

11) Dewitte L., Manpower Leveling of PERT Networks. Data Processing for Science/Engineering. March-April 1964.

12) DOD and NASA Guide. PERT/Cost. Office of the Secretary of Defense and National Aeronautics and Space Administration. Washington D.C., 1962.

13) Elmaghraby S.E., The Sequencing of N jobs on M Parallel Processors. Unpublished paper. North Carolina State University. Raleigh 1967.

14) Fisher Marshall Lee. Optimal Solution of Resource-Constrained Scheduling Problems. Technical Report No 56. Operations Research Center. MIT. September 1970.

15) Fulkerson D.R., A Network Flow Computation for Project Activity Sequencing. IRE Transaction on Engineering Management. September 1960.

16) Gorenstein Samuel. An Algorithm for Project(Job) Sequencing with Resource Constraints. Operations Research. Vol23. No2. July–August 1972. pp 835–850.

17) Gutjahr A. L., and Nemhauser G.L., An Algorithm for the Line Balancing Problem. Management Science. November 1964.

18) Handa V.K., Project Cost Curve Equivalent Linear Graphs. Paper Presented at ORSA Meeting. Boston. May 1965.

19) Hastings N.A.J., On Resource Allocation in Networks. Operational Research Quarterly. Vol 23. No 2. June 1972. pp 217–221.

20) Hooper P.C., Resource Allocation and Leveling. Paper Presented at 3rd Annual CPA Study Group Symposium of the Operational Research Society. May 1965.

21) Jewell W.S., Risk Taking in Critical Path Analysis. Management Science. January 1965.

22) Johnson Thomas J.R., An Algorithm for the Resource Constrained Project Scheduling Problem. Unpublished Ph.D Thesis. School of Management. MIT. August 1967.

23) Kelly J.E. Jr., and Walker M.R., Critical – Path Planning and Scheduling. 1959 Proceeding of the Eastern Joint Computer Conference.

24) Kelly J.E. Jr., Critical Path Planning and Scheduling: Mathematical Basis. Operations Research. Vol 9. No 3. May–June 1961. pp 296–320.

25) Levy F.K., Thompson G.S., and Weist J.D., Multi-Ship Multi-Shop Workload Smoothing Program Naval Research Logistics Quarterly, March 1968.

26) MacCrimmon R.K. and Rayvec C.A., An Analytical Study of PERT Assumptions, Operation Research, Vol 12, No 1, February 1964., pp 16-37.

27) Malcom D.G., Roseboom J.H., and Clark C.E., Application of a Technique for Research and Development Program Evaluation, Operations Research, Vol 7, No 5, September 1959, pp 646- 669.

28) Meyer W.L., and Shaffer L.R., Extensions of the Critical Path Method Through the Application of Integer Programming, Department of Civil Engineering, University of Illinois, July 1963.

29) Moshman J., Johnson J., and Larsen M., RAMPS -A Technique for Resource Allocation and Multi-project Scheduling, Proceedings, Spring Joint Computer Conference, 1963.

30) Moder J.J. and Phillips C.R., Project Management with CPM and PERT, Reinhold Corp., 1970.

31) O'Brien James J., CPM in Construction Management, Mcgraw-Hill, New York, 1971.

32) O'Rourke J., Some Recent Improvement in Network Based Resource Allocation Techniques, Presented at INTERNET Conference, Vienna, 1967.

33) Parikh S.C., and Jewell W.S., Decomposition of Project Networks. Management Science. January 1965.

34) Phillips C.R., Fifteen Key Features of Computer Programs for CPM and PERT. Journal of Industrial Engineeing. January-February 1964.

35) Prager W., A Structural Method of Computing Project Cost Curves. Management Science. Vol 19. 1963. p 394.

36) Pristker A. A. B., Walters Lawrence J., and Wolfe Philip M., Multi-project Scheduling with Limited Resources: A Zero-One Programming Approach. Management Science. Vol 10. No 1. September 1969. pp 93-108.

37) Sunaga Teuro. A Method of Optimal Scheduling for a Project with Resource Restriction. Journal of Operations Research Society of Japan. March 1970.

38) Weist Jerome D., A Heuristic Scheduling and Resource Allocation Model for Evaluating Alternative Weapon System Programs. Memorandum RM-5769-PR. The Rand Corporation. August 1969.

39) Weist Jerome D., The Scheduling of Large Projects With Limited Resources. Unpublished Ph.D Thesis. Carnegie Institute of Technology. 1963.

40) Weist Jerome D., Heuristic Programs for Decision Making. Harvard Business Review. September-October 1965.

41) Weist Jerome D., A Heuristic Model for Scheduling Large Projects with Limited Resources. Management Science. Vol 13. No 6. February 1967. pp B 359-377.

42) Wilson R.C., Assembly Line Balancing and Resource Leveling. University of Michigan Summer Conference. Production and Inventory Control. 1964.

43) Woodgate H.S., The Planning Network as a Basis for Resource Allocation. Cost Planning and Project Profitability Assesment. Applications of Critical Path Techniques. The English Universities Press Ltd., London. 1968.

ADDITIONAL LITERATURE

1) Alfredo H.S.Tang and Wilson H.Tang. Probability Concepts in Engineering Planning & Design. John Wiley & Sons. New York. 1975.

2) Borch K., Risk & Uncertainty. St.Martin Press. New York. 1968.

3) Brian Talbot F., Resource Constrained Project Scheduling with Time Resource Tradeoffs: The Nonpreemptive Case. Management Science. Vol. 28. No 10. October 1982. pp 1197-1210.

4) Butler R.S., A Heuristic Method of Equipment Acquisitioning for Maximum Profit. Masters Thesis. Faculty of Engineering & Applied Science. Memorial University of Newfoundland. Canada. October 1971.

5) Construction Risks and Liability Sharing. Proceedings of Conference by ASCE Construction Division on Contract Administration & Tunneling & Underground Construction. 1979.

6) Cooper Dale F., Heuristics For Scheduling Resource-Constrained Projects: An Experimental Investigation. Management Science, Vol 22, No 11, July 1976, pp 1186-1194.

7) Dar-El E.M., and Tur Y., A Multi-Resource Project Scheduling Algorithm. AIIE Transactions, Vol 9, No 1, March 1977, pp 44-52.

8) Dar-El E.M., and Tur Y., Resource Allocation of a Multi-Resource Project for Variable Resource Availabilities. AIIE Transactions, Vol 10, No 3, September 1978, pp 299-306.

9) Davis E.W., Project Network Summary Measures Constrained Resource Scheduling. AIIE Transactions, Vol 7, No 2, June 1975, pp 132-141.

10) Donaldson William A., The Estimation of the Mean and Variance of a "PERT" Activity Time. Operations Research, Vol 13, No 3, September 1965, pp 382-385.

11) Elmaghraby S.E., Activity Networks: Project Planning and Control by Networks. John Wiley & Sons, New York, 1977

12) Hastings N.A.J & Peacock J.B., Statistical Distributions. London Butterworths, London, 1974.

13) Hess S.W. and Quigley, Analysis of Risk in Investments Using Monte Carlo Techniques. Chem. Eng. Prog. Symp., Ser. No 42, 59, 1963, pp 55-63.

14) Jozef Lukaszewiez. On the Estimation of Errors Introduced by Standard Assumptions Concerning the Distribution of Activity Duration in PERT Calculations. Operations Research. Vol. 13. NO 2. March–April 1965. pp 326–327.

15) Katsoulas. Peter C. and Sadowski Randal P.. A Branch and Bound Algorithm for Use in Resource Allocation. AIIE Transactions. Vol 8. No 2. June 1976. pp 226–233.

16) Levy J.. and Wiest J.A.. A Management Guide to PERT/CPM. 2nd ed.. Prentice Hall. Englewood Cliffs. N.J.. 1977

17) Lison M.W. & Shaifer E.F. Jr.. Decision and Risk Analysis for Construction Management. John Wiley & Sons. New York. 1980.

18) Robillard P. and Trahan M.. Expected Completion Time in PERT Network. Operations Research. Vol 24. No 1. January–February 1976. pp 177–182.

19) Robillard P. and Trahan M.. The completion Time of PERT Networks. Operations Research. Vol 25. No 1. January–February 1977. pp 15–29.

20) Ross R.C.. Uncertainty Analysis Helps in Business Decisions. Chem. Eng.. Sep. 20. 1971. pp 149–155.

21) Sculli D.. The Completion Time of PERT Networks. Operation Research. Vol 34. No 2. February 1983. pp 155–158.

22) Slowinski R., Two Approaches to Problems of Resource Allocation Among Project Activities - A Comparative Study. Operations Research, Vol 31, No 8, August 1980, pp 711-723.

23) Stinson J., A Branch and Bound Algorithm for a General Class of Resource-Constrained Scheduling Problems. AIIE Conference Proceedings, Las Vegas, Nevada, 1975, pp 337-342.

24) Stinson J.P., Davis E.W., and Basheer K. Khumawala, Multiple Resource Constrained Scheduling Using Branch and Bound. AIIE Transactions, Vol 10, No 3, September 78, pp 252-259

25) Welgrarz J., Blazewicz J., Cellary W., and Slowinski R., An Automatic Revised Simplex Method for Constrained Resource Network Scheduling. ACM Trans. Math. Software, Vol 3, No 3, September 1977, pp 295-300.

26) Zipkin P.H., A simple Ranking Methods for Allocation of one Resource. Management Science, Vol 26, 1980, pp 33-43.

APPENDIX A

DESCRIPTION OF REM

INTRODUCTION TO REM

The computer program for REM in FORTRAN language has been developed to accept the resource justified schedule as input, and to generate alternate values for 1) project completion time, 2) project cost and 3) performance probability. REM consists of a main program and seven subroutines the functions of which are given below.

1) Main Program:-

Main program of REM evaluates overall project cost and performance probability of each alternative.

2) Subroutine NORM:-

Subroutine NORM evaluates probability from normal distribution through numerical integration using Simpson's rule.

3) Subroutine COST

Subroutine COST evaluates resource cost from the respective usage profiles for Stage One Computation. In addition, it provides information on when uncertain resources are required for the first time and subsequent times by the new project during Stage One Computation.

4) Subroutine PROR

Subroutine PROR evaluates resource cost for Stage Two Computation. In addition, it provides information on when uncertain resources are required for the first time and subsequent times by the new project during Stage Two Computation.

5) Subroutine VALUE

Subroutine VALUE adjusts the schedule to initial value after each computation.

6) Subroutine PROC

Subroutine PROC evaluates probability from beta distribution through numerical integration using Simpson's rule.

7) Subroutine ADJUST

Subroutine ADJUST aids in Stage One Computation

8) Subroutine MADS

Subroutine MADS aids in Stage Two Computation.

INPUT VARIABLES AND OUTPUT OF REM

The input variables and output of REM can be discussed with the help of Figure A.1. The input requirement as illustrated in the figure is comprised of the following:

1) Resource justified schedule,
2) Resource data,
3) Cost data, and
4) Time estimates for uncertain resources availability

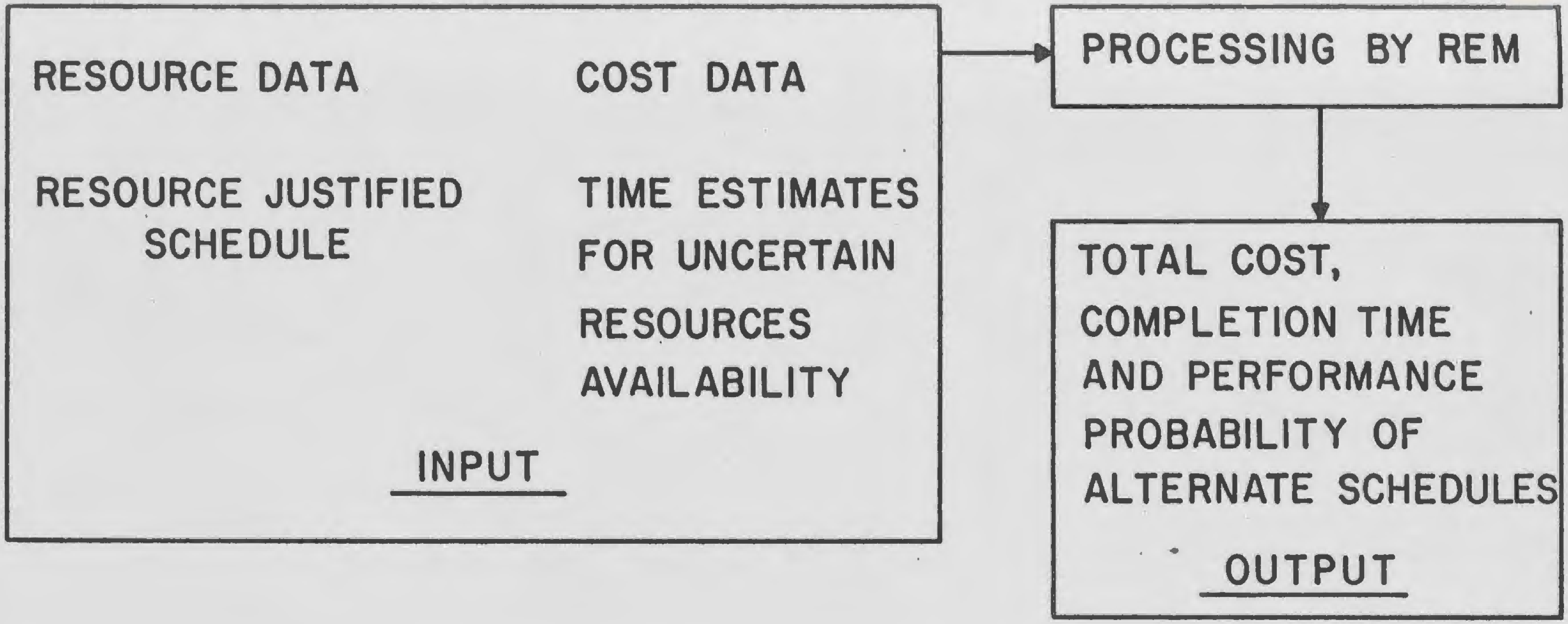
Each one of these input variables is further elaborated below.

Resource Justified Schedule

Requirement of each type of resource in each time unit of the resource justified schedule is the first input. This information is obtained from the resource allocation scheduling. Other major input data are as follows:

1) Number of certain and uncertain in-house resources as well as hired resources used, and
2) project duration obtained from CPM scheduling

Resource Data



INPUT - OUTPUT MODEL

FIGURE A-1

Resource data consists of the following:

1) Available number of in-house resources for use on new project.
   i) Certain resources
   ii) Uncertain resources from each source.
2) Available number of hired resources for use on new project

Cost Data

Various cost data required for each type of resource are as follows:

1) Cost of in-house resources.
   i) in operation, and
   ii) while being idle
2) Cost of hired resources.
3) Mobilization cost.
4) Other costs.
5) Overhead cost, and
6) Penalty.

Time Estimates for Uncertain Resource Availability

Data required to quantify the uncertainty due to resource availability are as follows:

1) Optimistic Time,
2) Most Likely Time,
3) Pessimistic Time,
4) Adjustment Factor,
5) Range of Interest, and
6) Type of Uncertainty

Description of Input Variables

The detailed description of different REM input variables in the same order as accepted by the program follows:

NR: –

NR refers to the number of groups of resource types required by the new project. Each set of multiple resource types from a single source is considered a group. Other groups are : each set of multiple resource types from dependent sources; each resource type from a single source; each resource type from multiple dependent sources; each resource type from multiple independent sources; and each resource type having no uncertain resource component.

NSP: -

NSP refers to the scheduled duration of the new project

NDU: -

NDU refers to the actual duration of the resource justified schedule.

OH: -

OH refers to the overhead cost for unit time.

CRP: -

CRP refers to penalty for unit time for exceeding the scheduled completion time.

IPATH(IR) : -

IPATH(IR) refers to the following code numbers which indicate the type of uncertainty associated with resource group IR.

2. a single uncertain resource type from multiple dependent sources.
3. a single uncertain resource type from

multiple independent sources.

4. multiple resource types from multiple dependent sources; multiple resource types from a single source; a single resource type from a single source; and a single resource type having no uncertain resource' component.

KEPE(IR):-

KEPE(IR) subclassifies the type of uncertainty if IPATH(IR) is 4. The following are the code numbers used.

1. a single type from a single source; multiple resource types from a single source; and single resource type having no uncertain resource component.
2. multiple resource types from multiple dependent sources.
0. This is the value of KEPE(IR), if IPATH(IR) is not equal to 4.

KITE(IR):-

If there are more than one resource type in resource group IR, it indicates the number of resource types in group IR. For example, if multiple resource types R1 and R2 are expected from a single activity of an ongoing project, KEPE(IR) is 2.

If there is only one resource type in group IR, it refers to the number of sources from which the resources are expected. For example, if a resource type R1 is expected from three uncertain sources, the value of KEPE(IR) is 3.

UUUR(IR,I):-

If there is only one resource type in the resource group IR, UUUR(IR,I) refers to the number of uncertain resources. If there are more than one resource type in resource group IR, it refers to the number of uncertain resources of type 'I' in the group IR. The same conditions are applicable to CCCR(IR,I),CCCRO(IR,I), CCCRO(IR,I), CCCRB(IR,I),CCCRT(IR,I) and PVALUE(IR,I) as well.

CCCR(IR,I):-

CCCR(IR,I) refers to number of certain resources.

CCCRO(IR,I):-

CCCO(IR,I) refers to operating cost of in-house resources.

CCCRO(IR,I):-

CCCRO(IR, I) refers to cost of idle in-house resources.

CCCRB(IR, I):-

CCCRB(IR, I) refers to cost of hired resources.

CCCRT(IR, I):-

CCCRT(IR, I) refers to mobilization cost of in-house resources.

PAVLUE(IR, I):-

PAVLUE(IR, I) refers to the number of hired resources available

DR(IR, K):-

If there are more than one type of resource in group IR, it refers to the optimistic time estimate for the availability of resource type K. If there is only one resource type in group IR, it refers to the optimistic time estimate for the release of resources from source K.

If the resources are available from independent sources, the time estimates are given with reference to start date of the respective ongoing project. If the resources are expected from dependent activities of the same project, the time estimate for the release of resources from first activity is given with reference to the start of the ongoing project. The time estimate for the release of resources from the next succeeding activity is given with reference to the completion time of the preceding activity and so on. If there is no uncertain resource component, the optimistic time estimate is zero.

If the uncertainty is not due to the project risk of an ongoing project, the time estimates are given with reference to the start date of the new project.

MR(IR,K) and BR(IR,K):-

MR(IR,K) and BR(IR,K) are the most likely and pessimistic time estimates respectively for the availability of uncertain resources. All conditions outlined against DR(IR,K) are applicable to these estimates as well.

KKUR(IR,I):-

If there are multiple resource types in the group IR, it refers to the time difference between start of the ongoing project from which resource type I of group IR is expected and the scheduled start date of the new project.

If there is only one resource type in the group IR, it refers to the time difference between the start of the ongoing project I and the new project.

RRR(IR,I,KM):-

RRR(IR,I,KM) refers to the requirement of resources of the type I in group IR on time unit KM. If the project duration is NDU, the final value of KM is (NDU+1). The resource requirement on time unit (NDU+1) is zero.

UUR(KM):_

UUR(KM) refers to the duration of the new project corresponding to resource requirement of RRR(IR,I,KM).

ME(IR,I):-

This is applicable only when IPATH(IR) is not equal to 4 i.e., when a single resource type has more than one dependent or independent source. This refers to the number of resources expected from source I.

MAPTH:-

MPATH refers to the range of interest discussed in section 3.6.1.0

ADD:-

ADD refers to 'other costs' of the project and it includes the cost of materials and noncritical resources not considered for resource allocation scheduling.

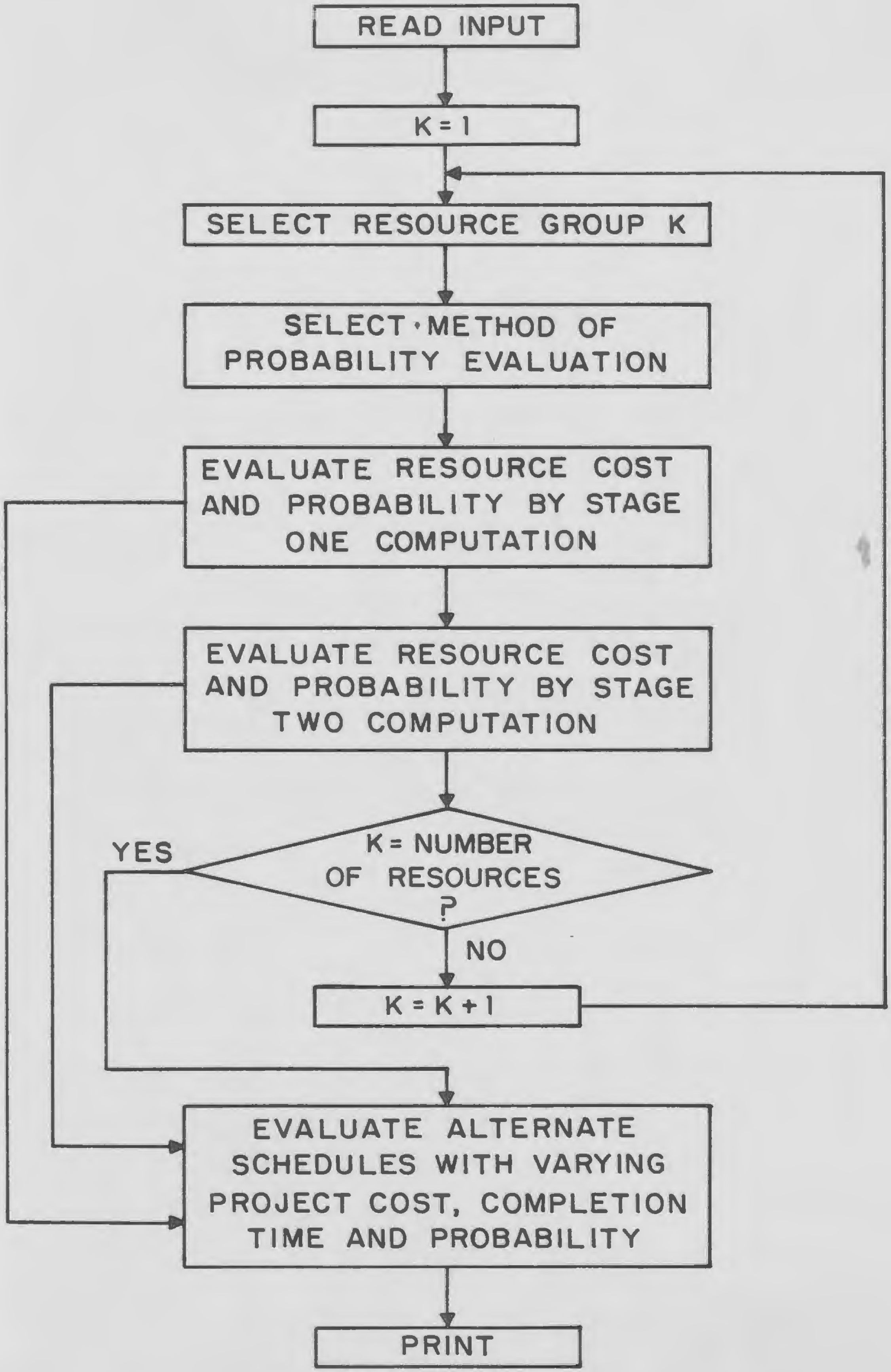
Output of REM

A large number of alternate schedules with varying project cost, completion time and performance probability is given as output by REM.

WORKING OF REM

Main program of REM consists of four modules. The first module evaluates cost and probability for the availability of single resource type multiple dependent sources. The second module evaluates cost and probability for the availability one or more resource types from the same source. The third module evaluates cost and probability for the availability of single resource type from multiple independent sources. The fourth module evaluates cost and probability for the availability of multiple resource types from multiple dependent sources.

The working of REM can be further discussed with the help of flow chart illustrated in Figure A.2. REM processes the individual resource groups in one of the four modules discussed in the preceding paragraph depending on the type of uncertainty associated with their availability. It computes the overall project cost from individual resource costs, penalty, and material, mobilization, overhead and other costs. It also obtains the performance probability from the probability of availability of individual resource groups. It finally prints the completion time, cost and performance probability of each alternative in the order mentioned.



WORKING OF REM
FIGURE A.2

Array Sizes

The various arrays used in the program can handle a maximum of 20 resource groups, 10 sources either dependent or independent for single as well as multiple resource types, 100 time units for project duration, 50 resources from a source, and 50 peaks for resource usage profile. If higher sizes are needed, the size of the respective array needs to be increased in the main program as well as in the relevant subroutines.

Deck Arrangement

The arrangement of the program is as follows:

* Control statements for the system,
* main program,
* seven subroutines in any order, and
* data file

Computer Time Requirement

Computer time is needed for obtaining several resource justified schedules using standard package program for resource allocation as well as for processing REM. This program was tried in IBM/370 using cards as input media. PMS IV (Project Management System) was used for resource allocation. For obtaining the complete solution for the example described in Chapter 4, approximately 2 minutes of CPU time was needed. In fact, the computational time required can not be generalized and it varies with the following factors.

* <u>Network Characteristics</u>
  - i) Duration of the project,
  - ii) Number of activities, and
  - iii) Complexity of the network
* <u>Resource Characteristics</u>
  - i) Number of resource types,
  - ii) Number of each type of resource required, and
  - iii) Type and nature of uncertainty associated with availability of each resource type
* Priority rules adopted for allocation

APPENDIX B

PROGRAM LISTING

MAIN PROGRAM

```
************************************************************************
C     MAIN PROGRAM TO EVALUATE COMPLETION TIME, TOTAL COST AND          *
C     PERFORMANCE PROBABILITY                                            *
************************************************************************


      DIMENSION PROL(20,5),PRC(20),MR(20,5),PROBE(50),PROZ(100),OVC(20,50),
     COOVC(20,50,10),ME(20,10),KE(50),KNT(100),OC(100),KITE(20),
     CUUUR(20,10),CCCR(20,10),PROBEN(20,50),PROCHN(20,50,50),
     CPR(50),RP(50,50),PROB(50),KU(50),PVALUE(20,10),
     CCCCRO(20,10),CCCROI(20,10),CCCRB(20,10),CCCRT(20,10),IPATH(20),
     CU(50),R(100),PROCH(20,50),KKUR(20,10),RRR(20,20,100),BIG(100),
     COOC(20,10),TEP(20,50),TP(50),DR(20,10),BR(20,10),
     CREM(50),TTM(50),TTC(50),PT(50,50),PZ(50,10,10) ,KEPE(20)
      DIMENSION RAP(50),RAPK(20,50)
C     READ STATEMENTS
      READ(5,10) NR,NSP,NDU
   10 FORMAT(3I3)
      N = NDU + 1
      READ(5,15) OH,CRP
   15 FORMAT(2F8.2)
      READ(5,22) ( U(IE),IE = 1,N)
    6 DO 30 IR = 1,NR
      READ(5,16) KITE(IR),KEPE(IR),IPATH(IR)
   16 FORMAT(3I3)
      KZ = KITE(IR)
      IF(IPATH(IR) .NE. 4) GO TO 2001
      DO 28 I = 1,KZ
      READ(5,18) UUUR(IR,I),CCCR(IR,I),CCCRO(IR,I),CCCROI(IR,I),
     +CCCRB(IR,I),CCCRT(IR,I), PVALUE(IR,I),KKUR(IR,I)
   18 FORMAT(7F8.0,I5)
      READ(5,20) DR(IR,I),BR(IR,I),MR(IR,I)
   20 FORMAT(2F8.0,I3)
      READ(5,22)(RRR(IR,I,IE),IE = 1,N)
   22 FORMAT(80(16F5.2/))
   28 CONTINUE
      GO TO 2006
 2001 READ(5,19) UUUR(IR,1),CCCR(IR,1),CCCRO(IR,1),CCCROI(IR,1),
     +CCCRB(IR,1),CCCRT(IR,1),PVALUE(IR,1)
   19 FORMAT(7F8.0)
      READ(5,22) (RRR(IR,1,KM),KM = 1,N)
      DO 2005 I = 1,KZ
      READ(5,20) DR(IR,I),BR(IR,I),MR(IR,I)
      READ (5,2004) ME(IR,I) ,KKUR(IR,I)
 2004 FORMAT(2I2)
 2005 CONTINUE
 2006 CONTINUE
   30 CONTINUE
```

```
      READ(5,31) MPATH ,ADD
   31 FORMAT(I2,F8.0)
 4110 FORMAT(5X,I5)
  815 FORMAT(1H0,8X,F10.0,15X,I3,16X,F5.2)
  804 FORMAT(5X,F10.0,F9.2)
      NUK = N-1
      IF(NUK .GT. MPATH) NUK = MPATH
   35 DO 800 IR = 1,NR
      KIT = KITE(IR)
      KEP = KEPE(IR)
      IF(KIT .LT. 3) ME(IR,3)= 0.0
C     PROCESSING BASED ON TYPE OF UNCERTAINTY BEGINS
      KRUN = IPATH(IR)
      GO TO (40,160,400,2000),KRUN


*************************************************************************
C     COST AND PROBABILITY EVALUATION FOR THE AVAILABILITY OF          *
C     SINGLE RESOURCE TYPE MULTIPLE DEPENDENT SOURCES                  *
*************************************************************************


  160 UR = UUUR(IR,1)
      MP = 1
      KU(2) = 0
      KU(3) = 0
      CRO = CCCRO(IR,1)
      CRT = CCCRT(IR,1)
      KU(1) = KKUR(IR,1)
      CVAL = PVALUE(IR,1)
      CRB = CCCRB(IR,1)
      CROI = CCCROI(IR,1)
      CR = CCCR(IR,1)
      M1 = ME(IR,1)
      M2 = ME(IR,2)
      M3 = ME(IR,3)
      DO 162 I = 1,N
  162 R(I) = RRR(IR,1,I)
      CALL COST(N,CR,UR,CRO,CROI,CRB,R,U,TTC,TP,PR,KISS,KONT,BIG)
      IF(BIG(1)-(CR+UR)) 164,164,166
  164 OC(IR) = TTC(KISS) + BIG(1) * CRT
      GO TO 168
  166 OC(IR) = TTC(KISS) + (CR+UR)*CRT
  168 CONTINUE
      IF(KONT .EQ. 0) GO TO 239
  170 IF(PR(1) -M1) 172,172,182
  172 D = DR(IR,1)
      B = BR(IR,1)
      M = MR(IR,1)
      K = TP(1) + KU(1)
      B4 = K
      IF(K .GE. BR(IR,1)) B4 = BR(IR,1)
```

```
178 CALL PROC(D,B,M,K,PROB,NAR)
    PROZ(1) = PROB(NAR)
    GO TO 187
182 IF(PR(1) - (M1 + M2)) 184,184,186
184 DT = BR(IR,1) + BR(IR,2)
    DDT = 4 * (MR(IR,1) + MR(IR,2))
    CT = DR(IR,1) + DR(IR,2)
    CEAN = (DT+DDT+CT)/6
    VARI= (BR(IR,1)-DR(IR,1))**2./36.+(BR(IR,2)-DR(IR,2))**2./36.
    K = TP(1) + KU(1)
    B4 = K
    IF(K .GE. BR(IR,1) + BR(IR,2)) B4 = BR(IR,1) + BR(IR,2)
    IF(BR(IR,1) .EQ. DR(IR,1) .OR. BR(IR,2) .EQ. DR(IR,2))
   C GO TO 185
    CALL NORM (CEAN,VARI,CT,DT,K,PLK)
    PROZ(1) = PLK
    GO TO 187
185 B = DT
    M = DDT
    D = CT
    CALL PROC(D,B,M,K,PROB,NAR)
    PROZ(1) = PROB(NAR)
    GO TO 187
186 DT = BR(IR,1) + BR(IR,2) + BR(IR,3)
    DDT = MR(IR,1) + MR(IR,2) + MR(IR,3)
    CT = DR(IR,1) + DR(IR,2) + DR(IR,3)
    CEAN = (DT+ 4* DDT + CT)/6
    VARI = (BR(IR,1)-DR(IR,1))**2./36. +
   +(BR(IR,2)-DR(IR,2))**2./36. + (BR(IR,3) - DR(IR,3))**2./36.
    K = TP(1) + KU(1)
    IF(BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,2) .EQ. DR(IR,2)
   C .OR. BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,3) .EQ. DR(IR,3) .OR.
   C BR(IR,2) .EQ. DR(IR,2) .AND. BR(IR,3) .EQ. DR(IR,3)) GO TO 179
    CALL NORM (CEAN,VARI,CT,DT,K,PLK)
    PROZ(1) = PLK
    GO TO 187
179 B = DT
    M = DDT
    D = CT
    CALL PROC(D,B,M,K,PROB,NAR)
    PROZ(1) = PROB(NAR)
187 CONTINUE
    IF(KONT .EQ. 1) GO TO 230
    DO 228 I = 2,KONT
    IF(PR(I) - M1) 188,188,190
188 PROZ(I) = PROZ(I-1)
    GO TO 226
190 IF(PR(I) -(M1+M2)) 192,192,208
192 IF(PR(I-1)-M1) 196,196,198
198 PROZ(I) = PROZ(I-1)
    GO TO 226
196 D = B4 + DR(IR,2)
```

```
      B = B4 + BR(IR,2)
      M = B4 + MR(IR,2)
  201 K = TP(I) + KU(1)
      B4 = K
      IF(K .GE. BR(IR,1) + BR(IR,2)) B4 = BR(IR,1) + BR(IR,2)
  206 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(I) = PROB(NAR) * PROZ(I-1)
      GO TO 226
  208 IF(PR(I-1) - (M1 + M2 )) 210,210,212
  212 PROZ(I) = PROZ(I-1)
      GO TO 226
  210 IF (PR(I-1) - M1 ) 214,214,216
  214 CEAN = B4      +(DR(IR,2) + DR(IR,3)+4*MR(IR,2) + 4*MR(IR,3)
     ++BR(IR,2) + BR(IR,3))/6.
      CT = B4      + DR(IR,2) + DR(IR,3)
      DT = B4      + BR(IR,2) + BR(IR,3)
  217 K = TP(I) + KU(1)
      VARI= (BR(IR,3)-DR(IR,3))**2./36.+(BR(IR,2)-DR(IR,2))**2./36.
      IF (BR(IR,3) .EQ. DR(IR,3) .OR. BR(IR,2) .EQ. DR(IR,2)) GO TO 202
      CALL NORM (CEAN,VARI,CT,DT,K,PLK)
      PROZ(I) = PROZ(I-1) * PLK
      GO TO 226
  202 B = DT
      M = MR(IR,2) + MR(IR,3) + B4
      D = CT
      CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(I)=PROZ(I-1) * PROB(NAR)
      GO TO 226
  216 D = B4 + DR(IR,3)
      M = B4 + MR(IR,3)
      B = B4 + BR(IR,3)
  223 K = TP(I) + KU(1)
  224 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(I) = PROZ(I-1) * PROB(NAR)
  226 CONTINUE
  228 CONTINUE
  230 CONTINUE
      PROBEN(IR,MP) = PROZ(KONT)
      CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 170
      GO TO 240
  239 PROBEN(IR,MP) = 1.0
      CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
  240 CONTINUE
      MP = 1
      KU(1) = KKUR(IR,1)
      KD = 1
      KS = 1
      KAR = 0
      MAR = 0
      KF = BR(IR,1) -KKUR(IR,1)
      IF(KF .GE. NUK) KF = NUK
```

```
 242 CALL PROR(N,CR,UR,CRO,CROI,CRB,R,U,TTM,PT,RP,LE,KNT,REM,NUK,CVAL)
     DO 370 L = KS,KF
     IF(TTM(L) .EQ. 0.0) OVC(IR,L) = 0.0
     IF(OVC(IR,L) .EQ. 0.0) GO TO 790
     KILL = KNT(L)
     IF(KILL .EQ. 0) GO TO 375
     IF(REM(L)-(CR+UR)) 252,254,254
 252 OVC(IR,L) = TTM(L) + REM(L) * CRT
     GO TO 256
 254 OVC(IR,L) = TTM(L) + (CR+UR) * CRT
3000 FORMAT(5X,F8.3)
 256 CONTINUE
     IF(PT(L,1) .EQ. 0.0) GO TO 375
 270 IF(RP(L,1) -M1) 272,272,282
 272 D = DR(IR,KD) + KAR + MAR
     B = BR(IR,KD) + KAR + MAR
     M = MR(IR,KD) + KAR + MAR
     K = PT(L,1) + KU(1)
     B4 = K
     Z1 = BR(IR,KD) + MAR + KAR
     IF(K .GE. Z1) B4 = Z1
 278 CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(1) = PROB(NAR)
     GO TO 287
 282 IF(RP(L,1) - (M1+M2)) 284,284,286
 284 DT = BR(IR,KD) + BR(IR,(KD+1))    + KAR
     CT = DR(IR,KD) + DR(IR,(KD+1))  +KAR
     DDT = 4 * (MR(IR,KD) + MR(IR,(KD+1)))+ 4*KAR
     PL1 = (BR(IR,KD) -DR(IR,KD))**2./36.
     PL2 = (BR(IR,(KD+1))-DR(IR,(KD+1)))**2./36.
     CEAN = (DT+DDT+CT)/6
     VARI = PL1 + PL2
     K = PT(L,1) + KU(1)
     B4 = K
     Z2 = BR(IR,KD) + BR(IR,(KD+1)) + KAR
     IF(K .GE.Z2) B4 = Z2
     IF(BR(IR,KD) .EQ. DR(IR,KD) .OR. BR(IR,(KD+1)) .EQ.
    C DR(IR,(KD+1))) GO TO 285
     CALL NORM (CEAN,VARI,CT,DT,K,PLK)
     PROZ(1) = PLK
     GO TO 287
 285 B = DT
     D = CT
     M = DDT/4.
     CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(1) = PROB(NAR)
     GO TO 287
 286 DT = BR(IR,KD) + BR(IR,(KD+1)) + BR(IR,(KD+2))
     DDT = MR(IR,KD) + MR(IR,(KD+1)) + MR(IR,(KD+2))
     CT = DR(IR,KD) + DR(IR,(KD+1)) + DR(IR,(KD+2))
     K = PT(L,1) + KU(1)
     IF(BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,2) .EQ. DR(IR,2)
```

```
  C .OR. BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,3) .EQ. DR(IR,3) .OR.
  C BR(IR,2) .EQ. DR(IR,2) .AND. BR(IR,3) .EQ. DR(IR,3)) GO TO 289
    CEAN = (DT+ 4* DDT + CT)/6
    PL1 = (BR(IR,KD) -DR(IR,KD))**2./36.
    PL2 = (BR(IR,(KD+1))-DR(IR,(KD+1)))**2./36.
    PL3 = (BR(IR,(KD+2))-DR(IR,(KD+2)))**2./36.
    VARI = PL1+ PL2+ PL3
    CALL NORM (CEAN,VARI,CT,DT,K,PLK)
    PROZ(1) = PLK
    GO TO 287
289 B = DT
    D = CT
    M = DDT
    CALL PROC(D,B,M,K,PROB,NAR)
    PROZ(1) = PLK
287 CONTINUE
    IF(KILL .EQ. 1) GO TO 330
    DO 328 I = 2, KILL
    IF (RP(L,I) - M1 ) 288,288,290
288 PROZ(I) = PROZ(I-1)
    GO TO 326
290 IF (RP(L,I) - (M1+M2)) 292,292,308
292 IF(RP(L,(I-1)) - M1) 296,296,298
298 PROZ(I) = PROZ(I-1)
    GO TO 326
296 D = B4 + DR(IR,(KD+1))
    B = B4 + BR(IR,(KD+1))
    M = B4 + MR(IR,(KD+1))
301 K = PT(L,I) + KU(1)
    B4 = K
    Z2 = BR(IR,KD) + BR(IR,(KD+1)) + KAR
    IF(K .GE.Z2) B4 = Z2
306 CALL PROC(D,B,M,K,PROB,NAR)
    PROZ(I) = PROB(NAR) * PROZ(I-1)
    GO TO 326
308 IF (RP(L,(I-1)) - ( M1 + M2 )) 310,310,312
312 PROZ(I) = PROZ(I-1)
    GO TO 326
310 IF(RP(L,(I-1)) - M1) 314,314,316
314 CEAN =           (DR(IR,2) + DR(IR,3)+4*MR(IR,2) + 4*MR(IR,3)
  ++BR(IR,2) + BR(IR,3))/6.  + B4
    CT = B4          + DR(IR,2) + DR(IR,3)
    DT = B4          + BR(IR,2) + BR(IR,3)
317 K = PT(L,I) + KU(1)
    VARI= (BR(IR,3)-DR(IR,3))**2./36.+(BR(IR,2)-DR(IR,2))**2./36.
    IF (BR(IR,3) .EQ. DR(IR,3) .OR. BR(IR,2) .EQ. DR(IR,2)) GO TO 318
    CALL NORM (CEAN,VARI,CT,DT,K,PLK)
    PROZ(I) = PROZ(I-1) * PLK
    GO TO 326
318 B = DT
    D = CT
    M = B4 + MR(IR,2) + MR(IR,3)
```

```
      CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(I) = PROZ(I-1) *PROB(NAR)
      GO TO 326
  316 D = B4 + DR(IR,3)
      M = B4 + MR(IR,3)
      B = B4 + BR(IR,3)
  323 K = PT(L,I) + KU(1)
  324 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(I) = PROZ(I-1) * PROB(NAR)
  326 CONTINUE
  328 CONTINUE
  330 CONTINUE
      MZ = L
      PROCHN(IR,MZ,MP) = PROZ(KILL)
      CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 270
      KU(1) = KKUR(IR,1)
      MP = 1
  370 CONTINUE
      KD = KD + 1
      IF(KF .EQ. NUK) GO TO 390
      IF(KS .EQ.1) GO TO 380
      KS = BR(IR,1) + BR(IR,2) + 1 -KKUR(IR,1)
      KF = NUK
      MP = 1
      KU(1) = KKUR(IR,1)
      MAR = BR(IR,2)
      CR = CR + M1
      UR = UR - M1
      M1 = M3
 3005 FORMAT(3X,3I3)
      KU(2) = 0
      KU(3) = 0
      GO TO 242
  380 KS = BR(IR,1) + 1 - KKUR(IR,1)
      KF = BR(IR,1) + BR(IR,2) -KKUR(IR,1)
      IF(KF .GE. NUK) KF = NUK
      KAR = BR(IR,1)
      CR = CR +M1
      UR = UR - M1
      M1 = M2
      M2 = M3
      MP = 1
      KU(1) = KKUR(IR,1)
      WRITE(6,3005) KS,KF KD
      KU(2) = 0
      KU(3) = 0
      GO TO 242
  375 CONTINUE
      NEP = L-1
      IF(L .EQ.1) NEP = NEP+ 1
      IF(L .EQ.1) OVC(IR,NEP) = OC(IR)
```

```
      OND = OVC(IR,NEP)
      DO 385 I = L,NUK
      MZ = I
      OVC(IR,I) = OND
      PROCHN(IR,MZ,MP) = 1.0
      CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
      MP = 1
  385 CONTINUE
  390 CONTINUE
      GO TO 790
 2000 OC(IR) = 0.0
      IF(KIT .EQ. 2) TEP(1,3) = 0.0
      IF(KIT .LT.3) KU(3) = 0
      IF(KIT .LT.2) KU(2) = 0
      IF(KIT .LT. 3) KKUR(IR,3) = 0
      IF(KIT .LT. 2) KKUR(IR,2) = 0
      MP = 1
      DO 2030 L = 1,KIT
      UR = UUUR(IR,L)
      CRT = CCCRT(IR,L)
      CR = CCCR(IR,L)
      CROI = CCCROI(IR,L)
      CRO = CCCRO(IR,L)
      CRB = CCCRB(IR,L)
      KU(L) = KKUR(IR,L)
      DO 2010 I = 1,N
 2010 R(I) = RRR(IR,L,I)
      CALL COST(N,CR,UR,CRO,CROI,CRB,R,U,TTC,TP,PR,KISS,KONT,BIG)
      IF(BIG(1)-(CR+UR)) 2015,2015,2020
 2015 OOC(IR,L) = TTC(KISS) + BIG(1)*CRT
      GO TO 2025
 2020 OOC(IR,L) = TTC(KISS) + (CR+UR) * CRT
 2025 TEP(1,L) = TP(1)
      OC(IR) = OC(IR) + OOC(IR,L)
 2030 CONTINUE
      GO TO (2040,2100),KEP


***********************************************************************
C     COST AND PROBABILITY EVALUATION FOR THE AVAILABILITY OF ONE     *
C     OR MORE RESOURCE TYPES FORM THE SAME SOURCE                     *
C     - BY DELAYING THE PROJECT START                                 *
***********************************************************************


 2040 CONTINUE
      IF(BR(IR,1) .EQ. 0.0) PROBEN(IR,MP) = 1.0
      IF(BR(IR,1) .EQ. 0.0 ) GO TO 86
      TP1 = N-1
      DO 2060 L = 1, KIT
      IF(TEP(1,L) - TP1 )  2045,2045,2050
```

```
 2045 TP1 = TEP(1,L)
 2050 CONTINUE
 2060 CONTINUE
      IF(TP1 .EQ. 0.0) TP1 = BR(IR,1)
      D = DR(IR,1)
      B = BR(IR,1)
      M = MR(IR,1)
 2065 K = TP1 + KU(1)
   57 FORMAT(2X,2F5.0,2I5)
 2075 CALL PROC(D,B,M,K,PROB,NAR)
      PROBEN(IR,MP) = PROB(NAR)
   85 FORMAT(5X,F6.2)
  86  CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 2065
      GO TO 2530

**********************************************************************
C     COST AND PROBABILITY EVALUATION FOR THE AVAILABILITY OF          *
C     MULTIPLE RESOURCE TYPES FROM DEPENDENT UNCERTAIN SOURCES         *
C     - BY DELAYING THE START OF THE PROJECT                           *
**********************************************************************


 2100 CONTINUE
      MP = 1
      TP1 = TEP(1,1)
      TP2 = TEP(1,2)
      TP3 = TEP(1,3)
  808 FORMAT(3F5.0)
      IF(TP3 .EQ. 0.0 .AND. TP2 .EQ. 0.0 .AND.
     CTP1 .EQ. 0.0) GO TO 2150
      IF(TP3 .EQ. 0.0 .AND. TP2 .EQ. 0.0) GO TO 2150
      IF(TP3 .EQ. 0.0 .AND. TP1 .EQ. 0.0) GO TO 2300
      IF(TP1 .EQ. 0.0 .AND. TP2 .EQ. 0.0 ) GO TO 2400
      IF(TP1 .EQ. 0.0 .AND. TP3 .GT. TP2) GO TO 2300
      IF(TP3 .EQ. 0.0 .AND. TP1 .GE. TP2) GO TO 2300
      IF(TP1 .EQ. 0.0 .AND. TP2 .GE. TP3) GO TO 2400
      IF(TP2 .EQ. 0.0 .AND. TP1 .GE. TP3) GO TO 2400
      IF(TP2 .EQ. 0.0 .AND. TP3 .GT. TP1) GO TO 2450
      IF(TP3 .EQ. 0.0  .AND. TP2 .GT. TP1 ) GO TO 2150
      IF(TP3 .GT. TP2  .AND. TP2 .GT. TP1) GO TO 2150
      IF(TP1 .GE. TP3 .AND. TP3 .GT. TP2) GO TO 2300
      IF(TP3 .GE. TP1 .AND. TP1 .GT. TP2) GO TO 2300
      IF(TP2 .GE. TP1 .AND. TP1 .GE. TP3) GO TO 2400
      IF(TP1 .GE. TP2 .AND. TP2 .GE. TP3) GO TO 2400
      IF(TP2 .GE. TP3 .AND. TP3 .GT. TP1) GO TO 2450
 2150 K = TP1 + KU(1)
      B4 = K
      IF(K .GE. BR(IR,1)) B4 = BR(IR,1)
      IF(TP1 .EQ. 0.0) GO TO 2170
```

```
      D = DR(IR,1)
      M = MR(IR,1)
      B = BR(IR,1)
 2165 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(1) = PROB(NAR)
      GO TO 2175
 2170 PROZ(1) = 1.0
 2175 CONTINUE
      IF(TP2 .EQ. 0.0 ) GO TO 2210
      B = B4 + BR(IR,2)
      D = B4 + DR(IR,2)
      M = B4 + MR(IR,2)
 2190 K = KU(1) + TP2
      SS = K
      Z1 = BR(IR,1) + BR(IR,2)
      IF( K.GE. Z1) SS = Z1
 2205 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(2) = PROB(NAR)
      GO TO 2212
 2210 PROZ(2) = 1.0
 2212 CONTINUE
 2215 IF(TP3 .EQ. 0.0 ) GO TO 2250
 2225 D = SS + DR(IR,3)
      B = SS + BR(IR,3)
      M = SS+ MR(IR,3)
 2230 K = TP3 + KU(1)
 2245 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(3) = PROB(NAR)
      GO TO 2255
 2250 PROZ(3) = 1.0
 2255 CONTINUE
      PROBEN(IR,MP) = PROZ(1) *PROZ(2) * PROZ(3)
      CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 2150
 2260 CONTINUE
      GO TO 2530
 2300 CONTINUE
      MP = 1
 2302 K = TP2 + KU(2)
      SS = K
      Z1 = BR(IR,1) + BR(IR,2)
      IF( K .GE.Z1) SS = Z1
      DT = BR(IR,1) + BR(IR,2)
      DDT = 4 * (MR(IR,1) + MR(IR,2))
      CT = DR(IR,1) + DR(IR,2)
      IF(BR(IR,1) .EQ. DR(IR,1) .OR. BR(IR,2) .EQ. DR(IR,2)) GO TO 2304
      CEAN = (DT+DDT+CT)/6
      VARI= (BR(IR,1)-DR(IR,1))**2./36.+(BR(IR,2)-DR(IR,2))**2./36.
  810 FORMAT(5X,4F8.2,I4)
      CALL NORM (CEAN,VARI,CT,DT,K,PLK)
      PROZ(2) = PLK
      GO TO 2305
```

```
2304 M = MR(IR,1) + MR(IR,2)
     B = BR(IR,1) + BR(IR,2)
     D = DR(IR,2) + DR(IR,1)
     CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(2) = PROB(NAR)
2305 IF(TP3 .EQ. 0.0) GO TO 2335
2310 D = SS + DR(IR,3)
     B = SS + BR(IR,3)
     M = SS + MR(IR,3)
2315 K = KU(3) + TP3
2330 CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(3) = PROB(NAR)
     GO TO 2340
2335 PROZ(3) = 1.0
2340 PROBEN(IR,MP) = PROZ(2) * PROZ(3)
     CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
     IF(LAR .EQ. 1) GO TO 2302
     GO TO 2530
2400 DT = BR(IR,1) + BR(IR,2) + BR(IR,3)
     K = KU(3) + TP(3)
     DDT = MR(IR,1) + MR(IR,2) + MR(IR,3)
     CT = DR(IR,1) + DR(IR,2) + DR(IR,3)
     IF(BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,2) .EQ. DR(IR,2)
    C .OR. BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,3) .EQ. DR(IR,3) .OR.
    C BR(IR,2) .EQ. DR(IR,2) .AND. BR(IR,3) .EQ. DR(IR,3)) GO TO 2410
     CEAN = (DT+ 4* DDT + CT)/6
     VARI = (BR(IR,1)-DR(IR,1))**2./36. +
    +(BR(IR,2)-DR(IR,2))**2./36. + (BR(IR,3) - DR(IR,3))**2./36.
     CALL NORM (CEAN,VARI,CT,DT,K,PLK)
     PROBEN(IR,MP) = PLK
     GO TO 2415
2410 D = CT
     M = DDT
     B = DT
     CALL PROC(D,B,M,K,PROB,NAR)
     PROBEN(IR,MP) = PROB(NAR)
2415 CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
     IF(LAR .EQ. 1) GO TO 2400
     GO TO 2530
2450 MP = 1
2455 K = KU(1) + TP1
     TP1 = K
     IF(K .GE.BR(IR,1)) TP1 = BR(IR,1)
     D = DR(IR,1)
     B = BR(IR,1)
     M = MR(IR,1)
2465 CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(1) = PROB(NAR)
     K = TP3 + KU(3)
     IF(DR(IR,2) .EQ. BR(IR,2) .OR. DR(IR,3) .EQ. BR(IR,3)) GO TO 2481
2480 CT = TP1 + DR(IR,3)+ DR(IR,2)
     DT = TP1 + BR(IR,3) + BR(IR,2)
```

```
      DDT = TP1 + MR(IR,3) + MR(IR,2)
      CEAN = (DT + DDT *4 + CT) /6
      VARI= (BR(IR,3)-DR(IR,3))**2./36.+(BR(IR,2)-DR(IR,2))**2./36.
      CALL NORM (CEAN,VARI,CT,DT,K,PLK)
      PROZ(3) = PLK
      GO TO 2485
2481  D = TP1 + DR(IR,2) + DR(IR,3)
      B = TP1 + BR(IR,2) + BR(IR,3)
      M = TP1 + MR(IR,2) + MR(IR,3)
      CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(3) = PROB(NAR)
2485  PROBEN(IR,MP) = PROZ(1) * PROZ(3)
      CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 2455
      GO TO 2530
2530  CONTINUE
      DO 2533 MZ = 1,NUK
2533  OVC(IR,MZ) = 0.0
      DO 2535 L = 1,KIT
      UR = UUUR(IR,L)
      CVAL = PVALUE(IR,L)
      CR = CCCR(IR,L)
      CRO = CCCRO(IR,L)
      CROI = CCCROI(IR,L)
      CRB = CCCRB(IR,L)
      CRT = CCCRT(IR,L)
      KU(L) = KKUR(IR,L)
      DO 2560 I = 1,N
2560  R(I) = RRR(IR,L,I)
      CALL PROR(N,CR,UR,CRO,CROI,CRB,R,U,TTM,PT,RP,LE,KNT,REM,NUK,CVAL)
      DO 2595 MZ = 1,NUK
      IF(TTM(MZ) .EQ. 0.0) RAPK(L,MZ) = 0.0
      IF(TTM(MZ) .EQ. 0.0 ) GO TO 2596
      RAPK(L,MZ) = 1.0
      IF(REM(MZ) -(CR+UR)) 2575,2575,2580
2575  OOVC(IR,MZ,L) = TTM(MZ) + REM(MZ)*CRT
      GO TO 2585
2580  OOVC(IR,MZ,L) = TTM(MZ) + (CR+UR)*CRT
2585  OVC(IR,MZ) = OOVC(IR,MZ,L) + OVC(IR,MZ)
      PZ(MZ,1,L) = PT(MZ,1)
2590  CONTINUE
2595  CONTINUE
2596  CONTINUE
2535  CONTINUE
      DO 3015 MZ = 1,NUK
      RAP(MZ) = 1.0
      DO 3013 L = 1,KIT
3013  IF(RAPK(L,MZ) .EQ. 0.0 ) RAP(MZ) = 0.0
      IF(RAP(MZ) .EQ. 0.0 ) GO TO 2536
3015  CONTINUE
2536  CONTINUE
      DO 3550 MZ = 1,NUK
```

```
      IF( RAP(MZ) .EQ. 0.0) OVC(IR,MZ) = 0.0
      IF(RAP(MZ) .EQ. 0.0) WRITE(6,31) MZ
      IF(OVC(IR,MZ) .EQ. 0.0) GO TO 790
      IF(KIT .EQ. 2) PZ(MZ,1,3) = 0.0
      GO TO (3040,3100),KEP

*******************************************************************
C     COST AND PROBABILITY EVALUATION FOR THE AVAILABILITY OF ONE *
C     OR MORE RESOURCE TYPES FORM THE SAME SOURCE                 *
C     - BY REPLACING THE UNCERTAIN RESOURCES WITH HIRED RESOURCES *
*******************************************************************

 3040 CONTINUE
      TP1 = N-1
      DO 3060 L = 1,KIT
      IF(PZ(MZ,1,L)-TP1) 3045,3045,3050
 3045 TP1 = PZ(MZ,1,L)
 3050 CONTINUE
 3060 CONTINUE
      MP = 1
      IF(BR(IR,1) .EQ. 0.0) PROCHN(IR,MZ,MP) = 1.0
      IF(BR(IR,1) .EQ. 0.0) GO TO 3076
      IF(TP1 .EQ. 0.0) TP1 = BR(IR,1)
      D = DR(IR,1)
      B = BR(IR,1)
      M = MR(IR,1)
 3065 K = TP1 + KU(1)
 3075 CALL PROC(D,B,M,K,PROB,NAR)
      PROCHN(IR,MZ,MP) = PROB(NAR)
 3076 CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 3065
      GO TO 3540

*******************************************************************
C     COST AND PROBABILITY EVALUATION FOR THE AVAILABILITY OF     *
C     MULTIPLE RESOURCE TYPES FROM DEPENDENT UNCERTAIN SOURCES    *
C     - BY REPLACING THE UNCERTAIN RESOURCES WITH HIRED RESOURCES *
*******************************************************************

 3100 CONTINUE
      TP1 = PZ(MZ,1,1)
      TP2 = PZ(MZ,1,2)
      TP3 = PZ(MZ,1,3)
      MP = 1
      IF(TP3 .EQ. 0.0 .AND. TP2 .EQ. 0.0 .AND.
     CTP1 .EQ. 0.0) GO TO 3150
      IF(TP3 .EQ. 0.0 .AND. TP2 .EQ. 0.0) GO TO 3150
      IF(TP3 .EQ. 0.0 .AND. TP1 .EQ. 0.0) GO TO 3300
      IF(TP1 .EQ. 0.0 .AND. TP2 .EQ. 0.0 ) GO TO 3400
      IF(TP1 .EQ. 0.0 .AND. TP3 .GT. TP2) GO TO 3300
```

```
      IF(TP3 .EQ. 0.0 .AND. TP1 .GE. TP2) GO TO 3300
      IF(TP1 .EQ. 0.0 .AND. TP2 .GE. TP3) GO TO 3400
      IF(TP2 .EQ. 0.0 .AND. TP1 .GE. TP3) GO TO 3400
      IF(TP2 .EQ. 0.0 .AND. TP3 .GT. TP1) GO TO 3450
      IF(TP3 .EQ. 0.0  .AND. TP2 .GT. TP1 ) GO TO 3150
      IF(TP3 .GT. TP2  .AND. TP2 .GT. TP1) GO TO 3150
      IF(TP1 .GE. TP3 .AND. TP3 .GT. TP2) GO TO 3300
      IF(TP3 .GE. TP1 .AND. TP3 .GT. TP2) GO TO 3300
      IF(TP2 .GE. TP1 .AND. TP1 .GE. TP3) GO TO 3400
      IF(TP1 .GE. TP2 .AND. TP2 .GE. TP3) GO TO 3400
      IF(TP2 .GE. TP3 .AND. TP3 .GT. TP1) GO TO 3450
 3150 K = TP1 + KU(1)
      B4 = K
      IF(K .GE. BR(IR,1)) B4 = BR(IR,1)
      IF(TP1 .EQ. 0.0) GO TO 3170
      D = DR(IR,1)
      M = MR(IR,1)
      B = BR(IR,1)
 3165 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(1) = PROB(NAR)
      GO TO 3175
 3170 PROZ(1) = 1.0
 3175 CONTINUE
      IF(TP2 .EQ. 0.0) GO TO 3210
      B = B4 + BR(IR,2)
      D = B4 + DR(IR,2)
      M = B4 + MR(IR,2)
 3190 K = KU(1) + TP2
      SS = K
      Z1 = BR(IR,1) + BR(IR,2)
      IF( K.GE. Z1) SS = Z1
 3205 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(2) = PROB(NAR)
      GO TO 3212
 3210 PROZ(2) = 1.0
 3212 CONTINUE
 3215 IF(TP3 .EQ. 0.0) GO TO 3250
 3225 D = SS + DR(IR,3)
      B = SS + BR(IR,3)
      M = SS+ MR(IR,3)
 3230 K = KU(1) + TP3
 3245 CALL PROC(D,B,M,K,PROB,NAR)
      PROZ(3) = PROB(NAR)
      GO TO 3255
 3250 PROZ(3) = 1.0
 3255 CONTINUE
      PROCHN(IR,MZ,MP) = PROZ(1)*PROZ(2)*PROZ(3)
      CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 3150
      GO TO 3540
 3300 CONTINUE
      MP = 1
```

```
3303 K = TP2 + KU(2)
     SS = K
     Z1 = BR(IR,1) + BR(IR,2)
     IF( K .GE.Z1) SS = Z1
     IF(BR(IR,1) .EQ. DR(IR,1) .OR. BR(IR,2) .EQ. DR(IR,2)) GO TO 3304
     DT = BR(IR,1) + BR(IR,2)
     DDT = 4 * (MR(IR,1) + MR(IR,2))
     CT = DR(IR,1) + DR(IR,2)
     CEAN = (DT+DDT+CT)/6
     VARI= (BR(IR,1)-DR(IR,1))**2./36.+(BR(IR,2)-DR(IR,2))**2./36.
     CALL NORM (CEAN,VARI,CT,DT,K,PLK)
     PROZ(2) = PLK
     GO TO 3305
3304 M = MR(IR,1) + MR(IR,2)
     B = BR(IR,1) + BR(IR,2)
     D = DR(IR,2) + DR(IR,1)
     CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(2) = PROB(NAR)
3305 IF(TP3 .EQ. 0.0) GO TO 3335
3310 D = SS + DR(IR,3)
     B = SS + BR(IR,3)
     M = SS + MR(IR,3)
3315 K = KU(3) + TP3
3330 CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(3) = PROB(NAR)
     GO TO 3340
3335 PROZ(3) = 1.0
3340 PROCHN(IR,MZ,MP) = PROZ(2) *PROZ(3)
     CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
     IF(LAR .EQ. 1) GO TO 3303
     GO TO 3540
3400 DT = BR(IR,1) + BR(IR,2) + BR(IR,3)
     K = KU(3) + TP3
     DDT = MR(IR,1) + MR(IR,2) + MR(IR,3)
     CT = DR(IR,1) + DR(IR,2) + DR(IR,3)
     CEAN = (DT+ 4* DDT + CT)/6
     VARI = (BR(IR,1)-DR(IR,1))**2./36. +
    +(BR(IR,2)-DR(IR,2))**2./36. + (BR(IR,3) - DR(IR,3))**2./36.
     IF(BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,2) .EQ. DR(IR,2)
    C .OR. BR(IR,1) .EQ. DR(IR,1) .AND. BR(IR,3) .EQ. DR(IR,3) .OR.
    C BR(IR,2) .EQ. DR(IR,2) .AND. BR(IR,3) .EQ. DR(IR,3)) GO TO 3410
     CALL NORM (CEAN,VARI,CT,DT,K,PLK)
     PROCHN(IR,MZ,MP) = PLK
     GO TO 3415
3410 D = CT
     B = DT
     M = DDT
     CALL PROC(D,B,M,K,PROB,NAR)
     PROCHN(IR,MZ,MP) = PROB(NAR)
3415 CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
     IF(LAR .EQ. 1) GO TO 3400
     GO TO 3540
```

```
3450 MP = 1
3455 K = KU(1) + TP1
     TP1 = K
     IF(K .GE.BR(IR,1)) TP1 = BR(IR,1)
     D = DR(IR,1)
     B = BR(IR,1)
     M = MR(IR,1)
3465 CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(1) = PROB(NAR)
     K = TP3 + KU(3)
     IF(DR(IR,2) .EQ. BR(IR,2) .OR. DR(IR,3) .EQ. BR(IR,3)) GO TO 3481
3480 CT = TP1 + DR(IR,3) + DR(IR,2)
     DT = TP1 + BR(IR,3)+ BR(IR,2)
     DDT = TP1 + MR(IR,3) + MR(IR,2)
     CEAN = (DT + DDT *4 + CT) /6
     VARI= (BR(IR,3)-DR(IR,3))**2./36.+(BR(IR,2)-DR(IR,2))**2./36.
     CALL NORM (CEAN,VARI,CT,DT,K,PLK)
     PROZ(3) = PLK
     GO TO 3485
3481 D = TP1 + DR(IR,2) + DR(IR,3)
     B = TP1 + BR(IR,2) + BR(IR,3)
     M = TP1 + MR(IR,2) + MR(IR,3)
     CALL PROC(D,B,M,K,PROB,NAR)
     PROZ(3) = PROB(NAR)
3485 PROCHN(IR,MZ,MP) = PROZ(1)*PROZ(3)
     CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
     IF(LAR .EQ. 1) GO TO 3455
3540 CONTINUE
     KU(1) = KKUR(IR,1)
     KU(2) = KKUR(IR,2)
     KU(3) = KKUR(IR,3)
3550 CONTINUE
3560 CONTINUE
     GO TO 790


*********************************************************************
C    COST AND PROBABILITY EVALUATION FOR THE AVAILABILITY OF        *
C    SINGLE RESOURCE TYPE FROM MULTIPLE INDEPENDENT SOURCES         *
*********************************************************************


 400 UR = UUUR(IR,1)
     KIT = KITE(IR)
     DO 401 I = 1,KIT
     KU(I) = KKUR(IR,I)
 401 CONTINUE
     IF(KIT .LT. 3) KU(3) = 0
     IF(KIT .LE. 3) BR(IR,3) = 0.0
     IF(KIT .LT. 3) KKUR(IR,3) = 0
     MP = 1
     CR = CCCR(IR,1)
```

```
      CVAL = PVALUE(IR,1)
      CRO = CCCRO(IR,1)
      CROI = CCCROI(IR,1)
      CRB = CCCRB(IR,1)
      CRT = CCCRT(IR,1)
      DO 410 I=1,N
  410 R(I) = RRR(IR,1,I)
      CALL COST(N,CR,UR,CRO,CROI,CRB,R,U,TTC,TP,PR,KISS,KONT,BIG)
      IF(BIG(1)-(CR+UR)) 415,415,420
  415 OC(IR)=TTC(KISS)+BIG(1)*CRT
      GO TO 425
  420 OC(IR)=TTC(KISS)+(CR+UR)*CRT
  425 IF(KONT .EQ. 0) GO TO 600
  430 DO 550 I=1,KONT
      D = DR(IR,1)
      B = BR(IR,1)
      M = MR(IR,1)
      K = TP(I) + KU(1)
  445 CALL PROC(D,B,M,K,PROB,NAR)
      PROL(I,1)=PROB(NAR)
  460 M1 = ME(IR,1)
      M2 = ME(IR,2)
      M3 = ME(IR,3)
      IF(PR(I)-M1) 465,465,470
  465 PROL(I,2)=1.0
      PROL(I,3)=1.0
      GO TO 540
  470 D = DR(IR,2)
      B = BR(IR,2)
      M = MR(IR,2)
      K = TP(I) + KU(2)
  485 CALL PROC(D,B,M,K,PROB,NAR)
      PROL(I,2)=PROB(NAR)
  495 IF(PR(I)- (M1+M2)) 500,500,515
  500 PROL(I,3)=1.0
      GO TO 540
  515 D = DR(IR,3)
      B = BR(IR,3)
      M = MR(IR,3)
      K = TP(I) + KU(3)
  530 CALL PROC(D,B,M,K,PROB,NAR)
      PROL(I,3)=PROB(NAR)
  540 CONTINUE
  550 CONTINUE
      DO 590 J=1,3
      PRC(J)=1.0
      DO 580 I=1,KONT
      IF(PROL(I,J)-PRC(J)) 560,560,570
  560 PRC(J)=PROL(I,J)
  570 CONTINUE
  580 CONTINUE
  590 CONTINUE
```

```
      PROBEN(IR,MP) = PRC(1)*PRC(2)*PRC(3)
      CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 430
      GO TO 610
  600 PROBEN(IR,MP) = 1.0
      CALL ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
  610 CONTINUE
      KD = 1
      KS = 1
      IF(BR(IR,1) .EQ. BR(IR,2) .AND. BR(IR,1) .EQ. BR(IR,3)) GO TO 612
      IF(BR(IR,1) -KKUR(IR,1) .GE. NUK) GO TO 612
      KF = BR(IR,1) -KKUR(IR,1)
      GO TO 614
  612 KF = NUK
  614 CONTINUE
      IF(BR(IR,3) .EQ. 0.0 .AND. BR(IR,1) .EQ. BR(IR,2)) KF = NUK
  617 CALL PROR(N,CR,UR,CRO,CROI,CRB,R,U,TTM,PT,RP,LE,KNT,REM,NUK,CVAL)
      KU(1) = KKUR(IR,1)
      KU(2) = KKUR(IR,2)
      KU(3) = KKUR(IR,3)
      DO 775 L = KS,KF
      IF(TTM(L) .EQ. 0.0) OVC(IR,L) = 0.0
      IF(OVC(IR,L) .EQ. 0.0) GO TO 790
      KILL=KNT(L)
      IF(KILL .EQ. 0) GO TO 765
      IF(REM(L)-(CR+UR)) 615,620,620
  615 OVC(IR,L)=TTM(L)+REM(L)*CRT
      GO TO 625
  620 OVC(IR,L)=TTM(L)+ (CR+UR)*CRT
  625 CONTINUE
      MP = 1
      IF(RP(L,1) .EQ. 0.0) GO TO 765
      KILL=KNT(L)
  630 DO 730 I=1, KILL
      D = DR(IR,KD)
      B = BR(IR,KD)
      M = MR(IR,KD)
      K = PT(L,I) + KKUR(IR,KD)
  640 CALL PROC (D,B,M,K,PROB,NAR)
      PROL(I,1)=PROB(NAR)
      M1 = ME(IR,KD)
      ME(IR,5) = 0
      ME(IR,4) = 0
      M2 = ME(IR,(KD+1))
      M3 = ME(IR,(KD+2))
  650 IF(RP(L,I) - M1) 655,655,660
  655 PROL(I,2)=1.0
      PROL(I,3)=1.0
      GO TO 720
  660 D = DR(IR,(KD+1))
      B = BR(IR,(KD+1))
      M = MR(IR,(KD+1))
```

```
      K = PT(L,I) + KKUR(IR,(KD+1))
  675 CALL PROC (D,B,M,K,PROB,NAR)
      PROL(I,2)=PROB(NAR)
  685 IF(RP(L,I) -M1 - M2) 690,690,695
  690 PROL(I,3)=1.0
      GO TO 720
  695 D = DR(IR,(KD+2))
      B = BR(IR,(KD+2))
      M = MR(IR,(KD+2))
      K = PT(L,I) + KKUR(IR,(KD+2))
  710 CALL PROC (D,B,M,K,PROB,NAR)
      PROL(I,3)=PROB(NAR)
  720 CONTINUE
  730 CONTINUE
      DO 760 J=1,3
      PRC(J)=1.0
      DO 750 I=1,KILL
      IF(PROL(I,J)-PRC(J)) 735,735,740
  735 PRC(J)=PROL(I,J)
  740 CONTINUE
  750 CONTINUE
  760 CONTINUE
      MZ = L
      PROCHN(IR,MZ,MP) = PRC(1)*PRC(2)*PRC(3)
      CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
      IF(LAR .EQ. 1) GO TO 630
      GO TO 770
  765 NEP = L-1
      IF(L .EQ.1) NEP = NEP+ 1
      IF(L .EQ.1) OVC(IR,NEP) = OC(IR)
      DO 766 KN = L,NUK
      OVC(IR,KN) = OVC(IR,NEP)
      MZ = KN
      PROCHN(IR,MZ,MP) = 1.0
      CALL MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
      MP = 1
  766 CONTINUE
      GO TO 789
  770 CONTINUE
  775 CONTINUE
      IF(KF .EQ. NUK) GO TO 789
      IF(KF .EQ. BR(IR,2)-KKUR(IR,2)) GO TO 785
      IF(BR(IR,1)-KKUR(IR,1) .EQ. BR(IR,2)-KKUR(IR,2)) GO TO 777
      CR = CR + ME(IR,1)
      UR = UR - ME(IR,1)
      KD = KD+1
      KF = BR(IR,2) -KKUR(IR,2)
      IF(BR(IR,3) .EQ. 0.0) KF = NUK
      IF(BR(IR,2) -KKUR(IR,2) .EQ. BR(IR,3) -KKUR(IR,3)) KF = NUK
      IF(BR(IR,2) -KKUR(IR,2) .GE. NUK) KF = NUK
      GO TO 780
  777 CR = CR + ME(IR,1) + ME(IR,2)
```

```
      UR = UR - ME(IR,1) - ME(IR,2)
      KD = KD + 2
      KF = NUK
  780 KS = BR(IR,1) -KKUR(IR,1) + 1
      GO TO 617
  785 UR = UR - ME(IR,2)
      CR = CR + ME(IR,2)
      KD = KD + 1
      KF = N-1
      KS = BR(IR,2) + 1     -KKUR(IR,2)
      GO TO 617
  789 CONTINUE
   40 CONTINUE
  790 CONTINUE


*********************************************************************
C     STAGE ONE AND STAGE TWO COMPUTATIONS                          *
*********************************************************************


  800 CONTINUE
      WRITE(6,72)
   72 FORMAT(10X,'TOTAL COST',12X,'PROJECT',12X,'PERFORMANCE')
      WRITE(6,71)
   71 FORMAT(12X,'$',15X,'COMPLETION  TIME',7X,'PROBABILITY')
      KZ = 1
      PRN = 1.0
      NUS1 = N-1
      OSC = 0.0
      PR1 = 1.0
      OLP = 0.0
  805 DO 811 I = 1,NR
      OSC = OSC + OC(I)
      OSP = OSC
      PRN = PRN * PROBEN(I,KZ)
      PR1 = PR1 * PROBEN(I,1)
  811 CONTINUE
      OSP = OSP + ADD
      OTC = OSP + (N-1) *OH + (NUS1 - NSP) * CRP
      IF(PR1 .GE. 0.99) PR1 = 1.0
      IF(PRN.GE. 0.99) PRN = 1.0
      WRITE(6,815) OTC,NUS1,PRN
      IF(PR1 .EQ. 1.0) GO TO 1510
      IF(PRN - 1.0) 860,820,820
  860 IF(PRN .LT. 0.5 .OR. PRN .GT. 0.8 ) GO TO 825
      NUS1 = NUS1 + 1
      KZ = KZ + 1
      GO TO 850
  825 NUS1 = NUS1 + 2
```

```
    KZ = KZ + 2
850 CONTINUE
    OSC = 0.0
    PRN = 1.0
    GO TO 805
820 CONTINUE
    PR1 = 1.0
    NUS1 = N-1
    KZ = 1
    DO 870 J = 1,NR
870 KE(J) = 1
    DO 940 J = 1,NR
    KEM = KE(J)
875 CONTINUE
    OTC = OSP + OVC(J,KEM) - OC(J) + (N-1)*OH + (NUS1-NSP)*CRP
    IF(OVC(J,KEM) .EQ. 0.0) GO TO 930
    PRN = PROCHN(J,KEM,KZ)
    IF ( J .EQ. 1) GO TO 884
    LZ = J-1
    DO 882 IN = 1,LZ
    PR1 = PR1 *PROBEN(IN,1)
882 PRN = PRN*PROBEN(IN,KZ)
884 IF(J .EQ.NR) GO TO 888
    LZ = J+1
    DO 886 IN = LZ,NR
    PR1 = PR1 **PROBEN(IN,1)
    PRN = PRN * PROBEN(IN,KZ)
886 CONTINUE
888 CONTINUE
    IF (PRN .GE.0.99) PRN = 1.0
    WRITE(6,815) OTC,NUS1,PRN
    PR2 = PR1 *PROCHN(J,KEM,1)
    IF(PRN - 1.0) 900,920,920
900 IF(PRN .LT. 0.5 .OR. PRN .GT. 0.8) GO TO 910
    PR1 = 1.0
    NUS1 = NUS1 + 1
    KZ = KZ + 1
    GO TO 875
910 NUS1 = NUS1 + 2
    PR1 = 1.0
    KZ = KZ+2
    GO TO 875
920 CONTINUE
925 IF(PROCHN(J,KEM,1) .EQ. 1.0) GO TO 930
    KEM = KEM+ 1
    IF (KEM .GT. (N-1)) GO TO 930
    IF(PR2 .GE. 0.99) GO TO 930
    CALL VALUE(NUS1,KZ,PR1,PRN,N)
    GO TO 875
930 CONTINUE
    CALL VALUE(NUS1,KZ,PR1,PRN,N)
940 CONTINUE
```

```
      IF(NR .EQ. 1) GO TO 1510
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      NUN1 = NR-1
      DO 1030 I = 1,NUN1
      I1 = I + 1
      KEM1 = KE(I)
      DO 1020 J = I1 , NR
      KEM2 = KE(J)
 941  CONTINUE
      OTC = OSP + OVC(I,KEM1) + (NUS1 -NSP)*CRP + OVC(J,KEM2)-OC(I)
     Q-OC(J) + (N-1)*OH
      IF(OVC(J,KEM2) .EQ. 0.0) GO TO 1000
      IF(OVC(I,KEM1) .EQ. 0.0) GO TO 980
      PRN1 =    PROCHN(I,KEM1,KZ) * PROCHN(J,KEM2,KZ)
      DO 950 K = 1,NR
      IF(K .EQ.I .OR. K .EQ. J ) GO TO 945
      PRN = PRN*PROBEN(K,KZ)
      PR1 = PR1 *PROBEN(K,1)
 945  CONTINUE
 950  CONTINUE
      PRN= PRN*PRN1
      IF(PRN .GE. 0.99) PRN = 1.0
      WRITE(6,815) OTC,NUS1,PRN
      PR2 = PR1 *PROCHN(I,KEM1,1)*PROCHN(J,KEM2,1)
      IF(PRN -1.0) 955,970,970
 955  IF(PRN .LT. 0.5 .OR. PRN .GT. 0.8) GO TO 960
      NUS1 = NUS1 + 1
      KZ = KZ + 1
      GO TO 942
 960  NUS1 = NUS1 + 2
      KZ = KZ+2
 942  PR1 = 1.0
      PRN = 1.0
      GO TO 941
 970  CONTINUE
      IF(PROCHN(I,KEM1,1) .EQ. 1.0) GO TO 980
      KEM1 = KEM1 + 1
      IF(KEM1 .GT. (N-1)) GO TO 980
      IF(PR2 .GE. 0.99) GO TO 980
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 941
 980  KEM1 = KE(I)
      IF(PROCHN(J,KEM2,1) .EQ. 1.0) GO TO 1000
      KEM2 = KEM2 + 1
      IF(KEM2 .GT. (N-1)) GO TO 1000
      IF(PR2 .GE. 0.99) GO TO 1000
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 941
1000  CONTINUE
1010  CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
1020  CONTINUE
```

```
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1030 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      IF(NR .EQ. 2) GO TO 1510
      NUN2 = NR - 2
      DO 1160 I = 1,NUN2
      I1 = I+1
      NUN1 = NR-1
      DO 1150 J = I1 , NUN1
      J1 = J+1
      DO 1140 K = J1 ,NR
      KEM1 = KE(I)
      KEM2 = KE(J)
      KEM3 = KE(K)
 1035 CONTINUE
      OTC = OSP + OVC(I,KEM1) + OVC(J,KEM2) + OVC(K,KEM3) -OC(I)
     +-OC(J)-OC(K)+(N-1)*OH + (NUS1-NSP)*CRP
      IF(OVC(K,KEM3) .EQ. 0.0 ) GO TO 1120
      IF(OVC(J,KEM2) .EQ. 0.0) GO TO 1110
      IF(OVC(I,KEM1) .EQ. 0.0) GO TO 1100
      PRN1 =      PROCHN(I,KEM1,KZ) * PROCHN(J,KEM2,KZ)
     +*PROCHN(K,KEM3,KZ)
      DO 1060 KN = 1,NR
      IF(KN .EQ. I  .OR. KN .EQ. J .OR. KN .EQ. K) GO TO 1050
      PRN = PRN * PROBEN(KN,KZ)
      PR1=PR1 *PROBEN(KN,1)
 1050 CONTINUE
 1060 CONTINUE
      PRN= PRN*PRN1
      IF(PRN .GE. 0.99) PRN = 1.0
      WRITE(6,815) OTC,NUS1,PRN
      PR2 = PR1 *PROCHN(I,KEM1,1)*PROCHN(J,KEM2,1)*PROCHN(K,KEM3,1)
      IF(PRN - 1.0) 1070,1101,1101
 1070 IF(PRN .LT. 0.5 .OR. PRN .GT. 0.8) GO TO 1090
      NUS1 = NUS1 + 1
      KZ = KZ+ 1
      GO TO 1095
 1090 NUS1 = NUS1 + 2
      KZ = KZ + 2
 1095 PRN = 1.0
      PR1 = 1.0
      GO TO 1035
 1101 IF(PROCHN(I,KEM1,1) .EQ. 1.0) GO TO 1100
      KEM1 = KEM1 + 1
      IF(KEM1 .GT. (N-1)) GO TO 1100
      IF(PR2 .GE. 1.0) GO TO 1100
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1035
 1100 KEM1 = KE(I)
      IF(PROCHN(J,KEM2,1) .EQ. 1.0) GO TO 1110
      KEM2 = KEM2 + 1
      IF(KEM2 .GT. (N-1)) GO TO 1110
```

```
      IF(PR2 .GE. 0.99) GO TO 1110
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1035
1110  KEM2 = KE(J)
      KEM1 = KE(I)
      IF(PROCHN(K,KEM3,1) .EQ.1.0) GO TO 1120
      KEM3 = KEM3 + 1
      IF(KEM3 .GT. (N-1)) GO TO 1120
      IF(PR2 .GE. 0.99) GO TO 1120
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1035
1120  CONTINUE
1130  CALL VALUE(NUS1,KZ,PR1,PRN,N)
1140  CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
1150  CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
1160  CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      IF (NR .EQ. 3) GO TO 1510
      NUN3 = NR- 3
      DO 1320 I = 1,NUN3
      I1 = I+1
      NUN2 = NR-2
      DO 1310 J = I1,NUN2
      J1 = J+1
      NUN1 = NR-1
      DO 1300 K = J1,NUN1
      K1 = K+1
      DO 1290 L = K1 , NR
      KEM3 = KE(K)
      KEM1 = KE(I)
      KEM2 = KE(J)
      KEM4 = KE(L)
1165  CONTINUE
      OTC = OSP + OVC(I,KEM1) + OVC(J,KEM2) + OVC(K,KEM3) +
     +OVC(L,KEM4)-OC(I)-OC(J)-OC(K)-OC(L)+(N-1)*OH+(NUS1-NSP)*CRP
      IF(OVC(L,KEM4) .EQ. 0.0) GO TO 1280
      IF(OVC(K,KEM3) .EQ. 0.0 ) GO TO 1270
      IF(OVC(J,KEM2) .EQ. 0.0) GO TO 1260
      IF(OVC(I,KEM1) .EQ. 0.0) GO TO 1250
      PRN1= PROCHN(I,KEM1,KZ) *PROCHN(J,KEM2,KZ) *
     +PROCHN(K,KEM3,KZ)*PROCHN(L,KEM4,KZ)
      DO 1180 KN = 1,NR
      IF(KN .EQ. I .OR. KN .EQ. J .OR. KN .EQ. K .OR. KN .EQ. L)
     +GO TO 1170
      PR1 = PR1 *PROBEN(KN,1)
      PRN = PRN*PROBEN(KN,KZ)
1170  CONTINUE
1180  CONTINUE
      PRN = PRN1 *PRN
      IF ( PRN .GE. 0.99) PRN = 1.0
```

```
      WRITE(6,815) OTC,NUS1,PRN
      PR2 = PR1 *PROCHN(I,KEM1,1) *PROCHN(J,KEM2,1)*
     APROCHN(K,KEM3,1)*PROCHN(L,KEM4,1)
      IF(PRN -1.0) 1200,1240,1240
 1200 IF(PRN .LT. 0.5  .OR. PRN .GT. 0.8) GO TO 1220
      NUS1 = NUS1 + 1
      KZ = KZ + 1
      GO TO 1225
 1220 NUS1 = NUS1 + 2
      KZ = KZ + 2
 1225 PRN = 1.0
      PR1 = 1.0
      GO TO 1165
 1240 CONTINUE
      IF(PROCHN(I,KEM1,1) .EQ. 1.0) GO TO 1250
      KEM1 = KEM1 + 1
      IF(KEM1 .GT. (N-1)) GO TO 1250
      IF(PR2 .GE. 0.99) GO TO 1250
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1165
 1250 KEM1 = KE(I)
      IF(PROCHN(J,KEM2,1) .EQ. 1.0) GO TO 1260
      KEM2 = KEM2 + 1
      IF(KEM2 .GT. (N-1)) GO TO 1260
      IF(PR2 .GE. 0.99) GO TO 1260
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1165
 1260 KEM2 = KE(J)
      KEM1 = KE(I)
      IF(PROCHN(K,KEM3,1) .EQ. 1.0) GO TO 1270
      KEM3 = KEM3 + 1
      IF(KEM3 .GT. (N-1)) GO TO 1270
      IF(PR2 .GE. 0.99) GO TO 1270
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1165
 1270 KEM3 = KE(K)
      KEM2 = KE(J)
      KEM1 = KE(I)
      IF(PROCHN(L,KEM4,1) .EQ. 1.0) GO TO 1280
      KEM4 = KEM4 + 1
      IF(KEM4 .GT. (N-1)) GO TO 1280
      IF(PR2 .GE. 0.99) GO TO 1280
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1165
 1280 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1290 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1300 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1310 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
```

```
1320 CONTINUE
     CALL VALUE(NUS1,KZ,PR1,PRN,N)
     IF(NR .EQ. 4 ) GO TO 1510
     NUN4 = NR-4
     DO 1500 I = 1, NUN4
     I1 = I+1
     NUN3 = NR-3
     DO 1490 J = I1,NUN3
     NUN2 = NR-2
     J1 = J+1
     DO 1480 K = J1,NUN2
     NUN1 = NR-1
     K1 = K+1
     DO 1470 L = K1 , NUN1
     L1 = L+ 1
     DO 1460 M = L1,NR
     KEM1 = KE(I)
     KEM2 = KE(J)
     KEM3 = KE(K)
     KEM4 = KE(L)
     KEM5 = KE(M)
1330 CONTINUE
     OTC = OSP + OVC(I,KEM1) + OVC(J,KEM2) + OVC(K,KEM3) +
    +OVC(L,KEM4)-OC(I)-OC(J)-OC(K)-OC(L)+(N-1)*OH+(NUS1-NSP)*CRP
    ++OVC(M,KEM5)-OC(M)
     IF(OVC(M,KEM5) .EQ. 0.0) GO TO 1450
     IF(OVC(L,KEM4) .EQ. 0.0) GO TO 1440
     IF(OVC(K,KEM3) .EQ. 0.0 ) GO TO 1430
     IF(OVC(J,KEM2) .EQ. 0.0) GO TO 1420
     IF(OVC(I,KEM1) .EQ. 0.0) GO TO 1410
     PRN1= PROCHN(I,KEM1,KZ) * PROCHN(J,KEM2,KZ)
    +*PROCHN(K,KEM3,KZ)*PROCHN(L,KEM4,KZ)*PROCHN(M,KEM5,KZ)
     DO 1350 KN = 1,NR
     IF(KN .EQ. I .OR. KN .EQ. J .OR. KN .EQ. K .OR. KN .EQ. L
    +.OR. KN .EQ. M) GO TO 1340
     PRN = PRN * PROBEN(KN,KZ)
     PR1 = PR1 *PROBEN(KN,1)
1340 CONTINUE
1350 CONTINUE
     PRN = PRN *PRN1
     IF(PRN .GT. 0.99) PRN = 1.0
     WRITE(6,815) OTC,NUS1,PRN
     PR2 = PROCHN(I,KEM1,1) *PROCHN(J,KEM2,1) *PROCHN(K,KEM3,1) *
    APROCHN(L,KEM4,1) *PROCHN(M,KEM5,1) *PR1
     IF(PRN-1.0) 1360,1400,1400
1360 IF(PRN .LT. 0.5 .OR. PRN .GT. 0.8) GO TO 1380
     NUS1 = NUS1 + 1
     KZ = KZ + 1
     GO TO 1385
1380 NUS1 = NUS1 + 2
     KZ = KZ + 2
1385 PRN = 1.0
```

```
      PR1 = 1.0
      GO TO 1330
 1400 CONTINUE
      IF(PROCHN(I,KEM1,1) .EQ. 1.0 ) GO TO 1410
      KEM1 = KEM1 + 1
      IF(KEM1 .GT. (N-1)) GO TO 1410
      IF(PR2 .GE. 0.99) GO TO 1410
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1330
 1410 KEM1 = KE(I)
      IF(PROCHN(J,KEM2,1) .EQ. 1.0) GO TO 1420
      KEM2 = KEM2 +1
      IF(KEM2 .GT. (N-1)) GO TO 1420
      IF(PR2 .GE. 0.99) GO TO 1420
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1330
 1420 KEM2 = KE(J)
      KEM1 = KE(I)
      IF(PROCHN(K,KEM3,1) .EQ. 1.0) GO TO 1430
      KEM3 = KEM3 + 1
      IF(KEM3 .GT. (N-1)) GO TO 1430
      IF(PR2 .GE. 0.99) GO TO 1430
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1330
 1430 KEM3 = KE(K)
      KEM2 = KE(J)
      KEM1 = KE(I)
      IF(PROCHN(L,KEM4,1) .EQ. 1.0) GO TO 1440
      KEM4 = KEM4 + 1
      IF(KEM4 .GT. (N-1)) GO TO 1440
      IF(PR2 .GE. 0.99) GO TO 1440
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1330
 1440 KEM4 = KE(L)
      KEM3 = KE(K)
      KEM2 = KE(J)
      KEM1 = KE(I)
      IF(PROCHN(M,KEM5,1) .EQ. 1.0) GO TO 1450
      KEM5 = KEM5 + 1
      IF(KEM5 .GT. (N-1)) GO TO 1450
      IF(PR2 .GE. 0.99) GO TO 1450
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
      GO TO 1330
 1450 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1460 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1470 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1480 CONTINUE
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1490 CONTINUE
```

```
      CALL VALUE(NUS1,KZ,PR1,PRN,N)
 1500 CONTINUE
 1510 CONTINUE
      STOP
      END
```

SUBROUTINE VALUE

```
C       SUBROUTINE TO SET THE SCHEDULE TO INITIAL CONDITIONS DURING
C       COMPUTATION PROCESS
        SUBROUTINE VALUE(NUS1,KZ,PR1,PRN,N)
        NUS1 = N-1
        KZ = 1.0
        PR1 = 1.0
        PRN = 1.0
        RETURN
        END
```

SUBROUTINE ADJUS

```
C      SUBROUTINE TO AID IN STAGE ONE COMPUTATION
       SUBROUTINE ADJUS(PROBEN,IR,MP,MPATH,LAR,KU)
       DIMENSION PROBEN(20,50)
       DIMENSION KU(50)
       IF(PROBEN(IR,MP) .EQ. 1.0) GO TO 20
       MP = MP+1
       KU(1) = KU(1) + 1
       KU(2) = KU(2) + 1
       KU(3) = KU(3) + 1
       LAR = 1
       GO TO 2092
    20 MP = MP + 1
       PROBEN(IR,MP) = 1.0
       IF(MP .LT. MPATH) GO TO 20
       LAR = 2
  2092 CONTINUE
       RETURN
       END
```

SUBROUTINE NORM

```
C     SUBROUTINE TO EVALUATE PROBABILITY FROM NORMAL DISTRIBUTION
C     THROUGH NUMERICAL INTEGRATION USING SIMPSON'S RULE
      SUBROUTINE NORM(CEAN,VARI,CT,DT,K,PLK)
      DIMENSION X(50),FX(50),T(11),Y(11)
      IF(K .GE. DT) GO TO 10
      IF(K .LE. CT) GO TO 15
      VARI = SQRT(VARI)
      D = (K-CT)/10.
      T(1) = CT
      DO 4 KM = 2,11
    4 T(KM) = T(KM-1) + D
C     T VALUES CREATED IN EACH INTERVAL
      DO 5 L = 1,11
    5 Y(L) = (1./(SQRT(2.*3.1416)*VARI))*(EXP(-.5*((T(L)-CEAN)
     A/VARI)**2))
      SUM1 = 0.0
      SUM2 = 0.0
      DO 6 I = 2,10,2
    6 SUM1 = SUM1 + 4.*Y(I)
      DO 7 I = 3,9,2
    7 SUM2 = SUM2 + 2.*Y(I)
      AREA = D/3.*(Y(1) + SUM1 + SUM2 + Y(11))
      PLK = AREA
      IF(PLK .LE. 0.01) PLK = 0.00
      IF(PLK .GE. .99) PLK = 1.0
      GO TO 30
   10 PLK = 1.0
      GO TO 30
   15 PLK = 0.0
   30 CONTINUE
      RETURN
      END
```

SUBROUTINE MADS

```
C     SUBROUTINE TO AID IN STAGE TWO COMPUTATION
      SUBROUTINE MADS(PROCHN,IR,MZ,MP,MPATH,LAR,KU)
      DIMENSION KU(50)
      DIMENSION PROCHN(20,50,50)
      IF(PROCHN(IR,MZ,MP) .EQ. 1.0) GO TO 20
      MP = MP+1
      KU(2) = KU(2) + 1
      KU(1) = KU(1) + 1
      KU(3) = KU(3) + 1
      LAR = 1
      GO TO 30
   20 MP = MP + 1
      PROCHN(IR,MZ,MP) = 1.0
      IF(MP .LT. MPATH) GO TO 20
      LAR = 2
   30 CONTINUE
      RETURN
      END
```

```
C                          SUBROUTINE COST

      SUBROUTINE COST(N,CR,UR,CRO,CROI,CRB,R,U,TTC,TP,PR,KISS,KONT,BIG)
C     SUBROUTINE TO EVALUATE COST OF A RESOURCE, GIVEN IDLE
C     RESOURCE COST,OPERATING COST, HIRED RESOURCE COST,NUMBER OF
C     CERTAIN AND UNCERTAIN RESOURCES, AND RESOURCE USAGE PROFILE
C     A-EVALUATION OF RESOURCE LEVELS
      DIMENSION R(100),BIG(100),U(50),TMAX(50),PR(50),TTC(50),CRE(50),
     CCREI(50),TP(50),B(50),TC(50)
      K=1
      BIE=0.0
      KOUNT=1
      L=N-1
   35 DO 130 J=K,L
      IF(BIE .GT. R(J)) GO TO 130
      BIE=R(J)
      TMEX=U(J)
  130 CONTINUE
      BIG(KOUNT)=BIE
      TMAX(KOUNT)=TMEX
      K=TMAX(KOUNT)+1
      KOUNT=KOUNT+1
      BIE=0.0
      IF(K-(N-1)) 35,35,140
  140 CONTINUE
      IF(BIG(1) .LE. CR) TP(1) = 0.0
      KOUNT=KOUNT-1
C     B- COST CALCULATIONS
      KONT=1
      BEG=0.0
      K=TMAX(1)
      DO 500 I=1,K
      IF(R(I)-BEG) 180,180,250
  180 IF(BEG-CR) 190,190,200
  190 CRE(I)=R(I)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 320
  200 IF(BEG-CR-UR) 210,210,220
  210 CRE(I)=R(I)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 320
  220 C=BEG-CR-UR
      IF(R(I)-C) 230,230,240
  230 CRE(I)=R(I)*CRB
      CREI(I)=(C-R(I))*CRB+(BEG-C)*CROI
      GO TO 320
  240 CRE(I)=C*CRB+(R(I)-C)*CRO
```

```
      CREI(I)=(BEG-R(I))*CROI
      GO TO 320
  250 BEG=R(I)
      IF(BEG-CR) 260,260,261
  260 GO TO 180
  261 IF(BEG-(CR+UR)) 263,263,264
  263 TP(KONT)=U(I)
      PR(KONT)=BEG-CR
      GO TO 265
  264 TP(KONT)=U(I)
      PR(KONT)=UR
  265 KONT=KONT+1
      GO TO 180
  320 TC(I)=CRE(I)+CREI(I)
  500 CONTINUE
      KONT=KONT-1
      IF(TMAX(1)-(N-1)) 505,800,800
  505 KI=KOUNT-1
      DO 710 J=1,KI
      NA=TMAX(J)+1
      NE=TMAX(J+1)
  508 DO 700 I=NA,NE
      BEG=BIG(J+1)
      IF(BEG-(CR+UR))510,510,520
  510 CRE(I)=R(I)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 600
  520 C=BEG-CR-UR
      IF(R(I)-C) 530,530,540
  530 CRE(I)=R(I)*CRB
      CREI(I)=(C-R(I))*CRB+(UR+CR)*CROI
      GO TO 600
  540 CRE(I)=C*CRB+(R(I)-C)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 600
  600 TC(I)=CRE(I)+CREI(I)
  700 CONTINUE
  710 CONTINUE
  800 CONTINUE
      TTC(1)=TC(1)
      KISS=TMAX(KOUNT)
      DO 810 I=2,KISS
  810 TTC(I)=TTC(I-1)+TC(I)
      RETURN
      END
```

SUBROUTINE PROC

```
      SUBROUTINE PROC(D,B,M,K,PROB,NAR)
C     TO EVALUATE PROBABILITY OF AVAILABILITY OF INDIVIDUAL RESOURCE TYPE
C     FROM BETA DISTRIBUTION
C     GIVEN THE PESIMISTIC,OPTIMISTIC AND MOST LIKELY DURATIONS
C     A-SOLUTION OF CUBIC EQUATION
      DIMENSION XE(50),T(50),PRO(50),YE(50),PRA(50),XA(50)
      DIMENSION PROB(50)
      DIMENSION E(11),Y(11)
      DIMENSION A(4),XR(3),AQ(3)
      IF(D .EQ. B .AND. K .GT. B) GO TO 15
      IF(D .EQ. B .AND. K .LE. B) GO TO 21
      NAR = K-D + 1
      IF(K-B) 10,15,15
   15 PROB(NAR) = 1.0
      GO TO 1410
   10 IF(K-D) 20,20,25
   20 NAR = D-K + 1
   21 PROB(NAR) = 0.0
      GO TO 1410
   25 CONTINUE
      A(1)=(M-D)**3+3.*(M-D)**2*(B-M)+(B-M)**3+3.*(B-M)**2*(M-D)
      A(2)=3.*(M-D)**2*(B-2.*M+D)+6.*(M-D)*(B-M)*(B-2.*M+D)
     A+(M-D)**2*(B-M)+3.*(B-M)**2*(B-2.*M+D)-34.*(M-D)*(B-M)**2
     B+(B-M)**3
      A(3)=3.*(M-D)*(B-2.*M+D)**2+3.*(B-2.*M+D)**2*(B-M)+
     A2.*(M-D)*(B-M)*(B-2.*M+D)-34.*(B-M)**2*(B-2.*M+D)
      A(4)=(B-2.*M+D)**2*(B-M)+(B-2.*M+D)**3
      IPATH=2
      EX=1./3.
      IF(A(4))1006,1004,1006
 1004 XR(1)=0
      GO TO 1034
 1006 A2=A(1)*A(1)
      Q=(27.*A2*A(4)-9.*A(1)*A(2)*A(3)+2.*A(2)**3)/(54.*A2*A(1))
      IF(Q) 1010,1008,1014
 1008 Z=0
      GO TO 1032
 1010 Q=-Q
      IPATH=1
 1014 P=(3.*A(1)*A(3)-A(2)*A(2))/(9.*A2)
      ARG=P*P*P+Q*Q
      IF(ARG) 1016,1018,1020
 1016 Z=-2.*SQRT(-P)*COS(ATAN(SQRT(-ARG)/Q)/3.)
```

```
      GO TO 1028
 1018 Z=-2.*Q**EX
      GO TO 1028
 1020 SARG=SQRT(ARG)
      IF (P) 1022,1024,1026
 1022 Z=-(Q+SARG)**EX-(Q-SARG)**EX
      GO TO 1028
 1024 Z=-(2.*Q)**EX
      GO TO 1028
 1026 Z=(SARG-Q)**EX-(SARG+Q)**EX
 1028 GO TO (1030,1032),IPATH
 1030 Z=-Z
 1032 XR(1)=(3.*A(1)*Z-A(2))/(3.*A(1))
 1034 AQ(1)=A(1)
      AQ(2)=A(2)+XR(1)*A(1)
      AQ(3)=A(3)+XR(1)*AQ(2)
C     B-SOLUTION OF QUADRATIC EQUATION
      X1=-AQ(2)/(2.*AQ(1))
      DISC=X1*X1-AQ(3)/AQ(1)
      IF(DISC) 1050,1065,1060
 1050 X2=SQRT(-DISC)
      XR(2)=X1
      XR(3)=X1
      XI=X2
      XR(3) = 0.0
      XR(2) = 0.0
      GO TO 1080
 1065 XR(2)=X1
      XR(3)=X1
      XI=0.0
      XR(2) = ABS(XR(2))
      XR(3) = ABS(XR(3))
      GO TO 1080
 1060 X2=SQRT(DISC)
      XR(2)=X1+X2
      XR(3)=X1-X2
      XI=0
      XR(2) = ABS(XR(2))
      XR(3) = ABS(XR(3))
 1080 CONTINUE
C     C-STANDARD BETA FUNCTION
      XR(1) = ABS(XR(1))
      IF(XR(1) .LT.0.0 .AND. XR(2) .LT. 0.0 .AND. XR(3) .LT. 0.0)
     AGO TO 1410
      IF(XI .NE. 0.0) GO TO 1140
      IF(XR(1)-XR(2)) 1100,1100,1110
 1100 IF(XR(2)-XR(3)) 1120,1120,1130
 1110 IF(XR(1)-XR(3)) 1120,1120,1140
 1120 BIG=XR(3)
      GO TO 1195
 1130 BIG=XR(2)
      GO TO 1195
```

```
1140 BIG=XR(1)
     GO TO 1195
1195 R=BIG
     Q=(R*(M-D)+(B-2.*M+D))/(B-M)
     H=0.10
     E(1)=0
     DO 1200 I=2,11
1200 E(I)=E(I-1)+H
     DO 1210 L=1,11
1210 Y(L)=E(L)**(Q-1.)*(1.-E(L))**(R-1.)
     SUM1=0.0
     SUM2=0.0
     DO 1220 I=2,10,2
1220 SUM1=SUM1+4.*Y(I)
     DO 1230 I=3,9,2
1230 SUM2=SUM2+2.*Y(I)
     AREA=H/3.*(Y(1)+SUM1+SUM2+Y(11))
C    D-INCOMPLETE BETA FUNCTION
     XE(1)=D
     NA=B-D+1
       MA=NA-1
     ME=NA+1
1235 NAR=K-D+1
     DEF=(B-D)/(B-D)
     DO 1300 I=2,NA
1300 XE(I)= XE(I-1)+DEF
     DO 1305 I=1,NA
1305 XA(I)=(XE(I)-D)/(B-D)
     DE=.1/(B-D)
     DO 1400 J=2,NAR
     T(1)=XA(J-1)
     DO 1310 KE=2,11
1310 T(KE)=T(KE-1)+DE
     DO 1320 L=1,11
1320 YE(L)=T(L)**(Q-1.)*(1.-T(L))**(R-1.)
     SUM1=0.0
     SUM2=0.0
     DO 1330 I=2,10,2
1330 SUM1=SUM1+4.*YE(I)
     DO 1340 I=3,9,2
1340 SUM2=SUM2+2.*YE(I)
     ARAA=DE/3.*(YE(1)+SUM1+SUM2+YE(11))
     PRO(1)=0.0
     PRO(J)=PRO(J-1)+ARAA
     PROB(J)=PRO(J)/AREA
1400 CONTINUE
     IF(PROB(NAR) .GE. 0.99) PROB(NAR) = 1.0
     GO TO 1430
1410 CONTINUE
1430 CONTINUE
     RETURN
     END
```

SUBROUTINE PROR

```
C       SUBROUTINE TO EVALUATE COST FOR STAGE TWO COMPUTATIONS
        SUBROUTINE PROR(N,CR,UR,CRO,CROI,CRB,R,U,TTM,PT,RP,LE,KNT,REM,NUK,
       +CVAL)
        DIMENSION PT(50,50),RP(50,50),TTM(50)
        DIMENSION REM(50)
        DIMENSION TTC(50)
        DIMENSION CRE(50),CREI(50),TC(50)
        DIMENSION KNT(100),R(100),BIG(100),U(50),TMAX(50),BEN(50),TME(50)
        IF ( UR .EQ. 0.0)  CVAL = 0.0
        K=1
        BIE=0.0
        KOUNT=1
        L=N-1
   35   DO 130 J=K,L
        IF(BIE .GT. R(J)) GO TO 130
        BIE=R(J)
        TMEX=U(J)
  130   CONTINUE
        BIG(KOUNT)=BIE
        TMAX(KOUNT)=TMEX
        K=TMAX(KOUNT)+1
        KOUNT=KOUNT+1
        BIE=0.0
        IF(K-(N-1))35,35,140
  140   KOUNT=KOUNT-1
C       B- COST CALCULATIONS
        MAT = NUK
        DO 500 LE=1,MAT
        KONT=1
        BEG=0.0
        K=1
        BEE=0.0
        KUNT=1
  169   DO 170 J=K,LE
        IF(BEE .GT. R(J)) GO TO 170
        BEE=R(J)
        TMEN=U(J)
  170   CONTINUE
        BEN(KUNT)=BEE
        TME(KUNT)=TMEN
        K=TME(KUNT)+1
        KUNT=KUNT+1
        BEE=0.0
        IF(K-LE)169,169,175
  175   KUNT=KUNT-1
```

```
    IF(BEN(1) -CR) 189,189,191
189 KZ = BEN(KUNT)
    GO TO 192
191 KZ = CR
192 BEG = 0.0
176 CONTINUE
    KUN=TME(1)
    DO 230 I=1,KUN
    IF(R(I)-BEG) 185,185,210
185 IF(BEG-CR) 190,190,195
190 CRE(I)=R(I)*CRO
    CREI(I)=(BEG-R(I))*CROI
    GO TO 215
195 C=BEG-CR
    IF(C .GT. CVAL) GO TO 498
    IF(R(I)-C) 200,200,205
200 CRE(I)=R(I)*CRB
    CREI(I)=(C-R(I))*CRB+CR*CROI
    GO TO 215
205 CRE(I)=C*CRB+(R(I)-C)*CRO
    CREI(I)=(BEG-R(I))*CROI
    GO TO 215
210 BEG=R(I)
    GO TO 185
215 TC(I)=CRE(I)+CREI(I)
230 CONTINUE
    IF(KUNT .EQ. 1) GO TO 283
235 KET=KUNT-1
    DO 282 J=1,KET
    NA=TME(J)+1
    NE=TME(J+1)
237 DO 280 I=NA,NE
240 BEG=BEN(J+1)
    IF(BEG-CR) 245,245,250
245 CRE(I)=R(I)*CRO
    CREI(I)=(BEG-R(I))*CROI
    GO TO 265
250 C=BEG-CR
    IF(R(I)-C) 255,255,260
255 CRE(I)=R(I)*CRB
    CREI(I)=(C-R(I))*CRB+(BEG-C)*CROI
    GO TO 265
260 CRE(I)=C*CRB+(R(I)-C)*CRO
    CREI(I)=(BEG-R(I))*CROI
265 TC(I)=CRE(I)+CREI(I)
280 CONTINUE
282 CONTINUE
283 IF(TME(KUNT) .EQ.N-1) GO TO 496
    IF(LE -TMAX(1)) 285,385,385
285 KEL=LE+1
    IF(BIG(1) .LE. CR) PT(LE,1) = 0.0
    REM(LE)=R(TMAX(1))
```

```
      IF(REM(LE) .GE. CR+UR) REM(LE) = CR+UR
      KEP=TMAX(1)
      BEG=0.0
      KONT=1
      DO 340 I=KEL,KEP
      IF(R(I)-BEG) 290,290,315
  290 IF(BEG-(CR+UR)) 295,295,300
  295 CRE(I)=R(I)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 330
  300 C=BEG-CR-UR
      IF(R(I)-C) 305,305,310
  305 CRE(I)=R(I)*CRB
      CREI(I)=(C-R(I))*CRB+(BEG-C)*CROI
      GO TO 330
  310 CRE(I)=C*CRB+(R(I)-C)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 330
  315 BEG=R(I)
      IF(BEG-CR) 320,320,325
  320 GO TO 290
  325 PT(LE,KONT)=U(I)
      IF(BEG-CR-UR) 326,326,328
  326 RP(LE,KONT)=BEG-CR
      GO TO 700
  328 RP(LE,KONT)=UR
      GO TO 700
  700 KONT=KONT+1
      GO TO 290
  330 TC(I)=CRE(I)+CREI(I)
  340 CONTINUE
      KONT=KONT-1
      KNT(LE)=KONT
      KI=KOUNT-1
      DO 382 J=1,KI
      NA=TMAX(J)+1
      NE=TMAX(J+1)
  345 DO 380 I=NA,NE
      BEG=BIG(J+1)
      IF(BEG-(CR+UR)) 350,350,355
  350 CRE(I)=R(I)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 370
  355 C=BEG-CR -UR
      IF(R(I)-C) 360,360,365
  360 CRE(I)=R(I)*CRB
      CREI(I)=(C-R(I))*CRB+(BEG-C)*CROI
  365 CRE(I)=C*CRB+(R(I)-C)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 370
  370 TC(I)=CRE(I)+CREI(I)
  380 CONTINUE
```

```
382 CONTINUE
    GO TO 496
385 KII=KOUNT-1
    IF(KOUNT .EQ. 1) GO TO 496
    DO 390 J=1,KII
    ME=LE+1
    IF(ME . GT. TMAX(J) .AND. TMAX(J+1) .GE. ME) GO TO 395
390 CONTINUE
395 JE=J
    MEG=LE+1
    REM(LE)=R(TMAX(JE+1))
    IF(BIG(JE+1) .LE.CR) PT(LE,1) = 0.0
    IF(REM(LE) .GE. CR+UR) REM(LE) = CR + UR
    NU=TMAX(JE+1)
    KONT=1
    BEG=0.0
    DO 445 I= MEG,NU
    IF(R(I)-BEG) 400,400,425
400 IF(BEG-(CR+UR))405,405,410
405 CRE(I)=R(I)*CRO
    CREI(I)=(BEG-R(I))*CROI
    GO TO 439
410 C=BEG-CR-UR
    IF(R(I)-C) 415,415,420
415 CRE(I)=R(I)*CRB
    CREI(I)=(C-R(I))*CRB+(BEG-C)*CROI
    GO TO 439
420 CRE(I)=C*CRB+(R(I)-C)*CRO
    CREI(I)=(BEG-R(I))*CROI
    GO TO 439
425 BEG=R(I)
    IF(BEG-CR) 430,430,434
430 GO TO 400
434 PT(LE,KONT)=U(I)
    IF(BEG-CR-UR)435,435,436
435 RP(LE,KONT)=BEG-CR
    GO TO 800
436 RP(LE,KONT)=UR
    GO TO 800
800 KONT=KONT+1
    GO TO 400
439 TC(I)=CRE(I)+CREI(I)
445 CONTINUE
    KONT=KONT-1
    KNT(LE)=KONT
    IF(JE .EQ. (KOUNT-1)) GO TO 496
    KI=KOUNT-1
    MIN=JE+1
    DO 495 J=MIN,KI
    KU=TMAX(J)+1
    KUM=TMAX(J+1)
    DO 490 I= KU,KUM
    BEG=BIG(J+1)
```

```
      IF(BEG-(CR+UR)) 450,450,455
450   CRE(I)=R(I)*CRO
      CREI(I)=(BEG-R(I))*CROI
      GO TO 470
455   C=BEG-CR-UR
      IF(R(I)-C) 460,460,465
460   CRE(I)=R(I)*CRB
      CREI(I)=(C-R(I))*CRB+(BEG-C)*CROI
      GO TO 470
465   CRE(I)=C*CRB+(R(I)-C)*CRO
      CREI(I)=(BEG-R(I))*CROI
470   TC(I)=CRE(I)+CREI(I)
490   CONTINUE
495   CONTINUE
496   TTC(1)= TC(1)
      KISS=(N-1)
      DO 497 I=2,KISS
497   TTC(I)=TTC(I-1)+TC(I)
      TTM(LE)=TTC(KISS)
      IF(TME(KUNT) .EQ. NUK) KNT(LE) = 0.0
      IF(TME(KUNT) .EQ. NUK) PT(LE,1) = 0.0
      IF(TME(KUNT) .EQ. NUK) REM(LE) = 0.0
      IF(KZ .GT. REM(LE)) REM(LE) = KZ
500   CONTINUE
      GO TO 499
498   DO 501 I = LE,NUK
501   TTM(I) = 0.0
499   CONTINUE
      RETURN
      END
```