THE UNIVERSITY OF ALBERTA

MANAGEMENT OF AN EXPLORATION PROCESS

by

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TO MY PARENTS

AND

FARIBA, AMIN, FARSHAD, RAMIN, HAMID, ...

Abstract

A demonstration computer program has been developed which simulates a petroleum exploration process and predicts the outcome of the exploration programs just prior to development drilling. The object is to locate reservoirs with sufficiently large deposits to justify the development drilling of the area.

The basis of the computer program is the conceptual model which describes the exploration process in three stages, that is, sensing, learning and solving, and treats the process as an information processing system. The sensing stage describes the survey of the areas of interest with methods such as seismic and gravity. As a result of these surveys, the prospects are drilled at the learning stage and the properties of the reservoirs are estimated. Information from these activities are then transmitted to the solving stage where the appraisal drilling is carried out on some of the prospects and the size of the deposits are estimated.

The aim of any activity in an exploration program is to learn (gather information) about the surface and the subsurface of the area, that is, information about the state of nature. In this thesis, the state of nature is described by 17 sets of actual characteristics which include elements such as a large trap with small oil deposits or no outcrop but an underground formation with

large deposits and poor or good reservoir properties, or no formation and hence no deposit, etc.

The theory of optimal search is used to develop the mathematical model. Also, several theorems are developed using search theory which describe the optimal allocation of capital resources amongst the areas of interest by considering petroleum exploration as a multiple target system.

The computer model provides rules or options at every stage of the exploration process which allows the prediction of the outcome under different decisions. Hence, the results of different courses of action can be compared.

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Notation

$F_D(H)$: the cumulative distribution function(c.d.f.) for the probability of detection with H effort

$f_D(H)$: the probability density function(p.d.f.) of target detection

$\delta(H)$: the detection rate

P_I : probability of detection, given the presence of target

g : surveys of the first stage

X : total capital resource for the first stage

x(g) : capital resources allocated to survey g

a : actual characteristics, $a \epsilon A$

$\lambda_A(a)$: expected number of prospects with actual characteristics $a \epsilon A$

r_X : rules provided for the first stage

b(g) : signal from survey g

b : states or sensed characteristics at the end of the sensing stage, $b \epsilon B$

$p(b,r_X)$: probability of state b with rule r_X

$\lambda_B(b)$: expected number of prospects in state $b \epsilon B$

c : categories defining the reservoir properties, $c \epsilon C$

p(c,FO): probability of category c when oil is found

p(a,b) : joint probability of actual and sensed characteristics

r_Y : rules for the learning stage

Y : total capital resource for the learning stage

$y(b)$: capital resource allocated to prospects in state b

$\lambda_C(c)$: expected number of prospects in category c

α : parameter defining the size of a trap

Z : total capital resource for the third stage

$z(\alpha)$: capital resource allocated to prospects with trap size α

$z(c)$: capital resource allocated to prospects in category c

d : parameter describing the size of the oil deposits

$p(d, r_Z)$: probability of a prospect with deposit size d using rule r_Z

i : index defining the target

j : index defining the subspace

p_{ij} : prior probability of target i in subspace j

$\bar{p}_{ij}$: posterior probability of target i in j

$p(H)$: probability of complete history

p_j : prior probability that there is a target in j

$\bar{p}_j$: posterior probability that there is a target in j

$E(N)$: expected number of targets detected

R : total capital resource

z_j : capital resource allocated to subspace j

z_{ij} : capital resource allocated to detect target i in j

β : probability of a target in an area, given that the area has not been searched

α : probability of a target in an area, given that the area has been searched and no target is detected

k : number of subspaces searched

t : number of targets detected after searching k subspaces

n/m : prior probability of target location when there are n targets and m regions, n<m and maximum one target is allowed at each region

$p(S_{AN})$: probability that area A has been searched and no target is detected

J : total number of subspaces

I : total number of targets

$E_I(N)$: expected number of targets detected when there are I targets

LGOOD : prospects with large deposit and good reservoir properties

LPOOR : prospects with large deposits but poor reservoir properties

SGOOD : prospects with small deposits and good reservoir properties

SPOOR : prospects with small deposits and poor reservoir properties

Chapter 1

Introduction

1.1 Background Information

Petroleum exploration is a high risk business, since it involves strong elements of uncertainty, but no oil field is ever found by refusing to investigate an interesting area. Only through positive attitude and constructive thinking are oil-bearing formations located and only drilling can prove the presence of oil. In Texas, a well drilled to more than 25,000 feet, failed to produce either oil or gas.

The start of the modern petroleum industry is generally taken to be in 1857, when J.M.Williams drilled the first well for oil.

In 1912 as direct result of a geological survey the Cushing Field (Oklahama) was discovered by T. Sterry Hunt, using anticlinal theory. Now, the geologist is the prospector, the person in whose mind the oil field is visualized before a discovery is made. Geology is aided by geophysics to see into the earth's crust.

The companies involved in petroleum exploration and the exploration programs vary in size and complexity, but the planning and execution of the exploration programs are similar. The operator analyses an event, for example, the result of a seismic survey, and accordingly allocates capital resources for the next activity, for example, wildcat drilling at a certain location. The outcome of the drilling is uncertain as is the case with the other activities of the exploration process such as gravity, magnetic and seismic surveys.

During the exploration program and even before that a series of important decisions are made which are the result of the available information and capital resources, for example:

1. Decision to acquire land;
2. Decision to investigate the area;
3. Decision to do a particular geophysical survey;
4. Decision on the number of wildcat wells;
5. Decision to gather additional data after a well has reached oil to determine the locations of the appraisal wells.

The aim of these and other decisions connected with the exploration program is to purchase information to reduce the uncertainty associated with the prospects and ultimately to locate deposits sufficiently large to offset the exploration costs and provide a minimum acceptable rate of return to the company. Petroleum exploration, therefore, may be considered a classic example of decision making under uncertainty.

Under these uncertain conditions an important management problem is the allocation of capital resources to a stream of prospects. These prospects which are recommended by the geologist are either generated from within the company or as a result of the activities of other companies. Important elements of this management problem include :

a) What is the optimal strategy in terms of allocating the available funds to several prospects per year?

b) What is the optimal policy of budget allocation to a number of areas in search of say, oil-bearing formations?

c) If there is a possibility of several traps in a large area and there are several such areas, how should one allocate the funds to detect the traps?

These types of problems are presented and answers are discussed in this thesis.

To approach the above problems and similar ones, the exploration process had to be reviewed and defined clearly. To analyze the problem, search theory, the mathematical model used in this research, is reviewed in depth to become familiar with the theory and its applications, and in particular investigate its role in petroleum exploration. These reviews are presented in sections 1.2.1 and 1.2.2, respectively. This chapter then continues by stating the objectives and describing the organization of the thesis in section 1.3.

1.2 Literature Research

1.2.1 The Activities of the Process

The literature on the analysis of the petroleum exploration decision mostly concentrates on the drilling aspect of the process using decision tree diagrams. This method is noted in the operations research texts and explained in some detail by Newendorp(1975) and Grayson (1960). This thesis deals with the analysis of the resource allocation to the complete exploration process and not just the drilling portion. The exploration process, therefore, is defined from a point prior to the selection of a prospect for investigation until just prior to the production of petroleum, inclusive.

To define the activities reference was made to petroleum hand-books by Moody,G.B. (1961) and the staff of Royal Dutch /Shell Group of Companies (1983), and other references by Hobson (1973), Skinner (1981), Sheriff (1978) and Reedman (1979). The detailed description of the exploration process is given in Appendix (A).

Kauffman (1963) explains that the exploration starts with the initial investigation of the area followed by the reconnaissance exploration, for example, magnetic and gravity surveys. The prospect is then re-evaluated and either the decision for gathering more information is reached, which is followed by advanced exploration e.g., detailed seismic survey, and again the re-evaluation of the prospect, or if sufficient positive information is available wildcat drilling is carried out followed by re-evaluation. The prospect may then be considered for development drilling. At any time after the re-evaluation the project may be dropped.

After the review of the literature it was concluded that if no previous work has been done on the area, then the set of exploration activities may be divided into three stages:

1. Search for the favorable formation through geological and geophysical prospecting;
2. Wildcat drilling (to look for any sign of oil deposits and gather data on subsurface formations) and estimating the reservoir properties;
3. Appraisal drilling and estimating the size of the deposits.

If previous geological and geophysical information is available, then efforts may be saved by not doing one or more of the first stage surveys.

1.2.2 Applications of Search Theory

Search theory was one of the earliest problems studied by the operational research groups. The classical search problem is to find an object with limited capital resources. The target may be stationary or moving, intelligent, large or small size, etc. Stone (1975) has provided detailed information on various problems and their formulation. Some of the applications of search theory are:

1. Search & Rescue, e.g. search for missing aircraft and people;
2. Medical, e.g. detection of glaucoma which is a disease of the eye in which the sufferer has several blind spots, Robin,S. & Kolesar,P.(1978);
3. Industrial, e.g. discovering a defective component in a machine, Denby,D.C. (1967).

Detailed information on the applications of search theory is available, in Haley,K.B. & Stone, L.D (1980). In this reference (pp. 159-164), Field points out that exploration is so dissimilar in character to general search that it is counterproductive to use classical search theory other than for the first general survey stage of the process. Field mentions that the theory was developed and used primarily for finding lost objects. But the need of extending the theory for its use in exploration is also mentioned in the paper:

"One way of extending the classical theory is to divide the search problem into several stages. Each stage can be treated as a separate search problem with its own basic components. This multistage model, with the information from one stage used as input to the next stage, provides a likely transition from classical search theory to "exploration and mining theory." Given an overall system objective, an efficient plan for allocating and scheduling search / exploration resources between each stage can be determined."

The elements of the search problem include the physical description of the targets, prior knowledge of a)region of search, b)distribution of targets and c)constraints. The procedure for the solution involves a)determining the search budget, b)budget allocation between regions and stages of search, c)revision of the budget schedules in light of new data.

Simms,B.W. and Petersen,E.R.(1987) have developed an information processing model for organizations. The model has three stages. Events are generated and received by the first stage, called sensing. The second and the third stages are called learning and solving. Associated with the events are the actual characteristics. Resources are allocated to each stage which result in the expected number of events showing certain characteristics. The sensing, learning and solving activities are performed by the operational units of the organization. Models developed from the theory of optimal search are used to model the activities of each stage. At the second stage the sensed events are sorted into categories. If an event can not be classified, then it belongs to the category of events which are most difficult to solve. The outcome of the final stage is either success or failure. After the final stage, information is stored in the records section of the organization. This information may then be processed further to provide target information to each stage.

The literature search resulted in the following major findings:

1. The exploration activities can be grouped to form and define several stages for the process.
2. The target (purpose of search) for each stage is different.
3. Even after the discovery of petroleum the search does not end and the value of the discovery must be estimated.
4. To use the information processing model described above, the elements of the model must be defined with respect to petroleum exploration.

1.3 Objectives and Thesis Organization

Objectives of this thesis are:

1. To develop a demonstration computer program which is

capable of predicting the outcome of one or more petroleum exploration programs per year (under different courses of action). The computer model should be flexible enough so that it can be used by management of oil companies after appropriate improvements and modifications, or alternatively the program can be used as a game for professional management training.

2. To describe the optimal allocation of capital resources between the areas which are of interest for exploration purposes.

Chapter 2 provides examples on how an oil company senses the presence of a prospect, the decisions made during an exploration program, costs associated with the program and the success ratio for oil and gas wells. This chapter then describes the development of the conceptual model for the exploration process followed by a detailed description of the model. The model considers the exploration process as an information processing system.

Theory of optimal search is used to develop the mathematical model in Chapter 3. Section 3.5 in Chapter 3 describes the formulations for the random and exhaustive search processes.

Several theorems are presented in Chapter 4 describing the optimal allocation of capital resources amongst the areas of interest by considering the exploration process as a multiple target system. Problems such as allowing one or more targets(e.g., traps) per area are investigated in the first part of the chapter. The second part of Chapter 4 presents a study of multiple target systems by providing and analysing several examples when the search process is random. The aim is to observe the behaviour of multiple target systems, obtain the results for the examples provided and then prove the results for the general cases. The Kuhn-Tucker conditions are used to develop the theorems and solve the problems.

The conceptual and the mathematical models are used to develop a demonstration computer program to simulate the exploration process. In order to test the flexibility and effectiveness of the model and to determine the best possible decisions which may be made during the exploration program, demonstration data is used which is described in Chapter 5. The data is extracted from the total exploration costs in Alberta in 1974. The procedure taken to simulate the actual process according to different courses of action is described in the second part of Chapter 5. The results are tabulated in Chapter 6 followed by the discussion of the results in the same chapter. Conclusions and recommendations for further work are the subjects of chapters 7 and 8, respectively.

Appendix (A) provides a detailed description of an exploration process followed by the description of different types of traps.

Remaining results from Chapter 4, section 4.2.2 and their proofs are presented in Appendix (E), section E.2.

The definition of some of the terms used in this thesis, such as appraisal drilling and false targets are given in Appendix (G).

Chapter 2

The Conceptual Model

2.1 Introduction

2.1.1 Examples on Generation of Prospects, Decisions made in an Exploration Program, Exploration Costs and the Success Ratio

Consider a large firm, a major oil company, which has financial resources enabling it to hold thousands of acres in 'inventory'. This firm consists of several departments, such as exploration, production and scouting. It holds leases in several parts of the country and also in several foreign countries. It employs geologists, geophysicists, engineers, landmen, etc.

Assume that the management of the company is informed by the geologist or through scouting, about a possible potential area. The evidence and the observations are explained in recommending the area for exploration purposes.

Management considers the geology of the area, the reports about the competitor's activities in the area and the company budget. Assume that the basin is undeveloped, but the reports indicate that another company is considering a detailed seismic survey. At this time, it is possible that the cost of the lease in the area is not high, since no reservoir (or petroleum) has been discovered. The company has now evaluated the prospect and decides that it should wait for more results from the competitors activities before committing itself for an exploration program in this particular area. Perhaps, management is considering another area which looks more favorable. Assume that after some time reports are received indicating the discovery of petroleum by one or more companies. The cost of a lease for the land has increased considerably by now. The company decides that it may be a good time to enter the area. Hence, it obtains a lease for some part of the area and the exploration process begins. Assume that the geological and the geophysical surveys are carried out except the seismic. The results of the surveys are not exactly favorable and the company is now faced with the decision of leaving the area, drilling the first wildcat well or reducing the uncertainty associated with the possible presence of an oil-bearing formation by conducting a detailed seismic survey. The company is convinced that because petroleum has been discovered by competitors and since it has already spent capital resources on the area, then perhaps the cost of the seimic survey should be avoided by drilling the first well according to the available data. (Note that although drilling is more expensive than seismic, seismic is also an expensive geophysical tool and if available data is promising, then seismic may not be done. This may be an unlikely procedure in the industry). Consider that the well is a dry hole. The company may drill the second well which also proves to be dry. Assume that several more wells are drilled which do not reach a productive zone. Management has spent large sums of money and the prospect does not look good so a decision may be reached to leave the area and invest in another prospect.

The other companies have become aware of this company's findings and its loss and sometime later enter the area, perhaps as a joint venture. By a joint agreement they reduce their expenditure. The type of agreement varies from deal to deal. Assume that they carry out a well planned program, and possibly reach petroleum deposits.

This example, although explained in simple terms can demonstrate the complexity of the process and the decisions made. Consider the following questions:

1) Was the time of entry by the company wrong since it ended up spending larger sums of money on buying the lease?
2) Was it a mistake to drill the wildcat well before obtaining additional information from a seismic survey?

3) If another well was drilled in another location, could it reach petroleum?

4) If one or more wells were drilled deeper, could they reach productive zones?

5) Why did the company plan an exploration program in this particular area and did not leave until it spent large amount of money on several dry wells?

It is not a simple matter to answer all of these questions as it very much depends on the company and its policy and state of nature. It should be noted that the decision to avoid the cost of the seismic survey is not due to the carelessness of management. This particular course of action was taken after careful analysis of the data. The seismic survey and other surveys only provide imperfect information. Hence, it is the case of a decision not to purchase additional imperfect information. The lithology at a deep wildcat site may be predicted (but with uncertainty) from the geophysical data. It is possible that the original depth estimates made by the company were in error say, by more than half a mile. This means that the data obtained before the drilling is always subject to question. In many cases the first well drilled is dry but it can provide valuable information about the subsurface structure. The information may provide enough reasons to drill the second well.

Assume that the wildcat drilling is not carried out by the company and the company has the three options discussed before. Consider that the following costs are associated with the exploration program:

geological & geophysical surveys(without seismic) and other costs such as lease fees............................X

seismic........Z

the average cost per new field wildcat.......K

Should management decide on the drilling without the aid of a seismic survey and the well does not reach oil and the company leaves the area, it loses X+K. But if the second well is also drilled and fails, then the total cost is X+2K. If seismic is carried out and the first well fails, the cost is X+Z+K. The second well may also result in a dry hole, etc. A decision tree diagram is provided for this example in Fig. 2.1.1.1.

If a small company is in a situation where the wells fail to reach a productive zone and these failures continue, then eventually, because of the company's limited budget, the funds are exhausted, resulting in what is known as the gambler's ruin. Assume that this small company's policy is not to invest large sums of money in any one exploration program. It may then approach the first company with a deal.

A similar situation may arise where as a result of the seismic survey, management of the first company

l.f.: large oil field
s.f.: small oil field

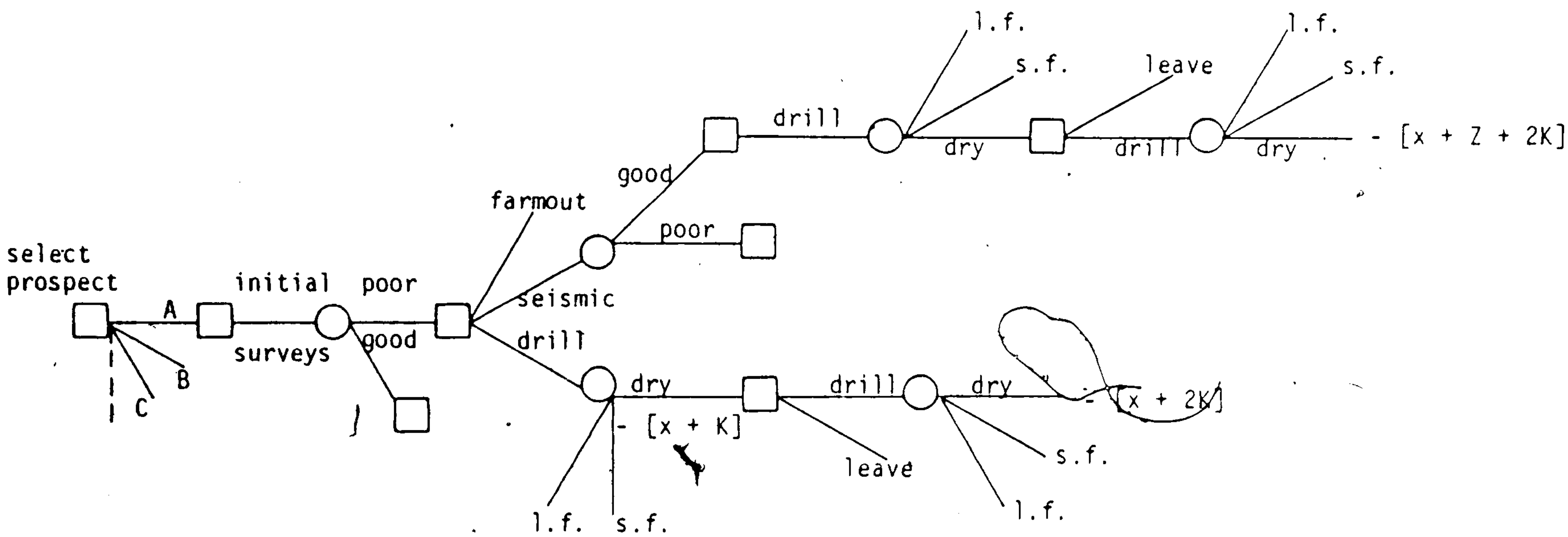

Fig. 2.1.1.1 A Simplified Decision Tree Diagram for Early Stages of Petroleum Exploration

decides the risks are too high if drilling is carried out. Then it is probable that the operator would try to farmout the acreage. A typical farmout agreement involves one company that holds the leases and another company which wants to earn an interest by drilling one or more wells.

The first company's options, may, therefore, be: to 1) drill the first exploratory well, 2) do seismic and 3) farmout the acreage.

The complexity of the decision maker's task can be appreciated for this one prospect. Consider that the company may not only be involved in this one venture but with several prospects per year.

Some of the questions which management answers before reaching a drilling decision is explained by Grayson (1960), for example:

1. What are the chances of discovering petroleum?
2. How much will it cost to produce it?
3. Are there enough funds to drill this well?
4. How much petroleum is there likely to be?

To give examples on the land holdings of a company, number of exploratory wells drilled by a company, their success ratio and the farmout agreements, information from the annual reports, 1985, of two companies are used.

According to the report of Dome Petroleum Limited, Dome continues to fund its exploration program mainly through farmouts. This enables the company to retain a portion of its expiry acreage, and to increase cash flow and revenues without capital investment. The number of gross exploratory wells drilled on the company's lands in 1985 were 277 of which 32 wells were drilled directly by Dome and 134 wells were drilled under farmout to Dome Canada and Home Oil and 111 wells were drilled under other farmout agreements.

The 1985 annual report of Suncor Inc. shows that the company purchased 120,164 net hectares of exploration lands in four western provinces of Canada at a cost of $27 million. The company's land holdings in 1985 in the western provinces of Canada were 831,000 hectares (gross) and 493,000 hectares (net). The number of exploratory wells completed were 142 (conventional oil and gas) out of which 19 reached oil, 31 discovered gas and 92 were dry, resulting in a success ratio of 35%. This information excludes wells completed under farmout agreements on company properties.

Detailed Information on Exploration Costs & Success Ratio

The exploration costs include obtaining acreage and paying yearly lease fees, the geological and geophysical surveys and drilling. The cost of finding oil has increased because of the need to explore difficult environments and to drill deeper wells. Also, the unit costs of all operations have risen everywhere.

According to the staff of the Royal Dutch/Shell group of companies (1983), the offshore seismic costs in 1982 were between $700,000 to $1,000,000 per crew-month, or $600 to $1,200 per kilometer surveyed. For onshore seismic $450,000 in desert areas ($3,000 per kilometer) and $1,200,000(up to $25,000 per kilometer) in tropical jungle per crew-month is typical. The data extracted from the financial returns of a number of Shell exploration companies show that in an onshore desert venture, the cost of drilling of two wells was $25,000,000. In an offshore venture the cost of drilling of one well was $25,000,000 (1982 US dollar). These are new exploration areas.

According to North,F.K. (1985), the total cost of drilling the world's wells is in the order of $\$20x10^9$ - $\$50x10^9$ annually. The cost of pre-drill exploration, including geologic and seismic surveys has been increasing at about 15% per year for a decade or more. Total seismic costs, including processing of data, are between $\$4x10^9$ and $\$5x10^9$ annually; one third of which occurs in the U.S.A.

The exploration costs for Alberta, from 1961 to 1983 is presented in Fig. 2.1.1.2. The costs include geological and geophysical surveys, drilling, land acquisitions and rentals and other.

The number of exploratory wells drilled in Western

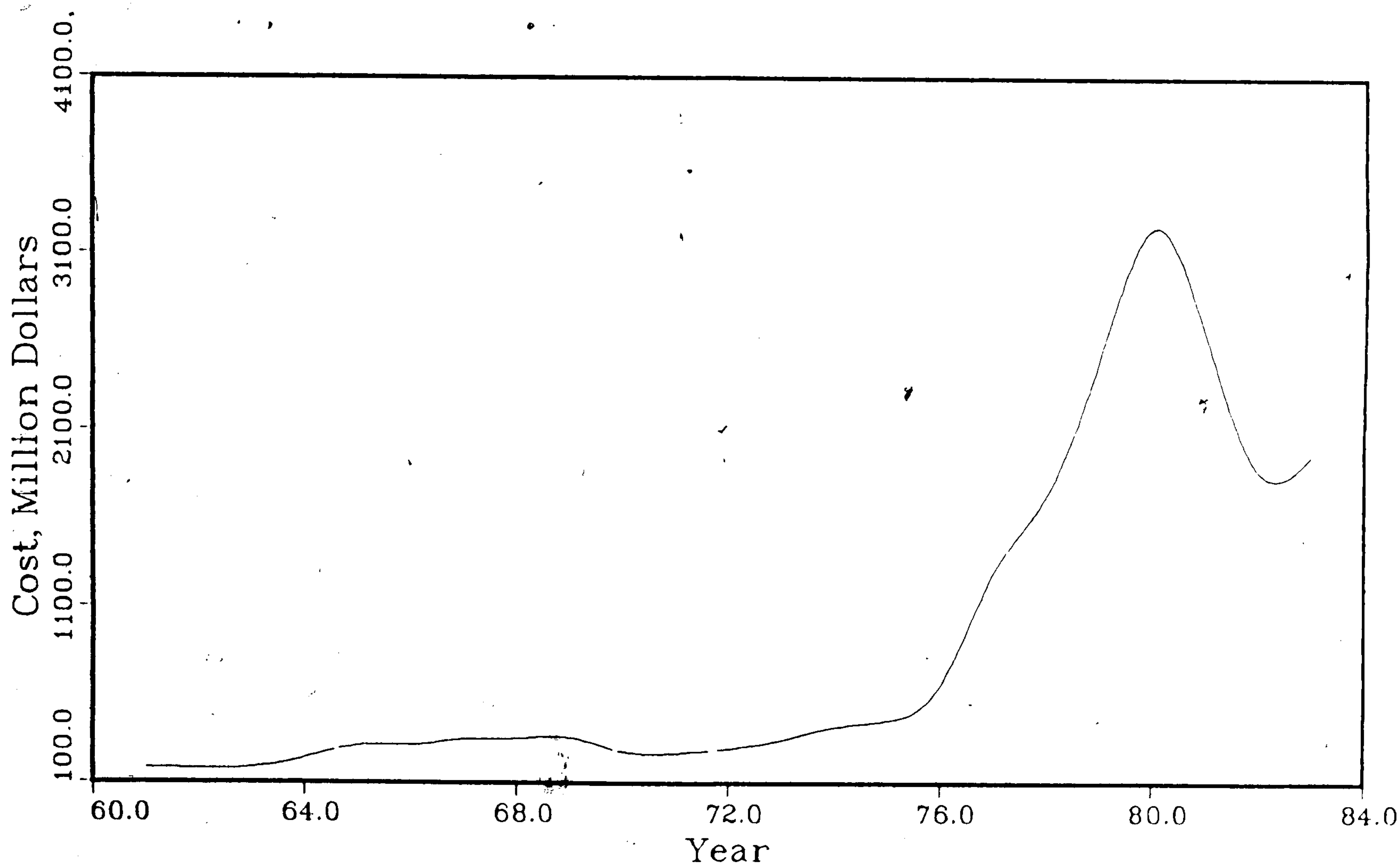

Fig. 2.1.1.2 Exploration Costs in Alberta

Canada, from 1947 to 1984, is presented in Fig. 2.1.1.3. The source of the data for the two figures are Canadian Petroleum Association's Statistical Year Book (1975) and Statistical Handbook.

To demonstrate the success ratio, data presented by Foat,K.D. and MacFadyen,A.J. (1983) is used to plot the success ratio for all exploratory wells (oil and gas) in Alberta from 1947 to 1975 in Fig. 2.1.1.4, (the original source of data is the ERCB's 'General Well Data File'). The data for 1947 includes all observations for 1947 and previous years. The information in this reference shows that in general, more gas success has occurred compared to oil success.

2.1.2 Development of the Conceptual Model

Some organizations may be viewed as information processing systems. Assume an event is received by an organization where according to information about the event, decisions are made and capital resources are allocated to solve the event. The consequence, as the classical decision model states , is a function of the state of the world and the action taken:

$$\text{Consequence} = f(\text{State of the world} , \text{Action}) \quad \ldots 2.1.2.1$$

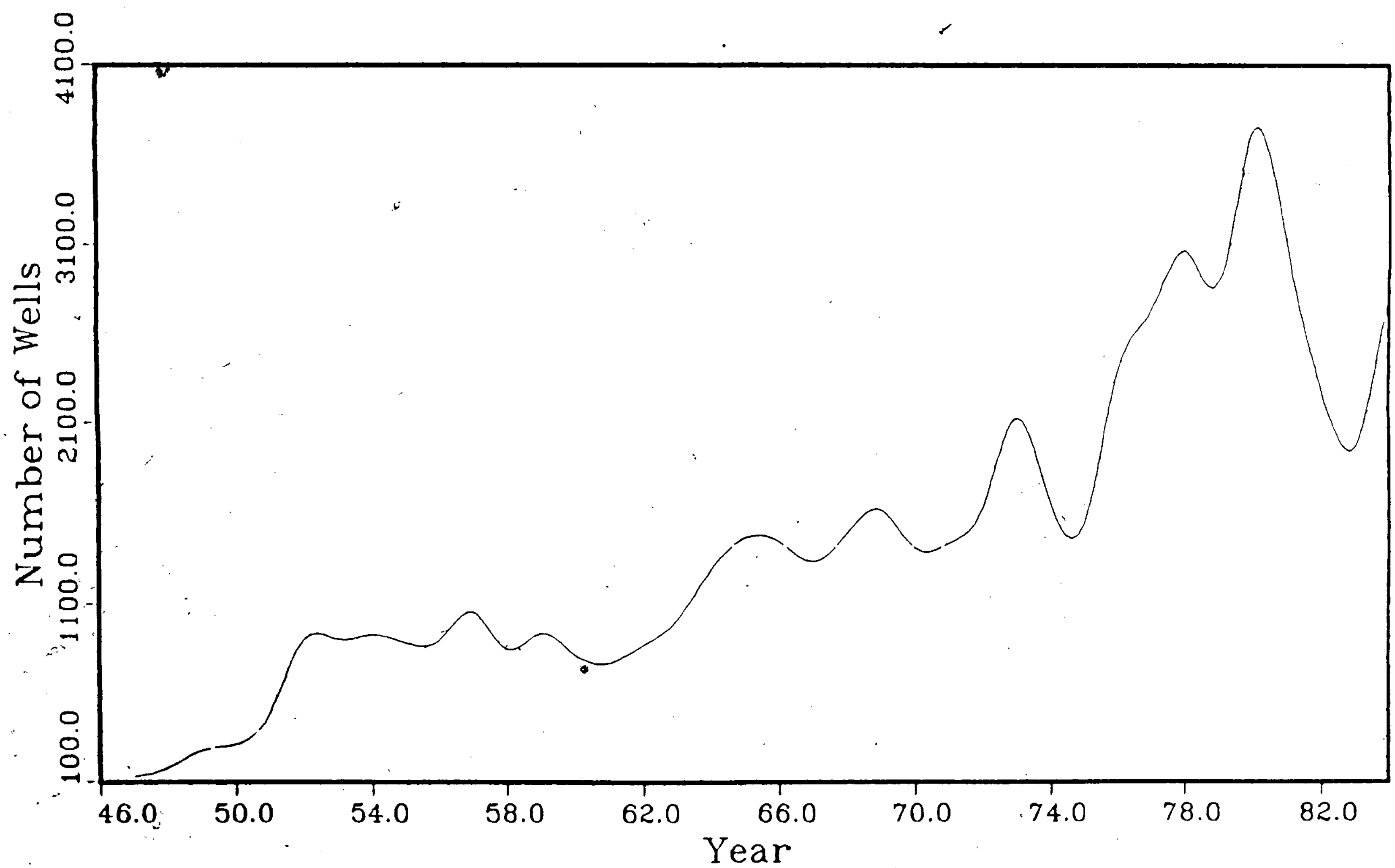

Fig. 2.1.1.3 Number of Exploratory Wells Drilled in Western Canada, 1947-1984

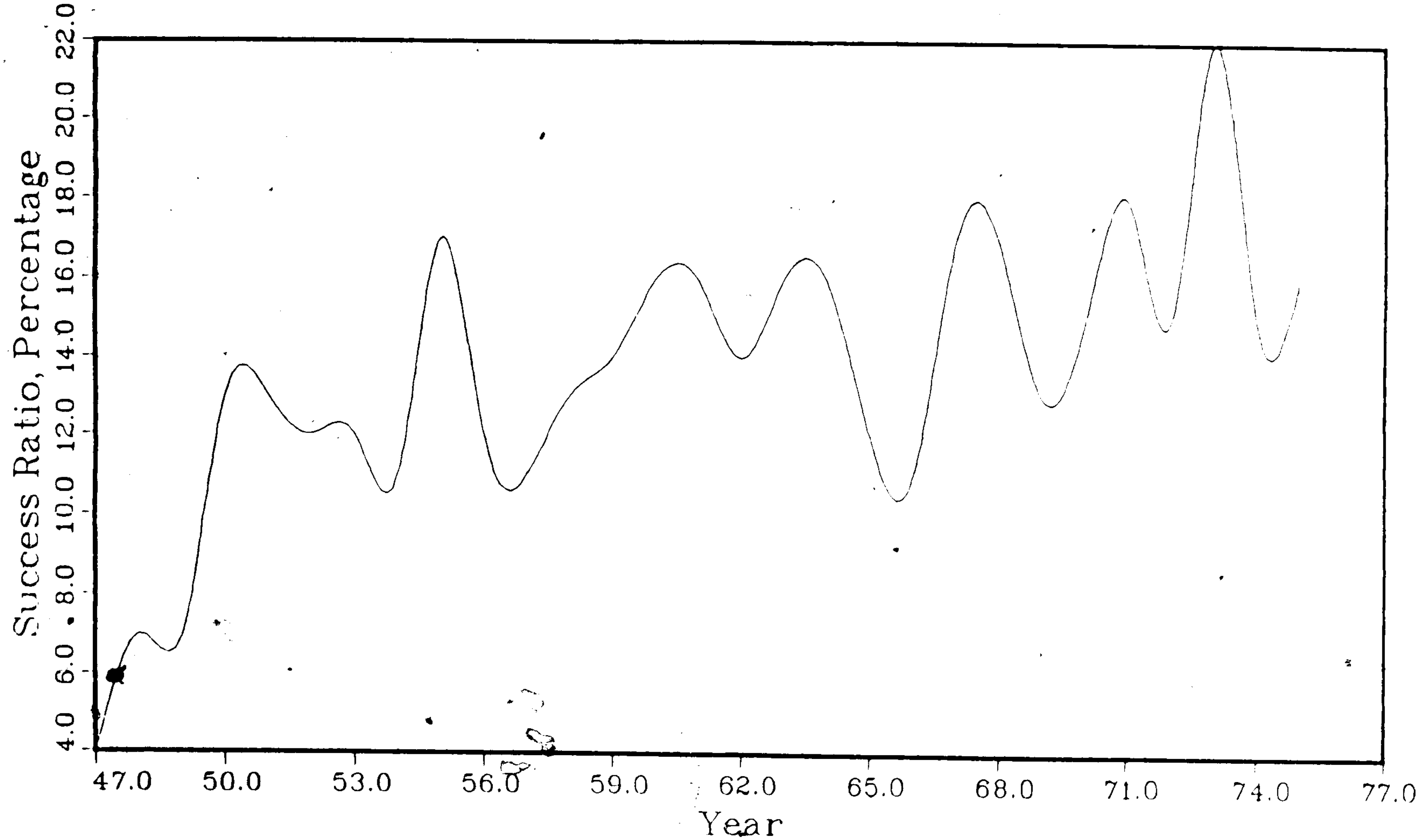

Fig. 2.1.1.4 Success Ratio in Alberta - All Exploratory Wells Oil & Gas

Consider an oil company involved in petroleum exploration. An event is the presence of a prospect which comes to the operator's attention. This event is generated either from within the company or from an outside activity such as the exploratory program of another company. Assuming that the prospect has been found interesting, the exploration program starts on the area during which different activities are carried out in stages. The operator receives information from an activity and decides on the next one. The outcome of one set of activities is used as an input for the next set. This flow of information between the stages allows the exploration program to be modeled as an information processing system.

The basis for the conceptual model developed in this thesis is the work done by B.W.Simms and E.R.Petersen (1987). The following elements of the model are presented in this chapter with respect to petroleum exploration:

1. the actual characteristics of the events;
2. the object of the search at each stage;
3. the activities of each stage;
4. the result of the activities.

This conceptual model is illustrated in Fig. 2.1.1.5. Associated with the prospects which come to the operator's attention are the actual characteristics of the prospects described as the state of the world in equation 2.1.2.1, for example, an area may have a large reservoir, no

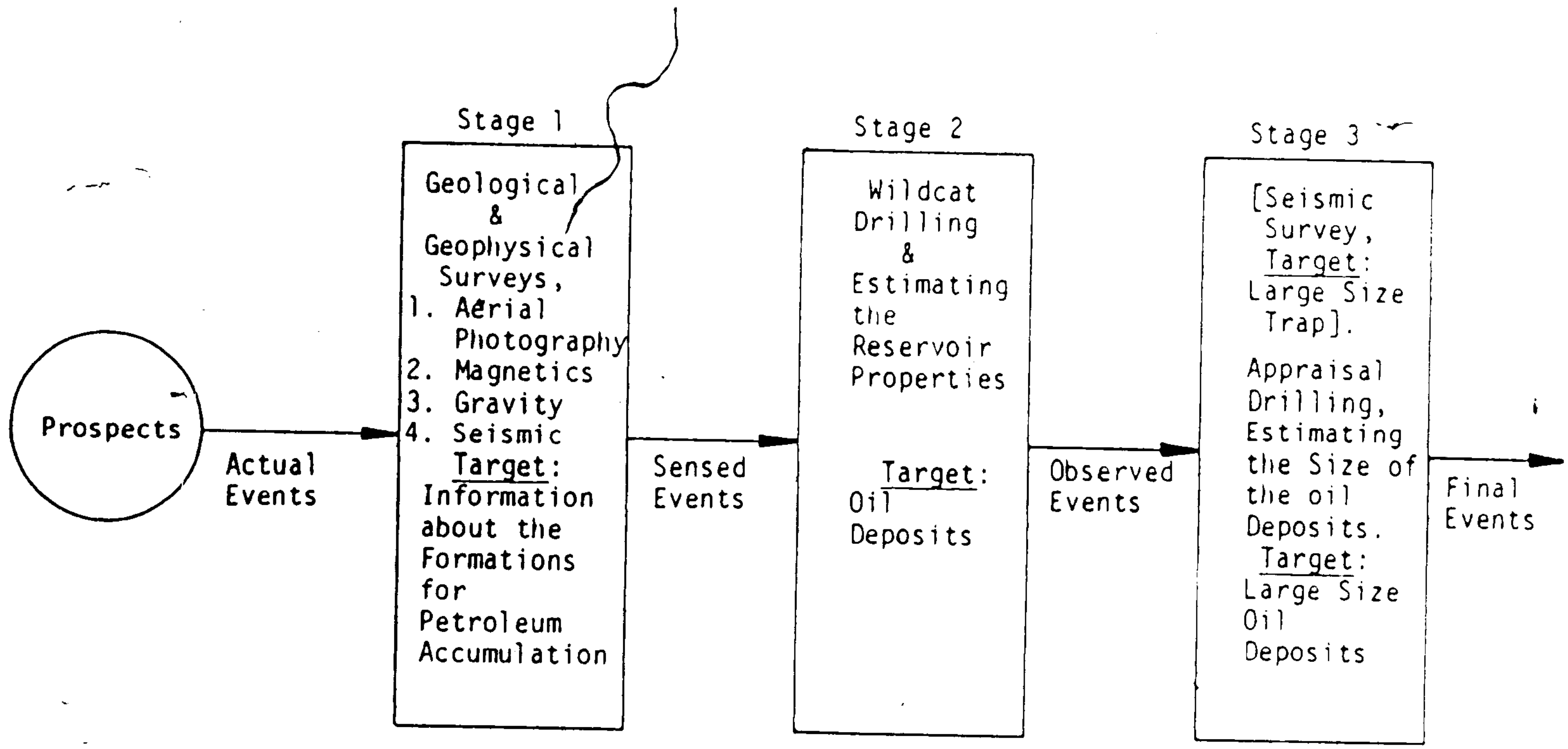

Fig. 2.1.1.5 Introduction to Conceptual Model

interesting surface feature etc. The effectiveness of the operator's decisions and the resulting actions at any stage of the process are determined by the actual characteristics of the prospect. Assume that the decision is to drill a wildcat well at a particular location. If the well is drilled at the correct place, then oil may be discovered which is the consequence.

The complex nature of petroleum exploration results from the uncertainty of the information obtained about the actual characteristics of the prospects. The activities result in imperfect information (perfect information describes the true state of the nature). This complexity makes it difficult to recognize the end of one phase of the process and the start of the next phase.

The approach taken in this thesis is to develop a simple model which follows the exploration process closely. Hence, a subset of the actual characteristics is chosen to describe the prospects. This results in a smaller number of possibilities for the outcome of an activity or a set of activities compared to an actual exploration program. The properties of the reservoirs are included in the actual characteristics, but the methods of estimating these properties such as electrical logging are not modeled. The concept of false targets is also not included. With these simplifications a demonstration computer model can be developed to represent and analyse the actual exploration process in some detail but within certain limits. A brief description of the conceptual model follows.

As it is shown in Fig. 2.1.1.5, at the first stage of the exploration process the geological and the geophysical surveys are carried out. These surveys are used to gather information about the underground formations and the surface features of the area. The geological surveys are summarized as aerial photography. The geophysical surveys are magnetic, gravity, and seismic reflection. Each survey results in a positive signal (information about the presence of a favorable formation) or a negative signal (indicating the possible absence of an interesting formation).

According to the judgement of the operator, one or more surveys may not be done. This can occur because of the already existing information, (such as Western Canada where aerial photography, magnetic and gravity surveys are now rarely carried out) or the constraint on the budget allocated to the program. The outcome of each survey is used to produce a map about the surface or the subsurface of the area. The outcome of this stage is referred to as the sensed events. Information about each event is the combination of the outcome of the four surveys on the prospects, and information about the prospects are transmitted to the next stage.

The activity of the second stage is the wildcat drilling of the prospects according to the result of the first stage surveys. The operator must decide on whether to drill a well after a careful study of the sensed events and sensed information. The object is to reach the oil deposits. As each well is drilled, new information about the subsurface formation may be learnt which are referred to as the observed properties of the reservoir. At the end of the learning stage the operator categorizes the prospects. Either a dry hole is reached or oil is discovered with good or poor reservoir properties. The prospects in these categories are called the observed events which arrive at the final stage of the process.

At the third and final stage, the size of the oil deposits are estimated. According to the outcome of the second stage, the operator decides on the prospects to be processed further. If enough information is not available then a decision may be reached to do a detailed seismic survey. The result of the survey is the information about the lithology of the subsurface. This information is used to drill the step-out well. As each well is drilled additional information is obtained about the reservoir. The result of this stage is the size of the oil deposits for those prospects drilled at the third stage.

The elements of equation 2.1.2.1 can now become clear for petroleum exploration by investigating Fig. 2.1.1.5.

The actions taken at every stage such as the number of wildcat wells at the second stage, together with the state of the world (for example an Anticline formation with small deposits), result in the outcome for each stage (the consequence) which are referred to here as the sensed, observed and final events.

The detailed model is discussed in section 2.2 where the actual characteristics of prospects are explained, together with the rules for each stage, the capital resource allocation to a particular activity, the result of the activity and the outcome of each stage. The stages are called sensing, learning and solving. The outcome of the stages are the sensed, observed and final characteristics of the prospects.

2.2 Detailed Description of the Model

2.2.1 The Actual Characteristics

The aim of the activities of the three stages of the process is to find information about the actual characteristics of the prospects. This is presented in Fig. 2.2.1, where the activities of each stage result in certain information (characteristics of the prospects) to better define the actual characteristics $a \epsilon A$ of the prospect. These characteristics include the surface features

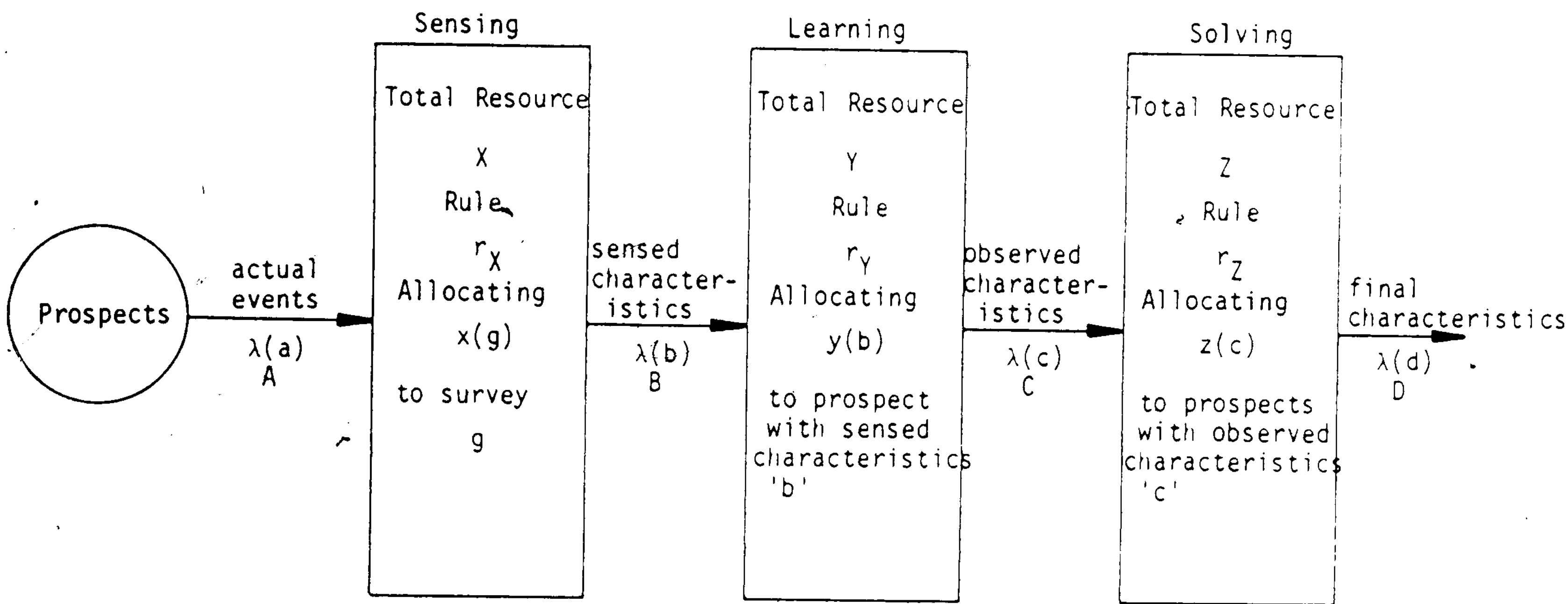

Figure 2.2.1 The Information Processing Model

indicating the possible presence of a trap, the type of trap [see Appendix (A.4)] and its size, the quality of reservoir (defined by the porosity, permeability, pay thickness, reservoir pressure and oil saturation) and the size of the oil deposits. The size of the area and the type of basin which the prospect belongs to is assumed to be known. There are basically three types of basins [Tatsch(1974)]:

a. Asymmetric basin [Alberta]: normally lie between a seismotectonomagmatic belt such as a mountain chain and the adjacent stable area and are considered favorable for accumulation of petroleum.

b. Open basin:normally occur on the margins of continents and are considered to have resulted from continental rifting.

c. Intracratonic basin:these basins differ from the other two types primarily by being underlain by continental crust rather than by the intermediate type crust.

The type of oil is also part of the actual characteristics. Oils vary in nature from the very heavy, viscous type, found in shallow reservoirs containing little or no dissolved gas, to extremely light, low-viscous types found in deep reservoirs, containing a large volume of dissolved gas.

A table of actual characteristics can be constructed to include all the above characteristics and their different values. But this results in a large number of elements forming the table, adding to the complexity of the analysis of the final results. For simplicity a set of characteristics has been selected for our demonstration computer program which describes the prospects in some detail and avoids the above problem. Also, the model does not differentiate between oil and gas which are referred to as oil deposits or petroleum in this thesis. The actual characteristics $a \in A$ are therefore defined by all possible combinations of the following:

a) the trap and the positive surface indications [indicating their presence];

b) the size of the trap [no trap, small or large];

c) the reservoir property [no reservoir, poor or good], (it should be noted that although a reservoir containing water may have good properties, such as porosity, etc., but since in this thesis only the petroleum reservoirs are considered then a dry hole may mean no reservoir or a reservoir containing water but no oil deposit);

d) the size of the oil deposits [no deposit, small or large].

This table is presented in Appendix (C). It is assumed that only large traps may contain large oil deposits.

2.2.2 Sensing

The first block of the information processing model, Fig. 2.2.1, represents the sensing stage.

It is assumed that prospects are generated according to the Poisson process at the annual rate of λ . Some of these prospects are selected according to either historical information or intelligence information, and others are the result of a random selection because of no information (provided that the company policy and the budget allows random selection). The arrival rate is therefore a decision variable controlled by the operator.

The expected number of prospects with actual characteristics $a \epsilon A$ is described by $\lambda_A(a)$ [see Fig. 2.2.1] and the probability of a prospect with actual characteristics 'a' is $p_A(a)$.

Next, the geological and the geophysical surveys are carried out. The set of surveys are described by $g \epsilon G$. There are four surveys, aerial photography (g=1), magnetics (g=2), gravity (g=3) and seismic reflection (g=4). The aim of these surveys is to obtain information about the surface and the subsurface of the area.

The signal received from each survey, b(g), is either positive[b(g)=1] or negative[b(g)=0], where b(g)=0 reduces the probability of presence of the object of search for survey g. If a survey is not to be done then its outcome is shown by b(g)=2. It is assumed that if all the surveys are to be carried out, then the order is from g=1 to g=4.

It is possible that the operator may decide to discontinue the process after obtaining a negative signal from a survey or a combination of signals from different surveys or a decision may be reached to allocate zero capital resource to one or more surveys. Hence, several rules, $r_X \epsilon R_X$, are provided for the operator to cover these situations. These rules (26 of them) are presented in Appendix (B.1). The last rule (r_X=26) is a special case where no survey is done.

The total capital resource for this stage is X . The resource allocation to survey 'g', x(g) is made, according to the rule used and the outcome of the previous survey(s). As an example assume that rule one is selected and each of the first three surveys has resulted in a negative signal,then x(4) units of capital resource is allocated to seismic given that b(1),b(2) and b(3) are zero and this is represented by: x(4) | b(1)=0,b(2)=0,b(3)=0. The matrix of the capital resource allocation is therefore

[x(1) , x(2)|b(1) , x(3)|b(1),b(2) , x(4)|b(1),b(2),b(3)]

where each signal may be a 0,1 or 2 and x(g) is ≥ 0.

Since there are four surveys and three possible outcomes from each one, (b(g)=0, 1 or 2), a prospect may be in any of the 3^4 or 81 states at the end of the sensing stage . This is shown by $B = [\ b(1),\ b(2),\ b(3),\ b(4)\ ]$. These states are presented in Appendix (D). They are the sensed characteristics $b \epsilon B$ which are transmitted to the second stage of the process.

2.2.3 Learning

As shown in Fig. 2.2.1, the expected number of prospects with sensed characteristics $b \epsilon B$, $\lambda_B(b)$, arrive at the learning stage. The object of this stage is to determine if oil is present through wildcat drilling.

At this stage, 15 rules, $r_Y \epsilon R_Y$, are provided for the operator. These rules are a function of 'b' and cover a combination of positive signals from one or more surveys,[see Appendix (B.2)]. Rule 15 is a special case where a selection of prospects is made for random drilling. This rule can only be used if rule 26 for the first stage is used.

The number of wells to be drilled is a function of the sensed characteristics.

The total capital resource for this stage is shown by Y and y(b) is the resource allocated to the prospects with sensed characteristics 'b' which is obtained by multiplying the number of wells and the cost per well.

The properties of each reservoir are estimated as each well is drilled, such as the porosity, permeability, the pressure at the end of the well, etc. These properties are shown by $c \epsilon C$ where $c=0$ refers to a dry hole (water reservoir, no oil deposits) and $c = 1,2$ indicate the discovery of oil but with poor and good reservoir properties, respectively.

The outcome of this stage is the expected number of prospects in category c, $\lambda_C(c)$. These categories are the observed characteristics and the information input to the final stage.

2.2.4 Solving

The last section of the information processing model, Fig. 2.2.1, is the solving stage.

As a result of the sensing and learning activities there is a flow of prospects into the third stage of the process with observed characteristics $c \epsilon C$. The aim of this stage is to identify the prospects with large size oil deposits. The activity is the appraisal drilling at certain locations.

It is possible that enough information is not available to determine the number of step-out wells. Hence, the operator may decide on a detailed seismic survey for obtaining additional data. This survey has been introduced to the model as a decision variable, causing two sets of rules , $r_Z \epsilon R_Z$, which are a function of the observed characteristics, c=1 or 2. The selection of the prospects for this stage includes either all the prospects in category 1 or 2 or both categories. The rules are presented in Appendix (B.3).

The total capital resource available for this stage is Z and z(c) is the capital resource allocated to the prospects with observed characteristics c.

If the decision is to do seismic, then large traps (possible accumulation of large oil deposits) may be detected and passed on for appraisal drilling. The size of the oil deposits is then estimated. The number of wells, times the cost per well is the total capital resource allocation to those prospects with large traps (α=2) and is shown by z(α=2).

If enough information is available, then the appraisal drilling is done directly. The number of wells is a function of 'c' and z(c) is the result of the product of this number and the cost per well.

The outcome of this stage is the expected number of prospects with final characteristics $d \epsilon D$, $\lambda_D(d)$, where d=0,1,2, representing no oil deposit, small and large deposits respectively.

The Recursive Model

The outcome of the exploration activities in the current model has been kept simple, hence, the rules provided at each stage are also simple. But in an actual exploration process, there are many possibilities for the outcome of any activity causing various courses of action which may be taken. To reflect this complex process, expert systems may be implemented in the model to evaluate the available data and select the next activity. This recursive model is shown in Fig. 2.2.2. For example, consider that at the first stage, a seismic survey has been carried out. The resulting information is analyzed by an expert system and another seismic survey may be done and so on. This loop may be discontinued if enough data is gathered from seismic and the rule at the second stage may be to farmout the area or to drill the first well or even to shelve the prospect.

The aim of this thesis is to develop a demonstration computer model which can simulate the exploration process under simple sets of rules. After the completion of the demonstration computer model, using the information processing model, Fig. 2.2.1, the above recursive model may be considered as the next best approach to continue this research and improve the current model.

ES: Expert System

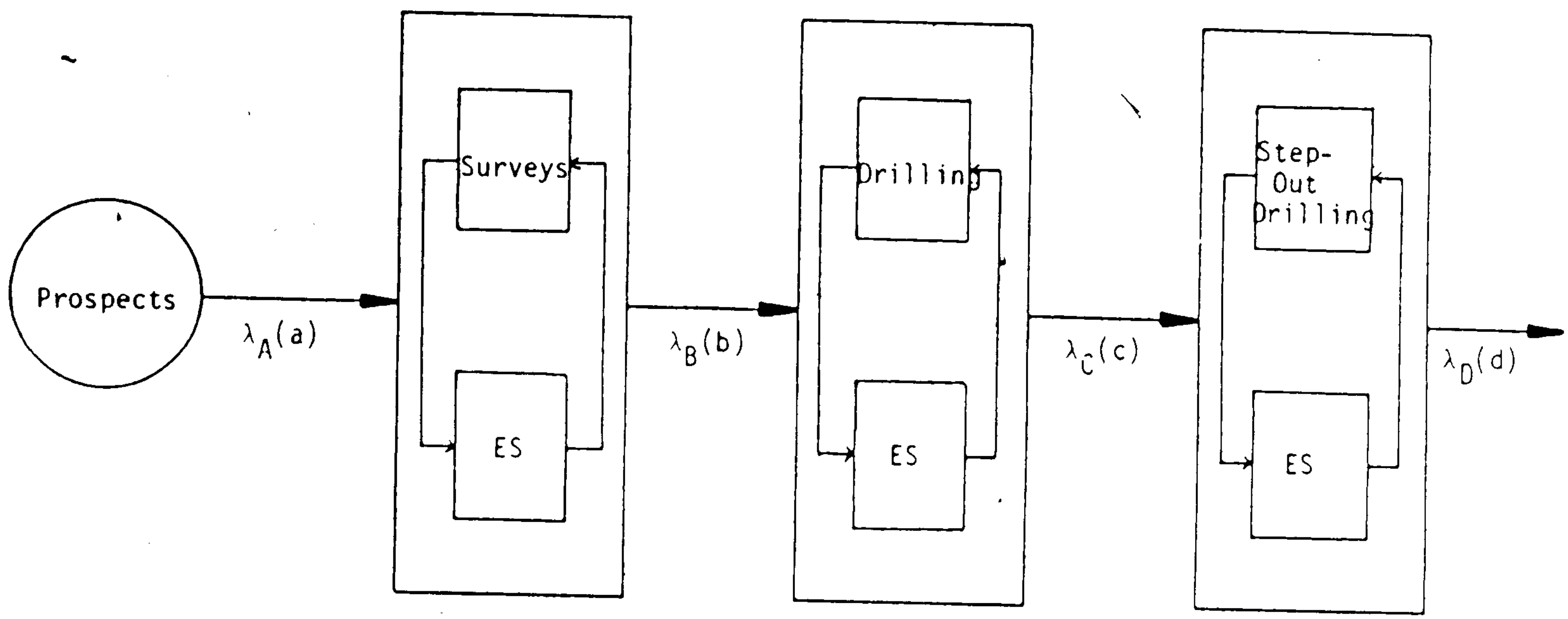

Fig. 2.2.2 The Recursive Model

Chapter 3

Mathematical Model

3.1 Introduction

Each stage of the exploration process is a search activity with limited capital resources. The aim is to detect the target(s) before exhausting the capital resource. The basis of the mathematical formulation is the theory of optimal search, defined by the elements:

$F_D(H)$: the cumulative distribution function (c.d.f.) for the probability of detection with H effort;

$f_D(H)$: the probability density function (p.d.f) of target detection;

$\delta(H)\, d(H)$: the probability of detection in the interval H+d(H), given no detection at or before H effort;

$\delta(H)$: the detection rate which is equal to $f_D(H) / [1-F_D(H)]$;

P_I : the probability of detection given the presence of a target.

The formulations are explained in sections 3.2, 3.3 & 3.4 for sensing, learning and solving stages, respectively. These formulations are used to develop the computer model and then simulate the actual exploration process using a combination of rules from each stage.

3.2 Sensing

The allocation for each survey is made according to the rule used, r_X, [Appendix(B.1)] and the outcome of the previous survey(s). There are 81 possible states or sensed characteristics at the end of the sensing stage for each prospect. These states are the result of all the possible combinations of the four surveys and are shown by 'b' an element of B where B = [b(1),b(2),b(3),b(4)].

The probability of the outcome of a survey when x(g) allocation is made to survey g, given actual characteristics 'a' and the result of the previous survey [b(g-1)] for the 2nd. 3rd & 4th. surveys is:

$$p_{B(g)}[\ b(g),x(g)\ \mid\ b(g-1),a\ ]\ ,\ \text{for } g > 1$$

and the probability of the outcome of the first survey with x(1) allocation and given 'a' is:

$$p_{B(1)}[\ b(1),x(1)\ \mid\ a\ ]\ ,\ \text{for } g = 1.$$

The probability of state 'b' using rule r_X and given 'a' is therefore:

$$p_B(\ b,r_X \mid a) = p_{B(4)}[\ b(4),x(4)\ \mid\ b(3),a]$$

$$p_{B(3)}[\ b(3), x(3)\ |\ b(2), a]$$
$$p_{B(2)}[\ b(2), x(2)\ |\ b(1), a]$$
$$p_{B(1)}[\ b(1), x(1)\ |\ a]\ .$$

Now, if b(g) are independent of each other and only depend on 'a', then:

$$p_{B(g)}[b(g), x(g)\ |\ b(g-1), a] = p_{B(g)}[b(g), x(g)|a] \text{ and}$$

$$p_B(b, r_X|a) = p_{B(4)}[b(4), x(4)|a]$$
$$p_{B(3)}[b(3), x(3)|a]$$
$$p_{B(2)}[b(2), x(2)|a]$$
$$p_{B(1)}[b(1), x(1)|a].$$

The probabilities of positive(1) and negative(0) signals given 'a' and x(g) allocation are:

$$p_{B(g)}[\ b(g)=1, x(g)\ |\ a\ ] = F_D[x(g)]\ p[b(g)=1|a]\ ,\ x(g)>0$$

$$p_{B(g)}[\ b(g)=0, x(g)\ |\ a\ ] = \{1-F_D[x(g)]\}p[b(g)=1|a]+$$
$$1-p[b(g)=1|a]\ ,\ x(g)>0.$$

In these formulations $p[b(g)=1|a]$ is the probability that a positive signal is available from survey g, given 'a'.

The probability of not doing any of the surveys, given 'a' and x(g) allocation depends on the rule used[whether or not x(g) is greater than or equal to zero]:

$$p_{B(g)}[\ b(g)=2, x(g)=0|a\ ] = 1$$

$p_{B(g)}[\ b(g)=2, x(g)>0 | a\ ] = 0.$

Next, the probability of state b using rule r_X can be calculated:

$$p(b, r_X) = \sum_a p(b, r_X | a)\ p_A(a)$$

where $p_A(a)$ is the probability of a prospect with actual characteristics 'a'.

The expected rate (number per year) of prospects belonging to state 'b', when the arrival rate is λ is

$$\lambda_B(b) = p(b, r_X)\ \lambda.$$

3.3 Learning

The probability of a prospect belonging to category c when oil is found(FO) is:

$$p(c,FO) = \sum_a \sum_b p(c,FO,r_Y \mid a,b)\ p(a,b) \qquad \text{3.3.1}$$

r_Y is a function of 'b' [Appendix(B.2)] and $p(c,FO,r_Y|a,b)$ is the probability of finding oil, categories c=1,2, using r_Y, given the actual and the sensed characteristics a and b; and p(a,b) is a joint probability equal to $p(b|a)\ p_A(a)$, where $p(b|a)$ is $p_B(b,r_X|a)$

calculated at the 1st. stage.

Now

$$p(c,FO,r_Y|a,b) = p(c|FO,a,b)\ p(FO,r_Y|a,b) \qquad \text{.........}3.3.2$$

and

$$p(FO,r_Y|a,b) = p(FO,r_Y|oil,a,b)\ p(oil|a,b) \qquad \text{.........}3.3.3$$

where 'oil' indicates the presence of oil.

It is assumed that the event of failing to detect a reservoir is independent for each well drilled. The probability of failure after y(b) is spent is $(1-P_I)^{y(b)}$ and the probability of detection is $1-(1-P_I)^{y(b)}$

$$p(FO,r_Y|oil,a,b) = [1-(1-P_I)^{y(b)}] \qquad \text{.........}3.3.4$$

where y(b) is the capital resources allocated to prospects with sensed characteristics 'b'. (An approximation if y(b) is not integer describing the number of wells drilled.)

Substituting 3.3.4 into 3.3.3

$$p(FO,r_Y|a,b) = [1-(1-P_I)^{y(b)}]\ p(oil|a,b),$$

so, 3.3.2 becomes

$$p(c,FO,r_Y|a,b) = p(c|FO,a,b)\ [1-(1-P_I)^{y(b)}]\ p(oil|a,b).$$

From 3.3.1

$$p(c,FO,r_Y) = \sum_{a,b} p(c|FO,a,b)\,[1-(1-P_I)^{Y(b)}]\; p(oil|a,b)\; p(a,b).$$

For c=0, p(c,FO) is zero. The probability of a dry hole, i.e, p(c=0) is:

$$1 - \sum_{c=1}^{2} p(c,FO,r_Y).$$

The expected number of prospects per year with c=1 or c=2 is therefore:

$$\lambda_C(c) = p(c,FO,r_Y)\;\lambda.$$

3.3 Solving

If it is decided to do the seismic for this stage, then the probability of a large trap (α=2), using rule r_Z (a function of the categories c=1,2) is:

$$p(\alpha=2,r_Z) = \sum_{c} p(\alpha=2,r_Z|c)\; p_C(c) \qquad \text{3.4.1}$$

where $p_C(c)$ is the same as $p(c,FO,r_Y)$.

Now if it is assumed that the failure to detect a large trap for each round of seismic survey is independent of the outcome of the others then:

$$p(\alpha=2, r_Z|c) = [1-(1-P_I)^{z(c)}]\ p(\alpha=2|c)$$

where P_I is the probability of detection given the presence of a large trap (may be different from P_I used in learning stage);
$1-(1-P_I)^{z(c)}$ is only an approximation if $z(c)$ is not an integer;
$z(c)$ is the capital resource allocated to events in category c, and $p(\alpha=2|c)$ is the probability of a large trap given observed characteristics, c

so, 3.4.1 becomes

$$p(\alpha=2, r_Z\ ) = \sum_c [1-(1-P_I)^{z(c)}]\ p(\alpha=2|c)\ p_C(c).$$

The probability of a large oil deposit(d=2) can now be calculated:

$$p(d=2, r_Z, \alpha=2) = p(d=2, r_Z|\alpha=2)\ p(\alpha=2),$$

and for independent events

$$p(d=2, r_Z) = [1-(1-P_I)^{z(\alpha=2)}]\ p(d=2|\alpha=2)\quad p(\alpha=2)$$

where $z(\alpha=2)$ is the capital resource allocated to the prospects with large trap, for out-step drilling. P_I is the probability of detection given the presence of large deposits and may be different from other P_I's.

$p(d=2|\alpha=2)$ is the probability of large deposit given large trap.

The expected number of prospects per year with final characteristics d:-

$$\lambda_D(d) = p(d, r_Z)\ \lambda.$$

If the decision is to go directly to appraisal drilling then the probability of d=2 using r_Z is calculated similar to the previous formulation:

$$p_D(d=2, r_Z) = \sum_c [1-(1-P_I)^{z(c)}]\ p(d=2|c)\ p_C(c)$$

where $p(d=2|c)$ is the probability of large oil deposit given 'c' and P_I is the probability of detection given the presence of large oil deposit.

3.5 Developments of the Model-Random and Exhaustive Search Processes

The two special cases in a search process are the exhaustive and random search of an area. If an exhaustive search process is selected, then the search starts at a location in the area followed by the exhaustive search of the total area. In this case a memory of the process is maintained. The discrete analog is sampling without replacement. If on the other hand, no memory is maintained then the search process is random and the discrete analog is sampling with replacement.

These two cases are the upper bound(exhaustive) and the lower bound(random) of the conditional probability of detection, $F_D(z)$, where z is the available capital resource. Detailed information on these processes is provided by Simms,B.W. and Petersen,E.R. (1987). In this reference it is shown that the value of $F_D(z)$ for an exhaustive search equals $P_I \mu z/A$ when z is less than or equal to A/μ, where μ is the search rate and A is the size of the search space. The value of $F_D(z)$ is approximatly equal to $1-(1-P_I)^{\mu z/A}$ when the area is searched many times. The ratio $\mu z/A$ is referred to as the normalized search effort, z'. It can be seen that when $z=A/\mu$, $z'=1$ and $F_D(z)=P_I$. The function $F_D(z)$ in the case of a random search equals $1-\exp(-\mu z P_I/A)$ The ratio $\mu z/A$ is the initial detection rate, $\delta(z)$.

The subject of this section is important when developing the demonstration computer program for simulating the exploration process. For example, at the learning stage, the function $1-(1-P_I)^{y(b)}$ can be replaced by the random search formula, if desired, which represents the random drilling of the area. The choice between exhaustive and random processes is given in the computer program as computing proceeds.

It should be noted that, for any activity, when there is a possibility for partial or incomplete searches for the target, the normalized effort for that activity can be non-integer.

Chapter 4

Petroleum Exploration as a Multiple Target System

4.1 Introduction

The aim of any search activity is to detect the object of the search or the maximum number of objects, before exhausting the capital resources. The searcher's knowledge about the location of the targets is limited. This causes problems when selecting the areas:
How should the areas be selected for the search activity, with limited information, so that the result obtained is optimal?

The first section of this chapter answers the above question by providing several theorems for various cases.

The second section investigates the multiple target systems through some examples for random search process. The object is to observe any pattern developing in the optimum number of detected targets in different situations and then prove these results for the general case . As a result of these experiments a theorem has also been developed which addresses the problem of distinguishing or not distinguishing between the targets when there are several areas and targets and a maximum of one target is allowed in each area. Apart from a few examples, most of the problems in this section assume this constraint on the number of targets per area.

4.2 Optimal Allocation of Search Effort Amongst the Areas of Interest

4.2.1 Theorems

Several theorems are presented which describe the optimal allocation of search effort (capital resource) amongst the areas of interest. The proofs are provided in Appendix(E). Two major problems are investigated:

1. Maximum one target per subspace(area);
2. Multiple targets may be present within each subspace.

If the unused capital resources are not allocated to solve other events, then the allocation mechanism is described as the batch process. If the unused capital resources are returned to solve other events, then the process is defined as sequential. Both processes are considered in developing the theorems. Further, the above cases are divided into two parts describing the problems of distinguishing or not distinguishing between the targets (i) in subspaces (j).

The difference between the problem of allowing a maximum of one target per subspace to that of multiple targets is in the conditions used to define the posterior probability of target location. If a maximum of one target is allowed in each area, then the possible presence of a target in area j requires the constraint of no previous detection in j. Hence, the condition used in defining the posterior probability of target location is the complete history of the search process:

Define $\bar{p}_{ij}$ as the probability that target i is in area j given the complete history (H) and target i has not been found,

$$\bar{p}_{ij} = [1-F_{D_{ij}}(z_{ij})]\ p_{ij}\ /\ p(H)$$

where p_{ij} is the prior probability that target i is in j and $1-F_{D_{ij}}(z_{ij})$ is the probability that target i has not been detected, given that i is in j.

Define $\bar{p}_j$ as the probability that there is a target in j, given the complete history and no target has been found in j,

$$\bar{p}_j = [1-F_{D_j}(z_j)]\ p_j\ /\ p(H)$$

where p_j is the prior probability that there is a target in j and $1-F_{D_j}(z_j)$ is the probability that no target has been detected in j given that there is a target in j.

If multiple targets may be present per subspace, and they are distributed independent of each other then whether or not one or more targets are detected in j does not effect the possible presence of other targets in j (assuming no constraint on the maximum number of targets per area).

Define $\bar{p}_{ij}$ as probability that target i is in j, given failure of detecting i previously,

$$\bar{p}_{ij} = [1-F_{D_{ij}}(z_{ij})]\ p_{ij}\ /\ [1-\sum_j p_{ij}\ F_{D_{ij}}(z_{ij})]$$

Define $\bar{p}_j$ as the probability that there is a target in j, given no detection previously,

$$\bar{p}_j = [1-F_{D_j}(z_j)]\ p_j\ /\ (\sum_j p_j\ [1-F_{D_j}(z_j)])$$

where p_j is the prior probability that there is a target in j.

Baye's rule is used to obtain the above four expressions for the posterior probabilities.

The objective is to maximize the expected number of targets detected, E(N). In the followings R is the total available capital resource.

<u>Maximum One Target Per Subspace</u>

<u>Allocating z_{ij} to j</u>

THEOREM 1

Batch Process

$$\text{Max. } E(N) = \sum_{i}\sum_{j} p_{ij} \; F_{D_{ij}}(z_{ij})$$

$$\text{Constraint } \sum_{i}\sum_{j} z_{ij} \leq R, \quad z_{ij} \geq 0.$$

The necessary conditions for optimality are satisfied if search effort is allocated to subspaces where the unconditional detection rate for target i stays constant and equal to u/p(H), for $z_{ij} > 0$, where u is a constant.

THEOREM 2

Sequential

$$\text{Max. } E(N) = \sum_{i}\sum_{j} p_{ij} \; F_{D_{ij}}(z_{ij})$$

$$\text{Constraint } \sum_{i}\sum_{j} \left[\int_{0}^{z_{ij}} z f_D(z)\,dz\right] + z_{ij}\left[1 - F_{D_{ij}}(z_{ij})\right] \leq R, \quad z_{ij} \geq 0.$$

Allocate capital resource for target i in j such that $p_{ij}\ \delta_{ij}(z_{ij})$ is constant, for $z_{ij} > 0$, [$\delta_{ij}(z_{ij})$ is the detection rate in subspace j for target i].

<u>Allocating z_j to j</u>

THEOREM 3

Batch Process

$$\text{Max. } E(N) = \sum p_j F_D(z_j)$$

Constraint $\sum_j z_j \leq R,\ z_j \geq 0.$

Allocate capital resources to subspaces where the unconditional detection rate $p_j\ \bar{\delta}_j(z_j)$ remains identical for $z_j > 0$ and equal to $u/p(H)$.

THEOREM 4

II. Sequential

$$\text{Max. } E(N) = \sum_j p_j F_D(z_j)$$

$$\text{Constraint } \sum [\int_0^{z_j} z f_D(z)\ dz] + z_j [1 - F_{D_j}(z_j)] \leq R,\ z_j \geq 0.$$

Search effort should be allocated to subspaces where $p_j\ \delta_j(z_j)$ stays constant for $z_j > 0$, [$\delta_j(z_j)$ is the detection rate in subspace j].

Multiple Targets per Subspace

Allocating z_{ij} to j

THEOREM 5

Batch Process

$$\text{Max. } E(N) = \sum_{ij}\sum p_{ij}\ F_{D_{ij}}(z_{ij})$$

$$\text{Constraint } \sum_{ij}\sum z_{ij} \leq R,\ z_{ij} \geq 0$$

Capital resources are allocated such that the unconditional detection rate for target i in j stays constant and equal to the detection rate for target i, i.e.

$$\overline{\delta}_{ij}(z_{ij}) = \delta_i(z_i) = u/[1-F_D(z_i)]$$

THEOREM 6

II. Sequential

$$\text{Max. } E(N) = \sum_i\sum_j p_{ij} F_{D_{ij}}(z_{ij})$$

$$\text{Constraint } \sum_i\sum_j [\int_0^{z_{ij}} z f_D(z)dz] + z_{ij}[1-F_{D_{ij}}(z_{ij}) \le R, \quad z_{ij} \ge 0.$$

Capital resources are allocated for target i in j such that $p_{ij}\ \delta_{ij}(z_{ij})$ stays constant for $z_{ij}>0$.

Allocating z_j to j

THEOREM 7

Batch Process

$$\text{Max. } E(N) = \sum_j p_j F_{D_j}(z_j)$$

$$\text{Constraint } \sum_j z_j \le R, \quad z_j \ge 0.$$

Capital resources are allocated such that the unconditional detection rate in the subspaces is maximized and stays constant for $z_j>0$.

THEOREM 8

Sequential

$$\text{Max. } E(N) = \Sigma\ p_j\ F_D(z_j)$$

Constraint $\sum_j [\int_0^{z_j} z f_{D_j}(z)\, dz] + z_j [1 - F_{D_j}(z_j)] \le R, \; z_j \ge 0.$

Allocate search effort to subspaces where $p_j \;\; \delta_j(z_j)$ are identical for $z_j > 0$.

<u>Search Process when k Subspaces are Searched and t Targets are Detected when More than One Target is Not Allowed at Each Subspace</u>

Assume that there are n targets and m regions, where n<m and a maximum of one target is allowed per subspace. Also, assume that each region has an equal probability of target location before starting the search process, i.e., n/m. Also, if k subspaces are searched then the probability of a target in the areas which have been searched are the same and the probability of a target in areas which have not been searched are equal.

THEOREM 9

If k regions are searched and t targets are detected then the probability that there is a target in an area given that it has not been searched is higher than an area which has been searched with no detection.

<u>Proof by Induction</u>:

Define α: probability that there is a target in an area given that it has been searched and no target has been found,

β: probability that there is a target in an area given that it has not been searched.

Assume that the first area has been searched with no detection, then using Baye's rule the expressions for α and β can be obtained:

$$\alpha = [(1-F_D(H))(n/m)] / p(ND)$$

$$\beta = \{[(1-F_D(H))(n-1/m-1) + 1-(n-1/m-1)](n/m)\} / p(ND)$$

where $1-F_D(H)$ is the probability of failure after H effort given that a target is in an area which has been searched and p(ND) is the probability of no detection. The expression in the numerator of β is the probability of no detection in an area which has been searched given that there is a target in an area which has not been searched.

Now:

$$(n-1 / m-1)\ F_D(H) < F_D(H)$$

Multiplying by -1 and adding 1 to both sides of the inequality :

$$1-(n-1/m-1)\ F_D(H) > 1-F_D(H)$$

or

$$-(n-1/m-1)+(n-1/m-1)+1-[(n-1/m-1)\ F_D(H)]>1-F_D(H)$$

or

$$(1-F_D(H))(n-1/m-1)+1-(n-1/m-1) > 1-F_D(H)$$

Comparison between this inequality and the expressions for α and β shows that $\beta > \alpha$ when one area has been searched with no detection.

Assume now that $\beta>\alpha$ for the general case of searching k subspaces with t detections, where k>t. If area k+1 has been searched with no detection, then:

$$\alpha' = (1-F_D(H))\beta/p(ND)$$

$$\beta' = [(1-F_D(H))\beta_0 + 1-\beta_0]\beta/p(ND)$$

where β_0 is the probability that there is a target in an area which has been searched with failure given that there is target in an area which has not been searched, k+1 areas have been searched and t targets are detected.

Now since:

$$\beta_0\ F_D(H) < F_D(H)$$

similar to the above proof it can be shown that:

$$(1-F_D(H))\beta_0 + 1-\beta_0 > 1-F_D(H)$$

and hence, $\beta' > \alpha'$.

Assume now that k+1 subspaces have been searched and t+1 targets are detected, then, the expression for α'' remains as α' and β_0 in the expression for β' changes to a new value β_1 to give β''. The proof is as above and $\beta''>\alpha''$. Since to this point β's > α's, the proof is complete.

Special Cases

1. This theorem shows that the areas which have been searched with failure should never be searched until all the areas are searched, therefore, if there are an infinite number of areas, these areas with no detection will never be searched again.

2. If no target is detected after k searches, then t=0 and $\alpha<n/m$, if k=m, and t=0 then $\alpha=\alpha_{max}=n/m$ and if a search has not started then k=0 or $\beta=n/m$.

3. Let, P_I, the probability of detection given the presence of a target, be equal to 1, then define $p(S_{AN})$ as the probability that area A has been searched with no detection, then, the probability that there is a target in A, given that A has been searched with no detection is:

$$\alpha=p(A|S_{AN})=[\ p(S_{AN}|A)\ p(A)\ ]/\ p(S_{AN})$$

where p(A) is the prior probability

that there is a target in A when the previous area(before A) was searched. But given that there is a target in A, then the probability that A will be searched with no detection is:

$$p(S_{AN}|A)=1-P_I.$$

Now, since n-t targets are left, then, $[m-k]\beta+[k-t]\alpha=n-t$ and, for $P_I=1$, $\alpha=0$, and $\beta=(n-t)/(m-k)$. This states that because $P_I=1$, then there were t targets in $t < k$ subspaces, hence, the remaining targets are in the remaining areas or the areas which have not been searched. When k=m, all the n targets must be detected, i.e., k=m areas are searched and t=n targets are detected.

3. Let, $P_I=0$, and assume that area k has been searched with no detection. The probability that there is a target in k, given that it has been searched and no target is detected is:

$$\alpha=p(k|S_{KN})=[\ p(S_{kN}|k)\ p(k)\ ]\ /\ p(S_{kN}),$$

but the probability of searching k with no detction is: $p(S_{kN})=p(S_{kN}|\text{target in } k)p(k)+p(S_{kN}|\text{no target in } k)[1-p(k)]$ which reduces to $1-[P_I\ \ p(k)]$ or 1 since $P_I=0$. $p(k)$ is the probability that there is a target in k given that area k-1 has been searched with no detection($P_I=0$).

Now given that there is target in k, the probability that k will be searched with no detection is:

$$p(S_{kN}|k)=1-P_I=1,$$

and the conditional probability that there is a target in k , given that k-1 has been searched with failure is :

$$p(k)=p(k|S_{k-1,N})$$

but $p(k|S_{k-1,N})=[p(S_{k-1,N}|K)\ p(k|S_{k-2,N})]/1$ since $P_I=0$,

and $p(k|S_{k-2,N})=\ p(S_{k-2,N}|k)\ p(k|S_{k-3,N})$

.

$$p(k|S_{k-(k-2),N})=p(S_{k-(k-2),N})\ p(k|S_{k-(k-1),N})$$

$$p(k|S_{k-(k-1),N})=p(S_{k-(k-1),N})\ p_0(k)$$

where $p_0(k)$ is the original prior probability that there is target in k and is equal to n/m.

Hence, the probability of a target in k, given that it has been searched with no detection is:

$$\alpha=p(k|S_{kN})=p(S_{k-1,N}|k)p(S_{k-2,N}|k)\ldots p(S_{2,N}|k)p(S_{1,N}|k)\ n/m$$

but since no detection is possible($P_I=0$), all the probabilities on the right hand side of the above equation are equal to 1 and ,therefore, $\alpha=n/m$.

Also, using this value of α:

$$[m-k]\beta+[k](n/m)=n$$

$$\beta=n/m.$$

These values state that the probability of a target location will always be n/m, since targets can not be detected.

4.2.2 Investigating the Multiple Target Systems through Examples for Random Search Process

The aim of this section is to investigate the general behaviour of the maximized expected number of detected targets, when the total resource is varied.

The approach taken is to analyse several simple problems and then prove the results obtained for the general case.

Subspaces are shown by j and J is the number of subspaces, also, i are the targets and I is the maximum number of targets.

The objective functions used and their constraints are:

1. $$\text{Max. } E(N) = \sum_{i}\sum_{j} p_{ij}\, F_D(z_{ij}),$$
$$\text{subject to } \sum_{i}\sum_{j} z_{ij} \le R,$$
$$\text{where } z_{ij} \ge 0, \text{ all } (i,j),$$
[for random search $F_D(z_{ij}) = 1-\exp(-\delta_{ij} z_{ij})$].

2. $$\text{Max. } E(N) = \sum_{j} p_j\, F_D(z_j),$$
$$\text{subject to } \sum_{j} z_j \le R,$$
$$\text{where } z_j \ge 0, \text{ all } j,$$
[the search is random so, $F_D(z_j) = 1-\exp(-\delta_j z_j)$].

The Kuhn-Tucker conditions are used to find the optimal allocation of search effort at each subspace maximizing the expected number of targets detected.

The analysis is done in three parts:

PART(1)

The number of subspaces and targets,and the detection rate are changed to produce the following problems:

Allocating z_j

The number of targets,I, is varied between 1 and the number of subspaces,J (J=2 and 3). Each problem is then analysed with the detection rate of δ_j and δ_j/I.

Allocating z_{ij}

The number of targets is changed from 1 to J+1, (J=2 and 3). The detection rate is δ_{ij}.Also an additional problem is considered here,when I = J with equal priors.

PART (2)

Allocating z_j

The number of subspaces is six. There are four problems with one, two, three and six targets. The cases of 2 & 6 targets are divided into subproblems where the detection rate is given the values of δ_j and δ_j/I and for the other two cases the detection rate is δ_j.

Allocating z_{ij}

The number of subspaces is six and the number of targets is varied between one and six. The detection rate

PART (3)

z_{ij} Allocation

The optimal value of the expected number of detected targets is calculated, and compared for the following two problems:

1) there are J=6 subspaces and I=J targets and the detection rate is kept constant in all j for target i and the priors are given equal value of 1/6;

2) there is one subspace, I=6 targets, the detection rate of the first problem is divided by the number of subspaces which is 6 to obtain the detection rate for this problem.

Data

The sets of data selected, are kept simple to provide an easy analysis of the final results.

The detection rate for target i in subspace j is assumed to be independent of the target such that $\delta_{ij}=\delta_j$ for all i. The values given are:

$\delta_1=.1$, $\delta_2=.2$, $\delta_3=.3$, $\delta_4=.4$, $\delta_5=.5$, $\delta_6=.6$

These values stay the same for all the problems considered except those presented in part (3).

In assigning the prior probabilities the following constraints are considered:

$$\sum_j p_j = 1 \text{ (for } z_j \text{ allocation)}$$

$$\sum\sum_{ij} p_{ij} = 1 \text{ and } \sum_j p_{ij} = 1 \text{ (for } z_{ij} \text{ allocation)}$$

The prior probabilities of target location are kept unchanged, for part (1), as new targets are introduced. Assume for example , that there are three subspaces and one target, and $p_{11}=.2$, $p_{12}=.3$ and $p_{13}=.5$. After obtaining the results for this particular problem, a second target is introduced to the system with , $p_{21}=.4$, $p_{22}=.5$ and $p_{23}=.1$. The priors for the first target remain as before.

Part (1)

Two Subspaces

$p_{11}=.3$	$p_{21}=.7$	$p_{31}=.6$
$p_{12}=.7$	$p_{22}=.3$	$p_{32}=.4$

Three Subspaces

$p_{11}=.2$	$p_{21}=.4$	$p_{31}=.4$	$p_{41}=.1$
$p_{12}=.3$	$p_{22}=.5$	$p_{32}=.2$	$p_{42}=.5$
$p_{13}=.5$	$p_{23}=.1$	$p_{33}=.4$	$p_{43}=.4$

When the problem of z_j allocation to subspace j is considered, then a maximum of one target per subspace is allowed and the priors in j are added to give p_j, for example, in the case of the three subspaces and one target, $p_1=.2$, $p_2=.3$, and $p_3=.5$. If the second target is introduced then:

$p_1=p_{11}+p_{21}\text{-->}p_1=.6, p_2=p_{12}+p_{22}\text{-->}p_2=.8, p_3=p_{13}+p_{23}\text{-->}p_3=.6$ and when the third target is considered, then $p_1=p_2=p_3=1$.

In this section the case of more than one target per subspace is allowed only when the targets are distinguished, i.e., z_{ij} allocation. Also for the z_{ij} allocation the additional problem considered has been given the equal priors of 1/2 and 1/3 when I = J=2 and 3.

Part (2)

The priors are kept constant for all i and j and equal to 1/6. When z_j allocation is made, then the priors for target location in j are added up for all targets, for example, if I=3, then the probability that there is a target in j is $p_j=p_{1j}+p_{2j}+p_{3j}$, resulting in $p_j=3/6$ or 1/2.

Part (3)

For problem 1: J=6, I=6, and for all i&j $p_{ij}=1/6, \delta_{ij}=.1$.

For problem 2: J=1, I=6, and for all i $p_{ij}=1$ & $\delta_{ij}=.1/6$.

Analysis and Discussion of the Results

To solve the Kuhn-Tucker conditions, a computer program is written in Basic and the analysis is carried out on an IBM PC. The program has two subroutines where z_{ij} and z_j allocations are considered. This program is listed in Appendix (F.3).

The results are tabulated in tables 4.1 to 4.3 for part (1), and tables 4.4 and 4.5 for part (2) and 4.6 for part 3. The results are plotted in the following figures:

Fig. 4.1 and 4.2	using	Table	4.1
4.3 and 4.4	"	"	4.2
4.5 " "	"	"	4.3
4.6 " "	"	"	4.4
4.7 " "	"	"	4.5

In the following sections $E_I(N)$ refers to the maximized expected number of detected targets when I targets are present.

Part(1)-Number of Subspaces and Targets are Varied

The data in tables 4.1 and 4.2 show that for a given problem, i.e., type of allocation and a given total capital resource the expected number of detected targets decreases as the number of targets reduces. The reverse is true when the normalized expected number of detected targets is considered,

$$E_3(N) > E_2(N) > E_1(N)$$

or

$$E_3(N)/3 < E_2(N)/2 < E_1(N)$$

suggesting that:

$$E_3(N)/3 < E_2(N)/2 \text{ ------> } E_3(N)/E_2(N) < 3/2$$

$$E_2(N)/2 < E_1(N)/1 \text{ ------> } E_2(N)/E_1(N) < 2/1$$

$$E_3(N)/3 < E_1(N)/1 \text{ ------> } E_3(N)/E_1(N) < 3/1 .$$

	$E(N)/I, z_j$							
	Two Subspaces			Three Subspaces				
	I							
	1	2		1	2		3	
R	δ_j	δ_j	$\delta_j/2$	δ_j	δ_j	$\delta_j/2$	δ_j	$\delta_j/3$
5	.442	.323	.196	.404	.316	.182	.308	.132
10	.614	.515	.323	.583	.491	.316	.477	.228
15	.723	.652	.427	.685	.612	.416	.602	.308
20	.802	.751	.515	.760	.705	.491	.697	.373
25	.858	.821	.589	.817	.775	.556	.769	.427
30	.898	.872	.652	.861	.829	.613	.824	.477
35	.927	.908	.705	.894	.870	.662	.866	.523
40	.947	.934	.751	.920	.900	.705	.898	.564
45	.962	.953	.789	.939	.924	.743	.922	.602
50	.973	.966	.821	.953	.942	.775	.941	.636

Table 4.1 Normalized Expected Number of Targets Detected when z_j is Allocated to Subspace j

R	$E(N)/I, z_{ij}$						
	Two Subspaces			Three Subspaces			
	I						
	1	2	3	1	2	3	4
	Detection Rate of δ_j						
5	.442	.226	.153	.404	.231	.167	.132
10	.614	.364	.253	.582	.362	.272	.230
15	.723	.472	.339	.685	.456	.348	.307
20	.802	.555	.414	.760	.532	.411	.369
25	.858	.623	.479	.817	.595	.466	.420
30	.898	.681	.535	.861	.647	.515	.466
35	.927	.730	.584	.894	.692	.559	.507
40	.948	.771	.627	.919	.731	.598	.544
45	.962	.806	.666	.938	.766	.634	.578
50	.973	.836	.702	.953	.796	.666	.609

Table 4.2 Normalized Expected Number of Targets Detected when z_{ij} is Allocated to j

	E(N)/I, z_{ij}	
	J=2 I=2	J=3 I=3
R	δ_j	
5	.196	.132
10	.323	.228
15	.427	.308
20	.515	.373
25	.589	.427
30	.652	.477
35	.705	.523
40	.751	.564
45	.789	.602
50	.821	.636

Table 4.3 Normalized Expected Number of Targets Detected for z_{ij} Allocation-Equal priors of 1/2 and 1/3 for 2 and 3 Subspaces

	E(N)/I, z_{ij}					
	Six Subspaces					
	I					
	1	2	3	4	5	6
R	Detection Rate, δ_j					
5	.286	.171	.123	.097	.080	.068
10	.447	.286	.213	.171	.143	.123
15	.559	.374	.286	.232	.197	.171
20	.642	.447	.347	.286	.244	.213
25	.708	.508	.400	.333	.286	.251
30	.762	.559	.447	.374	.324	.286
35	.806	.603	.489	.412	.358	.318
40	.841	.642	.526	.447	.389	.347
45	.871	.676	.559	.479	.419	.374
50	.894	.708	.589	.508	.447	.400

Table 4.4 Normalized Expected Number of Targets Detected z_{ij} Allocation- Six Subspaces- 1 to 6 Targets

	E(N)/I, z_j					
	Six Subspaces					
	I					
	1	2	3	6	2	6
R	Detection Rate, δ_j				$\delta_j/2$	$\delta_j/6$
5	.286 -------------------->				.171	.068
10	.447 -------------------->				.286	.123
15	.559 -------------------->				.374	.171
20	.642 -------------------->				.447	.213
25	.708 -------------------->				.508	.251
30	.762 -------------------->				.559	.286
35	.806 -------------------->				.603	.317
40	.841 -------------------->				.641	.347
45	.871 -------------------->				.676	.374
50	.894 -------------------->				.707	.400

Table 4.5 Normalized Expected Number of Targets Detected z_j Allocation- 1,2,3,6 Targets

	$E(N)/I$, z_{ij}	
	J=6	J=1
	Six Targets	
R	δ_j=.1	δ_j=.1/6
5	.0137	------------>
10	.0270	------------>
15	.0400	------------>
20	.0540	------------>
25	.0670	------------>
30	.0799	------------>
35	.0926	------------>
40	.1051	------------>
45	.1175	------------>
50	.1296	------------>

Table 4.6 Comparison Between Normalized Expected Number of Targets Detected for the Cases of Six Subspaces, Detection Rate of 0.1 and One Subspace , Detection Rate of 0.1/6- z_{ij} Allocation

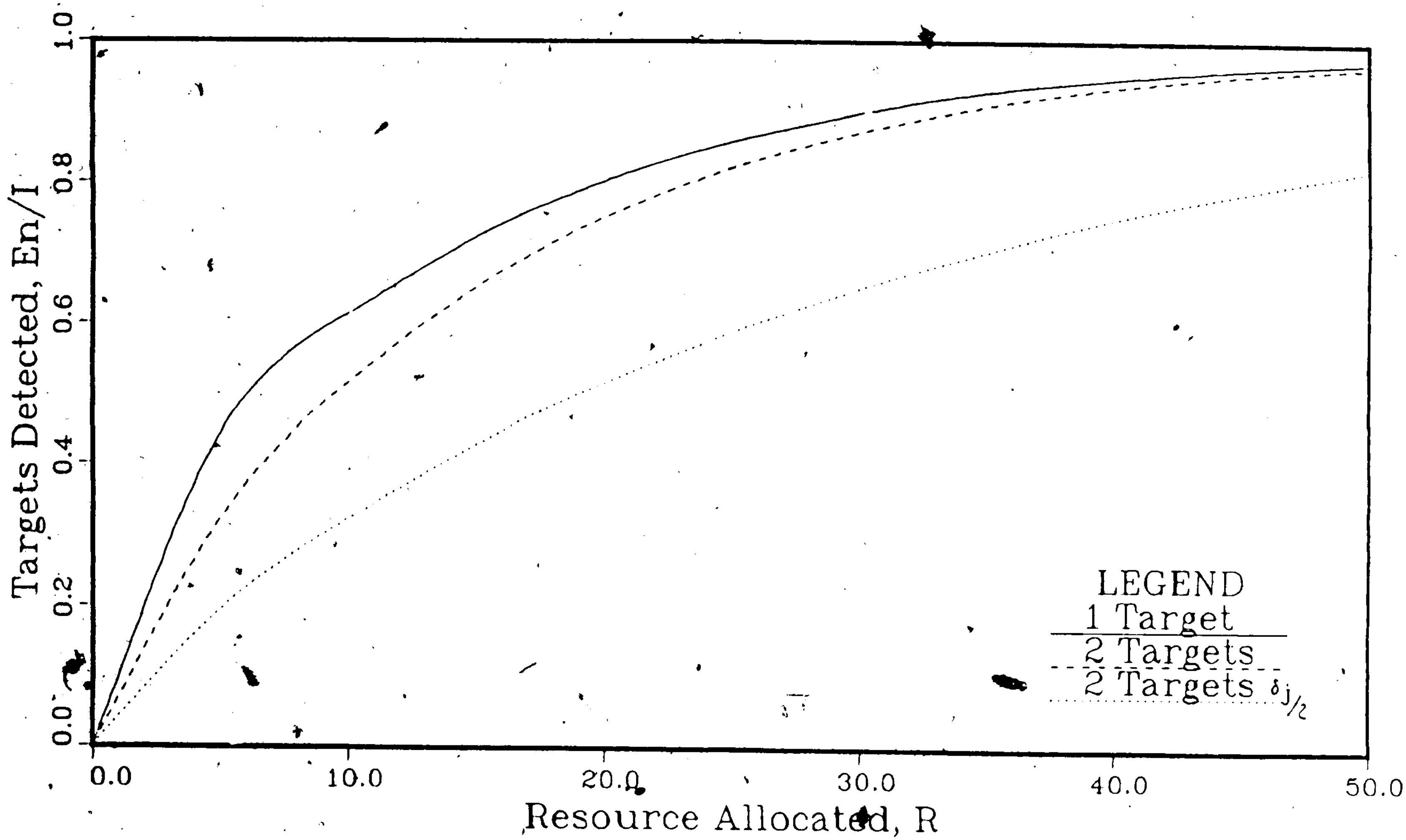

Fig. 4.1 Expected Number of Detected Targets, Normalized 2 Subspaces - Z_j Allocation

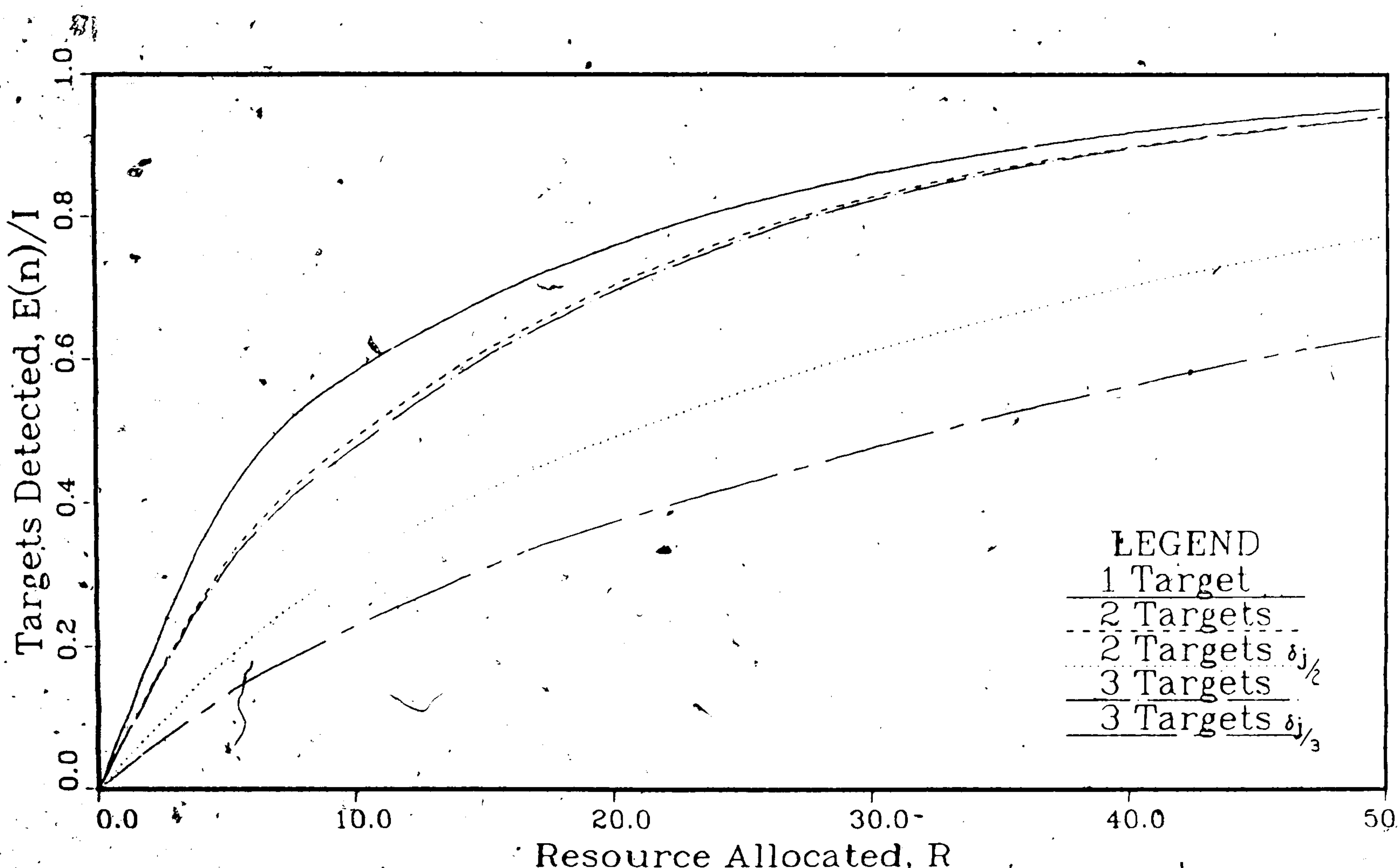

Fig. 4.2 Expected Number of Detected Targets, Normalized 3 Subspaces - Z_j Allocation

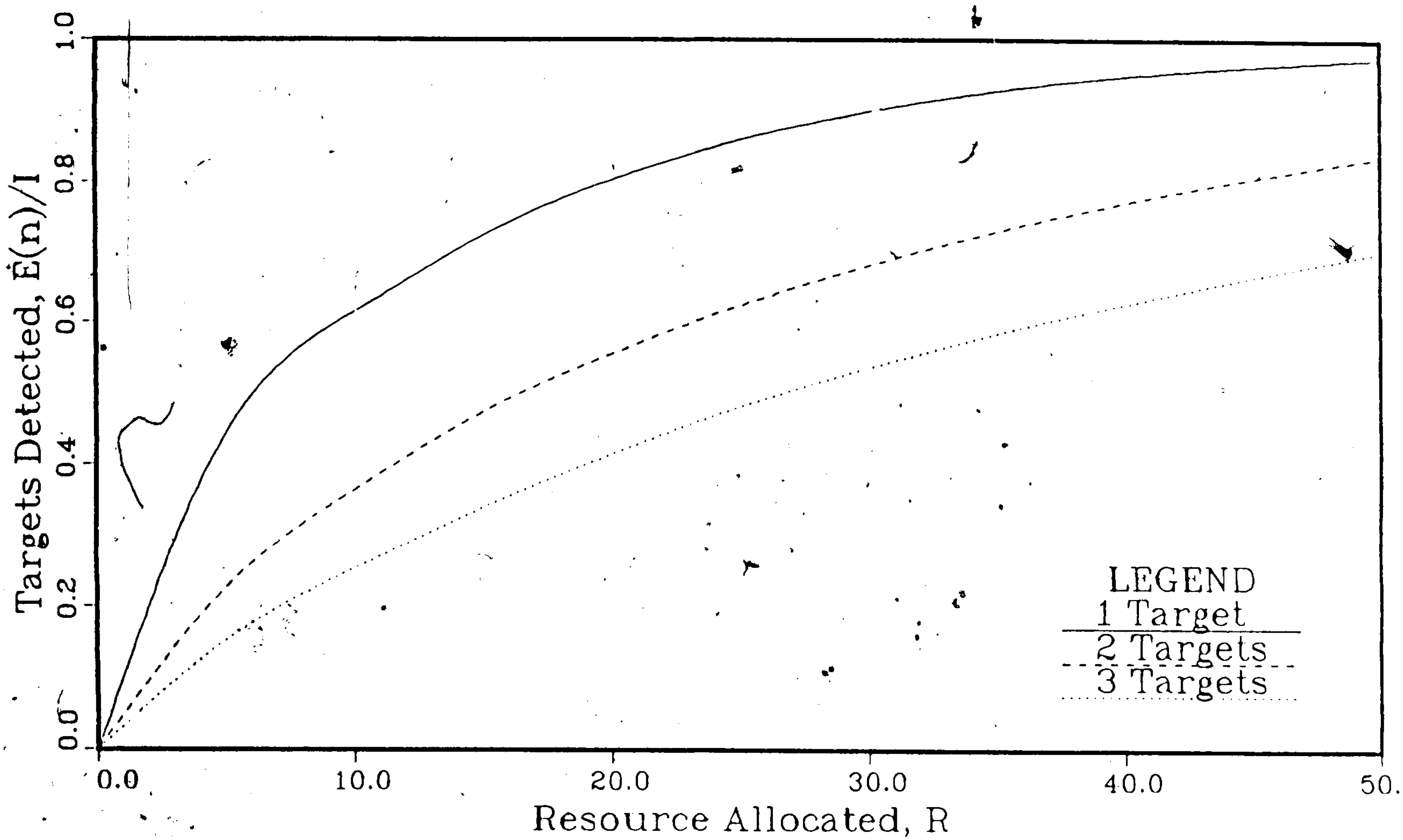

Fig. 4.3 Expected Number of Detected Targets, Normalized
2 Subspaces - Z_{ij} Allocation

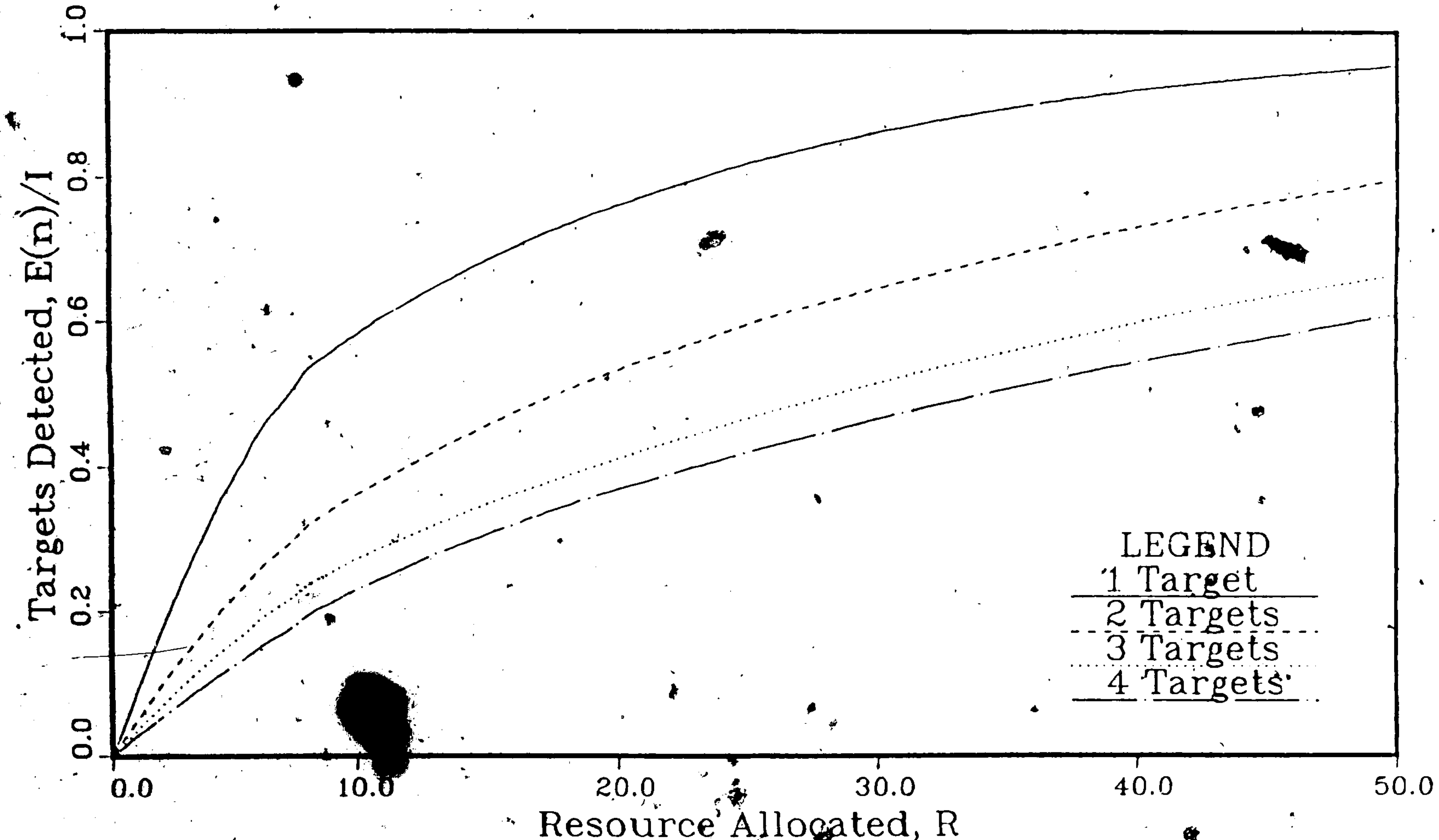

Fig. 4.4 Expected Number of Detected Targets, Normalized 3 Subspaces - Z_{ij} Allocation

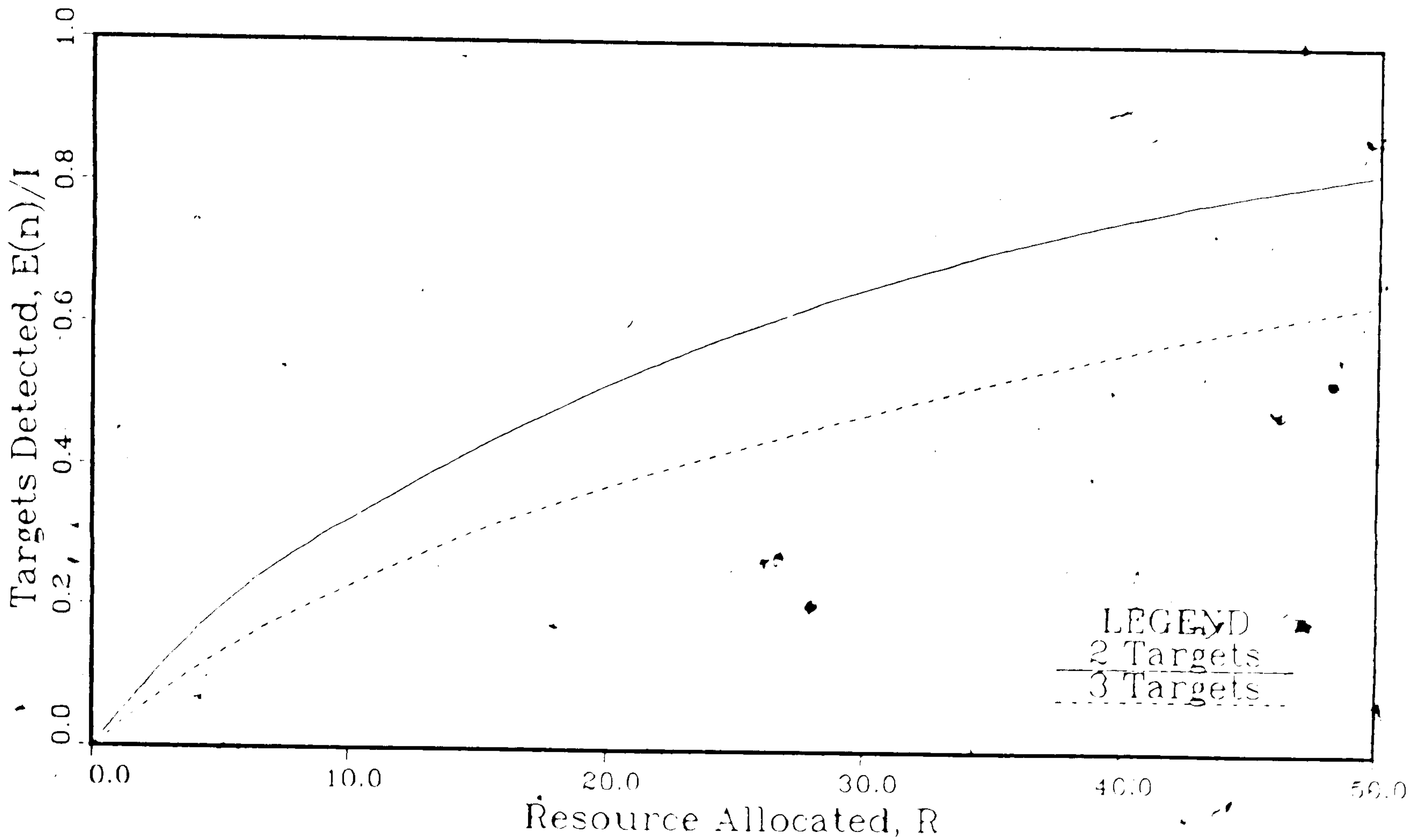

Fig. 4.5 Expected Number of Detected Targets, Normalized
2 Subspaces, 2 Targets, Priors - 1/2 - Z_{ij} Allocation
3 Subspaces, 3 Targets, Priors = 1/3 - Z_{ij} Allocation

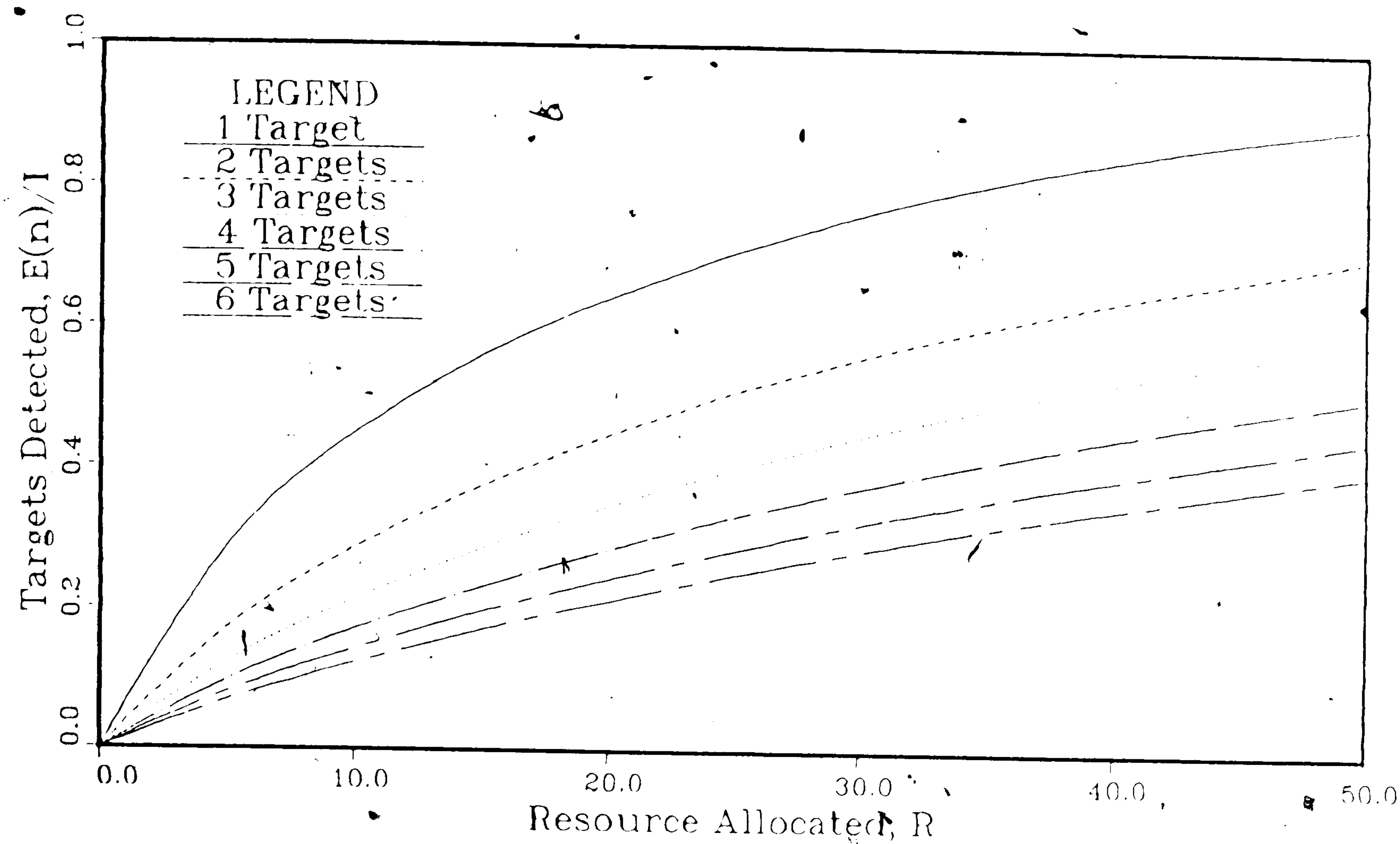

Fig. 4.6 Expected Number of Detected Targets, Normalized 6 Subspaces - Z_{ij} Allocation

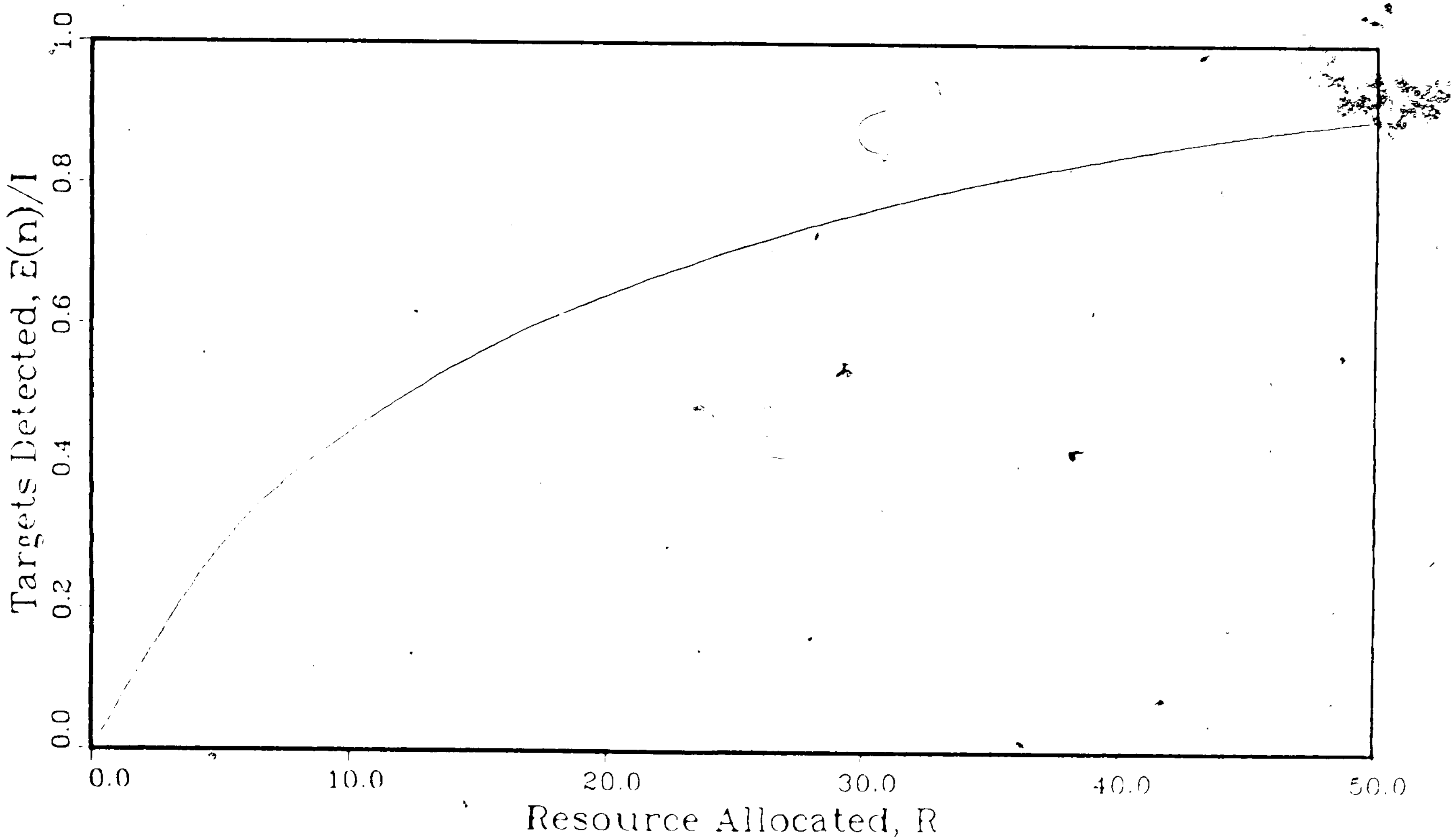

Fig. 4.7 Expected Number of Detected Targets, Normalized 6 Subspaces - Z_3 Allocation - 1, 2, 3, 6 Targets

Further investigation shows that if there are J subspaces and I=J targets and maximum one target is allowed at each subspace, and z_j is allocated to j and the detection rate in j is δ_j, then normalizing the $E_I(N)$, gives the problem of one target with the equal priors of 1/I, since, expanding the objective function:

$$E_I(N)/I = (1/I)\{p_1[1-\exp(-\delta_1 z_1)]+\ldots+p_J[1-\exp(-\delta_J z_J)]\}$$

but the priors are the same and equal to one,

$$p_1=p_2=\ldots=p_J=1$$

so,

$$E_I(N)/I=(1/I)\{J-[\exp(-\delta_1 z_1)+\ldots+\exp(-\delta_J z_J)]\}$$

$$=1-(1/J)[\exp(-\delta_1 z_1)]-(1/J)[\exp(-\delta_2 z_2)]+\ldots$$

This expression is similar to the case of one target and it can be written in the form:

$$\sum_j p_j \; [1-\exp(-\delta_j \; z_j)], \text{ where } p_j=1/J.$$

But this is less than $E_1(N)$ for a given problem, so the following statement is made that: if there are J subspaces and one target and the detection rate is δ_j, then if the priors are the same and equal to 1/J, the expected number of targets detected is always less than the case when the priors are not equal.

The other interesting result which is noted is that: E(N) [using δ_j/I, when I=J=2 and the allocation is z_j] = E(N) [using δ_j, equal priors of .5 when I=J=2 and the allocation is z_{ij}], for a given total capital resource. This is also noted when I=J=3. The proof follows:

$$E(N)=\sum_j p_j[1-\exp(-\delta_j z_j/I)]$$

now expanding this equation:

$$E(N)=p_1[1-\exp(-\delta_1 z_1/I)]+\ldots+p_J[1-\exp(-\delta_J z_J/I)]$$

but the number of subspaces and targets is the same so the priors are equal to 1,

$$p_1=p_2=\ldots=p_J=I/J=1$$

hence,

$$E(N)=J-[\exp(-\delta_1 z_1/I)+\ldots+\exp(-\delta_J z_J/I)] \quad \ldots.(4.2.3)$$

Now, for z_{ij} allocation,

$$E(N)=p_{11}\ [1-\exp(-\delta_1 z_{11})]+\ldots+p_{1J}[1-\exp(-\delta_J z_{1J})]$$

$$+p_{21}\ [1-\exp(-\delta_1 z_{21})]+\ldots+p_{2J}[1-\exp(-\delta_J z_{2J})]$$

.

.

$$+p_{I1}[1-\exp(-\delta_1 z_{I1})]+\ldots+p_{IJ}[1-\exp(-\delta_J z_{IJ}]$$

but the probability that target i is in j is 1/J,

$$p_{ij}=1/J \text{ for all } i\&j$$

therefore, $z_{1j}=z_{2j}=\ldots$, for all j, hence, $p_{ij}[1-\exp(\delta_j z_{ij})]$ is repeated I times, and since $z_j=Iz_{ij}$,

$$E(N)=\sum_j (I/J)\ [1-\exp(-\delta_j z_j/I)]$$

and expanding this function:

$$E(N)=(I/J)[1-\exp(-\delta_1 z_1/I)]+\ldots+(I/J)[1-\exp(-\delta_J z_J/I)]$$

$$=(I/J)J-(I/J)[\exp(-\delta_1 z_1)+\ldots+\exp(-\delta_J z_J/I)]$$

but I=J, hence,

$$E(N)=J-[\exp(-\delta_1 z_1/I)+\ldots+\exp(-\delta_J z_J/I)] \quad \ldots..(4.2.4)$$

There is only one optimal solution, therefore E(N) from (4.2.3) is the same as that from (4.2.4).

Part(2)-Constant Number of Subspaces, (J=6), but Targets Increase from 1 to 6

After investigating table 4.4, it is observed that the expected number of detected targets when there are I targets and the total capital resource is R, repeats for the case when I' targets are present and R', capital resource is available if R/R'=I/I' and R'>R, I'>I, i.e.:

$$E(N)/I \text{ [resource } R] = E(N)/I' \text{ [resource } R'].$$

This can be proved by expanding and comparing the expressions for E(N)/I and E(N)/I':

$$E(N)/I=\{\sum_i\sum_j p_{ij} [1-\exp(-\delta_{ij}z_{ij})]\}/I$$

$$= \{p_{11} [1-\exp(-\delta_1 z_{11})]+\ldots p_{IJ}[1-\exp(-\delta_J z_J)]\}/I,$$

but $p_{ij}=1/J$ for all i and j, therefore the allocation for target i in 1 stays the same, $z_{11}=z_{21}=\ldots$, similarly z_{i2} are equal, e.t.c., so noting that $z_j=Iz_{ij}$ then expanding the above equation results in:

$$E(N)/I=(1/J)\{J-[\exp(-\delta_1 z_1/I)+\ldots+\exp(-\delta_J z_J/I)]\}/I \quad \ldots\ldots(4.2.5)$$

Also, for I' and R', the expression for the normalized expected number of detected targets is obtained in a similar way:

$$E(N)/I'=(1/J)\{J-[\exp(-\delta_1 z_1'/I')+\ldots+\exp(-\delta_J z_J'/I')]\}/I' \quad \ldots\ldots(4.2.6)$$

Now, the total capital resource equals to the sum of the capital resources in all of the subspaces:

$$z_1+z_2+\ldots+z_J=R \text{ or } z_1/I+z_2/I+\ldots+z_J/I=R/I$$

and,

$$z_1'+z_2'+\ldots+z_J'=R' \text{ or } z_1'/I+z_2'/I+\ldots+z_J'/I=R'/I'.$$

But because of the optimality $z_j/I=z_j'/I'$, or $R/I=R'/I'$, so equations (4.2.5) & (4.2.6) are the same.

Further investigation of table 4.4 shows that:

$$E_I(N)/I > E_{I'}(N)/I' \text{ when } I>I'.$$

This result is evident because of the last proof, so

$$E_I(N)/E_{I'}(N) > I/I'.$$

Information from table 4.5 suggests that the normalized expected number of detected targets for a given level of total capital resource stays constant and is independent of the number of targets when δ_j is the detection rate: $E_1(N)/1 = E_2(N)/2 = E_3(N)/3 = E_6(N)/6$, for a given level of total capital resource.

To prove this finding, assume that $I>I'$, then, expanding $E(N)/I$:

$$E(N)/I=\{p_1[1-\exp(-\delta_1 z_1)]+\ldots+p_J[1-\exp(-\delta_J z_J)]\}/I$$

but the priors are the same and equal to $1/J$, hence,

$$E(N)/I=(1/J)\{J-[\exp(-\delta_1 z_1)+\ldots+\exp(-\delta_J z_J)]\}\ldots\ldots\ldots(4.2.7)$$

Now expanding the expression for I':

$$E(N)/I'=(1/J)\{J-[\exp(-\delta_1 z_1'+\ldots+\exp(-\delta_J z_J')]\}\ldots\ldots(4.2.8)$$

It can be seen from (4.2.7) and (4.2.8) that optimality requires $E(N)/I=E(N)/I'$.

Comparing z_j and z_{ij} Allocations, Tables 4.1 & 4.2

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If there are I targets and J subspaces and maximum one target is allowed per subspace, then, the optimal policy is: not to distinguish between the targets, provided that they do not have different importance.

Proof

z_j Allocation

After expanding the objective function, the following expression is obtained:

$$E(N)=p_1[1-\exp(-\delta_1 z_1)]+\ldots+p_J[1-\exp(-\delta_J z_J)]$$

and since $p_j=p_{1j}+p_{2j}+\ldots+p_{Ij}$, the first term of the expression can also be written as:

$$[p_{11}+\ldots+p_{I1}]-[p_{11}\exp(-\delta_1 z_1)+\ldots+p_{I1}\exp(-\delta_1 z_1)] \quad \ldots\ldots(4.2.13)$$

z_{ij} Allocation

The objective function is expanded and the expressions for j=1 are gathered:

$$[p_{11}+\ldots+p_{I1}]-[p_{11}\exp(-\delta_1 z_{11})+\ldots+p_{I1}\exp(-\delta_1 z_{I1})] \quad \ldots\ldots(4.2.14)$$

According to the Kuhn-Tucker conditions, for $z_j > 0$, $p_j\delta_j \exp(-\delta_j z_j)= u_1$, where u_1 is a constant. This equation can be solved for z_j:

$$z_j=(1/\delta_j)\ln(p_j\delta_j/u_1)$$

But $\sum_j z_j = R$, or ,

$$(1/\delta_1)\ \ln(p_1\delta_1/u_1)+\ldots+(1/\delta_J)\ \ln(p_J\ \delta_J\ u_1)\ R$$

The object is to find $\ln(u_1)$ from this equation and compare it to $\ln(u_2)$ which is obtained from a similar formulation when z_{ij} is allocated to j.

$$\ln(u_1)= \{R-\sum_j [\ln\delta_j+\ln(p_{1j}+p_{2j}+\ldots)](1/\delta_j)\}\ /\ -\sum_j 1/\delta_j$$

and in a similar way:

$$\ln(u_2)= \{R-\sum_j [I\ \ln\delta_j+\ln(p_{1j}\ p_{2j}\ \ldots)](1/\delta_j)\}/\ -I\ \sum_j 1/\delta_j$$

The comparison between the above two equations shows that $\ln(u_2) > \ln(u_1)$. Now, from the Kuhn-Tucker conditions $z_j=1/\delta_j\ \ln(p_j\delta_j)-(1/\delta_j)\ln(u1)$ or

$$\ln(u_1)=\ln(p_j)+\ln(\delta_j)-\delta_j z_j$$

also,

$$\ln(u_2)=\ln(p_{ij})+\ln(\delta_j)-\delta_j z_{ij}$$

but $\ln(u_2)>\ln(u_1)$, hence,

$$\ln(p_j)-\ln(p_{ij}) < \delta_j(z_j-z_{ij})$$

The left hand side of the inequality is positive because , $p_j>p_{ij}$, therefore:

$$\delta_j(z_j-z_{ij})>0$$

$$z_j > z_{ij}\ .$$

Hence, expression 4.2.13 is greater than 4.2.14 and $E(N)\ [z_j \text{ allocation}] > E(N)\ [z_{ij} \text{ allocation}]$.

If P_I is equal to zero, detection rate is zero and no detection is possible and if $0<P_I<1$, the above proof holds, since it is independent of the value of P_L.

Assume that the priors are equal, then, $p_{ij}=1/J$ $p_j=I/J$ and $\prod_i p_{ij}=(1/J)^I$, then if these values are substituated in the expressions for $\ln(u_1)$ and $\ln(u_2)$, $\ln(u_2) > \ln(u_1)$ and $\ln(p_j)-\ln(p_{ij}) < \delta_j(z_j-z_{ij})$ or:

$$\ln(I) < \delta_j\ (z_j-z_{ij})$$

$$z_j > z_{ij} \text{ for all } I>1.$$

If there is one target and J subspaces, then:

$$\ln(u_1)=\ln(u_2) \text{ and } p_j=p_{1j}$$

$$\delta_j(z_j-z_{1j})=0$$

$$z_j=z_{1j}.$$

If there is one target and one subspace:

$$\ln(u_1)=\{R-[(1/\delta_1)(\ln p_1+\ln\delta_1]\}\ /\ (-1/\delta_1)$$

and the expression for $\ln(u_2)$ is the same as above and the capital resource allocation is similar, since there is only one target.

The upper value of E(N) [z_{ij} allocation] is obtained when $z_{ij}=z_j$ and the objective functions are equal.

Examples in Petroleum Exploration Using Some of the Formulations Presented in this Chapter

Assume that an oil company is considering several prospects for the general first stage survey activities. Also, assume that more than one reservoir can not be present in each area due to the size of the area or other factors. The exploration personnel start gathering information about the surface and subsurface of the areas. At this stage, the activities may be a literature search about the areas or exploration geologists may gather information in the areas. Their method of search is assumed to be random. As a result of these activities some prospects may be selected for detailed tests.

To obtain the best results, they must not restrict themselves to a type of structure or formation and seek information only about that subsurface feature as other interesting formations may be present which can be missed and this results in the wasting of capital resources. The optimal policy is to obtain general data,(Theorem 10), providing the detection rate does not suffer.

Consider that several areas are selected and examined in detail. As each area is investigated (exaustively or random), then assuming that no oil bearing formation has been discovered,then, these prospects should not be investigated again as long as there is an area in the "inventory" which has not been surveyed,(Theorem 9), providing the prior probabilities are equal.

If some of the prospects are passed on for random drilling, then if management estimates the normalized expected number of detected reservoirs for the simple case of one reservoir,i.e.,$E_1(N)/1$,(using total capital resource of R) this ratio can then be used to estimate the expected number of discoveries for any number of reservoirs, (using the same level of total capital resource). For example, if $E_1(N)/1 = 0.70$, then if there is a possibility of 10 reservoirs, management can expect to discover $E_{10}(N) = (10)(0.70)$ or 7 oil bearing formations, provided that the type of reservoir is not considered, [Table 4.5]. If the reservoirs are distinguished, the relation $E_1(N)/1 > E_{10}(N)/10$ should be used, [Table 4.4], $E_{10}(N)/10 < 0.70$ or $E_{10}(N) < 7$, which suggests that the operator should expect to discover less than 7 traps.

Conclusions

The aim of this study was to experiment with various problems of multiple target systems and observe the variation of the expected number of detected targets when the solution was optimal.

As a result of this study valuable information is obtained which suggests that the general behaviour of E(N) can be predicted in various cases, for example:

1. For a given problem:

$$E_I(N)/E_{I'}(N) < I/I'$$

and from table 4.1, for R=5 units, I=3 and I'=2, the value of E(N) for I=3 is .924, but $.924/E_2(N) < 3/2$ or $E_2(N) > .616$, the actual value of $E_2(N)$ from table 4.1 is 0.623 .

2. Another interesting result from table 4.1 is that if there is one target and several subspaces, then, if the priors are given equal values, this will result in the smaller number of targets detected as compared to the case when the priors are different.

3. For z_{ij} allocation, $E(N)/I$ [capital resource R] is the same as $E(N)/I'$ [resource R'], if $I/I'=R/R$ and $I>I'$, $R>R'$.

4. For z_j allocation, for a given level of total capital resource if $p_j=I/J$, for all j, then $E(N)/I=E(N)/I'$, for any values of I and I'.

The study also resulted in a theorem describing that in order to detect the maximum number of targets, the targets should not be distinguished. In other words, distinguishing between the targets, results in the wasting of some of the capital resources, since, for example, if the searcher is looking for target i, then, he is blind to target i', and if i' is intersected it will not be detected. This is not necessarily true if several targets can be present at each subspace.

The common constraint on all the problems discussed is the maximum number of targets per area, which is one. By relaxing this constraint, a new set of problems develops which requires more detailed investigation before any conclusions can be reached.

Chapter 5

Demonstration Data and the Analysis

5.1 Demonstration Data

To demonstrate the effectiveness and the flexibility of the model, a set of data is needed that describes the expenditure in an exploration program which includes the capital resources used on each of the first stage surveys, the number of wildcat and appraisal wells drilled and the cost per well.

The Statistical Year Book from the Canadian Petroleum Association has provided data for different provinces of Canada. Since information for one exploration program is not available, the above reference is used to obtain data for Alberta and then estimate the capital resources spent in one venture. The most recent years with the required data are 1974 and 1975. The data for 1974 is used here.

The 1974 survey activities (crew month) for Alberta follows:

a)8 Geological b)138 Seismic c)25 Gravity d)19 Magnetic at a total cost of $\$112.4\text{x}10^6$. The number of new field wildcats drilled was 457 out of which 14 reached oil, 121 discovered gas, 313 were abandoned and 9 were suspended. The total number of outposts(appraisal wells) was 140.

There were also other exploratory tests such as new pool wildcats which make the total of 1369 wells at a cost of $\$146.5 \times 10^6$ (average $107,012.4 per well).

To consider the total expenditure of exploratory tests, the total number of wells is divided between the wildcat and the appraisal wells according to the ratio 457/140, hence, it is assumed that 1048 wildcats and 321 appraisal wells were drilled in Alberta in 1974. It is further assumed that 1% of these wells were drilled in one prospect. This makes about 10 wildcats and 3 appraisal wells. This percentage is also considered for the first stage surveys, i.e., $\$0.01 \times 112.4 \times 10^6$ per prospect.

To estimate the expenditure for each survey, 1.124×10^6 is divided between the surveys according to the percentage of the total survey activity. Hence, the following costs are obtained:

Geological...	$44,960
Magnetic.....	$112,400
Gravity......	$157,360
Seismic......	$809,280
	$1,124,000

It is assumed that the above costs include the processing of data and any other associated costs.

5.2 Analysis

The analysis is carried out on an IBM PC. Two programs are written in Basic, the main program, EXPLO, and a data file, DATAS, which provides data to the last two stages. Both programs are self explanatory and access each other through several sequential files. The list of the programs is given in Appendix (F).

A combination of rules from different stages are used to simulate the process. The total capital resource of each stage is kept constant and the rules are varied so that the best combination of rules from different stages can be determined. For example, since the total resource for stage 1 is $1,124,000, then if the rule specifies that only seismic should be done, this amount is allocated to seismic survey.

It is assumed that at the third stage of the process enough information is available so that appraisal drilling can be done without the aid of a seismic survey. Since the object of the process is to reach large oil deposits which may be contained in reservoirs with poor or good properties and also for simplicity, the rule for the third stage is selected to be the 3rd. rule which is estimating the size of the deposits for prospects with poor and good reservoir properties.

It is assumed that all the prospects have the same area and that an area is searched at a rate of 10^{-6} (all the activities). This number is selected after considering the capital resources for each method so that the normalized effort does not result in a very high value.

P_I, the probability of detecting the target, given its presence is varied for different rules and methods for the first stage and is kept constant at 0.5 for the other stages. In all, four sets of rules are considered which are shown in Table 5.1.

First Set of Rules

P_I=0.5 for all the activities

Stage 1	Stage 2
1 [do all surveys]	1 [drill if +ve seismic]
2 [stop if -ve signal]	...
21 [do only seismic]	...
11 [stop if 1st 3 are -ve]	...
12 [don't do 1st survey]	...
...	13 [drill if last 3 are +ve]
22 [only 1st survey]	4 [drill if +ve signal]
13 [don't do seismic]	11 [drill if 1st 3 are +ve]
4 [stop if 1st is -ve]	1 [drill if +ve seismic]

Second Set of Rules

P_I=0.7 for seismic and 0.5 for others

1 [do all surveys]	1 [drill if +ve seismic]
21 [only seismic]	...

Third Set of Rules

P_I=0.8 for aerial photography and 0.5 for the others

1 [do all surveys]	1 [drill if +ve seismic]
22 [only 1st. survey]	4 [drill if +ve result]

Fourth Set of Rules

P_I=0.5 for 1st survey, 0.2 for 2nd and 3rd surveys and 0.3 for seismic

1 [do all surveys]	1 [drill if +ve seismic]
2 [stop if -ve signal]	...
21 [only seismic]	...

Table 5.1 List of the Rules Used to Simulate Exploration Process

The first set assumes constant P_I for all the activities. For the second set P_I for seismic is increased to 0.7. The value of P_I in the third set for aerial photography is increased to 0.8 keeping the other P_I's at 0.5 and finally for the 4th. set of rules the values of 0.5(aerial ph.), 0.2(magnetic and gravity), 0.3(seismic) are assigned.

A prospect may have any of the 17 actual characteristics and the computer program simulates the exploration process for all the characteristics. After the sensing stage, the information about this prospect is transmitted to the learning stage where according to the rule used, a proportion of prospects (·1) with certain sensed characteristics are drilled. Also, at the third stage, a proportion of prospects with some observed characteristics are drilled. Assume that n appraisal wells are drilled per prospect. If n is multiplied by the total number of prospects per year, then the total number of appraisal wells is obtained and if the total number of prospects is multiplied by the outcome of the process, then the outcome of all the exploratiom programs is predicted.

The method of search is assumed to be exhaustive.

The aim of the exploration process is to reach reservoirs with large deposits but since the devices used in an actual process are not perfect sensors, $P_I<1$, other prospects with different characteristics may be assumed to contain large deposits and can be considered for development drilling. Assume that the underground formation of a prospect exhibits certain characteristics such that it is mistaken for a reservoir with large deposits. This may therefore be considered as a false target. Therefore, the information regarding different actual characteristics is followed in the computer program as computation proceeds. Now consider that a prospect with large size oil deposits and good reservoir properties may or may not have an interesting surface indication of possible presence of a trap [see Appendix (C)]. These sets of actual characteristics form the LGOOD group shown below. This procedure is repeated and the actual characteristics are grouped into five sets:

LGOOD [large deposit and good reservoir properties];

SGOOD [small deposit and good reservoir properties];

LPOOR [large deposit and poor reservoir properties];

SPOOR [small deposit and poor reservoir properties];

No Deposits.

This notation is used in the following chapter.

Chapter 6

Results and Discussion of the Results

6.1 Results

To determine the percentage of time that the computer program has correctly selected prospects with large oil deposits and eliminated prospects with small or no deposits, the results are tabulated in two columns as Observed (final outcome) and Not Observed (prospects which are not considered for development). Each column has been divided into 5 sets to show the expected number of actual prospects with different characteristics. The numbers in each column are then added to calculate the total number of prospects in the two categories, i.e., observed or not. The percentage of different sets of actual characteristics from the total of 17 sets are shown in the last column. For example, 6 out of 17 sets of actual characteristics are without deposits, (Tables 6.1 to 6.4).

A second table (Table 6.5) is presented that shows the number of prospects which are drilled at the second stage and the actual number of prospects with large deposits which are subject to development drilling. The comparison between the two will show whether or not the greater number of prospects drilled at the second stage result in a larger number of prospects with large deposit.

First Set of Rules, (start of Table 6.1)

Rule 1 (1st stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	7.7057E-03	.1099	2/17
LPOOR	6.4214E-03	.1112	2/17
SGOOD	1.1558E-02	.1649	3/17
SPOOR	1.2843E-02	.2224	4/17
No Deposit	0	6/17	6/17
	.03852	.96147	

Rule 2 (1st stage) Rule 1 (2nd stage)

	Observed	Not Observed	
LGOOD	3.0302E-05	.1176	2/17
LPOOR	3.0312E-05	.1176	2/17
SGOOD	6.0604E-05	.1764	3/17
SPOOR	6.0594E-05	.2352	4/17
No Deposit	0	6/17	6/17
	1.8181E-04	.9998	

Rule 21 (1st stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	8.9492E-03	.108697	2/17
LPOOR	7.4576E-03	.110189	2/17
SGOOD	1.3423E-02	.163046	3/17
SPOOR	1.4915E-02	.220378	4/17
No Deposit	0	6/17	6/17
	.04474	.95525	

Rule 11 (1st stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	1.6720E-03	.11597	2/17
LPOOR	1.4139E-03	.11623	2/17
SGOOD	2.5693E-03	.17390	3/17
SPOOR	2.8274E-03	.23246	4/17
No Deposit	0	6/17	6/17
	8.4828E-03	.99151	

Rule 12 (1st stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	7.9374E-03	.10970	2/17
LPOOR	6.6144E-03	.11103	2/17
SGOOD	1.1906E-02	.16456	3/17
SPOOR	1.3229E-02	.22206	4/17
No Deposit	0	6/17	6/17
	3.9687E-02	.96031	

Rule 12 (1st stage) Rule 13 (2nd. stage)

	Observed	Not Observed	
LGOOD	1.1354E-05	.11763	2/17
LPOOR	9.4619E-06	.11763	2/17
SGOOD	1.7031E-05	.17645	3/17
SPOOR	1.8924E-05	.23527	4/17
No Deposit	0	6/17	6/17
	5.6771E-05	.99994	

Rule 22 (1st. stage) Rule 4 (2nd. stage)

	Observed	Not Observed	
LGOOD	5.2466E-03	.11240	2/17
LPOOR	5.2466E-03	.11240	2/17
SGOOD	1.0493E-02	.16597	3/17
SPOOR	1.0493E-02	.22480	4/17
No Deposit	0	6/17	6/17
	3.1479E-02	.96852	

Rule 13 (1st. stage) Rule 11 (2nd. stage)

	Observed	Not Observed	
LGOOD	1.2934E-05	.11763	2/17
LPOOR	1.2934E-05	.11763	2/17
SGOOD	2.5869E-05	.17644	3/17
SPOOR	2.5869E-05	.23526	4/17
No Deposit	0	6/17	6/17
	7.7607E-05	.99992	

Rule 4 (1st. stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	1.2122E-04	.11752	2/17
LPOOR	1.2122E-04	.11752	2/17
SGOOD	2.4245E-04	.17622	3/17
SPOOR	2.4245E-04	.23505	4/17
No Deposit	0	6/17	6/17
	7.2736E-04	.99927	

Table 6.1 Results Using First Set of Rules

Second Set of Rules

Rule 1 (1st. stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	1.0293E-02	.10735	2/17
LPOOR	8.5776E-03	.10907	2/17
SGOOD	1.5439E-02	.16103	3/17
SPOOR	1.7155E-02	.21813	4/17
No Deposit	0	6/17	6/17
	5.1465E-02	.94853	

Rule 21 (1st. stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	1.1016E-02	.10663	2/17
LPOOR	9.1800E-03	.10846	2/17
SGOOD	1.6524E-02	.15994	3/17
SPOOR	1.8360E-02	.21693	4/17
No Deposit	0	6/17	6/17
	5.5080E-02	.94492	

Table 6.2 Results Using Second Set of Rules

Third Set of Rules

Rule 1 (1st. stage) Rule 1 (2nd. stage)

	Observed	Not Observed	
LGOOD	7.7057E-03	.10994	2/17
LPOOR	6.4214E-03	.11122	2/17
SGOOD	1.1558E-02	.16491	3/17
SPOOR	1.2843E-02	.22245	4/17
No Deposit	0	6/17	6/17
	3.8528E-02	.96147	

Rule 22 (1st. stage) Rule 4 (2nd. stage)

	Observed	Not Observed	
LGOOD	8.3338E-03	.10931	2/17
LPOOR	8.3338E-03	.10931	2/17
SGOOD	1.6667E-02	.15980	3/17
SPOOR	1.6667E-02	.21862	4/17
No Deposit	0	6/17	6/17
	5.0003E-02	.94999	

Table 6.3 Results Using Third Set of Rules

Fourth Set of Rules(start of Table 6.4)

Rule 1 (1st. stage) Rule 1 (2nd. stage)

	Observed	Not observed	
LGOOD	3.3973E-03	.11425	2/17
LPOOR	2.8311E-03	.11481	2/17
SGOOD	5.0960E-03	.17137	3/17
SPOOR	5.6622E-03	.22963	4/17
No Deposit	0	6/17	
	1.6986E-02	.98301	

<u>Rule 2 (1st. stage)</u> <u>Rule 1 (2nd. stage)</u>

	<u>Observed</u>	<u>Not Observed</u>	
LGOOD	2.8621E-06	.11764	2/17
LPOOR	2.9683E-06	.11764	2/17
SGOOD	5.7242E-06	.17646	3/17
SPOOR	5.6179E-06	.23528	4/17
No Deposit	0	6/17	
	1.7172E-05	.9999	

Rule 21 (1st. stage) Rule 1 (2nd. Stage)

	Observed	Not Observed	
LGOOD	4.5174E-03	.11313	2/17
LPOOR	3.7645E-03	.11388	2/17
SGOOD	6.7762E-03	.16969	3/17
SPOOR	7.5291E-03	.22776	4/17
No Deposit	0	6/17	6/17
	2.2587E-02	.97741	

Table 6.4 Results Using Fourth Set of Rules

1st. Stage Rule	2nd Stage Rule	Prospects Drilled(2nd. Stage)	Prospects with Large Deposits
		First Set of Rules	
1	1	.1785	.01412
2	1	.000661	.000060
21	1	.2387	.0164
11	1	.0317	.003
12	1	.188	.0145
12	13	.0002128	.00002
22	4	.1432	.0105
13	11	.000282	.000026
4	1	.002644	.000242
		Second Set of Rules	
1	1	.3499	.0188
21	1	.458	.0200
		Third Set of Rules	
1	1	.1785	.01412
22	4	.354	.016
		Fourth Set of Rules	
1	1	.06426	.0062
2	2	.00006	.000005
21	1	.0874	.00828

Table 6.5 Comparison Between the Number of Prospects Drilled at the 2nd. Stage and the Prospects Reached for Development

6.2 Discussion of the Results

The results show that if only seismic method is used at the first stage of the process, the maximum number of prospects with large oil deposits (l.o.d.) are considered for development drilling.

The approach taken in discussing the results is to first determine which combination of rules from the first two stages results in a greater number of prospects selected for wildcat drilling. This is because in many cases if a greater number of prospects are drilled at the 2nd. stage this produces a better outcome for the exploration process. The reason for this behaviour is then investigated to reach the final conclusion.

Assume that the rule for stage 2 states that all the prospects which have resulted in a positive signal from the surveys should be drilled, i.e., state 1,1,1,1. If the probabilities of a positive signal from survey 1 to survey 4 is a,b,c and d then the number of prospects reached for drilling is abcd. Now, if only seismic is done and prospects with positive seismic are drilled then d' prospects are reached for drilling. But d' is greater than d since higher units of resources are allocated to seismic hence d'> abcd, [note that abc is less than 1]. Therefore, a larger number of prospects are drilled if seismic is the only survey at the first stage.

Now, let the last two surveys be carried out and the prospects with positive result from these surveys are drilled. The possible state is 2,2,1,1 where 2 indicates that the survey is not done. The probability of this state is (1)(1)(c)(d), and the expected number of prospects which are drilled is cd which is again less than d'.

This procedure can be repeated for any combination of rules from the first two stages and the same result will be obtained.

The comparison of results when only survey one is done to that of seimic shows that more prospects with large deposits are subject to development with the aid of a seismic survey. The investigation of the table of actual characteristics shows that 9 sets of characteristics out of 17 have outcrop(target for survey 1) out of which only two sets contain large deposits. The number of sets of characteristics with trap(target of seismic) is 15 out of which 4 sets contain l.o.d. This leads to the conclusion that since the target of seismic is repeated with the ultimate target in the table of the actual characteristics more often than that of aerial photography, hence better results are obtained with seismic. In other words, if a positive signal is received from seismic, the probability that l.q.d. is present is higher than that of aerial photography. This is true since the presence of an outcrop does not necessarily indicate the presence of a trap.

Further investigation of the results confirms the above conclusion since when all the surveys are done(P_I

for seismic=.7), .3499 prospects are drilled at the 2nd. stage and .0188 prospects with l.o.d are observed as compared to .354 prospects which are drilled when P_I for survey 1 is 0.8 [only survey 1 is done] and only .016 prospects with l.o.d reach for development,(see Table 6.5).The reason for this result is that gravity, magnetic and seismic can detect a trap which may contain large deposits. This result also shows as expected, that drilling a larger number of prospects does not necessarily mean a better final outcome of the process.

The comparison between this finding and the previous conclusion shows that by doing only one survey which can detect a trap(seismic),a maximum number of prospects with possible large deposits are drilled and better results should be expected at the 3rd. stage.

The target for the last three surveys is assumed to be a trap in the present model. Therefore, it is expected to obtain similar results with gravity or magnetic only, provided that the second stage rule specifies the drilling of prospects with a positive signal from say, gravity. The current model confirms the presence of a trap as the last 3 surveys give positive signals. Assuming that a positive signal from these surveys indicates the definite presence of a trap (no false targets), then if in an actual exploration program a positive signal is obtained, there will be no need to do any other survey(assume no other information can be obtained). Hence it is best to allocate the available resources to one of these methods. The results also show that as P_I increases, more prospects with l.o.d. are detected which is as expected. Hence, the survey selected must have the highest P_I.

It is observed that only a small percentage of prospects reach for development drilling. It must be noted that the capital resources considered here for one exploration program is 1% of the total expenditure in Alberta in 1974. It is also assumed that other costs such as processing the data and data correction are all included. The rate at which the area is searched is assumed to be 10^{-6}. The increase in the amount of capital resources or the search rate will result in a larger number of prospects with l.o.d.

The percentage of time that the model is right is approximately 76 which is obtained by adding the number of prospects with l.o.d. which are considered for development drilling and the number of prospects without large deposits which are eliminated during the computation and are not considered for development.

Chapter 7

Conclusions

This thesis presented a demonstration computer program which simulates the petroleum exploration process and predicts the outcome under different decisions just prior to the development drilling. Also several theorems are developed which describe the optimal allocation of the available capital resources in the areas of interest (prospects). The theorems consider a variety of problems such as allowing one or more targets(e.g.,traps) per area.

The structure of the conceptual model which divides the complex process of exploration into stages and the use of the theory of optimal search have resulted in the development of a model which has given accurate predictions of the outcome of the process for the current set of actual characteristics. For example, the model shows that although larger number of prospects may be drilled as a result of the initial surveys, only a few may contain enough deposits justifying development drilling. This is also the case in actual practice.

For demonstration purposes, the total exploration cost in Alberta in 1974 was used and one percent of this cost was considered for one exploration program. This created a constraint on the total number of prospects with large oil deposits reached for development drilling.

Approximately, 76 percent of the time the model selected the right prospects (prospects with large oil deposits) and eliminated the unfavorable ones.

The results showed that for a given capital resource at the general first stage survey, it is better to allocate the capital resources to one survey only. It was concluded that this survey should be able to detect traps. This was also shown mathematically.

The model is flexible and accurate because:

1. The computer program is developed considering that the aim of all the activities in petroleum exploration is to learn about the state of the nature as each activity is carried out. The state of nature is described by 17 sets of actual characteristics in this thesis and the program simulates the process considering all of these characteristics. The outcome, as is the case in an actual exploration process, is a function of the state of nature, the activities, and the amount of capital resources allocated to each activity. Also, since the devices used to gather information in actual practice are not perfect, parameter P_I, the probability of detection given the presence of the object of search, was varied, demonstrating that the use of more reliable devices (large values of P_I) would result in a better outcome, as expected. The model also allows different courses of action to be taken, for example, doing only one survey

instead of four surveys, or random drilling of the area. Therefore, the model is flexible, closely following the actual process.

2. The mathematical formulation used to develop the model is the theory of optimal search which has proved its usefulness in different areas where the aim is to detect the object of the search, or target, with limited capital resources. The target of search for each activity is defined in the model. The flow of information in an actual exploration program allows the process to be treated as an information processing system resulting in the detection of the ultimate target, reservoirs with large deposits.

Even though every attempt was made to develop a simple model which would describe the exploration process in some detail and within certain limits, the complex nature of the process required extensive investigation and analysis in some parts of this thesis, for example, when examining the behaviour of multiple target systems in Chapter 4. Also, at times, the process had to be simplified to the extent that certain parts would require re-modelling, for example, the sensing stage and the set of actual characteristics.

The use of the expert systems which can be implemented in the model and accurate definition of the state of nature as the actual characteristics, describing in detail the type of information which is received from each exploration method and the concept of false targets, allows the model to be used to accurately predict the outcome of one or many actual exploration programs.

Chapter 8

Recommendations for Further Work

One of the most important factors in developing a model for the exploration process is the description of actual characteristics. A table must be constructed with an accurate definition of the state of the nature. This should include all the possible elements and their combinations. These elements must also define the target of each activity. The information about the subsurface formation may be scattered through the table, where appropriate. This will allow the detection of one or more targets by different methods, if the targets are shared. For example, assume that a particular information can be obtained by two surveys. This information as well as each survey's unique target should be considered as the targets of each survey. Important information about subsurface features should be related to the type of trap.

After the table of actual characteristics is completed, the concept of false targets should be included in the model. The computer model should then be modified and tested.

In improving and testing the model, care must be taken to accurately reflect the actual process of petroleum exploration. The following questions and similar ones may be helpful. It should be noted that the answers to these questions may not be available from literature sources but can be provided by an oil company involved in exploration.

1. Should an area with good reservoir properties and small deposits be developed?...This is important because if the properties of a reservoir are good, then the cost of extracting deposits may be low. Perhaps another category can be introduced to better define the reservoir properties, such as "excellent", so that the areas with reservoirs in this category are allowed to be developed, even though there may be small deposits present. The above question also relates to a better definition about what the goal of the exploration process should be.

2. Are there additional important methods which are not included?....Special attention should be given to geological prospecting and the sensing stage.

3. How reliable or sensitive are the instruments used? The answer to this question can be used to estimate the probability of detection, given the presence of a target,

4. What are the typical costs for one exploration program? This includes the processing of data. Any other information such as number of wells should also be obtained.

5. What is the rate at which the area is searched?...By obtaining appropriate information, estimates of the value of this parameter for each activity can be made.

The importance of the sensing stage is obvious, when considering that the prospects are drilled as a result of the initial surveys and that drilling is expensive. It is not sufficient to define the target(s) of each activity for the first stage but also the area to be surveyed by each method should be considered since it reduces as each survey is carried out. For example, the magnetic survey eliminates the unfavorable locations and gives information on the limits of basins, the gravity survey provides data on the fault locations and the shape and extent of the basins, etc. Once these activities are completed, seismic reflection is carried out to provide detailed information about the subsurface such as the types of structures. This continuity of the process eliminates a large portion of the area and locates certain parts for wildcat drilling. Hence, an accurate representation of this process is essential.

After discovering petroleum, the exploration process does not end and the size and value of the deposits must be estimated. The current model assumes that the value of the findings is directly proportional to the size of the deposits. It may be necessary to be more specific in defining the value of oil deposits by considering the type of the oil discovered as well as its size, so that the combination of the two can give estimates of the value of the discovery.

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* IHRDC stands for International Human Resources Development Corporation.

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Appendix (A)

Exploration Methods and Description of Traps

The success of an exploration program depends largely on the information obtained from the initial surveys (geological & geophysical) combined with the drilling effort. The surveys provide valuable information about the surface and subsurface of the area so that the location of the exploratory wells is determined.

There are four sections in this appendix describing the geological and geophysical prospecting, wildcat and appraisal drilling. The last section presents a list of traps with a brief description of them.

A.1 Geological & Geophysical Prospecting

The study of the surface features of an interesting area is the first task of the geologist. Depending on the area and its location, the geologist may use a helicopter or land vehicle. Careful examination of rocks and any interesting features on the surface are included. Specimens are collected and examined in the laboratory to gather data on the rock characteristics. The surface evidence of hydrocarbons, if they exist, include seepages, mud volcanoes, burnt clays, sulfur in soils, etc. At this stage the search is assisted by pictures taken from air.

Each photograph overlaps those adjoining. This is a method of determining the surface geology, and is known as photogeology in the industry. These pictures are then examined under the stereoscope, where a three dimentional picture of the area is obtained. This method is specially ideal for mapping large areas.

The exploration program continues by the geophysical prospecting which is a relatively new area of technology, about 50 years old. It combines the sciences of physics & geology. The three geophysical methods of greatest use in petroleum exploration are gravity, magnetic and seismic.

Petroleum is found in sedimentary rocks. These rocks are less magnetic compared to the others, so the magnetic survey is used to eliminate the unfavorable locations in an area. The instrument used is the magnetometer. It may be towed from a plane and the survey is done from the air. Information such as the limits of basins and the depth to basement can be estimated. The magnetic objects such as the power lines, rails,etc. are avoided since they create a local magnetic field that effects the readings.

Gravity survey is based on the concept that the earth's gravity field is affected by variations in the density of rocks. For this survey, the ground should preferably be reasonably flat, otherwise corrections are made because of the height differences. The instrument is the gravimeter. From this survey information such as basin shape and extent, fault locations, etc. is learnt. In the early phases of exploration, magnetic and gravity surveys are very important tools in providing information on the basins.

There are two types of seismic surveys, 1) seismic reflection, 2) seismic refraction. The refraction method is now little used in the industry. Seismic reflection works on the echo sounding principle. Explosives are planted in the holes at certain locations (intervals of about 1/4 mile) in a line. The energy waves generated are reflected from a number of beds in a rock and the information is received by instruments called geophones at the surface. In populated areas, heavy weights are used to pound the ground, generating energy waves. From this survey, the types of structures, the structural character, unconformities, etc. can be learnt.

A.2 Wildcat Drilling

Drilling a well is a round the clock shift operation. Because of the high cost of drilling, it is essential to perform the initial surveys before drilling begins. The location of the exploratory wells is determined by the geological analysis of all the available data. The method of drilling is known as 'rotary'. In this method the bit is attached to a string of steel pipes and is rotated. Drilling mud is continously circulated through the hollow string and the bit and through the annulus between the drilling string and the hole and the cuttings are flushed out of the hole.

The first well, in many cases, is usually a dry hole but valuable information can sometimes be obtained to justify further drilling.

Some Information on the Subsurface Geology

The geologist, by studying the rock cuttings taken during the drilling of a well, can obtain lithological information about the formation. These samples are examined closely for shows of petroleum. If a particular zone is of interest to the geologist, core sample of rock from that zone can be taken by a core barrel, which cuts out a long cylindrical piece of rock. Information on the porosity, permeability, the type and amount of fluid which occupies the pore space in the rock, is obtained from cores.

The geophysical logs are widely used by the exploration geologist. The logging tools, in general, consist of an electrical or radioactive device, which is lowered into the wellbore on a cable to take certain measurements. Some of the major types of logs are:

1). Electrical surveys- resistivity logging is used to measure the electrical resistivity of the formation surrounding the wellbore. These logs provide information on the type of fluid which occupies a pore space of a rock and also helps to determine the relative saturations of oil and water in the formations.

2) Radioactive logging- used to measure the natural and induced radiation of the formation to define the porosity, lithology, dip and strike of different beds,etc.

The drill stem test is used to test the potential pay zones of a well for presence of petroleum. It is a temporary completion of a well during drilling.

Some Information on the Geochemical Prospecting

The geochemical prospecting is used to detect the traces of hydrocarbon. It is based on the theory that hydrocarbons migrate upwardly from the subterranean reservoir and the presence of hydrocarbon in the surface or near-surface zones of earth is indicative of the probable presence of a subterranean reservoir. The cuttin-ngs and cores obtained during the drilling are examined for their content of gaseous, liquid and solid hydrocarbo-ns. Ultraviolet light is used for examining for solid and liquid hydrocarbons. To inspect for gaseous hydrocarbons, the rock sample is disintegrated in the presence of water, so the pore spaces are opened and the gaseous hydrocarbons are freed and collected for testing by a hot wire gas detector.

A.3 Appraisal Drilling

After the discovery of petroleum, limits of the reservoir and the importance of the findings is investigated by appraisal (step-out) drilling. The number of wells and their location depends on the available data. If, for example, an anticline trap is present, then the wells are drilled in two lines perpendicular to one another or if a large trap is suspected then the wells may be drilled at larger distances. Onshore appraisal wells may later be used for production purposes. These wells provide useful data to assess the potential of the discovery for development.

A.4 Traps

Oil and gas are accumulated in traps and are sealed in by cap rocks or other sealing agents. This requires the boundary between the cap rock and the reservoir rock be, in principle, convex upwards.

1. Anticline: A structure in the form of a sine curve as shown on the figure below.

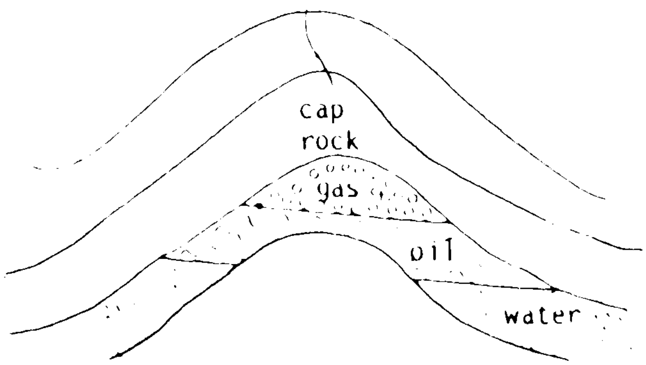


Fig. A.4.1 Anticline Trap

2. Fault: A reservoir rock being cut off at its upper end by a fault which seals the rock.

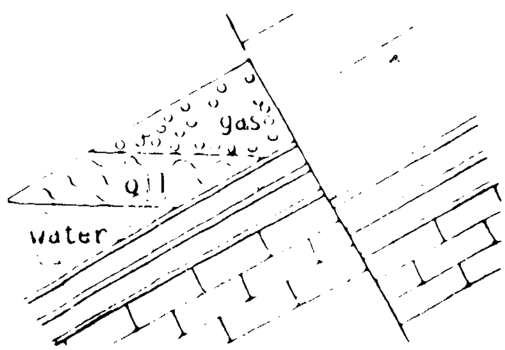


Fig. A.4.2 Fault Trap

3. Unconformity: A layer of say sandstone lying on a layer of limestone forms an unconformity; a surface separating two rocks.

4. Reef: A trap made up of the skeletal remains of marine animals.

There are also combination and other stratigraphic traps.Information on the traps are obtained from Hobson,G. D. and Pohl,W. (1973) and Langenkam.R.D. (1982).

Appendix (B)

Rules for the Three Stages

This appendix is divided into three sections presenting the rules for the stages of the process as follows:

B.1 Sensing;

B.2 Learning;

B.3 Solving;

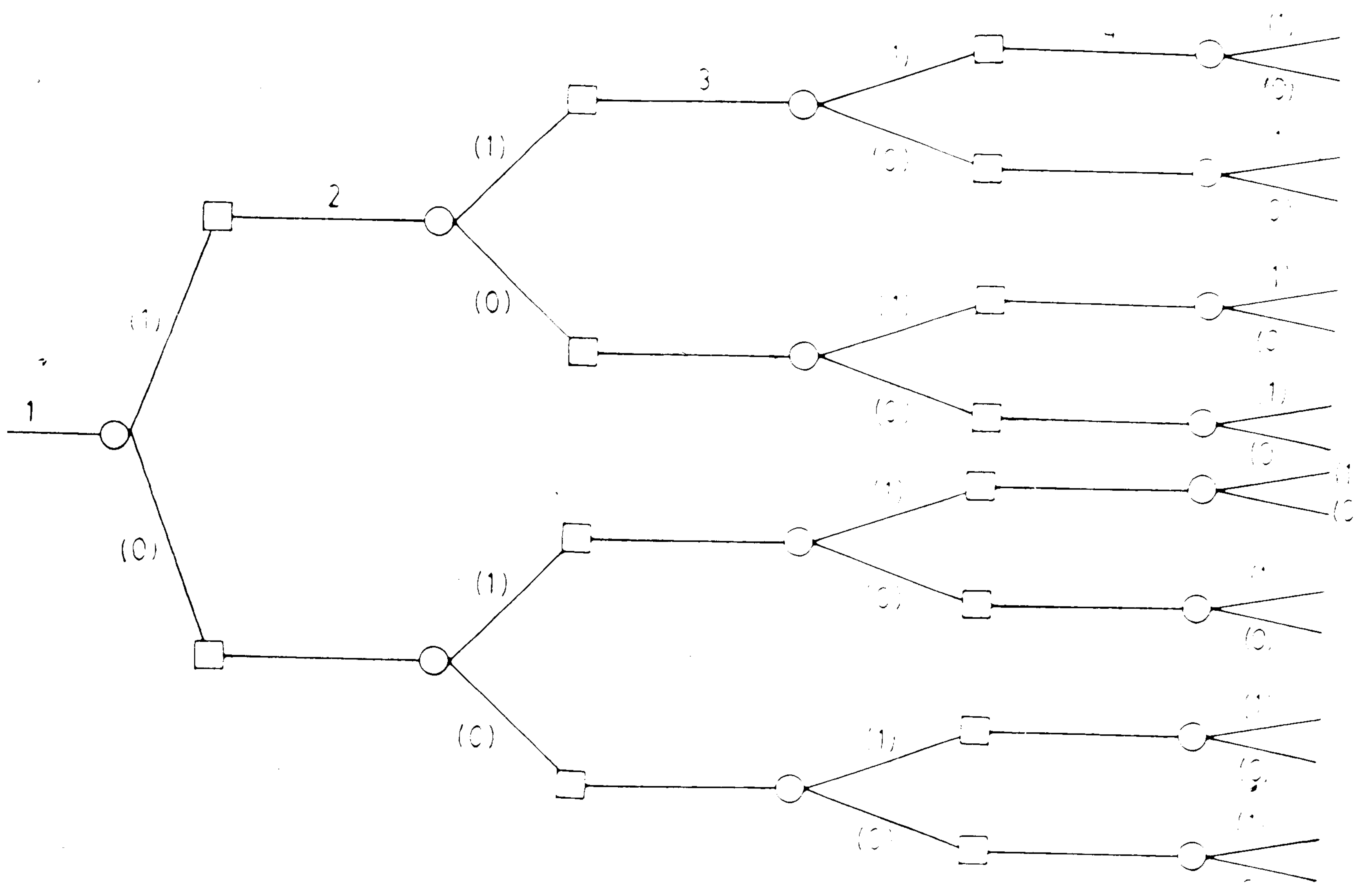
B.1 Sensing

There are 26 rules for this stage. The last rule(26) is a special case where no capital resources are spent allowing random drilling at the second stage if desired.

Rule	Description
1	Do all the surveys
2	Stop if there is a -ve signal(0)
3	1st or 3rd survey is 0
4	1st survey is 0
5	1st or 2nd survey is 0
6	2nd survey is 0
7	3rd survey is 0
8	1st & 2nd surveys are 0
9	1st & 3rd surveys are 0

10	Stop if 1st survey is 0 or 1st survey is 1 and the next two surveys are 0
11	Stop if the first three surveys are 0
12	Do not do the 1st survey
13	4th
14	3rd
15	2nd
16	first two surveys
17	last two surveys
18	1st & 4th surveys
19	2nd & 4th surveys
20	2nd & 3rd surveys
21	first three surveys
22	Do only the 1st survey
23	3rd
24	2nd
25	Do not do the 1st & 3rd surveys
26	Do not do any surveys at stage 1

The following figures are the decision tree diagrams for the first eleven rules. These diagrams help see the rules clearly and also the possible states (sensed characteristics) as a result of these rules.


1
2
3
(1)
(0)
(1)
(0)
(1)
(0)

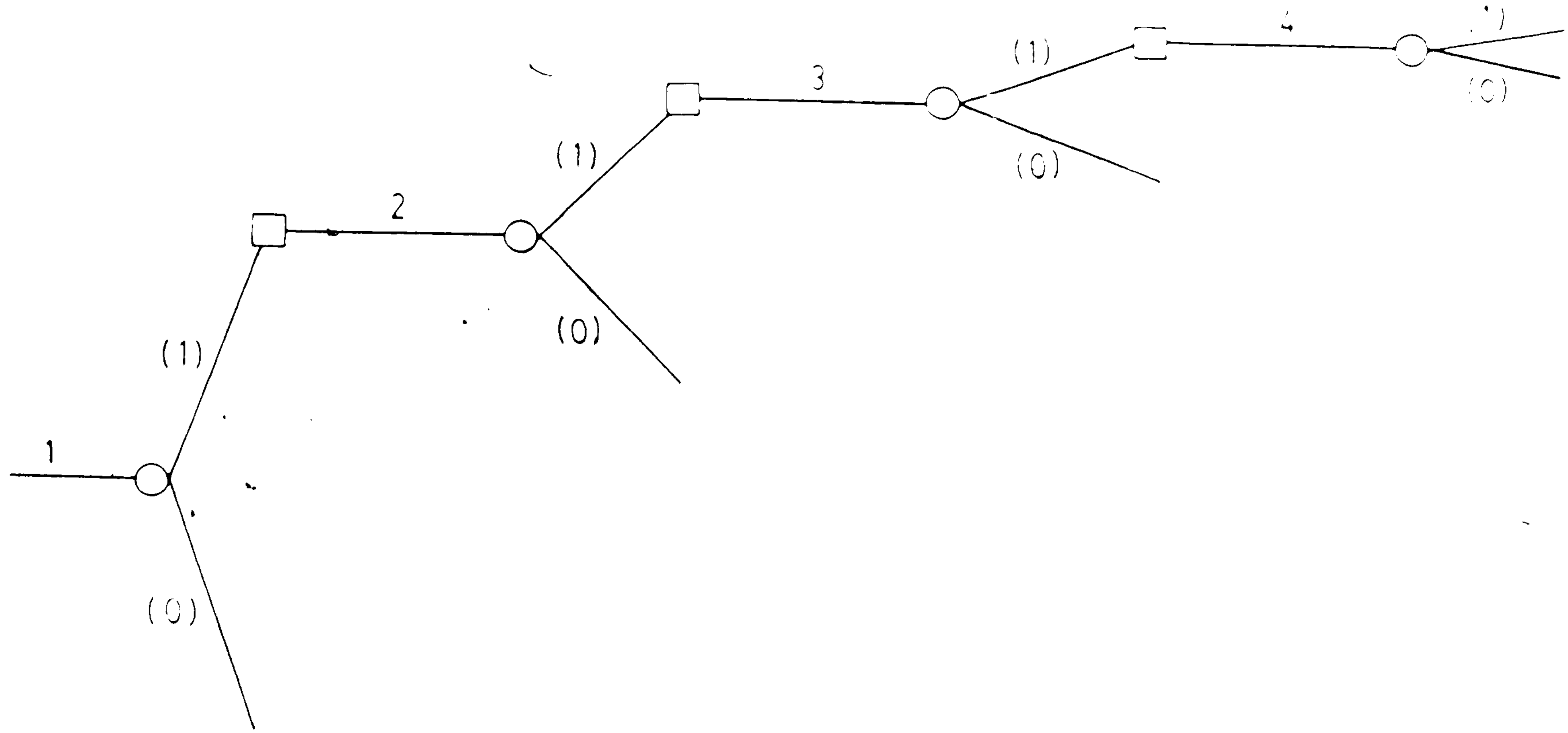


Fig. B.1.2 Rule 2 - Sensing Stage

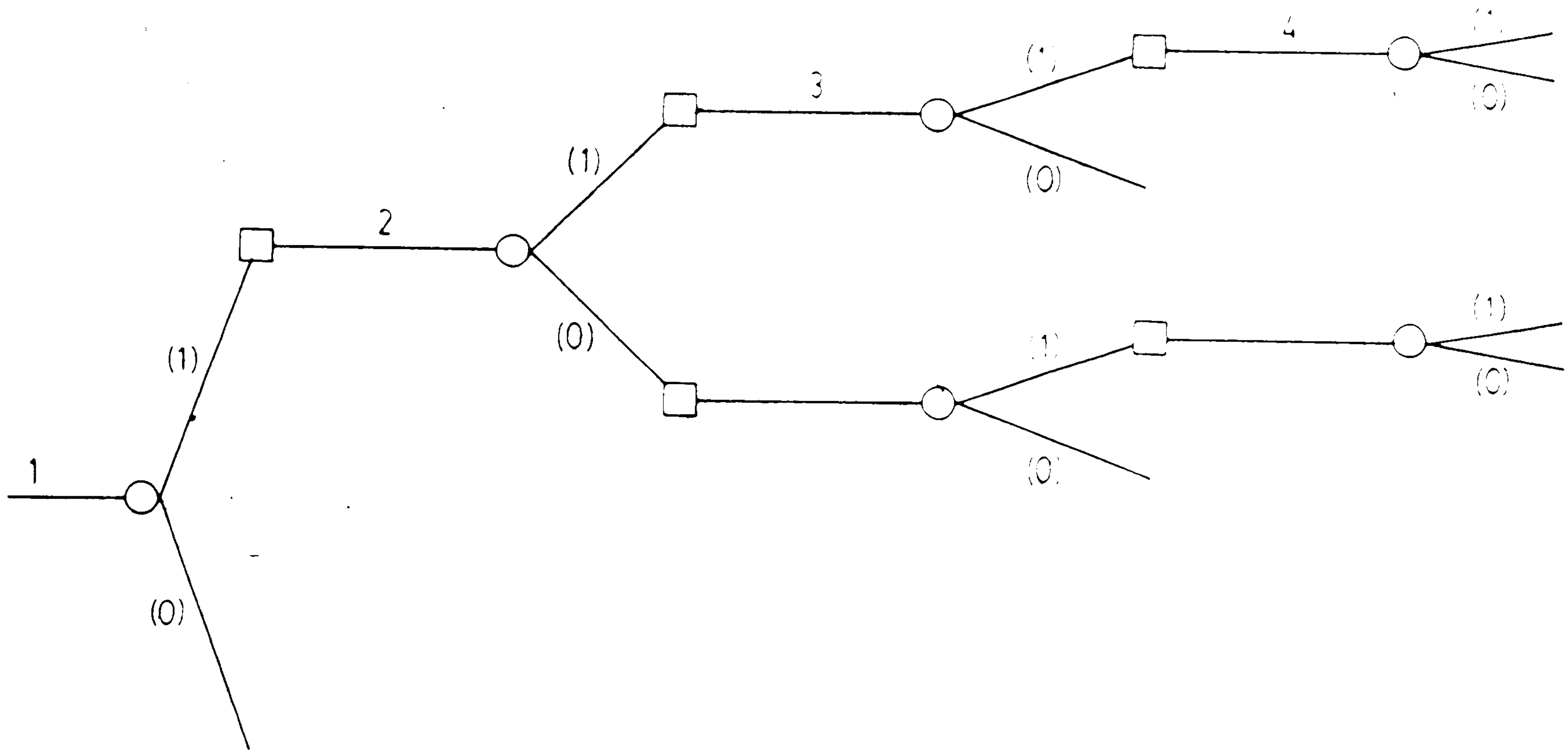


Fig. B.1.3 Rule 3 - Sensing Stage

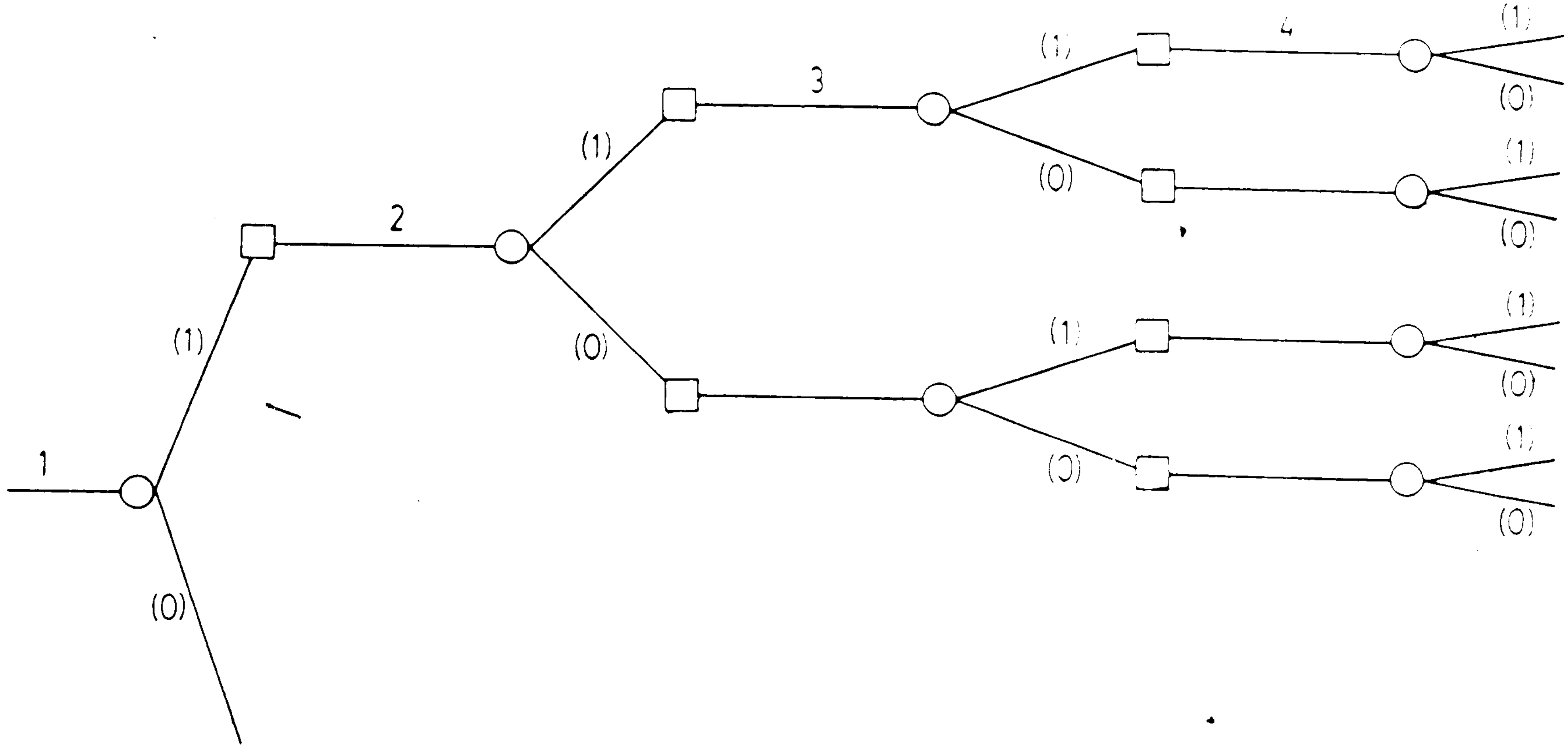


Fig. B.1.4 Rule 4 - Sensing Stage

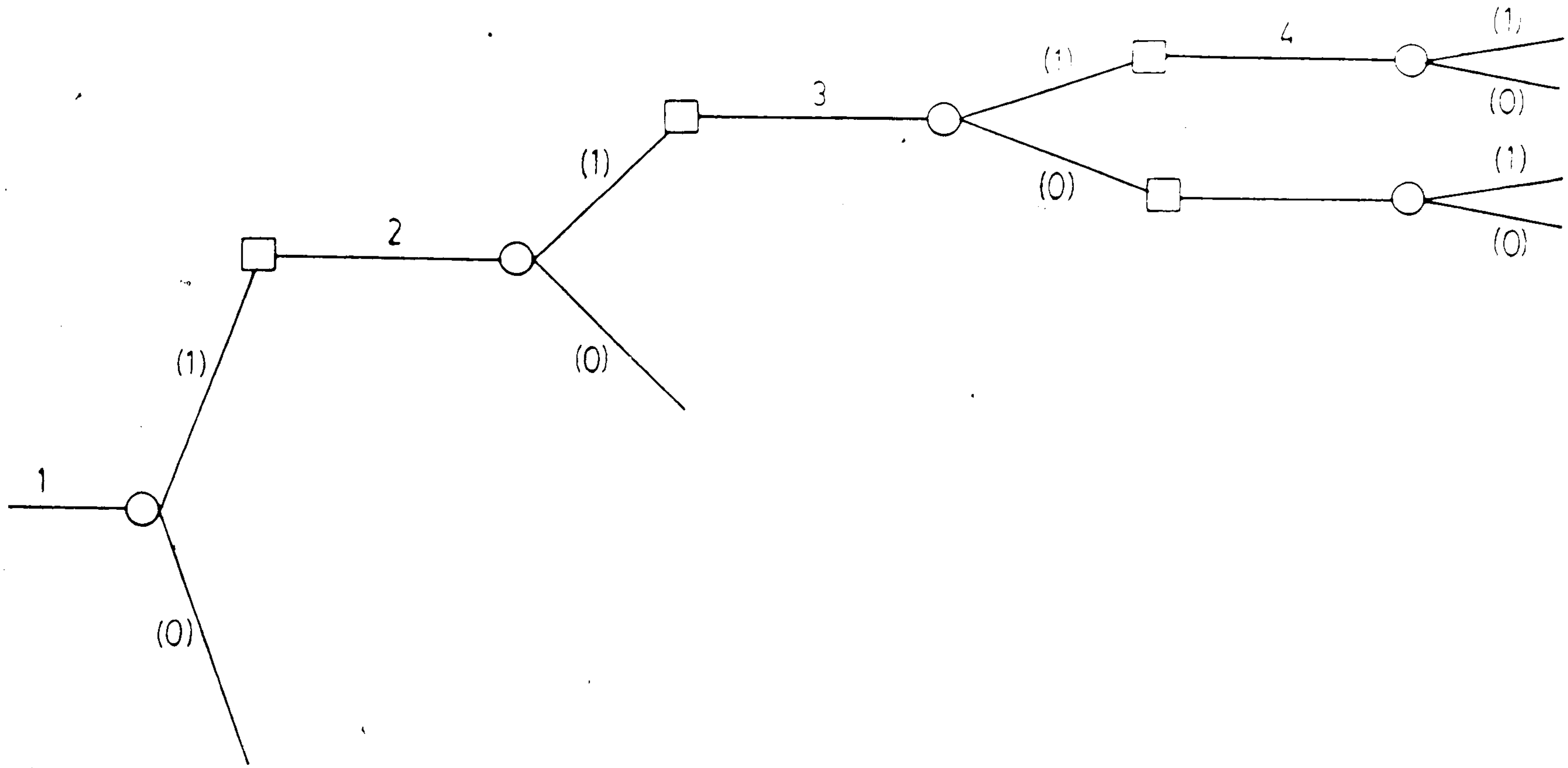


Fig. B.1.5 Rule 5 - Sensing Stage

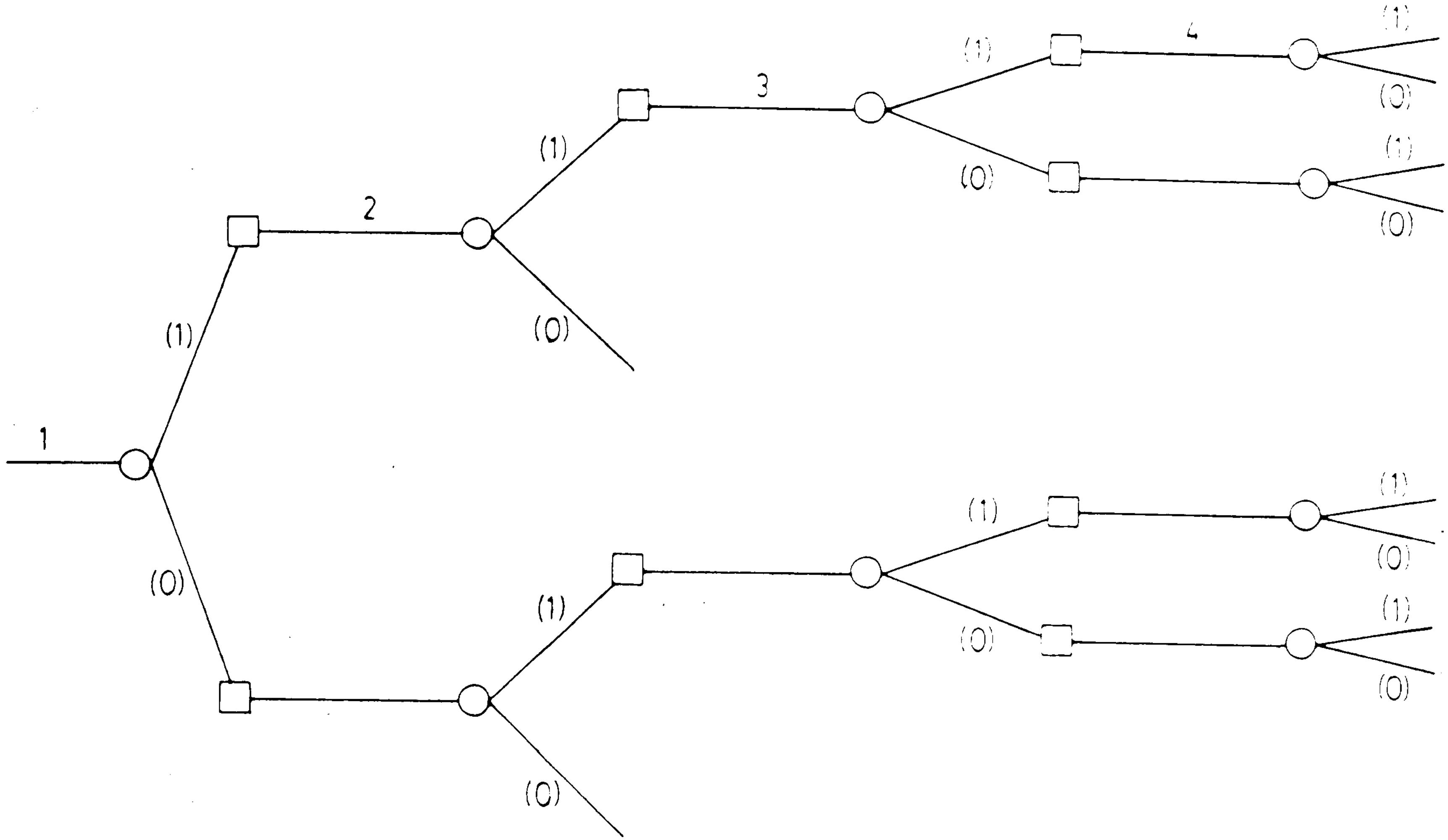


Fig. B.1.6 Rule 6 - Sensing Stage

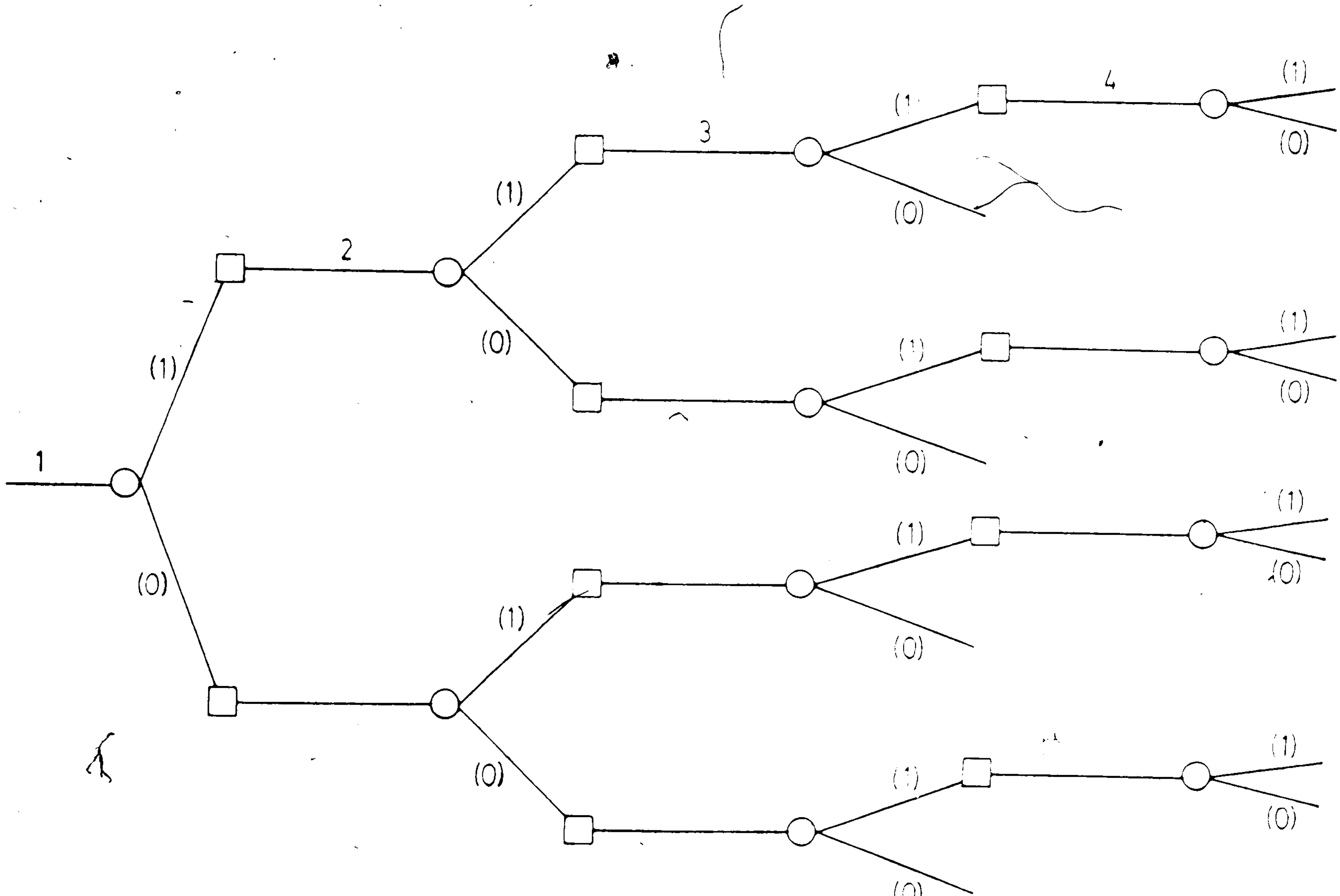


Fig. B.1.7 Rule 7 - Sensing Stage

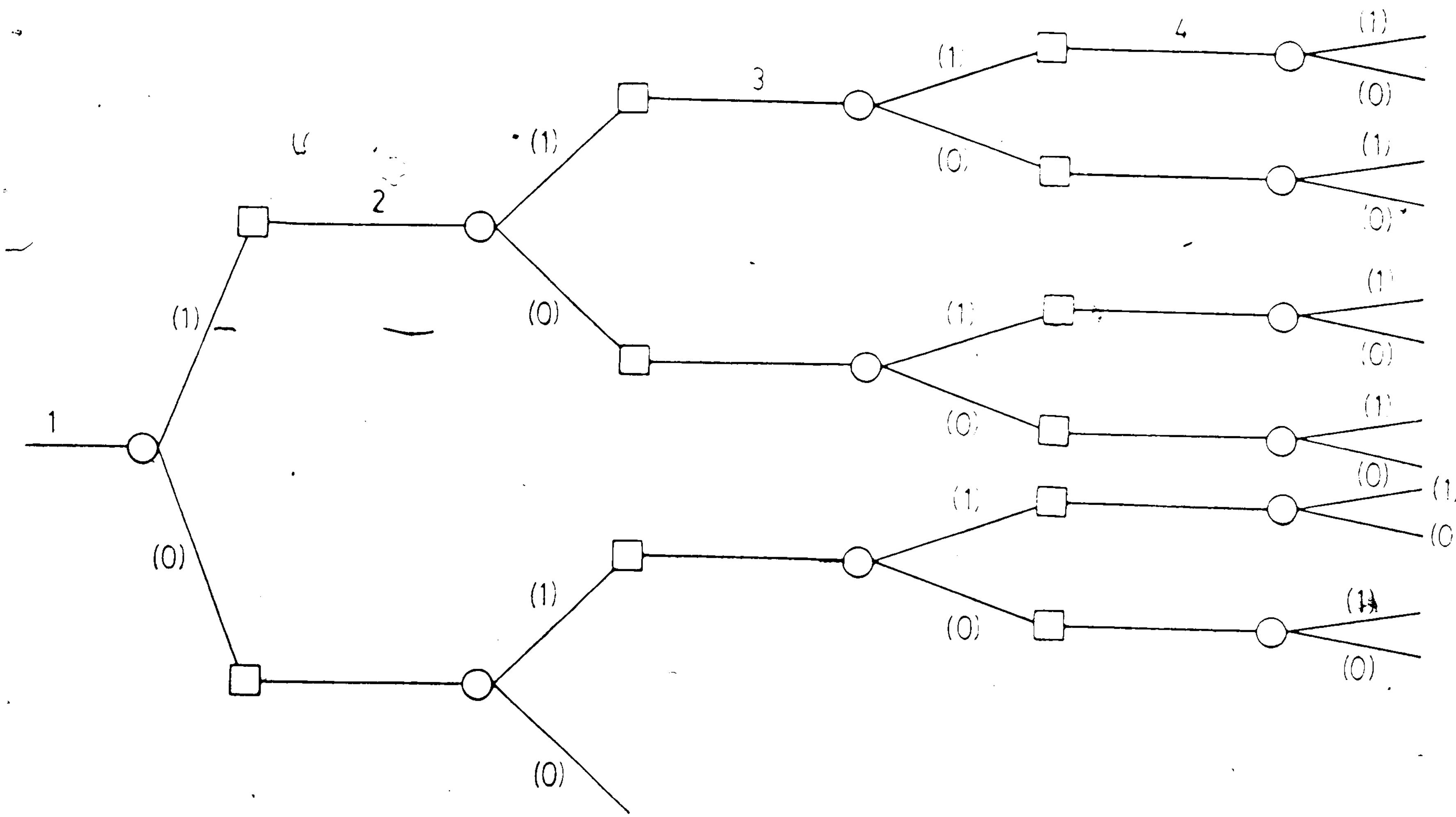


Fig. B.1.8 Rule 8 - Sensing Stage

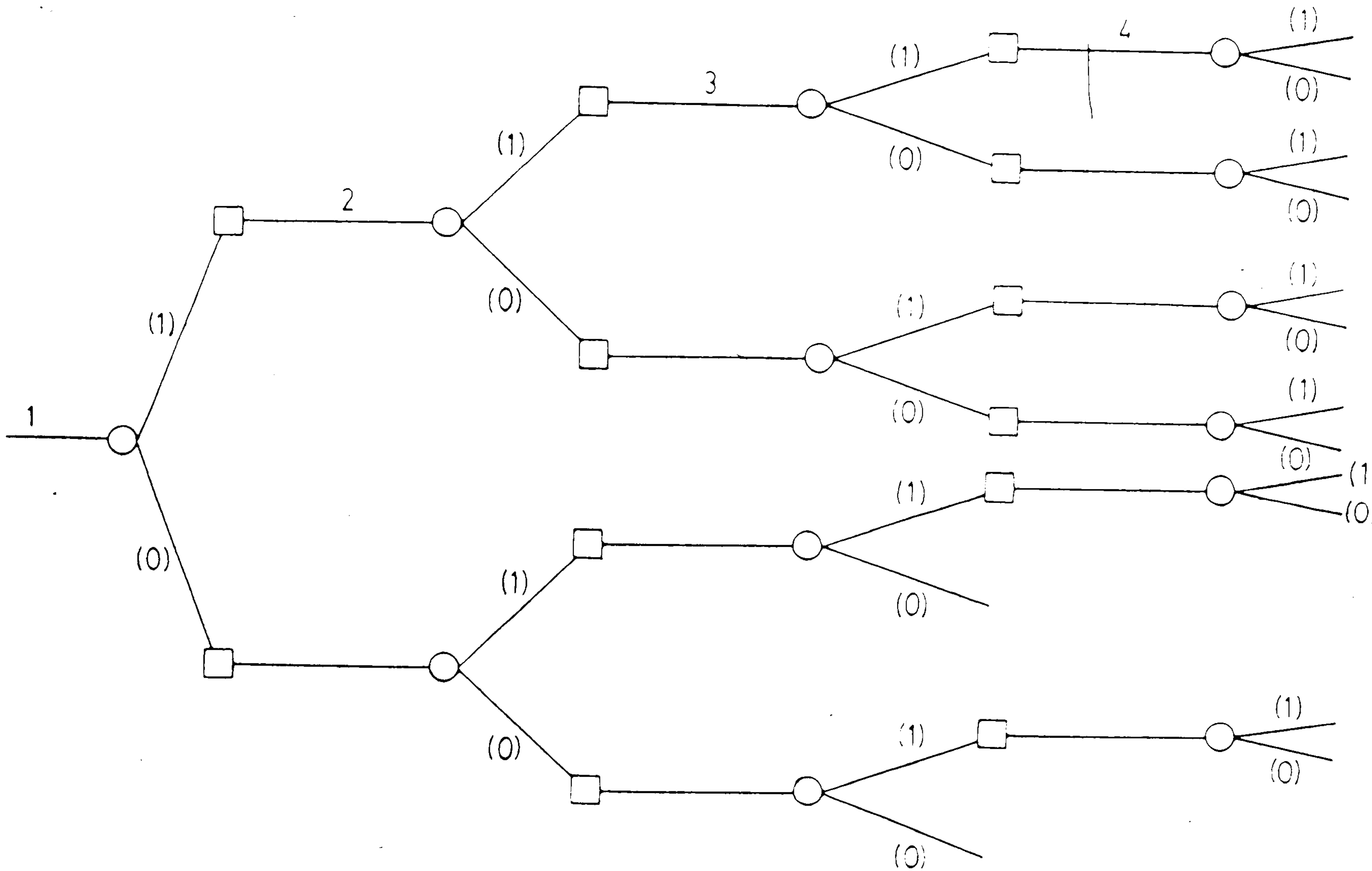


Fig. 8.1.9   Rule 9 - Sensing Stage

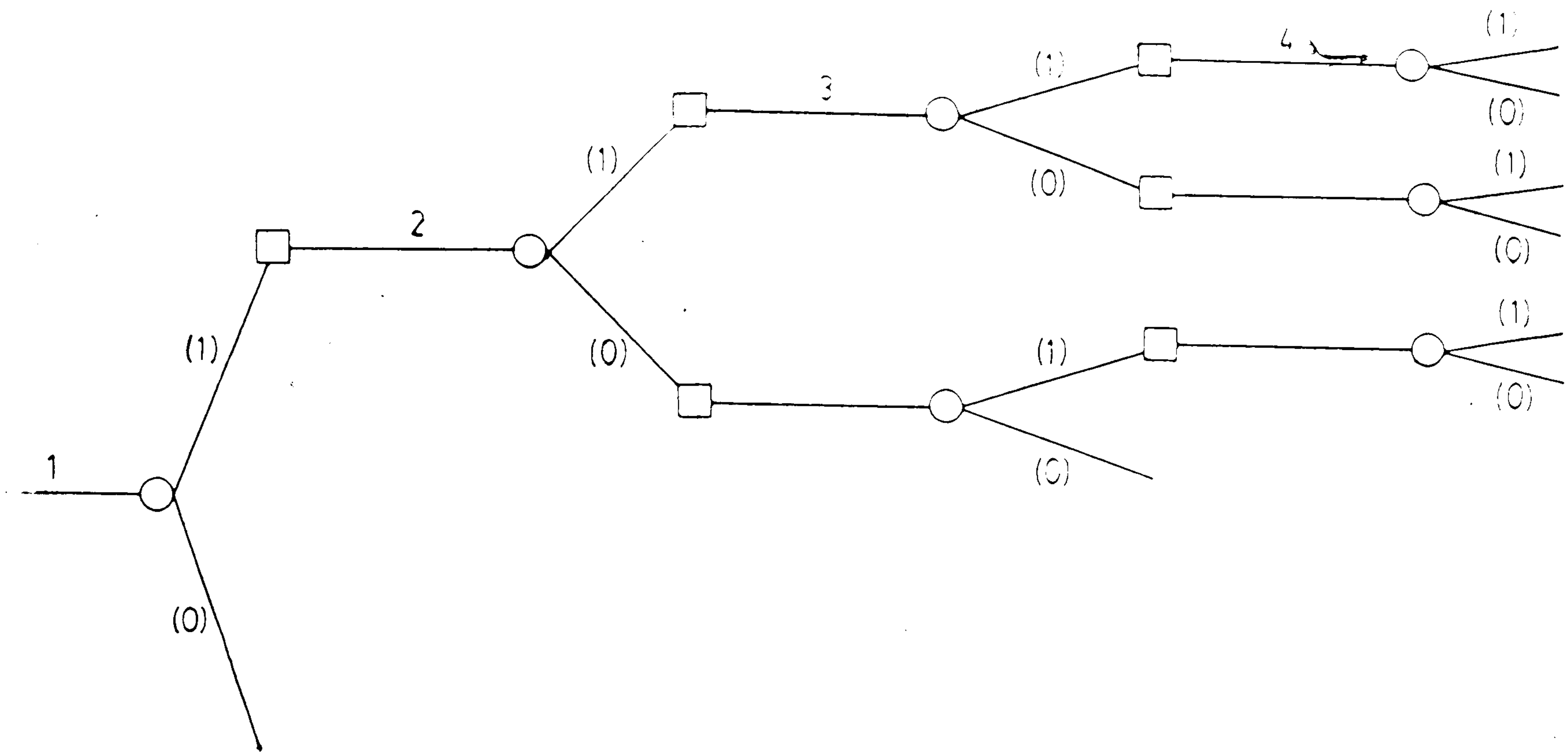


Fig. B.1.10 Rule 10 - Sensing Stage

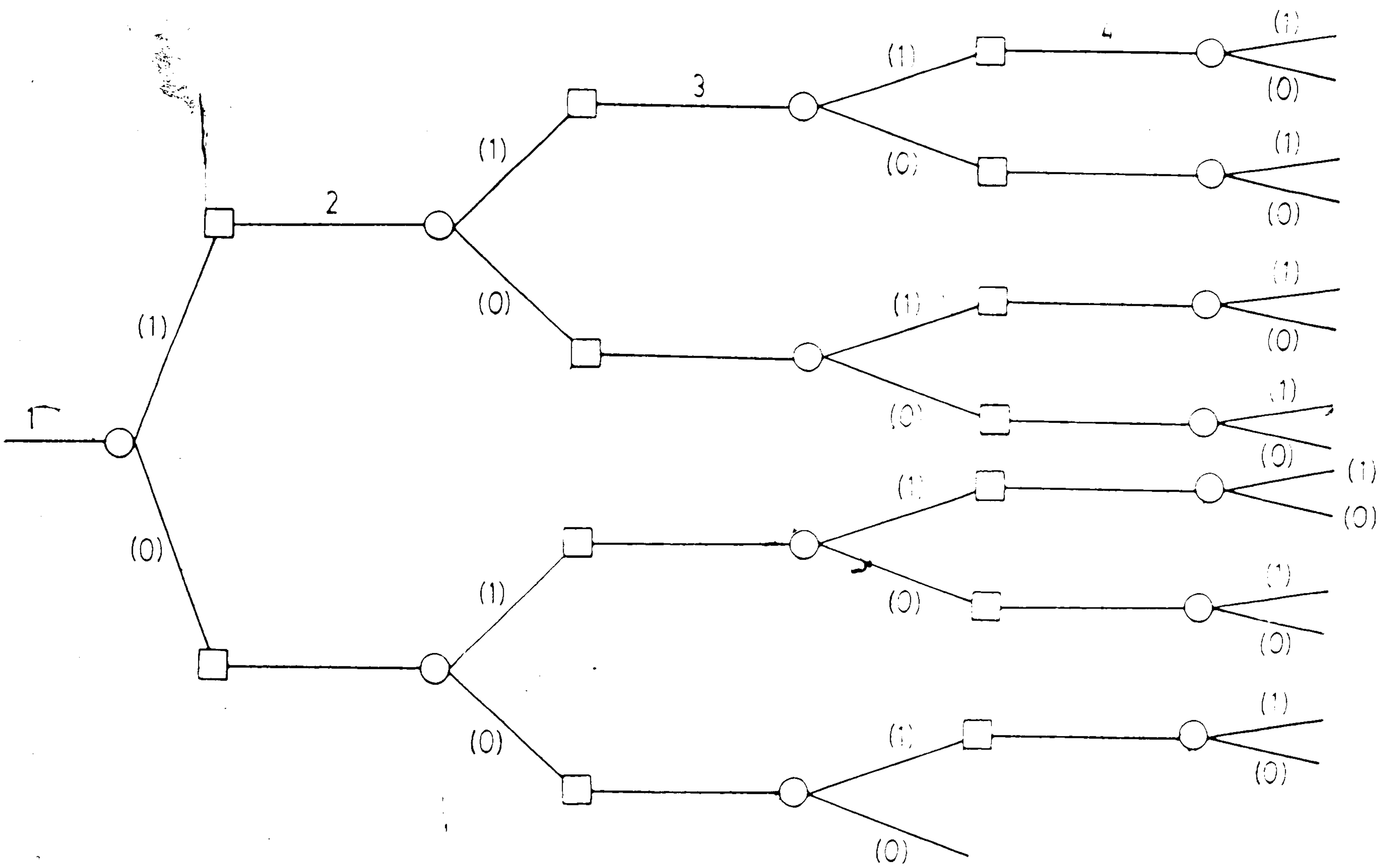


Fig. B.[illegible] Rule [illegible] - Sensing Stage

B.2 Learning

There are 15 rules for this stage as tabulated below. All the possible combinations of the four surveys resulting in a positive signal(1) is considered. The operator makes the selection of prospects for wildcat drilling according to these rules. Rule 15 is a special case and can only be used if rule 26 is used for the first stage. This rule enables the operator to carry out the random drilling of the area.

In the following table, b(g) is the signal from survey g.

Rule	Drill if			
r_Y	b(1)	b(2)	b(3)	b(4)
1				1
2			1	
3		1		
4	1			
5	1	1		
6	1		1	
7	1			1
8		1	1	
9		1		1

10			1	1
11	1	1	1	
12	1	1		1
13		1	1	1
14	1	1	1	1
15	Random dilling of the area			

B.3 Solving

There are two sets of rule for this stage, depending if seismic is done. These rules are a function of the outcome of the learning stage,the observed characteristics c, for c=1,2 indicating the discovery of oil but with poor or good resrevoir properties,respectively.

The first set, with seismic

Rule r_Z	Do seismic if c
1	1
2	2
3	1 & 2

The outcome of seismic is summarized as the size of the trap. It is assumed that only large traps may contain large oil deposits hence, appraisal drilling is done for

Large traps only.

The second set, without seismic

Rule	Do Appraisal drilling if
r_2	0
1	1
2	2
3	1 & 2

Appendix (C)

Table of the Actual Characteristics,a-A

T:Trap, O:Positive Surface indications, L:Large, S:Small c:Reservoir Properties...0 (No Oil Deposit), 1 (Poor, Oil Deposits), 2 (Good, Oil Deposits). Aerial Photography can detect surface indications and trap may be detected by Magnetic, Gravity and Seismic surveys.

a	T &/or O	c	Size of the Deposits	Size of the Trap
1	O&T	1	S	S
2	O&T	1	S	L
3	O&T	0	0	S
4	O&T	0	0	L
5	O&T	2	S	S
6	O&T	2	L	L
7	O	0	0	0
8	T	1	S	S
9	T	1	S	L
10	T	0	0	S
11	T	0	0	L
12	T	2	S	S
13	T	2	L	L
14	NONE	0	O	0
15	O&T	1	L	L
16	T	1	L	L
17	O&T	2	S	L

Appendix (D)

List of the Sensed Characteristics, b/B

	Signal from Survey			
b	1	2	3	4
1	0	0	0	0
2	0	0	0	1
3	0	0	0	2
4	0	0	1	0
5	0	0	1	1
6	0	0	1	2
7	0	0	2	0
8	0	0	2	1
9	0	0	2	2
10	0	1	0	0
11	0	1	0	1
12	0	1	0	2
13	0	1	1	0
14	0	1	1	1
15	0	1	1	2
16	0	1	2	0
17	0	1	2	1
18	0	1	2	2
19	0	2	0	0
20	0	2	0	1

21	0	2	0	2
22	0	2	1	0
23	0	2	1	1
24	0	2	1	2
25	0	2	2	0
26	0	2	2	1
27	0	2	2	2
28	1	0	0	0
29	1	0	0	1
30	1	0	0	2
31	1	0	1	0
32	1	0	1	1
33	1	0	1	2
34	1	0	2	0
35	1	0	2	1
36	1	0	2	2
37	1	1	0	0
38	1	1	0	1
39	1	1	0	2
40	1	1	1	0
41	1	1	1	1
42	1	1	1	2
43	1	1	2	0
44	1	1	2	1
45	1	1	2	2
46	1	2	0	0
47	1	2	0	1

48	1	2	0	2
49	1	2	1	0
50	1	2	1	1
51	1	2	1	2
52	1	2	2	0
53	1	2	2	1
54	1	2	2	2
55	2	0	0	0
56	2	0	0	1
57	2	0	0	2
58	2	0	1	0
59	2	0	1	1
60	2	0	1	2
61	2	0	2	0
62	2	0	2	1
63	2	0	2	2
64	2	1	0	0
65	2	1	0	1
66	2	1	0	2
67	2	1	1	0
68	2	1	1	1
69	2	1	1	2
70	2	1	2	0
71	2	1	2	1
72	2	1	2	2
73	2	2	0	0
74	2	2	0	1

75	2	2	0	2
76	2	2	1	0
77	2	2	1	1
78	2	2	1	2
79	2	2	2	0
80	2	2	2	1
81	2	2	2	2

Appendix (E)

Proofs of the Theorems and More Results from Chapter 4

E.1 Proofs of the Theorems

E.1.1 Maximum One Target per Subspace

a) Allocating z_{ij} to j

THEOREM 1

I. Batch

The Kuhn-Tucker conditions are:

1. $p_{ij} \, f_{D_{ij}}(z_{ij}) - u \le 0$

2. $z_{ij}[p_{ij} \, f_{D_{ij}}(z_{ij}) - u] = 0$

3. $\sum_i \sum_j z_{ij} - R \le 0$

4. $u(\sum_i \sum_j z_{ij} - R) = 0$

5. $z_{ij} \ge 0$

6. $u \ge 0$

For $z_{ij} > 0$

$$p_{ij} \, f_{D_{ij}}(z_{ij}) - u = 0$$

multiplying by $\{[1-F_{D_{ij}}(z_{ij})]/[1-F_{D_{ij}}(z_{ij})]\}[1/p(H)]$

results in:

$$\{[1-F_{D_{ij}}(z_{ij})]p_{ij}/P(H)\} \, f_{D_{ij}}(z_{ij})/[1-F_{D_{ij}}(z_{ij})] = u/p(H)$$

$$\bar{p}_{ij}\ \delta_{ij} = u/p(H)$$

$$\bar{\delta}_{ij}(z_{ij}) = u/p(H)$$

where $\bar{\delta}_{ij}(z_{ij})$ is the unconditional detection rate for target i in subspace j.

THEOREM 2

II. Sequential

The Kuhn-Tucker conditions:

1. $p_{ij}\ f_{D_{ij}}(z_{ij}) - u[1 - F_{D_{ij}}(z_{ij})] \leq 0$

2. $z_{ij}\{p_{ij}\ f_{D_{ij}}(z_{ij}) - u[1 - F_{D_{ij}}(z_{ij})]\} = 0$

3. $\{\sum_{ij}\sum[\int_0^{z_{ij}} z f_D(z)dz] + z_{ij}[1 - F_{D_{ij}}(z_{ij})]\} - R \leq 0$

4. $u[\{\sum_{ij}\sum[\int_0^{z_{ij}} z f_D(z)dz] + z_{ij}[1 - F_{D_{ij}}(z_{ij})]\} - R] = 0$

5. $z_{ij} \geq 0$

6. $u \geq 0$

For $z_{ij} > 0$

$$[p_{ij}\ f_{D_{ij}}(z_{ij})]/[1 - F_{D_{ij}}(z_{ij})] = u$$

$$p_{ij}\ \delta_{ij}(z_{ij}) = u.$$

b) Allocating z_j to j

THEOREM 3

I. Batch

The Kuhn-Tucker conditions:

1. $p_j \; f_{D_j}(z_j) - u \le 0$

2. $z_j \; [p_j \; f_{D_j}(z_j) - u] = 0$

3. $\sum_j z_j - R \le 0$

4. $u(\sum_j z_j - R) = 0$

5. $z_j \ge 0$

6. $u \ge 0$

For $z_j > 0$

$$p_j \; f_{D_j}(z_j) - u$$

Multiply by $\{[1-F_{D_j}(z_j)]/p(H)\} \; 1/[1-F_{D_j}(z_j)]$

hence,

$$\{p_j \; [1-F_{D_j}(z_j)]/p(H)\} \; \{f_{D_j}(z_j)/[1-F_{D_j}(z_j)]\} = u/p(H)$$

$$\bar{p}_j \; \delta_j(z_j) = u/p(H)$$

$$\bar{\delta}_j(z_j) = u/p(H)$$

where $\bar{\delta}_j(z_j)$ is the unconditional detection rate in j.

THEOREM 4

II. Sequential

Kuhn-Tucker conditions:

1. $p_j f_{D_j}(z_j) - u[1-F_{D_j}(z_j)] \le 0$

2. $z_j\{p_j f_{D_j}(z_j) - u[1-F_{D_j}(z_j)]\} = 0$

3. $\{\sum_j [\int_0^{z_j} z f_D(z)\,dz] + z_j[1-F_{D_j}(z_j)]\} - R \le 0$

4. $u[\{\sum_j [\int_0^{z_j} z f_D(z)\,dz] + z_j[1-F_{D_j}(z_j)]\} - R] = 0$

5. $z_j \ge 0$

6. $u \ge 0$

For $z_j > 0$

$$[p_j f_{D_j}(z_j)]/[1-F_{D_j}(z_j)] = u$$

or

$$p_j \delta_j(z_j) = u \quad .$$

E.1.2 Multiple Targets per Subspace

a) Allocating z_{ij} to j

THEOREM 5

I. Batch

The Kuhn-Tucker conditions:

1. $p_{ij} f_{D_{ij}}(z_{ij}) - u \le 0$

2. $z_{ij}[p_{ij} f_{D_{ij}}(z_{ij}) - u] = 0$

3. $\Sigma\Sigma\, z_{ij} - R \le 0$

4. $u[\sum\sum_{ij} z_{ij} - R] = 0$

5. $z_{ij} > 0$

6. $u > 0$

For $z_{ij} > 0$

$$p_{ij} \; f_{D_{ij}}(z_{ij}) = u$$

Multiply by $\{[1-F_{D_{ij}}(z_{ij})]/[1-F_{D_{ij}}(z_{ij})]\}$ $1/[1-\sum_j p_{ij} \; F_{D_{ij}}(z_{ij})]$

$$\{p_{ij} \; [1-F_{D_{ij}}(z_{ij})]/[1-\sum_j p_{ij} \; F_{D_{ij}}(z_{ij})]\} \; f_{D_{ij}}(z_{ij})/[1-F_{D_{ij}}(z_{ij})] =$$

$$u/[1-\sum_j p_{ij} \; F_{D_{ij}}(z_{ij})] \quad \ldots (E.1)$$

But $1-\sum_j p_{ij} \; F_D(z_{ij}) = 1-F_{D_i}(z_i)$

where z_i is the capital resource allocated to detect target i. Hence, equation (E.1) becomes:

$$\bar{p}_{ij} \; \delta_{ij}(z_{ij}) = u/[1-F_{D_i}(z_i)] \quad \ldots (E.2)$$

$$\bar{\delta}_{ij}(z_{ij}) = u/[1-F_{D_i}(z_i)] \quad \ldots (E.3)$$

Also,

$$\delta_i(z_i) \; dz_i = \sum_j p_{ij} \; \delta_{ij}(z_{ij}) \; dz_{ij}$$

using equation (E.2)

$$\delta_i(z_i) \; dz_i = \{u/[1-F_{D_i}(z_i)]\} \sum_j dz_{ij} \quad \ldots (E.4)$$

But

$$\sum_j dz_{ij} = dz_i$$

Hence, (E.4) is simplified to:

$$\delta_i(z_i) = u/[1-F_{D_i}(z_i)] \qquad \ldots(E.5)$$

which gives the result:

$$u = f_{D_i}(z_i)$$

also, comparing (E.3) and (E.5) suggests that:

$$\delta_i(z_i) = \bar{\delta}_{ij}(z_{ij}).$$

The Kuhn-Tucker conditions for each of the following problems are the same as the problem of maximum one target per subspace, when similar allocations are made.

THEOREM 6

II. Sequential

$$[p_{ij}\ f_{D_{ij}}(z_{ij})]/[1-F_{D_{ij}}(z_{ij})] = u$$

$$p_{ij}\ \delta_{ij}(z_{ij}) = u.$$

b) Allocating z_j to j

THEOREM 7

I. Batch

For $z_j>0$

$$p_j\ f_{D_j}(z_j) = u$$

Multiplying by

$$[1-F_{D_j}(z_j)]/[\sum_j p_j(1-F_D(z_j)] \quad 1/[1-F_{D_j}(z_j)]$$

gives

$$(p_j \; [1-F_{D_j}(z_j)]/[\sum_j p_j(1-F_D(z_j)] \quad f_{D_j}(z_j)/[1-F_{D_j}(z_j)]=$$

$$u/[\sum_j p_j \; (1-F_{D_j}(z_j)]=$$

$$u', \; (\text{a constant})$$

$$\bar{p}_j \; \delta_j(z_j) = u'$$

Also,

$$\delta(R) \; dR = \sum_j p_j \; \delta_j(z_j)dz_j$$

$$= \bar{\delta}_j(z_j)dR$$

resulting in:

$$\delta(R) = \bar{\delta}_j(z_j).$$

THEOREM 8

II. Sequential

$$[p_j \; f_{D_j}(z_j)]/[1-F_{D_j}(z_j)] = u$$

$$p_j \; \delta_j(z_j) = u.$$

E.2 Remaining Results from Chapter 4 and Their Proofs

Table 4.1 shows that E(N)/I is repeated when δ_j and δ_j/I are used for a given problem, after I cycles, for example:

for J (subspaces)=2, I (targets)=2, after 2 cycles,

for J=3, I=2, after 2 cycles,

for J=3, I=3, after 3 cycles.

This can be proved by expanding the function E(N)/I when the number of targets is less than or equal to the number of subspaces, i.e., $J>I$:

$E(N)/I=$

$$(1/I)\{p_1[1-\exp(-\delta_1 z_1/I)]+\ldots+p_J[1-\exp(-\delta_J z_J/I)]\}$$
$$=1-(1/I)\{p_1[\exp(-\delta_1 z_1/I]+\ldots+p_J[\exp(-\delta_J z_J/I)]\}$$

.....(E.1)

where $z_1+z_2+\ldots+z_J=R$

or $z_1/I + z_2/I +\ldots+ z_J/I=R/I$.

Now, if δ_j is used for a total resources of $R'=R/I$,

$E(N)/I=$

$$1-(1/I)\{p_1[\exp(-\delta_1 z_1'+\ldots+p_J[\exp(-\delta_J z_J')]\} \quad \ldots(E.2)$$

where $z_1'+\ldots+z_J'=R'$.

Hence, E(N)/I from equations (E.1) and (E.2) are the same if $z_j'= z_j$ and $R'=R/I$. The functions for δ_j and δ_j/I will therefore repeat after I cycles (a function of the number of targets). If the number of targets and subspaces are the same, then the priors $p_j=1/J$ for all j and the proof is similar.

Further investigation of Table 4.1 shows that E(N)/I (using δ_j/I) is less than that when δ_j is used. This result is evident from previous finding where E(N)/I, using δ_j repeats after I cycles or when the capital total resource is increased by the factor I. As the total capital resource increases $E(N)/I$ becomes larger, hence:

$$E(N)/I\ [\text{using } \delta_j/I] < E(N)/I\ [\text{using } \delta_j]$$

for any level of total capital resource.

These results show that the lowest value of $E(N)/I$ is obtained when there are I J targets and the detection rate is δ_j/I, the largest value of $E(N)/I$ is when there is only one target.

Table 4.5 shows that:

$E_2(N)/2$ [using $\delta_j/2$ and the total resource of R'] is equal to $E_6(N)/6$ [using $\delta_j/6$ and total capital resource of 3R).

To prove this assume that $I > I'$, then the expansion of $E(N)/I$ results in:

$E(N)/I=$

$$(1/I)\{p_1[1-\exp(-\delta_1 z_1/I)]+\ldots+p_J[1-\exp(-\delta_J z_J/I)]\}$$

but the priors are equal and have the value of I/J:

$E(N)/I=$

$$(1/J)\{J-[\exp(-\delta_1 z_1/I)+\ldots+\exp(-\delta_J z_J/I)]\}\ldots\ldots(E.3)$$

Also,

$E(N)/I'=$

$$(1/J)\{J-[\exp(-\delta_1 z_1'/I')+\ldots+\exp(-\delta_J z_J'/I')]\}\ldots(E.4)$$

but

$$z_1/I+z_2/I+\ldots=R/I \text{ and } z_1'/I'+z_2'/I'+\ldots=R'/I'$$

therefore, (E.3) and (E.4) are the same and:

$z_j/I=z_j'/I'$, $R/I=R'/I'$ or $R'=(I'/I)R$. For example, if $I'=2$ and $I=6$, then $R'=(2/6)R$ or $R=3R'$.

The last result is from Table 4.6, where:

$E_6(N)/6$ [when $J=I=6, p_{ij}=1/6$ and $\delta_{ij}=.1$] is equal to $E_6(N)/6$ [when $J=1, I=6, p_{i1}=1, \delta_1=.1/6$], for a given total resource. The proof follows:

Let $J>J'=1$, then for J subspaces,

$$E(N)/I=(1/I)\{\sum_{i,j} p_{ij}[1-\exp(-\delta_{ij}z_{ij})]\}$$

or

$$E(N)/I=(1/I)\{p_{11}[1-\exp(-\delta_1 z_{11})]+\ldots+p_{I1}[1-\exp(-\delta_1 z_{I1})]$$
$$+p_{12}[1-\exp(-\delta_2 z_{12})]+\ldots+p_{I2}[1-\exp(-\delta_2 z_{I2})]$$
$$\ldots$$
$$+p_{IJ}[1-\exp(-\delta_J z_{IJ})]\}$$

but $p_{ij}=1/J$ and $\delta_{ij}=\delta$, for all i and j, therefore, $z_{ij}=z$ and the above equation reduces to:

$$E(N)/I=1-\exp(-\delta z). \qquad \ldots\ldots\ldots\ldots(E.5)$$

The expression when there is $J'=1$ subspace is:

$$E(N)/I=(1/I)\{\sum p_{i1}[1-\exp(-\delta_1 z_{i1})]\}$$

but all the priors are equal to 1, the z_{i1} are the same, hence, $E(N)/I = (1/I)\ \{\ I\ [1-\exp(-\delta_1 z_{i1})]\ \}$

but $\delta_1=\delta/J$, hence,

$$E(N)/I=[1-\exp(-\delta z_{i1}/J)] \qquad \ldots\ldots\ldots\ldots(E.6)$$

Now, for many subspaces, $\sum\sum_{ij} z_{ij}=R$, but z_{ij} are equal to z, hence, I.J.z=R, or z=R/(I.J). Also, in the case of one subspace, $\sum_i z_{i1}=R$ or $Iz_{i1}=R$, or $z_{i1}=R/I$.

Now, substituting z into (E.5) and z_{i1} into (E.6) gives the same equation, i.e.,

$$E(N)/I \quad 1-\exp\{-sR/(I.J)\}$$

so the $E(N)/I$ from (E.5) is the same as that from (E.6).

```
1  REM                                    Appendix (F)
2  REM                             List of the Computer Programs
3  REM
4  REM
10 REM    F.1 Main Program
30 REM
40 REM
50 REM         ****************************************************************
               *                                                              *
               *                                                              *
60 REM         * This program simulates the petroleum exploration process. The *
               * process has been divided into 3 stages: Sensing, Learning, and *
               * Solving. The activities of each stage are: Surveys (1st  stage)*
70 REM         * wildcat drilling (2nd. stage),appraisal drilling and estimating*
               * the size of the oil deposit (3rd  stage). The outcome of the   *
               * analysis is the expected number of prospects considered for    *
80 REM         * develpoment drilling.                                          *
90 REM         *                                                              *
               ****************************************************************
100 REM
110 DIM X(4),F(4,3),A(20,20),N(4,3),P(81,26),B(4),PP(81,26),M(20),RATE(81),TT(81
),ALLO(20,10),Y(10),DOLLAR(81),LC(1),PFO(81,17),OIL(17),RU(15,81),WELL(81),PPP(1
00),APP(10),NNN(81),PB(10)
120 DIM STATE(81),SUM(2),PR(4),POSI(4),NEG(4)
130 DIM OSS1(81),OSS8(81),OSL2(81),OSL9(81),TSS5(81),TSS12(81),TLL6(81),TLL13(81
),OLL15(81),OLL16(81),TSL17(81)
140 DIM OS1(81),OS8(81),OS2(81),OS9(81),TS5(81),TS12(81),TL6(81),TL13(81),OL15(8
1),OS(2),OL(2),TS(2),TL(2)
150 CLS:PRINT "                                PETROLEUM EXPLORATION":PRINT:PRINT:F
OR I=1 TO 80:PRINT "_";:NEXT I
160 REM
170 REM    ***************************
180 REM    * Explaining the program *
190 REM    ***************************
200 REM
210 INPUT "          IF information about the prog. is needed or doing the surveys f
or the 1st  stage type 1,for the 2nd. stage (wildcat drilling) type 2,for the 3r
d  stage   (estimating the size of the oil deposits) type 3";CHOOSE
220 PRINT: FOR I= 1 TO 80:PRINT "_";:NEXT I:PRINT
230 IF CHOOSE =1 THEN 250 ELSE IF CHOOSE=2 THEN 2990 ELSE 240
240 INPUT "Did you do seismic at the 3rd. stage...Type Y or N",SE$:IF SE$="Y" TH
EN 3820 ELSE 4100
250 CLS
260 FOR I= 1 TO 3:PRINT:NEXT I:FOR I= 1 TO 80:PRINT "_";:NEXT I:PRINT
270 PRINT TAB(20) "---------------------------------------------------"
280 PRINT TAB(20) "This program analyses the outcome of the petroleum"
290 PRINT TAB(20) "exploration process in three stages.             "
300 PRINT TAB(20) " The 1st. stage is the general survey stage"
310 PRINT TAB(20) "to learn about the surface and the subsurface of  "
320 PRINT TAB(20) "the area! the second stage is the wildcat drilling"
330 PRINT TAB(20) "and the last stage is the appraisal drilling and  "
340 PRINT TAB(20) "estimating the size of the deposits discovered.   "
350 PRINT TAB(20) "The outcome of each stage is the expected number  "
360 PRINT TAB(20) "of prospects in a certain state. For example, the "
370 PRINT TAB(20) "result of the 2nd. stage is the expected number of"
380 PRINT TAB(20) "prospects which are dry or contain petroleum with "
390 PRINT TAB(20) "good or poor reservoir properties."
400 PRINT TAB(20) "At the end of the computing, a summary of the "
410 PRINT TAB(20) "process is provided if required."
420 PRINT TAB(20) "There is also a data file called DATA5 which "
430 PRINT TAB(20) "provides data for the last two stages.  "
440 PRINT TAB(20) "Both programs are self explanatory and will explain"
```

```
450 PRINT TAB(20) "when to run each program."
460 PRINT TAB(20) "--------------------------------------------------"

470 FOR Q=1 TO 33000!:NEXT Q:C=0:Q=0:CLS
480 REM
490 REM                         *****************
500 REM                         *****************
                                * Sensing stage *
                                *****************
510 REM                         *****************
520 REM
530 PRINT "                                 SENSING STAGE   "
540 FOR I=1 TO 80:PRINT "_";:NEXT I
550 PRINT TAB(20) "The program now erqires the rule for the first stage"
560 PRINT TAB(20) "and the probability of detection for survey s, given"
570 PRINT TAB(20) "the presence of target for that survey. Also, the   "
580 PRINT TAB(20) "resource allocated to each survey is asked here.    "
590 PRINT "     Suveys are : Aerial Photography ....(S=1);
                             Magnetic survey .......(S=2);
                             Gravity survey ........(S=3);
600 PRINT "                & Seismic Reflection ....(S=4).":FOR I=1 TO 80:PRINT"
_";:NEXT I
610 REM
620 REM ***********************************************************************
630 REM *Asking for rule for the first stage.RR, the resource allocated to    *
        *survey s.X(s), also the probability of detection for survey s.given *
640 REM *the presence of target for the survey                                *
650 REM ***********************************************************************
660 REM
670 INPUT "Enter the rule for the sensing stage";RR
680 INPUT "Enter the resource for the aerial photography";X(1)
690 INPUT "                      magnetic survey";X(2)
700 INPUT "                      gravity survey";X(3)
710 INPUT "                      seismic survey";X(4)
720 OPEN "b:data9" FOR OUTPUT AS #1
730 WRITE #1,RR,X(1),X(2),X(3),X(4)
740 INPUT "Enter the prob. of a +ve signal from survey 1, given the target prese
nce, PR(1)";PR(1)
750 PRINT:INPUT"Enter the prob. of a +ve signal from survey 2. given the target
presence, PR(2)";PR(2)
760 PRINT:INPUT " Enter the prob. of a +ve signal from survey 3.given the target
 presence, PR(3)";PR(3)
770 PRINT:INPUT " Enter the prob. of a +ve signal from survey 4.given the target
 presence, PR(4)";PR(4)
780 FOR I= 1 TO 80:PRINT "_";:NEXT I:I=0:CLS
790 REM
800 REM Option of Exhaustive or Random survey of the area for each survey
810 REM
820 INPUT "WHAT IS THE RATE AT WHICH THE AREA IS SURVEYED";RATE:PRINT
830 INPUT "EXHAUSTIVE OR RANDOM FOR A. PHOTOGRAPHY.... E OR R";GEO$:PRINT
840 INPUT "EXHAUSTIVE OR RANDOM FOR MAGNETIC.....E OR R";MAG$:PRINT
850 INPUT "EXHAUSTIVE OR RANDOM FOR GRAVITY.....E OR R";GRA$:PRINT
860 INPUT "EXHAUSTIVE OR RANDOM FOR SEISMIC....E OR R";SEIS$
870 REM
880 REM ************************************
890 REM * A are the actual characteristics.*
900 REM ************************************
910 REM
920 FOR A= 1 TO 17
930 S=1
940 GOSUB 2630 'TO CAL. P(B;A)
950 IF RR<=11 THEN 960 ELSE 1180
960 IF S<>1 THEN GOSUB 5220 'TO CAL X(S)
970 GOSUB 4910 'TO CAL FF
980 REM
990 REM    B(S) : Signal from survey S. G : Signal from survey S-1;
```

```
            A(S,G): Probability of +ve signal from S given G,
            F(S,G): Probability of -ve signal from S given G,
1000 REM    N(S,G): Probability of not doing survey S given G
1010 REM
1020 B(S)=0
1030 FOR G= 0 TO 2
1040 IF B(S)=0 THEN 1050 ELSE IF B(S)=1 THEN 1080 ELSE 1110
1050 IF G=2 THEN 1060 ELSE 1070
1060 F(S,2)=0:GOTO 1120
1070 F(S,G)=(1-FF)*P+(1-P):GOTO 1120
1080 IF G=2 THEN A(S,G)=0 ELSE 1100
1090 GOTO 1120
1100 A(S,G)=FF*P:GOTO 1120
1110 IF RR=1 THEN N(S,G)=0 ELSE N(S,G)=1
1120 NEXT G
1130 B(S)=B(S)+1
1140 IF B(S)=3 THEN 1150 ELSE 1030
1150 S=S+1
1160 IF S=5 THEN 1450 ELSE 940
1170 REM *******************FOR RULES >11*********************
1180 IF S=1 THEN 1190 ELSE 1260
1190 IF X(1)=0 THEN 1200 ELSE 1220
1200 A(1,0)=0:F(1,0)=0:N(1,0)=1
1210 S=S+1:GOTO 940
1220 GOSUB 4910 'TO CALCULATE FF
1230 A(1,0)=FF*P
1240 F(1,0)=(1-FF)*P+(1-P)
1250 N(1,0)=0:GOTO 1210
1260 FOR G=0 TO 2
1270 IF X(S)=0 THEN 1280 ELSE 1330
1280 A(S,G)=0:F(S,G)=0:N(S,G)=0
1290 IF X(S-1)=0 THEN N(S,2)=1 ELSE 1310
1300 GOTO 1420
1310 N(S,1)=1:N(S,0)=1
1320 GOTO 1420
1330 A(S,G)=0:F(S,G)=0:N(S,G)=0
1340 IF X(S-1)=0 THEN 1350 ELSE 1390
1350 IF G=2 THEN 1360 ELSE 1420
1360 GOSUB 4910 'TO CALCULATE FF
1370 A(S,2)=FF*P:F(S,2)=(1-FF)*P+(1-P)
1380 GOTO 1420
1390 IF G=1 OR G=0 THEN 1400 ELSE 1420
1400 GOSUB 4910 'TO CAL. FF
1410 A(S,G)=FF*P:F(S,G)=(1-FF)*P+(1-P)
1420 NEXT G
1430 S=S+1
1440 IF S=5 THEN 1450 ELSE 940
1450 I=0:FOR M=0 TO 2:B(1)=M
1460 FOR J=0 TO 2:B(2)=J
1470 FOR K=0 TO 2:B(3)=K
1480 FOR L=0 TO 2:B(4)=L
1490 IF M=0 THEN MM=F(1,0) ELSE IF M=1 THEN MM=A(1,0) ELSE MM=N(1,0)
1500 IF J=0 THEN JJ=F(2,B(1)) ELSE IF J=1 THEN JJ=A(2,B(1)) ELSE JJ=N(2,B(1))
1510 IF K=0 THEN KK=F(3,B(2)) ELSE IF K=1 THEN KK=A(3,B(2)) ELSE KK=N(3,B(2))
1520 IF L=0 THEN LL=F(4,B(3)) ELSE IF L=1 THEN LL=A(4,B(3)) ELSE LL=N(4,B(3))
1530 IF RR=1 OR RR>11 THEN TEST=1 ELSE GOTO 1550
1540 GOTO 1560
1550 GOSUB 5830
1560 I=I+1
1570 P(I,A)=MM*JJ*KK*LL*TEST
1580 NEXT L:NEXT K:NEXT J:NEXT M
1590 REM ***********************************************************
          * P(I,A)= probability of state I, given <A>:(for a given rule,RR).*
          ***********************************************************
1600 REM
1610 REM
```

```
1620 REM ***************************************************************************
         * Testing that the sum of the probabilities for all the I, adds up to*
         * 1, for each <A>
1630 REM ***************************************************************************
1640 REM
1650 SUM=0
1660 FOR I=1 TO 81
1670 SUM=SUM+P(I,A)
1680 NEXT I
1690 PRINT:PRINT "The sum of P(I)=",SUM," A ",A
1700 NEXT A
1710 REM
1720 REM ****************************************************************
1730 REM *Calculating the probability of state I for a given rule  *
         *which is shown by PP(I,RR).                               *
1740 REM ****************************************************************
1750 REM
1760 INPUT "INPUT THE NO. OF PROSPECTS PER YEAR ",PROSP:PROP=0
1770 PRINT "                              THE E(N) OF ACTUAL PROSPECTS IN STATE I"
1780 FOR I=1 TO 81:SUM=0
1790 FOR A=1 TO 17
1800 SUM=SUM+P(I,A)
1810 NEXT A
1820 PP(I,RR)=SUM/17:PRINT "P(",I," rule",RR,")=",PP(I,RR),
1830 NEXT I
1840 REM
1850 REM ********************************************
         * Calculating the joint probability, P(I,A) *
         ********************************************
1860 REM
1870 FOR I=1 TO 81:FOR A= 1 TO 17:P(I,A)=(P(I,A))/17:NEXT A:NEXT I
1880 FOR I= 1 TO 81
1890 OSS1(I)=P(I,1):OSS8(I)=P(I,8):OSL2(I)=P(I,2):OSL9(I)=P(I,9):TSS5(I)=P(I,5)
1900 TSS12(I)=P(I,12):TLL6(I)=P(I,6):TLL13(I)=P(I,13):OLL15(I)=P(I,15):OLL16(I)=
P(I,16):TSLT7(I)=P(I,17)
1910 NEXT I:I=0
1920 REM
1930 REM ***************************************************************
         * Calculating the no. of prospects below in states mentioned by  *
         * all of the learning stage rules.
1940 REM * RATE(I) = expected no. of prospects in state I                  *
1950 REM ***************************************************************
1960 REM
1970 I=0:FOR T= 1 TO 15:M(T)=0:NEXT T:PRINT:PRINT
1980 CLOSE #1:I=0
1990 FOR AA= 0 TO 2:FOR BB= 0 TO 2:FOR CC= 0 TO 2:FOR DD= 0 TO 2
2000 I=I+1:RATE(I)=PP(I,RR)*(PROSP)
2010 IF (RATE(I))<>0 THEN 2020 ELSE 2370
2020 IF RR=26 THEN 2030 ELSE 2040
2030 M(15)=M(15)+RATE(I):GOTO 2370
2040 IF AA=1 THEN M(1)=M(1)+RATE(I) ELSE 2060
2050 RU(4,I)=I
2060 IF BB=1 THEN M(2)=M(2)+RATE(I) ELSE 2080
2070 RU(3,I)=I
2080 IF CC=1 THEN M(3)=M(3)+RATE(I) ELSE 2100
2090 RU(2,I)=I
2100 IF DD=1 THEN 2110 ELSE 2130
2110 M(4)=M(4)+RATE(I)
2120 RU(1,I)=I
2130 IF AA=1 AND BB=1 AND CC=1 AND DD=1 THEN M(14)=M(14)+RATE(I) ELSE 2150
2140 RU(14,I)=I
2150 IF BB=1 AND CC=1 AND DD=1 THEN M(13)=M(13)+RATE(I) ELSE 2170
2160 RU(13,I)=I
2170 IF AA=1 AND BB=1 AND DD=1 THEN M(12)=M(12)+RATE(I) ELSE 2190
2180 RU(12,I)=I
2190 IF AA=1 AND BB=1 AND CC=1 THEN M(11)=M(11)+RATE(I) ELSE 2210
```

```
2200 RU(11,I)=I
2210 IF CC=1 AND DD=1 THEN M(10)=M(10)+RATE(I) ELSE 2230
2220 RU(10,I)=I
2230 IF BB=1 AND DD=1 THEN M(9)=M(9)+RATE(I) ELSE 2250
2240 RU(9,I)=I
2250 IF BB=1 AND CC=1 THEN M(8)=M(8)+RATE(I) ELSE 2270
2260 RU(8,I)=I
2270 IF AA=1 AND DD=1 THEN M(7)=M(7)+RATE(I) ELSE 2290
2280 RU(7,I)=I
2290 IF AA=1 AND CC=1 THEN M(6)=M(6)+RATE(I) ELSE 2310
2300 RU(6,I)=I
2310 IF AA=1 AND BB=1 THEN M(5)=M(5)+RATE(I) ELSE 2370
2320 RU(5,I)=I
2330 REM                                   ******************
2340 REM                                   ******************
                                           * LEARNING STAGE *
                                           ******************
2350 REM                                   ******************
2360 REM
2370 NEXT DD:NEXT CC:NEXT BB:NEXT AA:PRINT:PRINT "
     Learning stage":PRINT:FOR I=1 TO 80:PRINT "_";:NEXT I:PRINT
2380 REM
2390 REM *******************************************************************
2400 REM Opening a file to save information for the end of the program when
         the summary of the process is required
2410 REM *******************************************************************
2420 REM
2430 OPEN "b.in" FOR OUTPUT AS #1
2440 FOR I=1 TO 81
2450 WRITE #1,RATE(I)
2460 NEXT I:CLOSE #1
2470 REM
2480 REM **********************************************************************
         * Calculating the no. of prospects (N) for a given learning rule(YY) *
         **********************************************************************
2490 REM
2500 INPUT "Enter rule for the second  stage";YY:IF YY=15 THEN 2510 ELSE 2520
2510 PRINT "no. of prospects with 0 allocation at stage 1=";M(15):RU(15,81)=81:N
=M(15):GOTO 2760
2520 IF YY=1 THEN N=M(4) ELSE IF YY=2 THEN N=M(3) ELSE 2530
2530 IF YY=3 THEN N=M(2) ELSE IF YY=4 THEN N=M(1) ELSE 2540
2540 IF YY=5 THEN N=M(5) ELSE IF YY=6 THEN N=M(6) ELSE 2550
2550 IF YY=7 THEN N=M(7) ELSE IF YY=8 THEN N=M(8) ELSE 2560
2560 IF YY=9 THEN N=M(9) ELSE IF YY=10 THEN N=M(10) ELSE 2570
2570 IF YY=11 THEN N=M(11) ELSE IF YY=12 THEN N=M(12) ELSE 2580
2580 IF YY=13 THEN N=M(13) ELSE IF YY=14 THEN N=M(14) ELSE 2760
2590 GOTO 2760
2600 REM
2610 REM ************************ SUBROUTINE ******************************
         * Assigning the value of the prob. of detection for S, given <A> *
         ******************************************************************
2620 REM
2630 IF S=1 THEN 2640 ELSE 2680
2640 IF A=1 OR A=2 OR A=3 OR A=4 OR A=5 OR A=6 OR A=7 OR A=15 OR A=17 THEN  2650
 ELSE  2660
2650 P=PR(1):GOTO 2670
2660 P=0
2670 RETURN
2680 IF A=1 OR A=2 OR A=3 OR A=4 OR A=5 OR A=6 OR A=8 OR A=9 OR A=10 OR A=11 OR
A=12 OR A=13 OR A=15 OR A=16 OR A=17 THEN  2710 ELSE  2690
2690 P=0
2700 RETURN
2710 IF S=2 THEN P=PR(2) ELSE IF S=3 THEN P=PR(3) ELSE P=PR(4)
2720 RETURN
2730 REM *******************************************************************
         * Opening a file to output into the data file the sensed chara..the
```

```
        * NNN(I). for inputing the number of  wildcat wells for these char *
2740 REM * in the data file & the no  of prospects to be drilled (N). also  *
        *the rule.YY.                                                        *
        **********************************************************************
2750 REM
2760 OPEN "b mmmm" FOR OUTPUT AS #1
2770 FOR I= 1 TO 81
2780 NNN(I)=RU(YY,I)
2790 WRITE #1,NNN(I),PP(I,RR)
2800 NEXT I
2810 WRITE #1,N,YY
2820 CLOSE #1
2830 REM
2840 REM ****************************************
        * Saving the joint probability P(I,A) *
        ****************************************
2850 REM
2860 OPEN "b p" FOR OUTPUT AS #2
2870 FOR I= 1 TO 81
2880 FOR A= 1 TO 17
2890 WRITE #2,P(I,A)
2900 NEXT A
2910 NEXT I
2920 CLOSE #2
2930 FOR I= 1 TO 80 PRINT "_"; NEXT I
2940 PRINT PRINT "Information from stage I is now available and stored in a file
 to be used by the data file. Run the data file now,i.e  run data5 for the 2nd s
tage"
2950 FOR I= 1 TO 81 PRINT "_"; NEXT I STOP
2960 REM
2970 REM ********************************
        Inputing data to Learning stage
        ********************************
2980 REM
2990 OPEN "b gggg" FOR INPUT AS 1
3000 FOR I= 1 TO 81
3010 INPUT #1,WELL(I) IF WELL(I)<>0 THEN NNN=WELL(I)
3020 NEXT I
3030 INPUT #1,DOLLAR,PI,PROP CLOSE #1
3040 OPEN "b cost" FOR OUTPUT AS #1
3050 WRITE #1,NNN,DOLLAR CLOSE #1
3060 INPUT "AT WHAT RATE THE AREA IS DRILLED",RATE
3070 OPEN "b p" FOR INPUT AS #2
3080 FOR I= 1 TO 81
3090 FOR A= 1 TO 17
3100 INPUT #2,P(I,A)
3110 NEXT A NEXT I
3120 C=1
3130 SUM(1)=0 SUM(2)=0
3140 OS1=0:OS8=0:OS2=0:OS9=0:TS5=0:TS12=0:TL6=0 TL13=0 OL15=0 OL16=0 TS17=0
3150 INPUT "ENTER PI,THE PROB. OF DET.%GIVEN OIL DEPOSIT",PI ADD=0
3160 FOR I= 1 TO 81
3170 FOR A= 1 TO 17
3180 GOSUB 3370 'To calculate OIL(A) & PFO(C,A)
3190 GOSUB 5040 'To calculate FF
3200 REM
3210 REM ****************************************************************
        *     ADD = prob. of a dry well, C=0.                            *
        * sum(C) = prob. of finding oil with reservoir property C=1,2    *
3220 REM *PFO(C,A)= p(finding oil & C | <A>).                            *
        *  OIL(A)= prob. of the presence of oil,given <A>                *
        * WELL(I)= The no. of wells for se. ch. I (form data file)       *
3230 REM * DOLLAR = The resource spent per well (data file).             *
        *      PI = prob. of datection,given oil is there (data file)    *
        * OS1 : Prospects with small deposits and poor res. property;    *
3240 REM * OL15             large                                        *
```

```
           * TS5 :        .        .    small       .      .    good   .     .     *
3250 REM * TL6 :          .        .    large       .                              *
3260 REM ****************************************************************************
3270 REM
3280 IF C=2 THEN 3300 ELSE 3290
3290 ADD=ADD+((((1-FF)*OIL(A))+1-OIL(A))*P(I,A))
3300 SUM(C)=SUM(C)+(PFO(C,A)*OIL(A)*P(I,A)*(FF))
3310 NEXT A
3320 NEXT I
3330 PRINT "Prob. of oil in category=";C," is ";SUM(C):C=C+1:IF C>2 THEN 3460 EL
SE GOTO 3160
3340 REM
3350 REM *********** SUBROUTINE ***********
           * Calculating OIL(A) & PFO(C,A). *
           **********************************
3360 REM
3370 IF A=3 OR A=4 OR A=7 OR A=10 OR A=11 OR A=14 THEN OIL(A)=0 ELSE OIL(A)=1
3380 IF C=1 THEN 3390 ELSE 3410
3390 IF A=1 OR A=2 OR A=8 OR A=9 OR A=15 OR A=16 THEN PFO(C,A)=1 ELSE PFO(C,A)=0
3400 GOTO 3420
3410 IF A=5 OR A=6 OR A=12 OR A=13 OR A=17 THEN PFO(C,A)=1 ELSE PFO(C,A)=0
3420 RETURN
3430 REM
3440 REM Calculating OS1,OL15,TS5 and TL6
3450 REM
3460 C=1
3470 FOR I= 1 TO 81:FOR A= 1 TO 17
3480 GOSUB 3370
3490 GOSUB 5040
3500 IF C=1 THEN 3510 ELSE 3540
3510 IF A=15 OR A=16 THEN 3530 ELSE 3520
3520 OS1(I)=PFO(1,A)*FF*OIL(A)*P(I,A):OS1=OS1+OS1(I):GOTO 3570
3530 OL15(I)=PFO(1,A)*FF*OIL(A)*P(I,A):OL15=OL15+OL15(I):GOTO 3570
3540 IF A=5 OR A=12 OR A=17 THEN 3550 ELSE 3560
3550 TS5(I)=PFO(2,A)*FF*OIL(A)*P(I,A):TS5=TS5+TS5(I):GOTO 3570
3560 TL6(I)=PFO(2,A)*FF*OIL(A)*P(I,A):TL6=TL6+TL6(I)
3570 NEXT A:NEXT I
3580 C=C+1:IF C=3 THEN C=0 ELSE 3470
3590 REM
3600 REM *******************************************************************
         * Inputing the probability of discovering petroleum, and the*
         * no. of prospects with good and poor res. properties into  *
3610 REM * data file                                                 *
         *******************************************************************
3620 REM
3630 REM
3640 PRINT OS1,OL15,TS5,TL6
3650 OPEN "b:rrrr" FOR OUTPUT AS #1
3660 WRITE #1,SUM(1),SUM(2),OS1,OL15,TS5,TL6
3670 CLOSE #1
3680 PRINT:PRINT "Prob. of Dry hole is = ";ADD
3690 PRINT:PRINT:PRINT "                                  Run data5 now, for the 3rd. stag
e."
3700 STOP
3710 REM
3720 REM                            *****************
3730 REM                            *****************
                                    * SOLVING STAGE *
                                    *****************
3740 REM                            *****************
3750 REM
3760 REM
3770 REM ***********************************************************************
         * Inputing the following from the data file (Seismic is  done for    *
         * assisting the appraisal drilling)                                  *
3780 REM * PPP(7) =prob. of large oil deposit.                                *
```

```
         *APP(SIZE)=resource for appraisal drilling                          *
         *       SIZE=size of the trap containing oil.(1,2 or small,large)   *
3790 REM * PB(SIZE)= prob. of large oil deposit given SIZE                   *
         *       ZZZ = rule used for the 3rd  stage                          *
         *PPP(SIZE)= prob. of large trap. SIZE = 1,2                         *
3800 REM **********************************************************************
3810 REM
3820 OPEN "b:xxxx" FOR INPUT AS 1
3830 INPUT #1,PPP(7),APP(1),APP(2),SIZE,PB(1),PB(2),ZZZ,PI,PPP(1),PPP(2),OS1,OL1
5,TS5,TL6,SUM(1),SUM(2):CLOSE #1
3840 INPUT "INPUT THE RATE AT WHICH THE AREA IS DRILLED",RATE
3850 GOSUB 5120:PPP(7)=PPP(7)+(FF)*PB(SIZE)*PPP(SIZE)
3860 IF ZZZ=3 THEN 3870 ELSE 3880
3870 SIZE=SIZE+1:IF SIZE>2 THEN 3880 ELSE 3850
3880 PRINT "Prob. of large oil deposit=",PPP(7)
3890 REM  The followings are considered  for development drilling
3900 REM SPOOR: no. of prospects with small deposit and poor reservoir property
3910 REM LPOOR:  "        "                  large
3920 REM SGOOD:  "        "                  small               good
3930 REM LGOOD:  "        "                  large
3940 REM
3950 SPOOR=((1/2)*PPP(7)*OS1)/(SUM(1))
3960 LPOOR=((1/2)*PPP(7)*OL15)/(SUM(1))
3970 SGOOD=((1/2)*PPP(7)*TS5)/(SUM(2))
3980 LGOOD=((1/2)*PPP(7)*TL6)/(SUM(2))
3990 PRINT:PRINT "          LARGE O.D  AND POOR RES. PROP = ",LPOOR
4000 PRINT:PRINT "          SMALL O.D  AND GOOD RES. PROP = ",SGOOD
4010 PRINT:PRINT "          LARGE O.D  AND GOOD RES. PROP = ",LGOOD
4020 PRINT:PRINT "          SMALL O.D  AND POOR RES. PROP = ",SPOOR
4030 IF SE$="Y" THEN END ELSE 4040
4040 INPUT "If you want to see the summary of process and all the data type 1 el
se type any other number",SUMMA
4050 IF SUMMA=1 THEN GOTO 4220 ELSE END
4060 REM
4070 REM **********************************************************************
         * Inputing data from the data file (no seismic in the 3rd  stage)   *
         *    ZZ = rule used for this stage                                  *
4080 REM * PB(C)= prob. of large oil deposit given C=1,2                      *
         *APP(C)=*resource for appraisal drilling                            *
         ********************************************************************
4090 REM
4100 OPEN "b.tttt" FOR INPUT AS 1
4110 INPUT #1,APP(1),APP(2),C,SUM(1),SUM(2),ZZ,PB(1),PB(2),PI,OS1,OL15,TS5,TL6
4120 CLOSE #1
4130 INPUT "PROB. OF DET. FOR LARGE OIL DEPOSIT";PI:INPUT "INPUT THE RATE AT WHI
CH THE AREA IS DRILLED",RATE
4140 GOSUB 5120 'To calculate FF
4150 PPP(7)=PPP(7)+(FF)*PB(C)*SUM(C)
4160 IF ZZ=3 THEN 4170 ELSE 3880
4170 C=C+1:IF C>2 THEN 3880 ELSE 4150
4180 REM
4190 REM **********************************************************************
         Files are opened here to input the information in order to provide a*
         summary of the total process.                                        *
4200 REM **********************************************************************
4210 REM
4220 OPEN "b:data9" FOR INPUT AS 1
4230 INPUT #1,RR:X(1),X(2),X(3),X(4):CLOSE #1
4240 OPEN "b:in" FOR INPUT AS 1
4250 FOR I= 1 TO 81
4260 INPUT #1,RATE(I)
4270 NEXT I
4280 CLOSE #1
4290 OPEN "b:mmmm" FOR INPUT AS 1
4300 FOR I=1 TO 81:INPUT #1,NNN(I),PP(I,RR):NEXT I:INPUT #1,N,YY:CLOSE #1
4310 OPEN "b:cost" FOR INPUT AS 1
```

```
4320 INPUT #1,NNN,DOLLAR
4330 CLOSE #1
4340 OPEN "b rrrr" FOR INPUT AS 1
4350 INPUT #1,SUM(1),SUM(2) CLOSE #1
4360 REM
4370 REM                              ************************
                                      Summary of the Process
4380 REM                              ************************
4390 REM
4400 CLS PRINT "                              SUMMARY OF THE PROCESS AT THE END OF THE YE
AR"
4410 PRINT "                          ************************ *********************"
:PRINT
4420 PRINT TAB(20) "The process started by selecting rule";RR;"for the 1st "
4430 PRINT TAB(20) "stage. The amount of resources allocated to each survey"
4440 PRINT TAB(20) "were:"
4450 PRINT TAB(20) "Aerial Photography ..$";X(1)
4460 PRINT TAB(20) "Magnetic Survey    ..$";X(2)
4470 PRINT TAB(20) "Gravity  Survey   ...$";X(3)
4480 PRINT TAB(20) "Seismic  Survey   ...$";X(4)
4490 PRINT TAB(20) "------------------------------------------------------------"
4500 PRINT:PRINT
4510 PRINT TAB(20) "For wildcat drilling it was decided to use rule";YY;"."
4520 PRINT TAB(20) "This resulted in the selection of ";N;". prospects for"
4530 PRINT TAB(20) "drilling  ";NNN;" wells were drilled per prospect at a"
4540 PRINT TAB(20) "cost of $";DOLLAR;" per well."
4550 PRINT TAB(20) "The following probabilities were obtained:"
4560 PRINT TAB(20) "Petroleum with poor reservoir property....";SUM(1)
4570 PRINT TAB(20) "Petroleum with good reservoir property....";SUM(2)
4580 PRINT TAB(20) "--------------------------------------------------------"
4590 PRINT:PRINT
4600 PRINT TAB(20) "For the final stage appraisal drilling was done without"
4610 PRINT TAB(20) "the aid of seimic survey and a total of ...$";APP(1)+APP(2)
4620 PRINT TAB(20) "was spent. This resulted in ";PPP(7);" prospects for "
4630 PRINT TAB(20) "further development. However, the actual number of prospects
"
4640 PRINT TAB(20) "with different actual characteristics included were:"
4650 PRINT TAB(25) "small deposit & poor reservoir property...";SPOOR
4660 PRINT TAB(25) "large deposit & poor reservoir property...";LPOOR
4670 PRINT TAB(25) "small deposit & good reservoir property...";SGOOD
4680 PRINT TAB(25) "large deposit & good reservoir property...";LGOOD
4690 CLS
4700 PRINT:PRINT "                    Results using rule";RR;"for 1st. stage...rule";Y
Y;"for 2nd. stage"
4710 PRINT "          ************************************************************
******":PRINT
4720 PRINT:PRINT
4730 PRINT
4740 PRINT TAB(20) "   Observed              Not Observed"
4750 PRINT TAB(17) "----------------------------------------"
4760 PRINT TAB(10) "LGOOD  :     ";LGOOD;"                ";(2/17)-LGOOD;"    :    2/1
7":PRINT
4770 PRINT TAB(10) "LPOOR  :     ";LPOOR;"                ";(2/17)-LPOOR;"    :    2/1
7":PRINT
4780 PRINT TAB(10) "SGOOD  :     ";SGOOD;"                ";(3/17)-SGOOD;"    :    3/1
7":PRINT
4790 PRINT TAB(10) "SPOOR  :     ";SPOOR;"                ";(4/17)-SPOOR;"    :    4/1
7":PRINT
4800 PRINT TAB(5) "No Deposit  :           0                        6/17    :
6/17"
4810 PRINT TAB(17) "----------------------------------------"
4820 PRINT:PRINT:PRINT TAB(26) "   ";PPP(7);"                 ";SOD
4830 END
4840 REM                    END OF THE MAIN PROGRAM
4850 REM
4860 REM
```

```
4870 REM ************************************************************************
4880 REM
4890 REM  SUBROUTINE FOR CALCULATING THE PROBABILITY OF DETECTION OR NO DETECTIO
     N FOR THE FIRST STAGE SURVEYS, WHETHER EXHAUSTIVE OR RANDOM
4900 REM
4910 IF S=1 THEN 4930 ELSE IF S=2 THEN 4940 ELSE 4920
4920 IF S=3 THEN 4950 ELSE 4960
4930 IF GEO$="E" THEN 4970 ELSE 5000
4940 IF MAG$="E" THEN 4970 ELSE 5000
4950 IF GRA$="E" THEN 4970 ELSE 5000
4960 IF SEIS$="E" THEN 4970 ELSE 5000
4970 IF ((RATE)*X(S))<1 THEN 4980 ELSE 4990
4980 FF=(RATE)*P*X(S):RETURN
4990 FF=1-((1-P)^((RATE)*X(S))):RETURN
5000 FF=1-(EXP(-(RATE)*P*X(S))):RETURN
5010 REM
5020 REM SUBROUTINE FOR CHECKING THE NORMALIZED EFFORT FOR WILDCAT DRILLING
5030 REM
5040 IF WELL(81)>0 THEN 5050 ELSE 5060
5050 FF=1-(EXP(-(1/PROP)*(RATE)*(PI)*WELL(I)*DOLLAR)):RETURN
5060 IF (RATE)*(DOLLAR)*(WELL(I))*(1/PROP)<1 THEN 5070 ELSE 5080
5070 FF=(RATE)*(DOLLAR)*(WELL(I))*(1/PROP)*PI:RETURN
5080 FF=1-((1-PI)^((RATE)*(1/PROP)*(DOLLAR)*WELL(I))):RETURN
5090 REM
5100 REM SUBROUTINE TO CHECK THE NORMALIZED EFFORT FOR APPRAISAL DRILLING
5110 REM
5120 IF SE$="Y" THEN 5130 ELSE 5160
5130 IF (RATE)*(APP(SIZE))<1 THEN 5140 ELSE 5150
5140 FF=(RATE)*(APP(SIZE))*PI:RETURN
5150 FF=1-((1-PI)^((RATE)*(APP(SIZE)))):RETURN
5160 IF (RATE)*(APP(C))<1 THEN 5170 ELSE 5180
5170 FF=(RATE)*(APP(C))*PI:RETURN
5180 FF=1-((1-PI)^((RATE)*(APP(C)))):RETURN
5190 REM
5200 REM SUBROURINE TO CALCULATE THE RESOURCE ALLOCATION TO SURVEYS
5210 REM
5220 IF RR=2 THEN 5230 ELSE 5290
5230 AA=A(2,1)*A(1,0):B=A(3,1)*A(2,1)*A(1,0)
5240 IF S=2 THEN 5250 ELSE IF S=3 THEN 5260 ELSE 5270
5250 IF A(1,0)=0 THEN 5280 ELSE X(2)=X(2)/A(1,0):GOTO 5280
5260 IF AA=0 THEN 5280 ELSE X(3)=X(3)/AA:GOTO 5280
5270 IF B=0 THEN 5280 ELSE X(4)=X(4)/B
5280 RETURN
5290 IF RR=3 THEN 5300 ELSE 5350
5300 IF S=2 OR S=3 THEN 5320 ELSE 5310
5310 G=A(3,1)*A(2,1)*A(1,0)+A(3,0)*F(2,1)*A(1,0):IF G=0 THEN 5340 ELSE X(4)=X(4)
/G:GOTO 5340
5320 IF A(1,0)=0 THEN 5340 ELSE 5330
5330 IF S=2 THEN X(2)=X(2)/A(1,0) ELSE  X(3)=X(3)/A(1,0)
5340 RETURN
5350 IF RR=4 THEN 5360 ELSE 5390
5360 IF A(1,0)=0 THEN 5380 ELSE 5370
5370 IF S=2 THEN X(2)=X(2)/A(1,0) ELSE IF S=3 THEN X(3)=X(3)/A(1,0) ELSE X(4)=X(
4)/A(1,0)
5380 RETURN
5390 IF RR=5 THEN 5400 ELSE 5460
5400 AA=A(2,1)*A(1,0):B=A(1,0)*A(2,1)
5410 IF S=2 THEN 5420 ELSE IF S=3 THEN 5430 ELSE 5440
5420 IF A(1,0)=0 THEN 5450 ELSE X(2)=X(2)/A(1,0):GOTO 5450
5430 IF AA=0 THEN 5450 ELSE X(3)=X(3)/A:GOTO 5450
5440 IF B=0 THEN 5450 ELSE X(4)=X(4)/B
5450 RETURN
5460 IF RR=6 THEN 5470 ELSE 5520
5470 B=A(2,1)*A(1,0)+A(2,0)*F(1,0):BB=A(1,0)*A(2,1)+F(1,0)*A(2,0)
5480 IF S=3 THEN 5490 ELSE IF S=4 THEN 5500 ELSE 5510
5490 IF B=0 THEN 5510 ELSE X(3)=X(3)/B:GOTO 5510
```

```
5500 IF BB=0 THEN 5510 ELSE X(4)=X(4)/BB
5510 RETURN
5520 IF RR=7 THEN 5530 ELSE 5570
5530 IF S=4 THEN 5540 ELSE 5560
5540 LET G=A(3,1)*A(2,1)*A(1,0)+A(3,0)*F(2,1)*A(1,0)+A(3,1)*A(2,0)*F(1,0)+A(3,0)
*F(2,0)*F(1,0)
5550 IF G=0 THEN 5560 ELSE X(4)=X(4)/G
5560 RETURN
5570 IF RR=8 THEN 5580 ELSE 5660
5580 IF S=3 THEN 5590 ELSE 5610
5590 LET H=A(2,1)*A(1,0)+F(2,1)*A(1,0)+A(2,0)*F(1,0)
5600 IF H=0 THEN 5650 ELSE 5630
5610 LET HH=A(1,0)+(F(1,0)*A(2,0))
5620 IF HH=0 THEN 5650 ELSE 5640
5630 X(3)=X(3)/H:GOTO 5650
5640 X(4)=X(4)/HH
5650 RETURN
5660 IF RR=9 THEN 5670 ELSE 5690
5670 IF S=4 THEN IF A(1,0)<>0 THEN X(4)=X(4)/(A(1,0)+A(3,1)*A(2,0)*F(1,0)+A(3,0)
*F(2,0)*F(1,0)) ELSE 5680
5680 RETURN
5690 IF RR=10 THEN 5700 ELSE 5790
5700 IF S=4 THEN 5710 ELSE 5740
5710 K=A(3,1)*A(2,1)*A(1,0)+F(3,1)*A(2,1)*A(1,0)+A(3,0)*F(2,1)*A(1,0)
5720 IF K=0 THEN 5780 ELSE X(4)=X(4)/K
5730 RETURN
5740 IF A(1,0)=0 THEN 5780 ELSE 5750
5750 IF S=2 THEN 5760 ELSE 5770
5760 X(2)=X(2)/A(1,0):GOTO 5780
5770 X(3)=X(3)/A(1,0)
5780 RETURN
5790 IF RR=11 AND S=4 THEN IF A(1,0)=0 THEN 5800 ELSE X(4)=X(4)/(A(1,0)+(A(2,0)*
F(1,0))+(A(3,0)*F(2,0)*F(1,0))) ELSE  5800
5800 RETURN
5810 REM SUBROUTINE TO TEST THE VALUE OF STATE I AFTER THE SENSING STAGE
5820 REM
5830 IF RR=2 THEN 5840 ELSE IF RR=3 THEN 5940 ELSE 5990
5840 IF B(1)=0 THEN 5850 ELSE IF B(2)=0 THEN 5870 ELSE 5890
5850 IF B(2)=2 AND B(3)=2 AND B(4)=2 THEN TEST=1 ELSE TEST=0
5860 RETURN
5870 IF B(3)=2 AND B(4)=2 AND B(1)<>2 THEN TEST=1 ELSE TEST=0
5880 RETURN
5890 IF B(3)=0 THEN 5900 ELSE 5920
5900 IF B(4)=2 AND B(2)<>2 AND B(1)<>2 THEN TEST=1 ELSE TEST=0
5910 RETURN
5920 IF B(1)=2 OR B(2)=2 OR B(3)=2 OR B(4)=2 THEN TEST=0 ELSE TEST=1
5930 RETURN
5940 IF B(1)=0 THEN 5950 ELSE IF B(3)=0 THEN 5970 ELSE 5920
5950 IF B(2)=2 AND B(3)=2 AND B(4)=2 THEN TEST=1 ELSE TEST=0
5960 RETURN
5970 IF B(4)=2 AND B(2)<>2 AND B(1)<>2 THEN TEST=1 ELSE TEST=0
5980 RETURN
5990 IF RR=4 THEN 6000 ELSE IF RR=5 THEN 6050 ELSE 6120
6000 IF B(1)=0 THEN 6010 ELSE 6030
6010 IF B(2)=2 AND B(3)=2 AND B(4)=2 THEN TEST=1 ELSE TEST=0
6020 RETURN
6030 IF B(1)=2 OR B(2)=2 OR B(3)=2 OR B(4)=2 THEN TEST=0 ELSE TEST=1
6040 RETURN
6050 IF B(1)=0 THEN 6060 ELSE IF B(2)=0 THEN 6080 ELSE 6100
6060 IF B(2)=2 AND B(3)=2 AND B(4)=2 THEN TEST=1 ELSE TEST=0
6070 RETURN
6080 IF B(3)=2 AND B(1)<>2 AND B(4)=2 THEN TEST=1 ELSE TEST=0
6090 RETURN
6100 IF B(1)=2 OR B(2)=2 OR B(3)=2 OR B(4)=2 THEN TEST=0 ELSE TEST=1
6110 RETURN
6120 IF RR=6 THEN 6130 ELSE IF RR=7 THEN 6160 ELSE 6190
```

```
6130 IF B(2)=0 THEN 6140 ELSE 5920
6140 IF B(3)=2 AND B(4)=2 AND B(1)<>2 THEN TEST=1 ELSE TEST=0
6150 RETURN
6160 IF B(3)=0 THEN 6170 ELSE 5920
6170 IF B(4)=2 AND B(2)<>2 AND B(1)<>2 THEN TEST=1 ELSE TEST=0
6180 RETURN
6190 IF RR=8 THEN 6200 ELSE IF RR=9 THEN 6230 ELSE 6260
6200 IF B(1)=0 AND B(2)=0 THEN 6210 ELSE 5920
6210 IF B(3)=2 AND B(4)=2 THEN TEST=1 ELSE TEST=0
6220 RETURN
6230 IF B(1)=0 AND B(2)<>2 AND B(3)=0 THEN 6240 ELSE 5920
6240 IF B(4)=2 THEN TEST=1 ELSE TEST=0
6250 RETURN
6260 IF RR=10 THEN 6270 ELSE 6320
6270 IF B(1)=0 THEN 6280 ELSE IF B(1)=1 AND B(2)=0 AND B(3)=0 THEN 6300 ELSE 592
0
6280 IF B(2)=2 AND B(3)=2 AND B(4)=2 THEN TEST=1 ELSE TEST=0
6290 RETURN
6300 IF B(4)=2 THEN TEST=1 ELSE TEST=0
6310 RETURN
6320 IF RR=11 THEN 6330 ELSE 6350
6330 IF B(1)=0 AND B(2)=0 AND B(3)=0 THEN 6340 ELSE 5920
6340 IF B(4)=2 THEN TEST=1 ELSE TEST=0
6350 RETURN
```

```
10 REM          Data File
20 REM
30 REM ************************************************************************
40 REM * This is the data file which is used by the main program EXPLO for the*
       * second and the 3rd  stages of the process                            *
50 REM * The program is accessed by EXPLO through several sequential files &  *
       * is self explanatory.                                                 *
60 REM ************************************************************************
70 DIM WELL(81),NNN(81),F(25),DIFF(40),SUM(10),Y(10),P(10),APP(10),PB(10),PPP(10
).X(10),PP(81,26)
80 DIM OS(1),OL(1),TS(2),TL(2)
90 CLS:PRINT:PRINT:PRINT:PRINT:PRINT "                   THIS IS THE DATA FILE FOR
PROGRAM EXPLO.": FOR I=1 TO 80:PRINT "~";:NEXT I
100 INPUT " For which stage of the process data is required, 2 or 3",STAGE
110 IF STAGE=1 THEN 120 ELSE IF STAGE=2 THEN 190 ELSE 620
120 PRINT "The program is used only for the last two stages"
130 GOTO 100
140 REM ***************************************************************
        Sequential file mmmm is used to access data from EXPLO.The data
        is the sensed characteristics which are not zero, number of
150 REM prospects to be drilled and the rule used for the 2nd. stage.
        ***************************************************************
160 REM
170 REM ***************************************************************
                          L E A R N I N G
        ***************************************************************
180 REM
190 OPEN "b:mmmm" FOR INPUT AS 1
200 FOR I= 1 TO 81
210 INPUT #1,NNN(I),PP(I,RR)
220 NEXT I
230 INPUT #1,N,YY
240 CLOSE #1
250 CLS:PRINT "                    You are drilling";N;" prospects "
260 PRINT:PRINT:PRINT TAB(11)"You will now be asked to allocate resources for ea
ch sensed"
270 PRINT TAB(10)" characteristics which is not zero. To allocate the resources"
280 PRINT TAB(10)" type a number from the following table(not zeros) press
290 PRINT TAB(10)" <RETURN>,then type the number of wells for that sensed ch.
300 PRINT TAB(11)"After all the allocations are mdae, type 0(zero) to leave "
310 FOR V=1 TO 22000:NEXT V:V=0:CLS
320 FOR I= 1 TO 80:PRINT "~";:NEXT I:I=0
330 PRINT:PRINT " This table shows the Sensed Characteristics ":PRINT
340 FOR I= 1 TO 81:PRINT NNN(I),:IF NNN(I)<>0 THEN PROP=PROP+PP(I,RR) ELSE 350
350 NEXT I
360 PRINT:PRINT "TYPE THE SENSED CH. I, TYPE O TO LEAVE";:INPUT I
370 IF I=0 THEN 420 ELSE 380
380 PRINT "INPUT THE NO. OF WELLS FOR THIS SENSED CHRACTERISTIC"
390 INPUT WELL(I):GOTO 360
400 REM *************************
        * DOLLAR:Cost per well *
410 REM *************************
420 INPUT "cost per well";DOLLAR
430 REM ******************************************************************
        File gggg is opened to input the number of wells,cost per well and
        the probability of detection given the presence of oil(PI), into
440 REM the main program.
        ******************************************************************
450 OPEN "b:gggg" FOR OUTPUT AS #1
460 FOR I= 1 TO 81
```

```
470 WRITE #1,WELL(I)
480 NEXT I
490 INPUT " Enter PI, the probability of detecting oil, given its presence";PI
500 WRITE #1,DOLLAR,PI,PROP
510 CLOSE #1
520 CLS:PRINT:PRINT:PRINT:PRINT
530 FOR I=1 TO 80:PRINT "_";:NEXT I
540 PRINT:PRINT "     The no. of wells and the cost per well is now stored in a f
ile to be used by the main program."
550 PRINT "                         Run prog. EXPLO now, for the 2nd. stage."
560 FOR I=1 TO 80:PRINT "_";:NEXT I:STOP
570 REM ***************************************************************
        Opening file rrrr to access info. from the main program.
        SUM(1) and SUM(2) are the probability of finding oil with
580 REM poor and good reservoir properties.
        ***************************************************************
590 REM
600 REM ***********************************************************************
                                 S O L V I N G
        ***********************************************************************
610 REM
620 OPEN "b:rrrr" FOR INPUT AS #1
630 INPUT #1,SUM(1),SUM(2),OS1,OL15,TS5,TL6
640 CLOSE #1
650 REM ***********************************************************************
        PI: Probability of detecting large structure, given the presence
        of this structure.
660 REM SEISMIC:The decision variable of value 1, if additional info
        is required before appraisal drilling. The data is obtained
        by seismic survey.
670 REM ***********************************************************************
680 INPUT "If Seismic Survey is required type 1";SEISMIC
690 IF SEISMIC=1 THEN 720 ELSE 1220
700 REM ***************************************************************
        *ZZ is the rule for the solving stage when seismic is used*
710 REM ***************************************************************
720 INPUT "Enter the rule for seismic survey";ZZ:INPUT "Enter PI, the probabilit
y of detecting large structure, given its presence";PI
730 IF ZZ=1 THEN 760 ELSE IF ZZ=2 THEN 770 ELSE 800
740 REM ****************************************************
        Y(c=1) is the resource for seismic, using rule 1 &
        Y(c=2) is the resource for seismic, using rule 2 &
750 REM ****************************************************
760 C=1:INPUT "allocation for seismic, c=1";Y(1):Y(1)=Y(1)/SUM(1):GOTO 800
770 C=2:INPUT "allocation for seismic, c=2";Y(2):Y(2)=Y(2)/SUM(2)
780 REM ******************************************************************
                     PPP(2) is  the probability of large
                     structure.
790 REM ******************************************************************
800 PPP(2)=0:IF ZZ=3 THEN 810 ELSE 850
810 INPUT "y(1)";Y(1):INPUT "y(2)";Y(2):Y(1)=Y(1)/(SUM(1)+SUM(2)):Y(2)=Y(2)/(SUM
(1)+SUM(2))
820 C=1
830 REM ***********************************************************************
        P(1) is the probability of large structure, given that the prospect
        is in category 1 and P(2) is the same probability given category 2.
840 REM ***********************************************************************
850 INPUT "INPUT THE RATE AT WHICH THE AREA IS SURVEYED";RATE
860 P(1)=.6667:P(2)=.6
870 GOSUB 1450:PPP(2)=PPP(2)+(FF)*P(C)*SUM(C)
880 IF ZZ=3 THEN 890 ELSE 900
890 C=C+1:IF C>2 THEN 900 ELSE 860
900 PRINT "Prob. of large structure=";PPP(2)
902 OS1=(4/7)*(PPP(2)/SUM(1))*OS1
904 OL15=(4/7)*(PPP(2)/SUM(1))*OL15
906 TS5=(3/7)*(PPP(2)/SUM(2))*TS5
```

```
920 TL6=(5/7)*(PPP(2)/SUM(2))*TL6
930 REM ******************************************
        ZZZ is the rule used for appraisal drilling
        ******************************************
940 REM Recording data which will be used to produce a summary of the process
        ****************************************************************
950 OPEN "b:sei" FOR OUTPUT AS #1
960 INPUT "rule for app. wells";ZZZ
970 WRITE #1,SUM,ZZ
980 CLOSE #1
990 IF ZZZ=1 THEN 1020 ELSE IF ZZZ=2 THEN 1030 ELSE 1040
1000 REM ***********************************************
        SIZE is the size of the structure, 1=small, 2=large
        APP(1) is the allocation for appraisal drilling
1010 REM when the structure is small and APP(2) is the
        allocation when the structure is large.
        ***********************************************
1020 SIZE=1:INPUT "How many wells for small str.";WE:INPUT "Cost per well";CO:AP
P(1)=WE*CO:GOTO 1040
1030 SIZE=2:INPUT "How many wells for large str.";WEL:INPUT "Cost per well";COST
:APP(2)=WEL*COST/PPP(2)
1040 PPP(7)=0:IF ZZZ=3 THEN 1050 ELSE 1080
1050 INPUT "Number of wells for small str.";G:INPUT "Cost per well";HO:APP(1)=G*
HO:INPUT "No. of wells for large str.";GH:INPUT "Cost per well";DF:APP(2)=GH*DF
1060 SIZE=1
1070 REM *******************************************************
        Information is saved to produce the summary of the process
        *******************************************************
1080 OPEN "b:app" FOR OUTPUT AS #1
1090 WRITE #1,APP(1),APP(2):CLOSE #1
1100 REM ***************************************************************
        PB(1) is the probability of large oil deposit given small structure
        PB(2) is the probability of large oil deposit given large structure
1110 REM These values and the previous ones i.e., P(1) and P(2) are
        calculated from the table of the actual characteristics.
        ***************************************************************
1120 PB(1)=0:PB(2)=.4445
1130 REM ****************************************************************
        Opening file xxxx to input the data into EXPLO for final calculation
        ****************************************************************
1140 OPEN "b:xxxx" FOR OUTPUT AS #1
1150 WRITE #1,PPP(7),APP(1),APP(2),SIZE,PB(1),PB(2),ZZZ,PI,PPP(1),PPP(2),OS1,OL1
5,TS5,TL6,SUM(1),SUM(2)
1160 CLOSE #1
1170 CLS:PRINT:PRINT:PRINT:FOR I= 1 TO 80:PRINT "_";:NEXT I:PRINT
1180 PRINT "                 Data is stored in a file. Run the main program now."
1190 FOR I= 1 TO 80:PRINT "_";:NEXT I:INPUT W
1200 REM ***************************************************************
        ZZ is the rule for the 3rd. stage when seismic is not required.
        PI is the probability of detecting large oil deposit given its
1210 REM presence.
        ***************************************************************
1220 INPUT "Enter the rule for the appraisal drilling rule";ZZ
1230 INPUT "Enter PI, the probability of detection, given large oil deposit";PI
1240 IF ZZ=1 THEN 1250 ELSE IF ZZ=2 THEN 1260 ELSE 1270
1250 C=1:INPUT "No. of wells for prospects in c=1";MN:INPUT "Cost per well";VB:A
PP(1)=(MN*VB)/(SUM(1)):GOTO 1270
1260 C=2:INPUT "No. of wells for prospects in c=2";ZX:INPUT "Cost per well";JK:A
PP(2)=(ZX*JK)/(SUM(2))
1270 PPP(7)=0:IF ZZ=3 THEN 1280 ELSE 1310
1280 INPUT "No. of wells for prospects in c=1";AG:INPUT "Cost per well";CM:APP(1
)=AG*CM:INPUT "No. of wells for prospects in c=2";QW:INPUT "cost per well";TY:AP
P(2)=QW*TY
1290 APP(1)=(APP(1))/(SUM(1)+SUM(2)):APP(2)=(APP(2))/(SUM(1)+SUM(2))
1300 C=1
1310 PB(1)=.3334:PB(2)=.4
```

```
1320 REM ********************************************************************
     Opening file tttt to input the data into EXPLO for final calculation
     ********************************************************************
1330 OPEN "b:tttt" FOR OUTPUT AS #1
1340 WRITE #1,APP(1),APP(2),C,SUM(1),SUM(2),ZZ,PB(1),PB(2),PI,OS1,OL15,TS5,TL6
1350 FOR I= 1 TO 80 PRINT "~";:NEXT I
1360 PRINT " Data is stored. Run the main program now, for the 3rd  stage."
1370 PRINT FOR I= 1 TO 80:PRINT"~";:NEXT I
1380 CLOSE #1
1390 REM ***************************************************************
     Recording the information to produce the summary of the process
     ***************************************************************
1400 OPEN "b:print" FOR OUTPUT AS #1
1410 WRITE #1,APP(1),APP(2),ZZ
1420 END
1430 REM                        END OF THE DATA FILE
1440 REM
1450 IF (RATE)*(Y(C))<1 THEN 1460 ELSE 1470
1460 FF=(RATE)*(Y(C))*PI:RETURN
1470 FF=1-((1-PI)^((RATE)*(Y(C)))):RETURN
```

```
20 REM    F.3  Program for Solving Kuhn-Tucker Conditions
30 REM
40 REM
50 REM This program solves the Kuhn-Tucker conditions for Random Search Process
60 REM There are two subroutines  zj and zij allocation
                                            NOTATION:
70 REM Total resource is varied between 0 & 50 units and is shown by Rh
       II=Total number of targets. JJ=Toatl number of subspaces. P(I,J) Probabi
       lity that target I is in subspace J
80 REM K(I,J)=The detection rate for target I in J. H(J)=The detection rate for
       subspace J, W(J)=Probability that there is a target in J, T(I,J)=A test
       parameter for the program to see if Z(I,J), the resourec allocation for
90 REM target I in J, is > or = to zero, Y(J)=A test parameter for Z(J)
       allocation as T(I,J), V=If the value of this variable is 1 then Z(I,J)
       allocation will be made, any other number will result in Z(J) allocation
100 REM For different problems, new set of data must be typed
110 REM ***********************************************************************
120 DIM P(50,50),K(50,50),T(50,50),F(50,50),W(50),H(50),Y(50),X(50),R(50),Q(50)
130 INPUT "What is the total number of targets",II
140 INPUT "How many subspaces";JJ
150 PRINT "----------TOTAL NO  OF TARGETS=",II,"----------"
160 PRINT "----------TOTAL NO. OF SUBSPACES=",JJ,"----------"
170 REM
180 REM L is the number of elements in the matrix of I & J  e.g. F(I,J)
190 REM
200 L=II*JJ
210 FOR I= 1 TO II
220 PRINT I
230 FOR J=1 TO JJ
240 READ P(I,J)
250 PRINT P(I,J)
260 READ K(I,J)
270 READ T(I,J)
280 NEXT J
290 NEXT I
300 REM
310 REM   Sample data for 2 targets & 2 subspaces. Note that this set of data
320 REM   can also be used for 2 subspaces and one target
330 REM
340 DATA .3,.1,1,.7,.2,1,.7,.1,1,.3,.2,1
350 FOR J= 1 TO JJ
360 W(J)=0
370 FOR I= 1 TO II
380 W(J)=W(J)+P(I,J)
390 H(J)=(K(I,J))
400 Y(J)=1
410 NEXT I
420 NEXT J
430 INPUT "Type 1 if the allocation is Z(I,J), if not type any other number",V.
440 KK=1
450 REM
460 FOR RR=0 TO 50 STEP 5
470 R(KK)=RR
480 PRINT "R=",R(KK)
490 LET M=0
500 FOR I= 1 TO II
510 FOR J= 1 TO JJ
520 T(I,J)=1
530 NEXT J
540 NEXT I
550 FOR J= 1 TO JJ
560 Y(J)=1
```

```
570 NEXT J
580 REM
590 REM M is the number of iterations till all the allocations are >or =0
600 REM
610 M=M+1
620 PRINT "ITERATION ",M
630 REM
640 REM Initializing C & D which are used for summation purposes also
650 REM N & S are set to zero. These two variables are used to test to see
660 REM if all the allocations are > or = to zero. This is satisfied if S=L
670 REM
680 B=0
690 A=0
700 LET C=0
710 LET D=0
720 LET N=0
730 LET S=0
740 IF V=1 THEN 770 ELSE 750
750 GOSUB 1460
760 IF (N=JJ) AND (S=JJ) THEN 790 ELSE IF (N=JJ) AND (S><JJ) THEN 610
770 GOSUB 940
780 IF (N=L) AND (S=L) THEN 790 ELSE IF (N=L) AND (S><L) THEN 610
790 KK=KK+1
800 NEXT RR
810 REM
820 REM      Printing the Normalized Expected No. of Detections
830 REM      for 5 to 50 units of Resources,[same order as 5 to 50].
840 REM
850 PRINT
860 PRINT "Normalized Expected No. of Targets Detected from 5 to 50 units of Res
ources":PRINT
870 FOR KK=2 TO 11
880 PRINT (Q(KK))/II
890 NEXT KK
900 END
910 REM ******************************************************************
920                        SUBROUTINE FOR Z(I,J) ALLOCATION
930 REM ******************************************************************
940 FOR I=1 TO II
950 FOR J=1 TO JJ
960 IF T(I,J)><0 THEN 970 ELSE 1010
970 B=(1/(K(I,J)))*(LOG((P(I,J))*(K(I,J))))
980 A=1/(K(I,J))
990 C=C+B
1000 D=D+A
1010 NEXT J
1020 NEXT I
1030 REM
1040 REM E is the constant of the Kuhn-Tucker conditions
1050 REM
1060 E=EXP((C-RR)/D)
1070 PRINT E
1080 FOR I=1 TO II
1090 FOR J=1 TO JJ
1100 N=N+1
1110 IF T(I,J)><0 THEN 1130 ELSE 1120
1120 GOTO 1220
1130 Z(I,J)=(1/(K(I,J)))*(LOG(((P(I,J))*(K(I,J)))/E))
1140 REM
1150 REM TESTING Z(I.J)
1160 REM
1170 IF Z(I,J)>=0 THEN 1220 ELSE PRINT "Z(";I;J;")=",Z(I.J)
1180 Z(I,J)=0
1190 T(I,J)=0
1200 IF N=L THEN 1210 ELSE 1240
1210 RETURN
```

```
1220 PRINT "Z(";I;J;")=",Z(I,J)
1230 S=S+1
1240 NEXT J
1250 NEXT I
1260 IF S=L THEN 1300 ELSE 1420
1270 REM
1280 REM Initializing Q, the expected number of targets detected
1290 REM
1300 LET Q=0
1310 FOR I=1 TO II
1320 FOR J=1 TO JJ
1330 REM
        F(I,J) is the c.d.f  of the probability of detection
1340 REM
1350 F(I,J)=1-(EXP(-(K(I,J)*Z(I,J))))
1360 G=P(I,J)*F(I,J)
1370 Q=Q+G
1380 NEXT J
1390 NEXT I
1400 PRINT "EXPECTED NO =",Q
1410 Q(KK)=Q
1420 RETURN
1430 REM *****************************************************************
1440 REM                         SUBROUTINE FOR Z(J) ALLOCATION
1450 REM *****************************************************************
1460 FOR J=1 TO JJ
1470 IF Y(J)><0 THEN 1480 ELSE 1520
1480 B=(1/H(J))*(LOG(W(J)*H(J)))
1490 A=1/(H(J))
1500 C=C+B
1510 D=D+A
1520 NEXT J
1530 E=EXP((C-RR)/D)
1540 FOR J= 1 TO JJ
1550 N=N+1
1560 IF Y(J)><0 THEN 1570 ELSE 1630
1570 U(J)=(1/(H(J)))*(LOG((W(J)*H(J))/E))
1580 IF U(J)>=0 THEN 1630 ELSE PRINT "Z(";J;")=";U(J)
1590 U(J)=0
1600 Y(J)=0
1610 IF N=JJ THEN 1620 ELSE 1650
1620 RETURN
1630 PRINT "Z(";J;")=";U(J)
1640 S=S+1
1650 NEXT J
1660 IF S=JJ THEN 1670 ELSE 1780
1670 LET Q=0
1680 FOR J=1 TO JJ
1690 REM
1700 REM X(J) is the c.d.f. of the probability of detection
1710 REM
1720 X(J)=1-(EXP(-(H(J)*U(J))))
1730 G=W(J)*X(J)
1740 Q=Q+G
1750 NEXT J
1760 PRINT "EXPECTED NO.=",Q
1770 Q(KK)=Q
1780 RETURN
```

Appendix (G)

Definitions of the Terms Used

Appraisal Drilling or Step-Out Drilling : Wells drilled nearby the exploratory well to investigate the extend of the oil-bearing structure and the importance of the findings.

Cap-Rock : Typical cap-rocks are clays and shales. The cap rock acts as a seal to prevent the escape of oil and gas from the reservoir.

Crew-Month : One way of expressing the geological and geophysical effort; it is the product of the number of crews and the number of month that they are active in a year.

Cuttings : Small fragments of rock brought to surface when drilling underground formations.

Development Wells : Wells drilled in an area which is proved to be productive.

Exploratory or Wildcat Well : A well drilled in an unproved area. In the early days, the wild animals forced hazardous sitituations on the prospectors so the name wildcat was applied to exploratory drilling.

False Target : An object which exhibits similar characteristics as the target.

Favorable Structure : Structure capable of containing oil.

Lithology : The study of rock characteristics.

Negative Signal : Signal from an activity indicating the possible absence of the target.

Net Acreage : The total area (land) which is held by a company is the gross acreage. If the interest of another company in the area (proportion of the area) is subtracted from the total area, then the remaining area is the net acreage which is held by the first company.

New Field Wildcat : A well drilled on a trap which has not previously produced oil or gas.

New Pool Wildcat : A test located to explore for a new pool on a trap already producing oil or gas.

Oil Pool : An underground single reservoir containing oil. An oil field may contain one or more pools.

Operator : The person responsible for making decisions and allocating the capital resources in an oil company.

Outcrop : A subsurface formation that appears on the surface in some locations because of the geological conditions.

Pay Thickness : The thickness of the producing zone.

Permeability : A measure of rock resistance for fluid motion.

Petroleum Reserves : Estimated amount of oil and gas which is capable of being recovered or produecd.

Petroleum Resources : The resources are always far in excess of the reserves and they may be:

a) known and recoverable petroleum;

b) known to have been left behind in pools that are not recoverable at present;

c) undiscovered and undeveloped pools.

Play : An exploratory venture, usually a new venture.

Porosity : An indication of the ability of rock to hold oil.

Positive Signal : Signal from an activity indicating the presence of the target.

Prospect : Area which may contain petroleum.

Reservoir : Sedimentary rock which is porous and permeable. and contains oil; a trap.

Saturation : Percentage of pore space occupied by oil.

Source Rock : The rock from where petroleum may originate. Petroleum may migrate through other rocks (carrier rocks) and accumulate into rocks which are referred to as the reservoir rocks.

Strategy : The art of devising or employing plans toward a goal.

Stratigraphic Trap : Type of trap formed by the change in the rock characteristics such as porosity.

Tactic : A method of employing men and equipment to achieve a purpose as part of a global goal.

Target : Object of the search.

Trap : Structure or formation containing oil; for different types of traps and their description see Appendix (A.4).