A MODIFIED GO METHODOLOGY FOR SYSTEM AVAILABILITY ASSESSMENT

A Thesis

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by

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ABSTRACT

System availability analysis methods are based on a physical appreciation of the basic functions and relationships for the components that make up the system. One of the more popular techniques for analyzing system availability is known as the GO method. This technique forms the basis of the studies reported in this thesis. The analysis of series components and systems consisting of series components normally assumes that the elements are independent when calculating the availability. The utilization of this assumption in series systems where no further failures can occur once a failure has occurred leads to an underestimation of system availability. The basic GO Methodology assumes independence of series elements in the determination of system availability.

The work presented in this thesis constitutes a study of the basic GO Methodology. The concept of independence and the effect of this assumption in series systems is examined. A modification is developed and incorporated in the calculation procedure which utilizes equivalent components in place of the individual series elements. The modified program is used to analyse a practical system and the results are compared with those obtained using the original approach. The effect on the calculated system availability due to the recognition of series component dependence is clearly illustrated.

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INTRODUCTION

System reliability and availability assessment and prediction have come to play a very important role in industry and have evolved steadily since the days when these concepts were primarily applied in the defence and space programs. Today, the growing complexity of systems together with the ever increasing competition for financial and physical resources have led to increasing utilization of reliability engineering in a wide range of applications. Knowledge regarding the theory and practice of reliability has been growing steadily and with better data, models and analysis techniques are continuing to improve. Reliability engineering finds application in many areas of engineering technology. Many areas of engineering applications have developed new definitions, concepts and approaches of their own. Areas such as power system reliability , software reliability and computers have some common concepts but have distinguishing definitions, models and techniques. Many organizations are active in the development of new methods and the modification and expansion of existing techniques in order that these approaches can be applied in a wide range of industries.

Reliability is defined as [1] "the probability of a piece of equipment or apparatus performing its task adequately for the period of time intended under the operating conditions encountered". A study of reliability involves a study of the causes, distribution and prediction of failure. A thorough understanding of the physical requirements of the system is essential before a quantitative assesment can be made. The relationship between the actual system and the network representation used to model the system should be clear before any analysis technique is used.

The word "reliability" is sometimes used to define probability of a piece of equipment or a system staying in the operating state for a designated period of time, during which repair may not be permitted (mission orientated systems) or where repair may be possible (repairable systems).

The word "availability" is used to designate the probability of a piece of equipment or system being found in the operating state at some point of time in the future [1]. The steady state availability is the ratio of the total system 'up time' or operating time, to the total time, which is the 'up time' and the 'down time' combined. over a long period of time. The concept of availability combines the concepts of reliability and maintainability. Availability assessment involves the consideration of repair whenever a component or the system has failed. Repair is the action which puts the system back into the operating state. Transitions between the operating state and the failed state are quantified by transition rates. The transition rate between the operating state and the failed state is known as the failure rate and that between the failed state and the operating state is the repair rate. These rates are basic component parameters and are used in the availability calculation of a system. There are many methods which can be used to determine system availability. One such method which was developed by the Kaman Sciences Corporation [2] for the defence industry in the early sixties, is the GO Methodology.

The GO methodology [2,3,4] is a success-oriented probabilistic system performance analysis technique which can be used to quantify system availability. This technique which was originally developed for the defence industry. was further developed and demonstrated in the probabilistic analysis and applications subprogram of the Electric Power Research Institute Nuclear Power Divison's Risk Assessment Program [4]. This approach, which employs a straightforward inductive logic to analyse system performance, has been used for evaluation of system availability and reliability to perform design verification and to quantify the effects of potential design changes in a system. This is done by means of a procedure which results in a model known as a GO model or a GO chart which is then used as an integral element in the analysis.

Methods such as Fault Tree Analysis [3] and the GO method can model and perform system analysis on systems that are made up of complex configurations. The GO model, to a large extent, resembles the original system configuration as the model elements and the system components have a close one to one correspondence. Reduction techniques exist [1] which can be used to analyze simple series and parallel configurations. The series elements in the GO model are integrated using the method of combining series elements. The final system availability index however is calculated in a different manner.

The product rule [1] that governs the combination of series elements assumes statistical independence of the individual components being considered. A series system can be compared to a chain in which the chain is only as strong as its weakest link. In actual fact, the chain can be much weaker than its weakest link. Failure of any component in a series system leads to the failure of the entire system. In some systems, the likelihood of component failure is reduced considerably if the system is not operating. Failure of this type of system eliminates any possibility of further failures occurring. The availability of such a system calculated assuming independence of the individual components, is an underestimation.

The GO methodology, during the process of calculation, combines series elements using the product rule. The assumption of independence, which is made while combining series elements, leads to an availability index that is an underestimation. The GO method, therefore, must be modified in order that dependence of series elements is considered while analysing the system. The effect that the assumption of independence of series elements has on the availability of the system is examined in this thesis and the use of equivalents to overcome this effect is discussed. The concept of using equivalents has been incorporated into the existing GO methodology so that series elements are no longer assumed to be statistically independent. The calculational routines of the GO concept have been modified so that series elements are not combined together simply by multiplying the availabilities of the individual components.

This thesis presents the GO methodology and the operators used in the modeling process together with a description of the modeling process itself. The theory of series systems and the concept of independence is examined and the use of equivalent transition rates to incorporate the concept of dependence is discussed. These modifications are then incorporated into the GO method so that the assumption of independence, which leads to a lower estimation of availability, is eliminated. The primary objective of the thesis is to modify the existing GO method by incorporating into it the concept of dependence associated with the series elements in a system.

The thesis can be broadly viewed as being made up of three parts. The first part presents the GO methodology in which the modeling and calculation procedure is explained in some detail. The second part examines, with the help of Markov models, the concept of independence existing in the study and analysis of series systems and discusses the modification that can be made in such cases. The last part shows how this modification can be incorporated into the GO methodology. The modified approach is then used to perform an availability study of a system which shows the improvement in the availability index compared to the one obtained using the original approach.

The thesis contains seven chapters which can be briefly described as follows:

Chapter 2 presents the GO methodology in detail. The operators used in the modeling procedure are described and the GO model is developed from the basic system schematic. Chapter 3 deals with the GO program in which the overall structure of the program is described. The algorithm contained in the chapter describes the actual working of the program. The transformation of the GO model into a form suitable for computer application and the availability calculation procedure is explained.

Chapter 4 discusses series systems and the effect of the assumption of independence of series elements on the availability index. Markov models are used to describe how a modification can be made using equivalents to replace the individual components. Chapter 5 then incorporates the developed modification into the GO methodology.

Chapter 6 presents the application of the modified method to a practical system and illustrates the resulting improvement in the calculated availability index.

The overall conclusions to the thesis are presented in Chapter 7.

Chapter 2

THE GO METHODOLOGY

2.1 Introduction

The GO methodology [2] is a system reliability and availability analysis technique initially developed by the Kaman Science Corporation. It was used in the safety and reliability analysis of nuclear weapons and missile systems in the defence and aerospace industry. In the course of time various other organizations started making use of it and applying it in the analysis of system performance. The Electric Power Research Institute in the U.S.A sponsored workshops and programs and further developed and extended its capabilities to the power industry.

The GO methodology is a probabilistic combinatorial analysis procedure. Component probabilities and interactions are combined to produce the probabilities of output events. There are two major aspects involved in this methodology. One is the use of a set of standardized functional operators which are used to model physical components found in the system. The other is a modeling technique whose result, called a GO chart, corresponds very closely to the physical layout or design schematic. The resulting GO chart can be translated into an input listing for a computer program which can then be used to calculate the availability of the system under study. The major part of the GO method is the development of the GO model of the system to be analyzed. This model is then used in the evaluation process. This chapter describes the GO model, the operators used in the modeling process and the development of the GO model from the system schematic.

2.2 The Theory Of GO

The GO Methodology is described in detail in References 2, 3 and 4. The following is a brief summary to explain the basic concepts. The GO method is based upon a success logic approach to analysis of systems. It uses a system flow approach to system modeling. The GO calculational routine determines the probabilities of the outcomes resulting from combining the probabilities of events that collectively describe system operation within a GO model. The component probabilities are combined by an event tree type process. Each event in a GO model represents a particular operational state of a component or subsystem. The GO routine computes the joint probability of each combination of component states by multiplying the probability of one component's state by the probability of another component's state and multiplying that result by the probability of a third component's state. This is done iteratively until all states of all components have been processed. When all of the combinations have been assessed, the probability of system success is computed by adding all of the joint probabilities which correspond to "successful" combinations. The probability of system failure is the result of adding the joint probabilities of all "failed" combinations.

In GO, this process is called "event tree analysis" because it can be represented graphically as a probability event tree. If a three event system such as the one shown in Figure 2.1 is considered, then the event tree is as shown in Figure 2.2. The system represents two components in series which must function correctly to get an output. The system also depends on human action for proper functioning. Each component operation and the human action can be considered as events which may or may not occur.

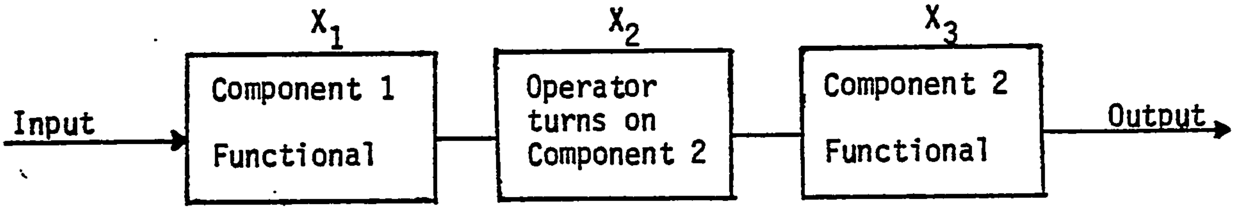


Figure 2.1 Three Event System

The events are designated as random variables X_1, X_2, and X_3 in order to describe the uncertain or random nature of the event functioning. The states of events X_1, X_2, and X_3 are represented in a probability tree as integers. These states are the various modes of functionability for each event. Event X_1 has two states, 1 and 2; Event X_2 has three states, 0, 1, and 2; Event X_3 has two states 1 and 2. The tree starts at X_1 which has a probability of 0.5 that component 1 will function and a 0.5 probability that it will not. These two states are labeled 1 and 2, respectively. Each of these states is combined with the states of X_2. These are 0 (that the operator turns on component 2 prematurely), 1 (that the operator turns on the component at the right time), and 2 (that the operator fails to turn on component 2). These states have probabilities of 0.2, 0.6, and 0.2, respectively.

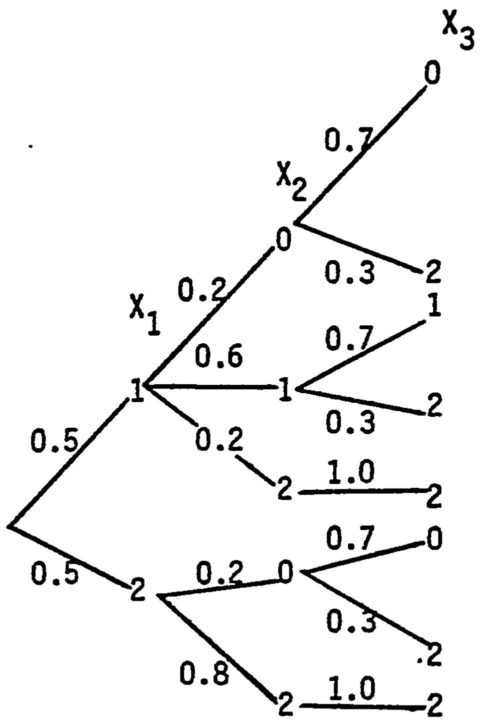


Figure 2.2 Probability Tree

When component 1 functions (state of X_1 is 1), then all three states of X_2 are possible and three separate branches appear in the tree at this point. When component 1 fails (X_1 is 2), whether the operator functions correctly or not makes no difference to the final outcome so the probabilities of the 1 and 2 states of X_2 are combined into one branch. However, when X_2 is 0, the operator could prematurely turn on component 2. So another branch is shown for $X_2 = 0$. Similar reasoning is applied to obtain the branches under X_3.

The outcomes for the combinations of the three events are joint probabilities and the entire set of joint probabilities is the joint probability distribution. This distribution for the three event system is as shown in Table 2.1. The sum of all the joint probabilities is 1.0 which is a check that the entire set of event combinations has been processed. The final distribution is the set of probability totals for each state of the system: 0,1, or 2. The final distribution for this example is shown in Table 2.2.

Table 2.1 Complete Joint Probability Distribution

X(1)	X(2)	X(3)	Probability
1	0	0	0.07
1	0	2	0.03
1	1	1	0.21
1	1	2	0.09
1	2	2	0.10
2	0	0	0.07
2	0	2	0.03
2	2	2	0.40

Table 2.2 The Final Distribution

Value of X(3)	Probability
0	0.14
1	0.21
2	0.65

This example shows how GO combines component probabilities and serves as a sample of the types of analysis that can be done with GO. Any probabilistic combinational evaluation can be performed as long as event states can be defined and probabilities for those states can be found.

2.3 Terminology Used In GO

There is a standard set of terminology that is utilized in the GO Methodology. While discussing the GO routine it was pointed out that component or event operation is defined by a set of states. In GO, these are designated by integers.

The integers that have been used here are '0' for the 'good' or the 'successful' operating state and '1' for the 'bad' or 'failed' state. There are many modelling situations for which the combinational process must depend on a function or algorithm that most appropriately describes the situation than does a simple multiplication process.

Algorithms for covering these situations have been incorporated into GO to allow modelling flexibility. These algorithms are called operators. In the GO methodology, there are presently 17 such operators. The operators are used to represent various component usages or logical combinations of components. Each operator is designated by its type number (1 through 17). In addition to type designators, each operator representing events requiring probability data must have a kind number assigned to it. This kind number corresponds to a data record which represents the reliability data associated with that component. Should an operator represent a component that is assumed never to fail, that operator is designated as perfect.

Operators are connected together to form a GO sequence. The paths connecting operators are given unique designations called signals. These signals emanate from one operator but may lead to more than one operator. In the GO evaluation process, the joint probability is computed at each signal beginning with inputs and ending with some final signals. Active signals are the number of signals which make up the joint distribution at any point in the sequence.

2.4 The GO Operators

GO operators are the building blocks in the GO method. They are used to represent the function of system components. The operators consist of symbols which were developed to represent, in mathematical terms, the way that physical components operate, or to represent logic functions for combining the relationship between components. At present there are seventeen GO operators. Each GO operator type is a unique mathematical algorithm which can be used to represent the functions of different types of physical elements. There are three basic types of GO operators, namely i) independent, ii) dependent and iii) logic.

The independent operators are used to represent components which require no input and are used to start the modeling process, (example water tanks, electric power) or in other words to provide an input to the model.

The dependent operators are used for representing such components as valves, pumps and relays.

The logic operators are used for combining the operators into the success logic of the system being modeled.

Each operator is designated by its type number which represents the operation of that particular operator. There is another number associated with each operator which is known as the kind number which identifies each component and has a set of probability data for that particular component. If an operator represents a component that is assumed never to fail then that component is known as a perfect operator. The different operators are connected together to form a GO sequence. The paths connecting operators are called signals.

There are seventeen operators in use and these are numbered one through seventeen. The most commonly used are 1,2,5,6,10 and 11 as most systems can be modeled using these operators alone.

2.4.1 Type 1: Two state component

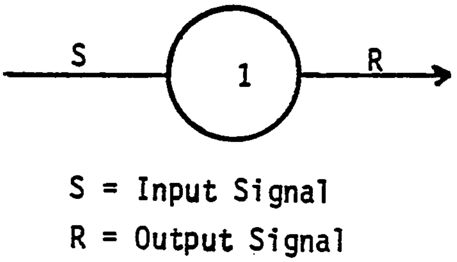
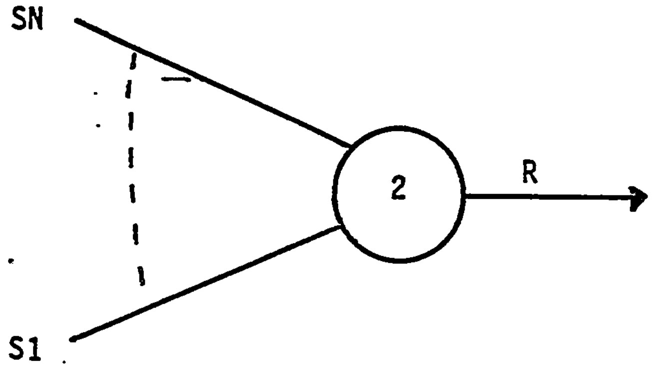


Figure 2.3 Type 1 Operator

The type 1 operator is perhaps the one most commonly used. It can be used to model any component which can exist in one of the two states - up or down. The operator is defined by two states; it has either a successful state or a failure state.

Any two state component can be modeled by a Type 1 operator. For example, a check valve can be considered a Type 1 operator since it either can let the fluid flow through, which is a success state, or it can fail to open and not let the flow pass through, which is a failure state.

2.4.2 Type 2: OR Gate



S1,...,SN = Input signals
R = Output signal

Figure 2.4 Type 2 Operator

The type 2 operator acts like an OR gate and is a logical operator. It is used to model a "connective OR gate", meaning that sections of the model are connected together with an "OR" function. In a two-state success oriented model, the "OR" function provides a success state output whenever one or more success states are present at the input.

2.4.3 Type 3: Triggered Generator

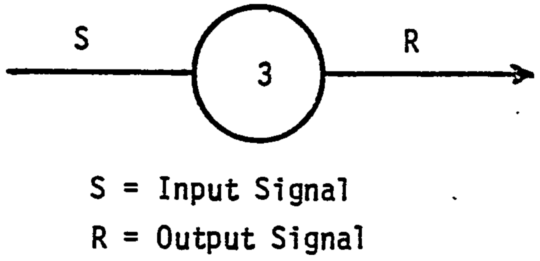


Figure 2.5 Type 3 Operator

This is a component with three operating modes: good (output occurs when input occurs), failed (no output), and premature (output occurs with no input).

2.4.4 Type 4: Multiple Signal Generator

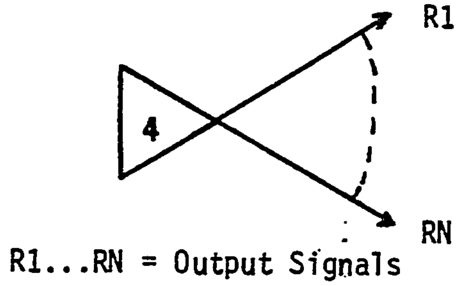


Figure 2.6 Type 4 Operator

This is a problem initiator which has no input of its own capable of generating two or more signals.

2.4.5 Type 5: Signal Generator

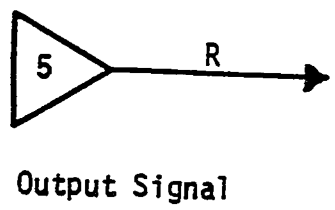
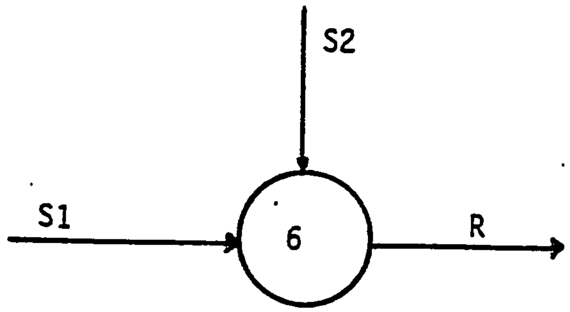


Figure 2.7 Type 5 Operator

This type of operator is used to generate values to initiate the sequence of operations and events modeled by a GO chart. Typically, Type 5 operators are represented with triangular symbols to identify the initiator. Such initiating signals are often the outputs from other systems or subsystems not being explicitly addressed. A component which requires no initiating signal to produce a signal can be modeled with a Type 5 operator.

Generators, batteries, water supplies are a few examples of the typical applications of the Type 5 operator.

2.4.6 Type 6: Component requiring actuation to pass signal



S1 = Primary input signal

S2 = Secondary input signal

R = Output signal

Figure 2.8 Type 6 Operator

The type 6 operator is used to represent components that do not produce an output signal unless they have two input signals, a primary signal and a secondary (or actuation) signal. The kind data must define probabilities for three states; success, failure and premature operation.

An example for a Type 6 operator would be a normally closed valve which would need some actuation to open to allow fluid to pass through.

2.4.7 Type 7: Component requiring actuation to inhibit signal

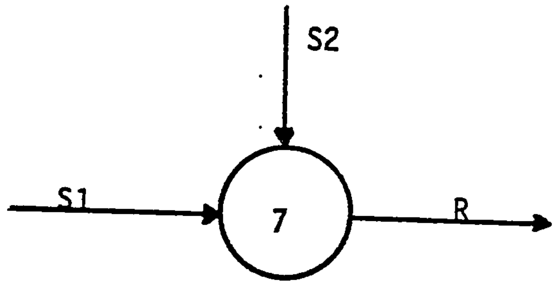


Figure 2.9 Type 7 Operator

This component is similar to Type 6, but requires actuation to stop S1.

2.4.8 Type 8: Delay Generator

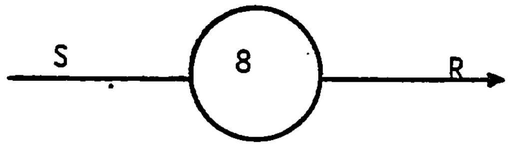


Figure 2.10 Type 8 Operator

This is used to model delays in component responses.

2.4.9 Type 9: Function Operator

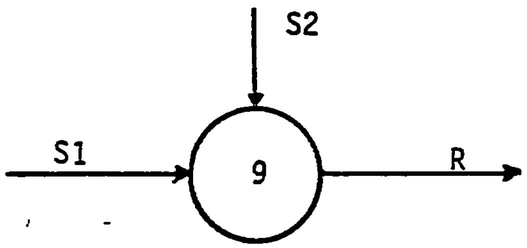
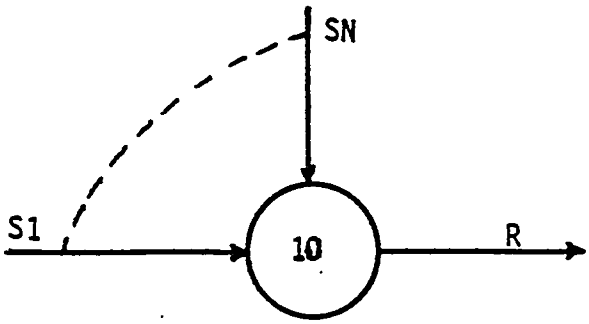


Figure 2.11 Type 9 Operator

This is a general purpose, state change operator which produces an output at a time determined by the difference between the times of S1 and S2. It can be used to model the more complex logical gates (NAND, XOR, etc.).

2.4.10 Type 10: AND Gate



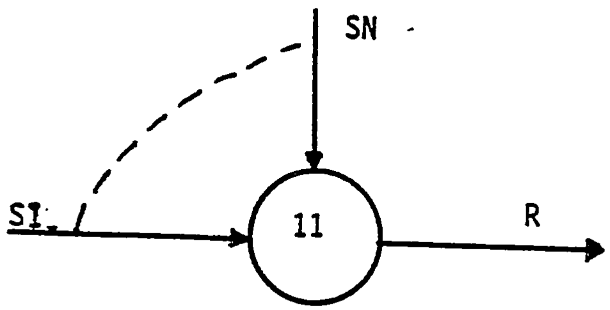
S1,....,Sn = Input signals

R = Output signals

Figure 2.12 Type 10 Operator

This operator is a logical operator. In many situations this turns out to be associated with an "AND" function. In a two-state model, the "AND" function implies success out whenever all inputs are successful.

2.4.11 Type 11: M out of N Gate



S1,...,Sn = Input signals

R = Output signals

Figure 2.13 Type 11 Operator

The Type 11 operator is used to simplify the modeling of the logical combination of m out of n signals. If there are n output signals from a certain system and only m signals are required (in a specific state) for the system success, where m is greater than one, then the Type 11 operator is used to determine the combination.

2.4.12 Type 12: Path splitter

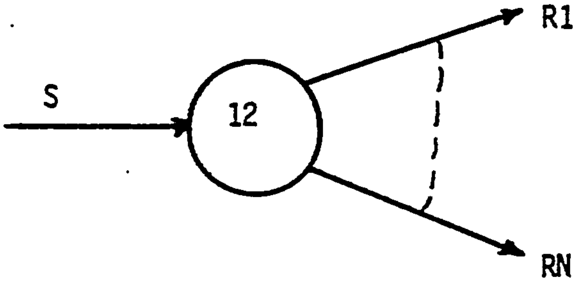


Figure 2.14 Type 12 Operator

This is a disjoint path splitter. The outputs are assigned probabilities.

2.4.13 Type 13: Multiple input/output generator

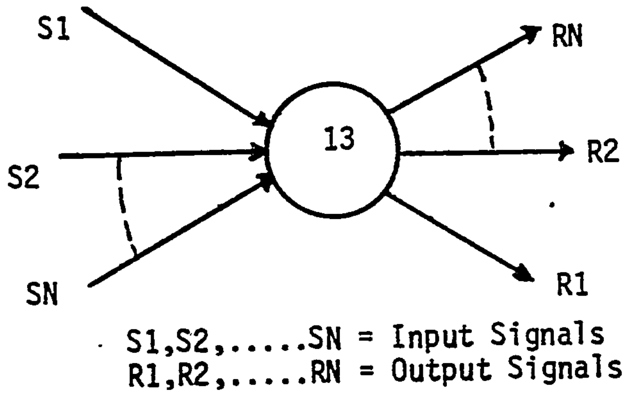
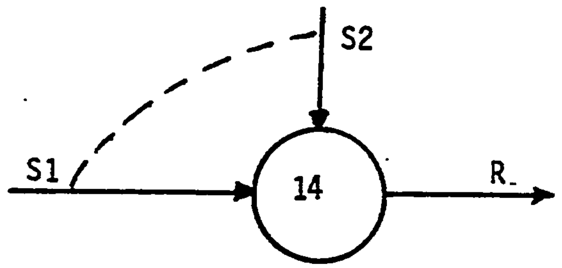


Figure 2.15 Type 13 Operator

2.4.14 Type 14: Linear Combination Generator



S1,...SN = Input Signals
R = Output Signal

Figure 2.16 Type 14 Operator

This is a linear combination generator.

2.4.15 Type 15: Value/Probability gate

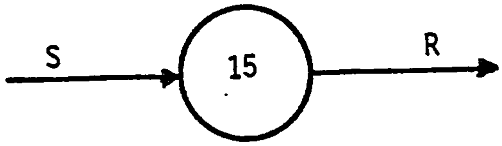


Figure 2.17 Type 15 Operator

This is a value probability gate used to control an output depending on the value of the input.

2.4.16 Type 16: Require deactivation to inhibit signal

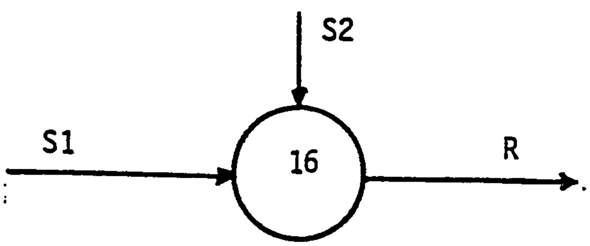


Figure 2.18 Type 16 Operator

This is an actuated normally open contact. The contact is closed at the start of the problem and opens when S2 arrives.

2.4.17 Type 17: Require deactivation to pass signal

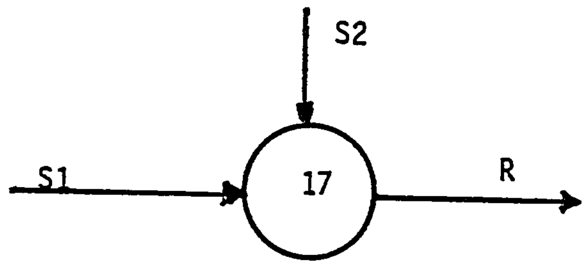


Figure 2.19 Type 17 Operator

This is an actuated normally closed contact. The contact is opened at the start of the problem and closed when S2 arrives.

2.5 System Analysis Using GO

System analysis in the broadest sense is the study of the functionability of a system by evaluating the reliability characteristics of its component parts. Some analytic techniques, such as fault tree analysis [3], assess only the events leading to system failure while other techniques look at the whole set of events which lead to all potential system functionability states. GO is in the latter category. The GO technique is a "success-oriented" approach, meaning that a GO model is constructed to represent the set of ways that a system can successfully function.

The analysis process is shown in Figure 2.20.

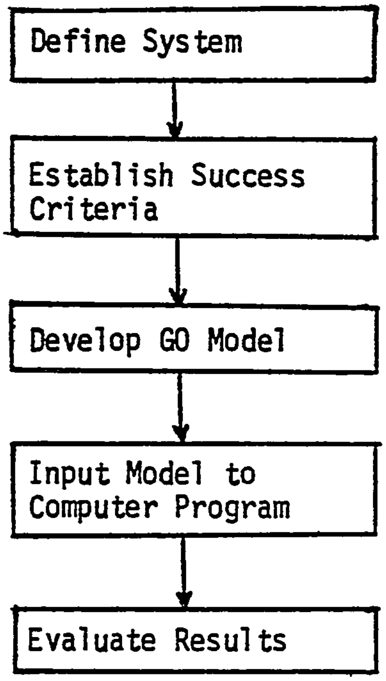


Figure 2.20 The GO Methodology Process

A description of the process is provided below.

2.5.1 System Definition

It is important to identify those components that are important to the system operation. Components that rarely fail can be excluded from the model. A simplified schematic of the system can be drawn, leaving out those components which are either unimportant or at a lower level of detail than is required for the analysis.

A proper analysis of a single system requires a clear definition of the system boundaries i.e., where the system receives its inputs and where it delivers its outputs.

2.5.2 Establish Success Criteria

The success criteria for a system are the set of minimum requirements for system operation. For example the success criteria for a fluid system could be "one out of three" pump trains available to deliver fluid through "two out of three" available valve trains. Success criteria may change from one mode of operation to another. The evaluation of total system reliability or availability must explicitly include these success criteria so that all possible ways to reach system success are included in the model.

2.5.3 Develop GO Model

The GO model is a graphical representation of the GO sequence which in turn corresponds to the key components and their logical combinations for successful operation. This is developed by "substituting" the GO operators for engineering elements as shown in the system schematic. The GO model displays all operators, their types and kinds and signal designations that describe the GO sequence.

2.5.4 Input model to program

The GO model is then translated into an input listing and supplied to the computer program.

2.6 The GO Model

The GO operators described earlier are the building blocks for the GO model. Starting from the system schematic, the GO operators can be used to build up a GO model. These operators are substituted for drawing symbols representing system components. The variety of operator types provides considerable flexibility in the construction of a GO model. In most instances, a single operator type may be used to represent an engineered element. This results in a one-to-one correspondence between the engineered elements and the operators in the GO model.

GO models often closely resemble the schematic drawing of the system being analyzed. A GO model is easily modified for the evaluation of alternate design congigurations, operating procedures, or changes in what is considered as success or failure.

The complete procedure involved in the development of the GO model is described in the following section.

2.7 GO Model Development

The development of the GO model can be shown using an example system. Figure 2.21 shows a fluid delivery system.

The primary input to this system is the water supply from the tank. There are two redundant flow paths. Each path has two pumps in parallel driven by electric power, a check valve and a set of control valves that are normally closed and have to be actuated in order to open. The criteria for successful operation is for either of the two paths or both of them to supply water. The water source is the primary input to the system and the electric power to the pumps and the actuation signals to the control valves are considered as the secondary input signals.

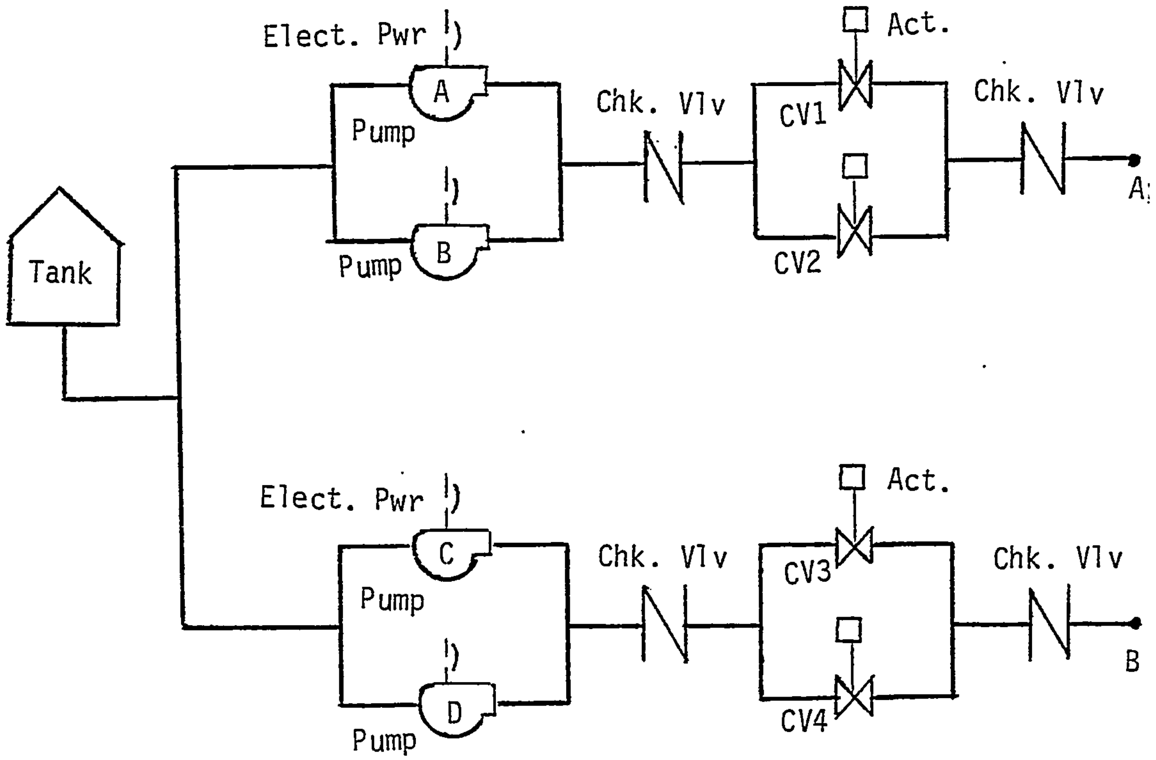


Figure 2.21 Example Fluid Delivery System

The GO model is developed using the following six steps.

1. Define system
2. Establish input/outputs
3. Draw functional GO chart
4. Define operator types
5. Define operator kinds
6. Define signal sequences

The steps are described in the following sections.

2.7.1 Define system:

The necessary information to perform an analysis is collected. Information needed may include system description, schematics and operating procedures. Figure 2.21 shows the schematic in this case.

2.7.2 Establish inputs/outputs:

Every GO model begins with at least one input and often has many inputs which represent the interfacing systems. The output of the model is determined by the success criteria selected. Table 2.3 shows the inputs and the outputs for the example system.

Table 2.3 Input and Output for example system

Inputs	Outputs
Tank	A
EP	B
Act	

2.7.3 Draw functional GO chart:

The system is first represented by the proper selection of GO symbols. Independent components are represented by triangle symbols and dependent components are represented by circle symbols. Figure 2.22 shows the functional GO chart.

The tank is the main input to the system. Every system has to have an independent input. Independent inputs are represented by triangle symbols. The pumps require an electric power supply and these supplies to the pumps are represented as triangle symbols. The control valves are normally closed and need to be actuated in order for them to open. The actuation to them is represented as inputs. The rest of the components are all dependent as they all need some sort of input to produce an output and they are represented as circle symbols.

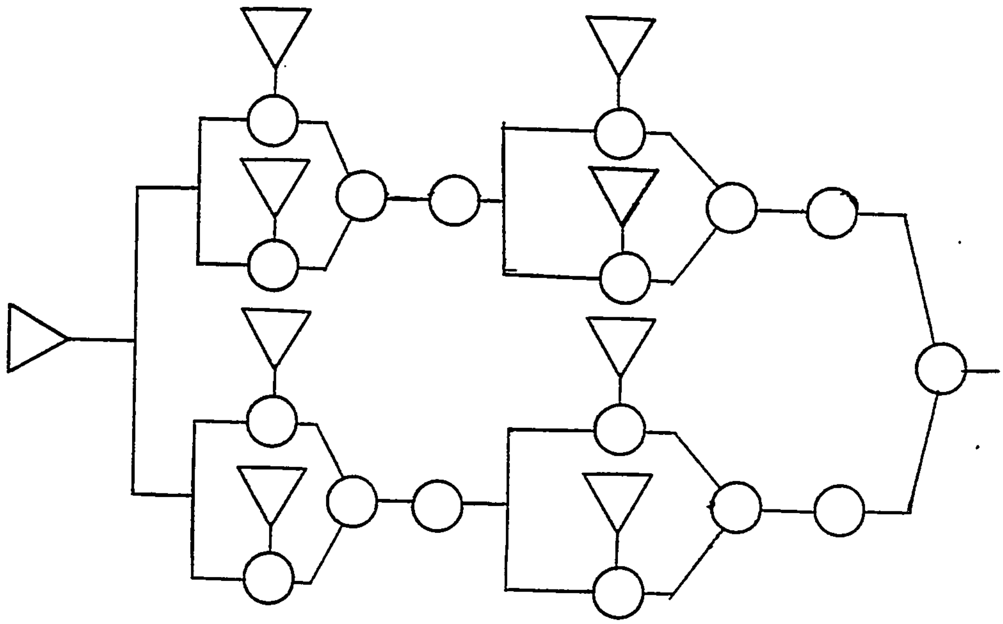


Figure 2.22 Functional GO chart of example system

2.7.4 Define Operator Types:

The operation of each component is analyzed and the GO operator type which most closely represents operation of that physical component is selected. The type number is the first of two numbers within each GO symbol. Figure 2.23 shows the operator types defined for the system.

The Type 5 operator represents a single signal generator. The main tank, the electric power inputs and the actuation signals are represented as Type 5 operators.

The pumps and the control valves are represented as Type 6 operators. The Type 6 operator has been described as one that needs two separate inputs in order to produce an output. The pumps need two inputs, the water from the tank and electric power in order to operate. The control valves need water and an actuation signal to open. Hence these are all represented as Type 6 operators.

The check valves can be represented as type 1 operators as they are simple two state components and can exist in either the up state or the down state and need a single input to produce an output.

The success criteria for this system is that either of the two legs or both have to supply water. The two outputs are combined together using the logical operator Type 2 which is an 'OR' operator.

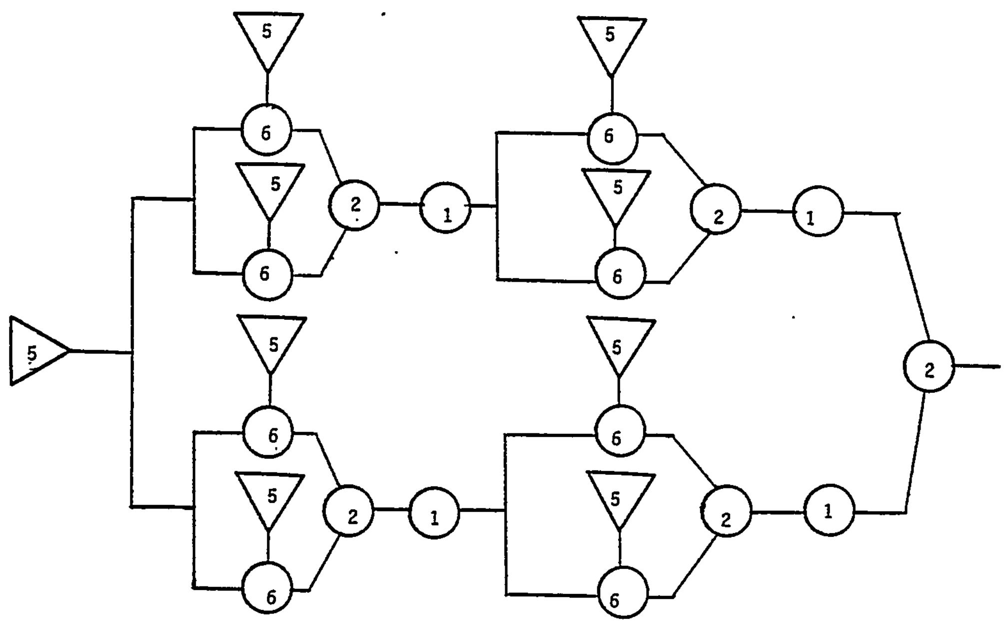


Figure 2.23 Definition of Operator Types

2.7.5 Define Operator Kinds:

Operator kinds identify each component uniquely.The kind number is the second of the two numbers within each GO symbol. Figure 2.24 shows the chart with the type and kind numbers.

The kind numbers uniquely identify each component and they correspond to the probability data in the data record of each component. The Type 2 operator has no kind number as logical operators have no probability data associated with them.

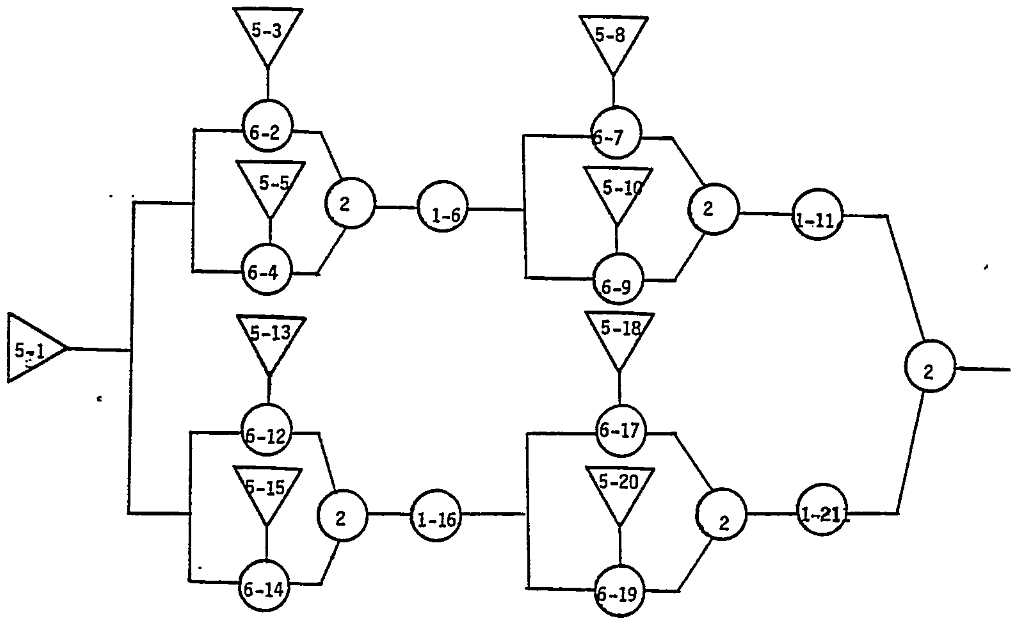


Figure 2.24 Definition of Operator Kinds

2.7.6 Define Signal Sequence:

The paths between GO operators are called signals. The signal numbers are arbitrarily assigned to identify the input/output relationship between GO operators. This is shown in Figure 2.25.

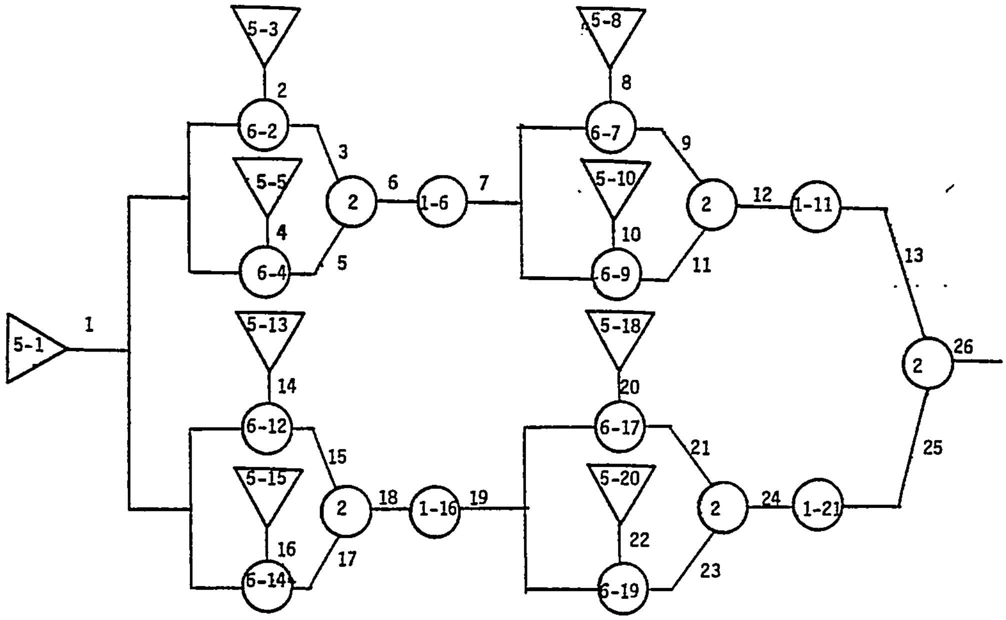


Figure 2.25 Definition of Signal Sequence

Once the model has been developed, the next step in the process is to translate the constructed GO model into an input listing for the GO computer program.

3.7 Conclusion

The GO methodology is a success-oriented probabilistic system analysis technique which can be used to determine system availability. Some of the key features of this method are that the system models follow the normal process flow and the model elements have an almost one-to-one correspondence with the physical components and elements of the system being modeled. The resulting functional GO chart very closely resembles the system schematic and gives a fairly good representation of the system being modeled. This chapter described the GO approach, the operators used in the building of the GO model and the development of the GO model from the basic system schematic.

Chapter 3

THE GO AVAILABILITY CALCULATION PROCESS

3.1 Introduction

The GO model which is developed from the basic system schematic has to be translated into an input listing for the computer program in a definite format. The program processes the input data and carries out the availability calculation. This chapter describes the translation of the model into an input listing for the program and the format of the input. The structure of the program is described and the actual calculation process is explained.

3.2 The Input Listing Format

The GO model has to be translated into an input for the computer program. This input has a definite format and contains the number of components making up the system and the data regarding each component. Each line in the input contains ten numbers and represents the data for a particular component. The data associated with each component contains the operator type and kind number, the active signals and the failure and repair rate for that particular component. As described in Chapter 2, there are three types of operators; independent, dependent and logical. The format for the independent and dependent operators differs from the format for the logical operators.

3.2.1 Independent And Dependent Operator Data

The data corresponding to independent and dependent operators is formatted as follows:

T,K,I,A,O,F,R,b,b,b

where

- T = Type number of component
- K = Kind number of component
- I = Number of the incoming signal
- A = Number of the activating signal
- O = Number of the outgoing signal
- F = Failure rate of component
- R = Repair rate of component
- b = zeroes

Each line in the data set corresponds to a particular component represented by the operator T-K, and the signal numbers represent the signals associated with that particular component. If any of them are absent, then a zero is placed in that position.

3.2.2 Logical Operator Data

Logical operators do not have any probability data associated with them, as described in chapter 2. The data that corresponds to the logical operators is formatted as follows:

T,M,N,S,...,b,..

where

T = Operator type

M = Number of signals required for system success

N = Total number of signals

S = Set of signals that have to be combined logically

b = zeroes

The logical operator can be Type 2, Type 10 or Type 11. If it is Type 2, then the success criteria will be the availability of any one signal. For Type 10, all signals need to be available and for Type 11, which is a majority vote operator, the value of M will depend on the success criteria required. The number of signals indicated by S will depend on the number of signals that have to be combined logically and the remaining spaces will be occupied by zeroes.

3.2.3 Termination Of The Process

The end of the input file is indicated by placing a zero in the first position of the last line in the input file. This is followed by the signals that need to be combined finally and the final output signal that is required.

3.3 The GO Calculational Routine

The program is divided into several modules. The data can be input to the main program in the format described in the previous section. Once the data is accepted by the program, it is checked for any errors. The data is then processed. This having been done, the program calls the subroutine AVAIL which is the major routine carrying out the availability calculation. There are a number of other subroutines used by AVAIL in the calculation of availability. Figure 3.1 shows the complete arrangement of the program together with all the subroutines used by the program.

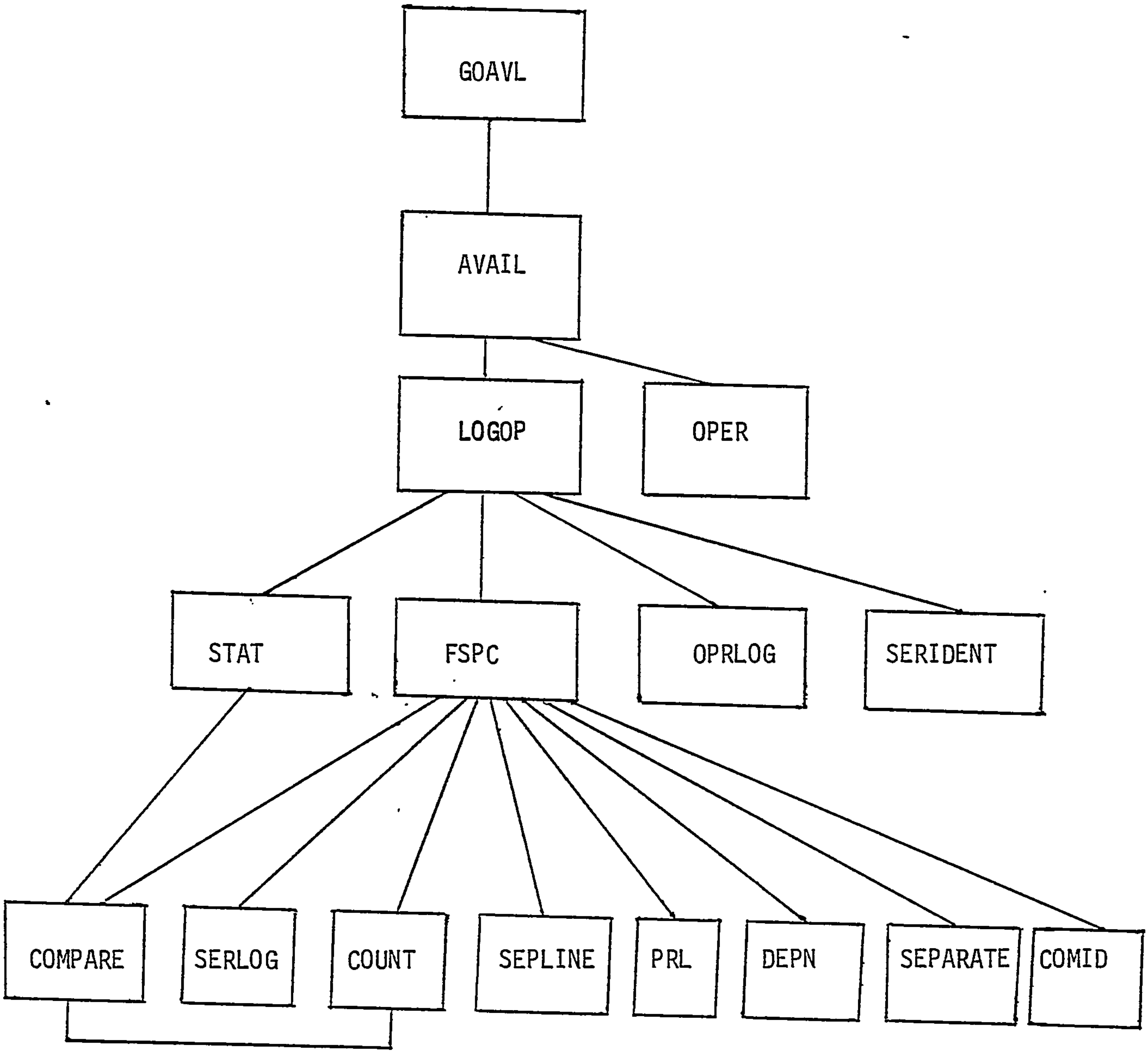


Figure 3.1 Structure of the GO program

3.4 Availability Calculation

The complete GO chart for the system shown in Figure 2.21 is given in Figure 2.25. The GO calculational routine uses the data input prepared from the GO chart in the required format. Once the data has been processed by the main program, the calculation process is initiated beginning with the main input to the system. The availability at each point in the GO chart is calculated. The availability at point 1 will be the availability of the component represented by the operator 5-1. The next operator encountered along the signal path is 6-2. The availability at point 1 is multiplied with that of the component represented by 5-3 and that of the component 6-2 itself. The value thus obtained is the availability of signal 3 in the GO chart. The availabilty at signal point 5 is similarly obtained. These two signals have to be combined logically and this is done by the logical operator 2. The operator encountered next is 1-6 and the availability of the component represented by this operator is multiplied by the value of signal 6. Values at signal points 9 and 11 are obtained as described above and these are again combined logically to obtain a value at signal point 12 which is then combined with the operator 1-11 and the value at point 13 is obtained. Signal point availabilities along the other leg are obtained in a similar manner and the final two values at signals 13 and 25 are combined to get the final value. The value at signal point 26 is the final availability index of the system.

The data for the individual components making up the system shown in Figure 2.21 are shown in Table 3.1.

Table 3.1 Component Data for System

Component Type	Failure Rate f/yr	Repair Rate r/yr
5	3	62
6	2	63
1	2	58

The GO chart shown in Figure 2.25 can be converted into an input listing for the program as shown below.

```
21
5,1,0,0,1,3,62,0,0,0
6,2,1,2,3,2,63,0,0,0
5,3,0,0,2,3,62,0,0,0
6,4,1,4,5,2,63,0,0,0
5,5,0,0,4,3,62,0,0,0
2,3,5,6,0,0,0,0,0,0
1,6,6,0,7,2,58,0,0,0
6,7,7,8,9,2,63,0,0,0
5,8,0,0,8,3,62,0,0,0
6,9,7,10,11,2,63,0,0,0
5,10,0,0,10,3,62,0,0,0
2,9,11,12,0,0,0,0,0,0
1,11,12,0,13,2,58,0,0,0
6,12,1,14,15,2,63,0,0,0
5,13,0,0,14,3,62,0,0,0
6,14,1,16,17,2,63,0,0,0
5,15,0,0,16,3,62,0,0,0
2,15,17,18,0,0,0,0,0,0
1,16,18,0,19,2,58,0,0,0
6,17,19,20,21,2,63,0,0,0
5,18,0,0,20,3,62,0,0,0
6,19,19,22,23,2,63,0,0,0
5,20,0,0,22,3,62,0,0,0
2,21,23,24,0,0,0,0,0,0
1,21,24,0,25,2,58,0,0,0
2,13,25,26,0,0,0,0,0,0
0,13,25,26,0,0,0,0,0,0
```

Table 3.2 shows the calculation carried out to obtain the availability at each signal point. In this table, A(X) denotes the availability of signal X. The availability is the product of the availabilities of the components and the signals involved with that particular signal.

Table 3.2 Calculation of Availability at individual signal points

Signal	Comp/Sig involved	Availability
1	5-1	0.9538462
3	A(1),6-2,5-3	0.8818280
5	A(1),6-4,5-5	0.8818280
6	A(3),A(5)	0.9484086
7	A(6),1-6	0.9167949
9	A(7),6-7,5-8	0.8475742
11	A(7),6-9,5-10	0.8475742
12	A(9),A(11)	0.9115685
13	A(12),1-11	0.8811829
15	A(1),6-12,5-13	0.8811829
17	A(1),6-14,5-15	0.8818279
18	A(15),A(17)	0.9484086
19	A(18),1-16	0.9167949
21	A(19),6-17,5-18	0.8475742
23	A(19),6-19,5-20	0.8475742
24	A(21),A(23)	0.9115685
25	A(24),1-21	0.8811829
26	A(13),A(25)	0.9105557

The overall availability of the system is the value obtained at signal point 26.

3.5 Conclusion

This chapter described the format of the input listing for the computer program, the structure of the program used in the study and the calculation of the availability of the system using the program and the GO model.

The GO process described in Chapter 2 is simple and easy to implement. The modeling permits great flexibility and modifications in the model can easily be made. The model corresponds very closely to the schematic of the original system and hence still maintains a good likeness to the physical configuration of the system unlike other modeling methods. The calculational routine follows the path of the signals and uses a combinatorial process to put together the probabilities of the components it encounters in that path before logically combining the outputs according to the success requirement. This combination process assumes independence of the components encountered in the path followed by the signals. The components encountered along a path are taken to be in series and this assumption of independence of series elements leads to an overestimation of unavailability. This concept is discussed in detail in the next chapter.

Chapter 4

SERIES SYSTEMS

4.1 Introduction

Chapter 3 concluded by stating that the GO calculation of system availability is an underestimation as independence of series elements is assumed whenever they are encountered by the calculation routines. A study of series systems using Markov models shows how this assumption affects the value calculated.

Most engineering systems are made up of a combination of series and parallel configurations. Simple reduction techniques exist [1] which can be used to sequentially reduce the overall configuration to a simple block. Series elements are combined together using the product rule [1]. This rule states that the reliability indices of the individual components making up the series chain are multiplied together to obtain the system reliability. The major assumption made here is that the individual components making up the series system are statistically independent. This assumption leads to an overestimation of the system unavailability. This chapter illustrates the modification that is required in order to correctly calculate the system availability.

4.2 Independence in Series Systems

Many engineering systems when examined from a reliability point of view, can be seen to be made up of a combination of elements which may be in series, in parallel, or some combination of the two. Series and parallel systems can be differentiated on the basis of the relationship that exists between the components.

A parallel system is defined as [1] "The components in a set are said to be in parallel from a reliability point of view if only one needs to be working for system success or all must fail for system failure".

A series system is defined as [1],"The components in a set are said to be in series from a reliability point of view if they must all work for system success or only one need fail for the system to fail".

Two points can be made regarding a series system. The first one is that the failure of any component in the system will lead to system failure. The second point is that once the system has failed, there may or may not be any possibility of any further failures occuring.

Consider the system shown in Figure 4.1 made up of ten identical components each with its failure rate λ= 2 f/yr and its repair rate $\mu = 250$ r/yr.

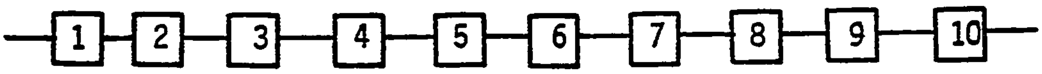


Figure 4.1 Ten component series system

The availability of each component is

$$A_c = \frac{\mu}{\lambda + \mu}$$

$$= 250/(2+250)$$

$$= 0.99206350$$

The availability of the ten component system is

$$A_s = (A_c)^{10}$$

$$= (0.99206350)^{10}$$

$$= 0.923410$$

The availability of the ten component series system is obtained simply by multiplying together the availabilities of the individual components. The assumption of statistical independence which is made assumes that further component failures are possible even if the system has failed. This can be illustrated using a simple two component series system and a Markov model of the system.

4.2.1 The Markov Model

Repairable components can generally exist in two states, the up or the working state and the down or the failed state. A system that is made up of components that have failure and repair characteristics associated with exponential distributions can be described as a Markov Process [1]. This is a memoryless process in which the previous history of the process does not affect the subsequent events. The conditional probability of a failure or repair during any fixed interval of time is constant for such systems. These systems can be modeled using the conventional Markov approach [1].

4.2.2 The Markov Model for a 2 unit series system

Consider a series system made up of 2 components, component 1 and component 2, as shown in Figure 4.2.

Figure 4.2 Two Component Series System

Let

λ_1 = failure rate of component 1

λ_2 = failure rate of component 2

μ_1 = repair rate of component 1

μ_2 = repair rate of component 2

The state space diagram for this system is shown in Figure 4.3.

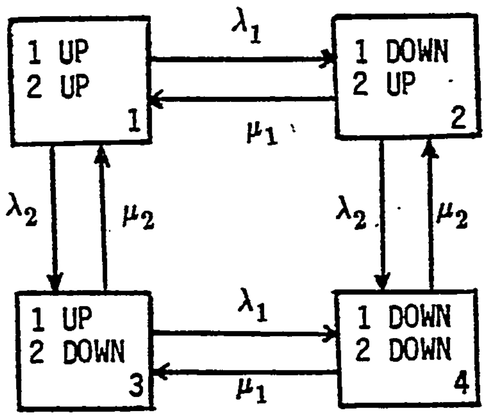


Figure 4.3 State Space Diagram for the two unit series system

The transition probabilities can be represented by the stochastic transitional probability matrix P shown in Equation 4.1.

$$P = \begin{bmatrix} 1-(\lambda_1+\lambda_2) & \lambda_1 & \lambda_2 & 0 \\ \mu_1 & 1-(\mu_1+\lambda_2) & 0 & \lambda_2 \\ \mu_2 & 0 & 1-(\mu_2+\lambda_1) & \lambda_1 \\ 0 & \mu_2 & \mu_1 & 1-(\mu_2+\mu_1) \end{bmatrix} \quad (4.1)$$

The steady state or limiting values of the state probabilities can be evaluated from this matrix using a technique involving the matrix multiplication method. The principle of this technique [1] is that, once the limiting state probabilities have been reached by the matrix multiplication method, any further multiplication by the stochastic transitional probability matrix does not change the values of the limiting state probabilities. If α represents the limiting probability vector and P is the stochastic transitional probability matrix, then

$$\alpha P = \alpha \tag{4.2}$$

where

$$\alpha = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 \end{bmatrix} \tag{4.3}$$

P is as shown in Equation 4.1

P_1, P_2, P_3, and P_4 are the probabilities of existing in states 1, 2, 3, and 4 respectively.

The system in Figure 4.2 is a series system and therefore,

$$P_{up} = P_1 \tag{4.4}$$

$$P_{dn} = P_2 + P_3 + P_4 \tag{4.5}$$

where

$$P_1 = \frac{\mu_1 \mu_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{4.6}$$

The availability of the system, therefore, is the probability of being found in state 1. This value can be more easily obtained from the product of the individual component availabilities.

Consider the system shown in Figure 4.2 to have the following transition rates

$\lambda_1 = 0.05$ f/hr

$\lambda_2 = 0.04$ f/hr

$\mu_1 = 0.4$ r/hr

$\mu_2 = 0.5$ r/hr

From the state transition diagram shown in Figure 4.3, the stochastic transitional probability matrix is

$$P = \begin{bmatrix} 0.91 & 0.05 & 0.04 & 0 \\ 0.4 & 0.56 & 0 & 0.04 \\ 0.5 & 0 & 0.45 & 0.05 \\ 0 & 0.5 & 0.4 & 0.1 \end{bmatrix}$$

From Equation 4.2, $\alpha P = \alpha$

where $\alpha = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 \end{bmatrix}$

Using Equation 4.2 and Equation 4.3 and solving for P_1, P_2, P_3, and P_4,

$P_1 = 0.82304530$

$P_2 = 0.10288070$

$P_3 = 0.06584360$

$P_4 = 0.00823045$

The availability of the system is given by P_1, the probability of being found in the 'up' state. The availability of the system is

$A = 0.82304530$

Using the product rule,

Availability of the system = $A_1 * A_2$

where

A_1 = Availability of component 1 = 0.4/(0.4+0.05)

= 0.88888890

A_2 = Availability of component 2 = 0.5/(0.5+0.04)

= 0.92592590

Availability of the system = $A_1 * A_2$

= (0.88888890)*(0.92592590)

= 0.82304530

4.2.3 The Concept of Dependence

The state space diagram of the two unit system described earlier is shown in Figure 4.3. The diagram shows all the possible states that the system can exist in and the transitions between these states. There are four states that are possible in this case and the system can exist in any one of the states shown. For the described system, State 1 of the state space diagram constitutes the 'up' or the success state and the remaining three states make up the 'down' or the failed states.

Failure of any component in a series system leads to the failure of the system and in certain systems no further failures can occur once the system has failed. Under this condition State 4 of the state space diagram shown in Figure 4.3 cannot exist.

State 1 of the diagram is the state in which both the components are working. Failure of Component 1 will send the system into State 2. The other possibility is the failure of Component 2, in which case the system will transit to State 3. In both of these cases, the system moves into a failed state. Since the system is no longer operational, having entered either of the two failed states, there is no possibility of any further failures occurring. This means that the system cannot travel into State 4 from either State 3 or State 2. Repair and installation of the failed component will put the system back into State 1. The transition rates between State 3 and State 4 and between State 2 and State 4 are therefore zero, and in effect State 4 does not exist. The state space diagram of a two component series system would, therefore, be as shown in Figure 4.4.

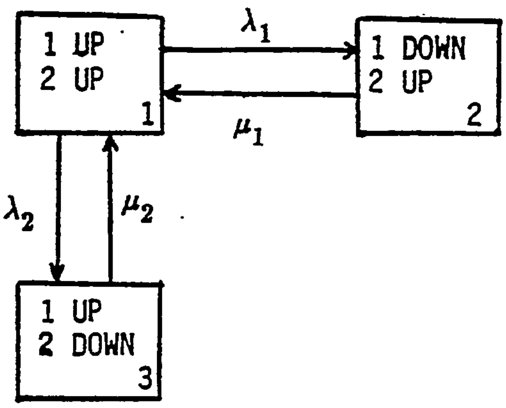


Figure 4.4 State Space Diagram for a two unit system without state 4.

Using the same example of the system shown in Figure 4.2, and considering the state space diagram shown in Figure 4.4, the stochastic transitional probability matrix is

$$P = \begin{bmatrix} 0.91 & 0.05 & 0.04 \\ 0.4 & 0.6 & 0 \\ 0.5 & 0 & 0.5 \end{bmatrix}$$

From Equation 4.2 and Equation 4.3, solving for P_1, P_2, and P_3,

$$P_1 = 0.82998755$$

$$P_2 = 0.10373440$$

$$P_3 = 0.06639000$$

The availability of the system, given by P_1, is

$$A = 0.82987550$$

This value is higher than the one obtained previously in the case where all the four states were considered. It can be concluded that the physical attributes of the system must be considered when conducting an availability analysis and it may not be correct to simply multiply the individual availabilities to obtain the overall availability of a system.

4.3 Equivalence in Series Systems

Billinton and Hosain [5] have examined the concept of reliability equivalents and suggested their applicability to the general reliability analysis of engineering systems. A reliability equivalent is a reduced model which retains the pertinent system parameters required for a particular study. The method of calculating the equivalent rates has been described in Reference [5].

Figure 4.3 shows the state space diagram for the simple two component series system described in Figure 4.2. The state space diagram assumes that all the states shown in the figure can exist.

The two components can be replaced by an equivalent component. This can be done by finding an equivalent failure rate λ_s, and an equivalent repair rate μ_s, of the equivalent component which represents the two components.

The availability of this equivalent component would then be

$$A_s = \frac{\mu_s}{(\lambda_s + \mu_s)} \quad (4.7)$$

Equation 4.6 gives the availability of a two independent component system. Equations 4.6 and 4.7 should be equal for the equivalent component to represent the two component system.

$$\frac{\mu_1 \mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} = \frac{\mu_s}{(\lambda_s+\mu_s)} \quad (4.8)$$

The transition rate from the system up state for the equivalent component is λ_s, and for the two component system is $\lambda_1 + \lambda_2$. Therefore,

$$\lambda_s = (\lambda_1 + \lambda_2) \quad (4.9)$$

Substituting Equation 4.9 into Equation 4.8 and replacing the repair rates, μ_i, by their reciprocals, the average repair times r_i, gives,

$$r_s = \frac{1}{\mu_s} = \frac{\lambda_1 r_1 + \lambda_2 r_2 + \lambda_1 \lambda_2 r_1 r_2}{\lambda_s} \qquad (4.10)$$

In some systems, the product $\lambda_i r_i$ is very small and therefore, $\lambda_1 \lambda_2 r_1 r_2$ <<< $\lambda_1 r_1$. Thus Equation 4.10 reduces to

$$r_s = \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_s} \qquad (4.11)$$

The reciprocal of r_s will give μ_s.

The failure and repair rates of a general n-component series system can be determined in a similar manner and are as follows:

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \quad (4.12)$$

$$r_s = \frac{\sum_{i=1}^{n} \lambda_i r_i}{\lambda_s} \quad (4.13)$$

$$\mu_s = \frac{1}{r_s} \quad (4.14)$$

The equivalent rates can be obtained in a more general way using Markov modeling concepts [1].

The system represented by Figure 4.4 can be reduced to the equivalent system shown in Figure 4.5.

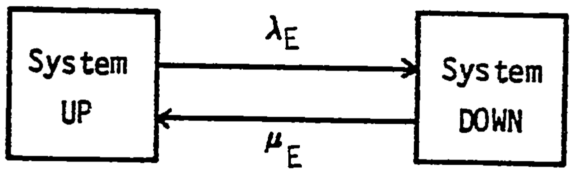


Figure 4.5 Equivalent System

The frequency of encountering the available state in the complete model must equal the frequency of encountering the same condition in the equivalent model. The frequency of encountering a state is given by the product of the probability of that state and the sum of the transitions out of that state [1]. P_1 is the probability of the available state in the complete model and the transitions out of the state are $\lambda_1+\lambda_2$. A is the probability of the available state in the reduced model and λ_E is the transition out of the state. Then,

$$P_1(\lambda_1+\lambda_2)= A\lambda_E \qquad (4.15)$$

but

$$P_1 = A \qquad (4.16)$$

therefore

$$\lambda_E = (\lambda_1+\lambda_2) \qquad (4.17)$$

Consider the system shown in Figure 4.4, where once a component failure has occurred, the system is in the failed state and no further component failures can occur. The solution of the Markov model for P_1, which is the availability of the system is given by Equation 4.18.

$$P_1 = \frac{\mu_1 \mu_2}{\mu_1 \mu_2 + \lambda_1 \mu_2 + \lambda_2 \mu_1} \tag{4.18}$$

Now,

$$A = \frac{\mu_E}{\lambda_E + \mu_E} \tag{4.19}$$

where A is the availability of the equivalent component and λ_E and μ_E are the equivalent transition rates. As the availabilities obtained by solving both the the equivalent model and the complete model must be equal,

$$\frac{\mu_E}{\lambda_E + \mu_E} = \frac{\mu_1 \mu_2}{\mu_1 \mu_2 + \lambda_1 \mu_2 + \lambda_2 \mu_1} \tag{4.20}$$

from which

$$\mu_E = \frac{\mu_1 \mu_2 (\lambda_1 + \lambda_2)}{\lambda_1 \mu_2 + \lambda_2 \mu_1} \tag{4.21}$$

and

$$r_E = \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_1 + \lambda_2} \tag{4.22}$$

It can be seen that Equation 4.22 is the same as Equation 4.11 which was obtained as an approximation. Equation 4.22 is an exact equation for the average downtime of a two component series system in which when one failure occurs no further failures can occur until the system is placed back in operation. The technique of combining series elements together and representing them by a single equivalent component incorporates into the analysis of series chains, the concept of dependence. The equivalent rates are obtained by considering only the transitions between the states that can exist in practice and hence the resulting value of availability is more accurate than that obtained assuming that all states are possible. The use of equivalent components with appropriate failure and repair rates provides an accurate means of calculating the availability of a series system.

The difference in the calculated values considering independence and dependence can be seen using the example three component series system shown in Figure 4.6.

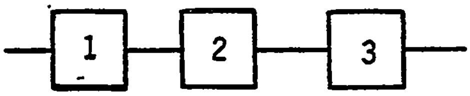


Figure 4.6 Example three component series system

The components making up the system have the following data

$\lambda_1 = 2$ f/yr $\quad \mu_1 = 250$ r/yr

$\lambda_2 = 3$ f/yr $\quad \mu_2 = 265$ r/yr

$\lambda_3 = 4$ f/yr $\quad \mu_3 = 270$ r/yr.

Considering Independence

Availability of component 1 = A_1 = 250/(2+250)

= 0.99206350

Availability of component 2 = A_2 = 265/(3+265)

= 0.98880600

Availability of component 3 = A_3 = 270/(4+270)

= 0.98540150

Availability of the system = A_s = $A_1 * A_2 * A_3$

= 0.96663780

Considering Dependence

From Equation 4.12,

$$\lambda_E = 9 \text{ f/yr.}$$

From Equation 4.13 and Equation 4.14,

$$\mu_E = 263.654250 \text{ r/yr.}$$

$$\text{System Availability, } A_s = \frac{\mu_E}{\lambda_E+\mu_E}$$

$$= 263.654250/(9+263.654250)$$

$$A_s = 0.96699120$$

It can be seen that the assumption of independence underestimates the availability of this system. The degree of underestimation depends on the failure and repair parameters, the number of components and the system configuration. Figure 4.7 shows the variation of unavailability with the increase in the number of series components for different individual component availabilities. Curve 1 of each set is obtained by considering independence and Curve 2 is obtained by considering dependence. The individual component data considered for each set of curves is contained in Table 4.1.

Table 4.1 Component Data for Curves of Figure 4.7

Set No.	Individual Component Data		
	f/yr	r/yr	Availability
1	1	350	0.9971510
2	2	350	0.9943182
3	4	350	0.9887000

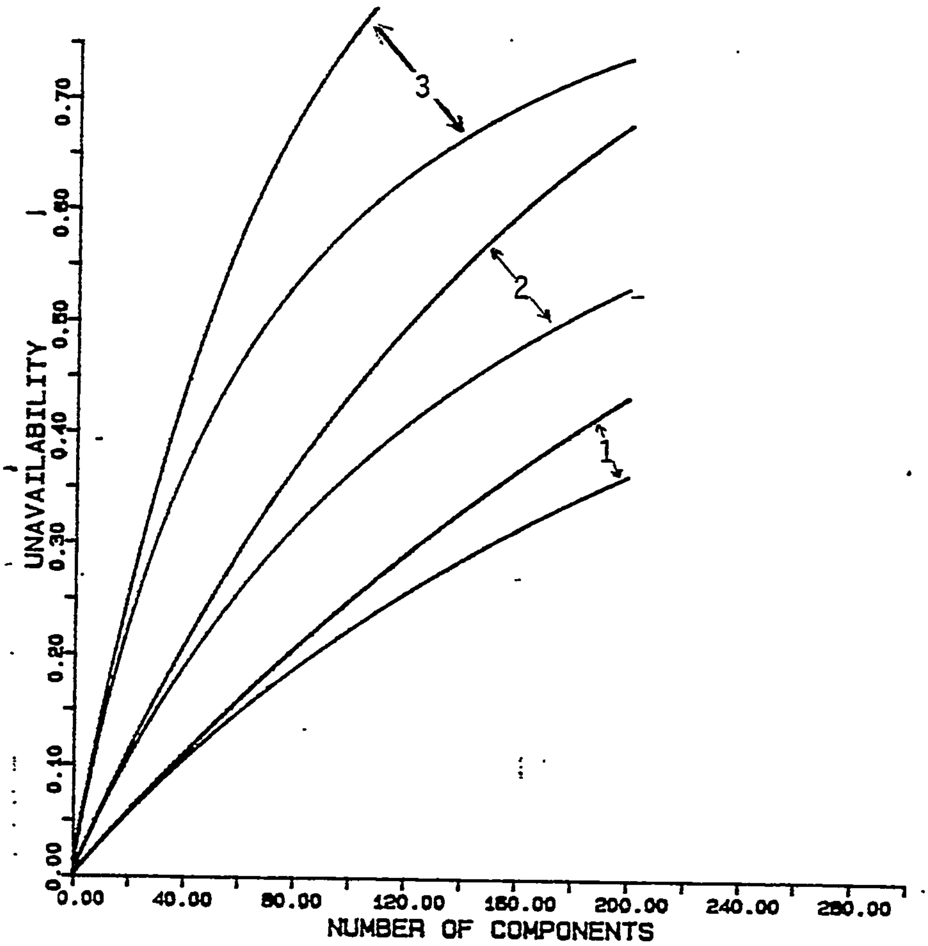


Figure 4.7 Variation of Unavailability with number of series components

Figure 4.8 shows the variation of error between the unavailability values calculated with and without independence for different individual component availabilities. The component data used is contained in Table 4.2.

Table 4.2 Component Data for Curves of Figure 4.8

Curve No.	Individual Component Data		
	f/yr	r/yr	Availability
1	1	350	0.9971510
2	2	350	0.9943182
3	3	350	0.9915014
4	4	350	0.9887000
5	5	350	0.9859155

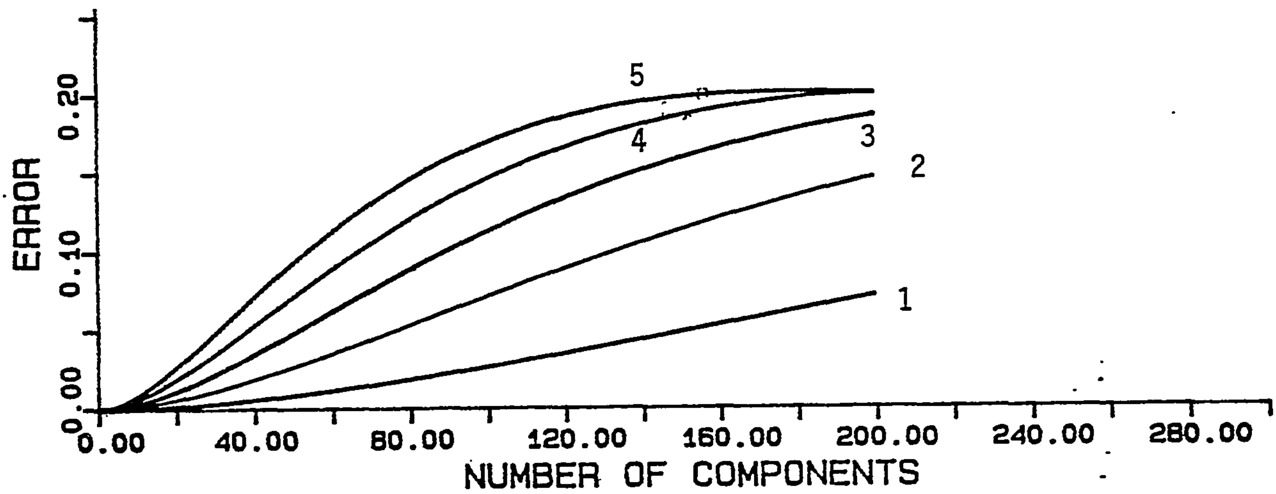


Figure 4.8 Variation of error with number of series components

4.4 Conclusion

This chapter has discussed the effect that the assumption of component independence in a series system has on the calculated availability index of a simple series system. The chapter described the concept of equivalent components replacing the individual components and the manner in which the equivalent failure and repair rates can be calculated. Systems are usually made up of a combination of series and parallel branches and other combinations. The series branches in such systems can be treated in the manner described in this chapter. In certain systems, this leads to a more accurate calculation of system availability. This modification can be incorporated into the GO routines so that series elements are not assumed to be independent.

Chapter 5

THE MODIFICATION OF THE GO METHOD

5.1 Introduction

Chapter Four discussed the use of equivalents in analysing series systems. The components in the series chain were represented as an equivalent component with an equivalent failure rate and an equivalent repair rate. The concept of dependence was introduced by considering the Markov model of the system to have all states containing more than a single failure eliminated. The calculated availability of the equivalent component which represents the individual components is higher than the availability calculated by considering the components individually and multiplying successively the availabilities of those components.

This approach can be incorporated into the GO calculational routine so that components are combined by forming equivalent components to represent the individual components in a series path. This chapter describes how this modification can be incorporated into the GO method.

5.2 The Modification

The calculation of availability using the GO method was described in Chapter Two. Chapter Four examined the effect of assuming independence of series elements in a system on the calculated availability. The use of equivalents was discussed and Eqn. 4.12 and Eqn. 4.14 described the equations that are used to calculate the failure and repair rates of the equivalent component.

Figure 5.1 shows the GO chart of a simple system which can be used to illustrate the formation of equivalent components.

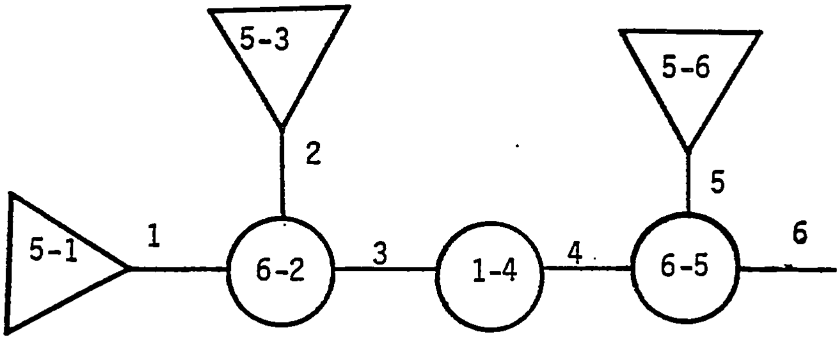


Figure 5.1 GO chart of system to illustrate formation of equivalent components.

The original GO method arrives at the availability at signal point 6 in the manner described below.

The availability of component 5-1, is given as A_1. The availability A_1 is then multiplied by the availabilities A2 and A_3 of components 6-2 and 5-3 respectively to produce A_4. The availability A_4 at signal point 3, is now further multiplied by A_5, the availability of component 1-4, to produce A_6, the availability at signal point 4. This process continues until the availability at signal point 6 is calculated. This process, therefore, successively multiplies the individual availabilities of the components encountered along the path, until all the series elements in a system are combined.

The same path can now be considered using the concepts described in Chapter Four. The components along the path can be combined successively to produce equivalent components to represent the individual components. Starting with component 5-1, the first components encountered are 6-2 and 5-3. Component 6-2 which is a type 6 operator, requires two inputs to produce an output, as was described in Chapter Two. Therefore components 5-1, 6-2 and 5-3 are essentially in series. These three components can now be combined together to form an equivalent component A as shown in Figure 5.2.

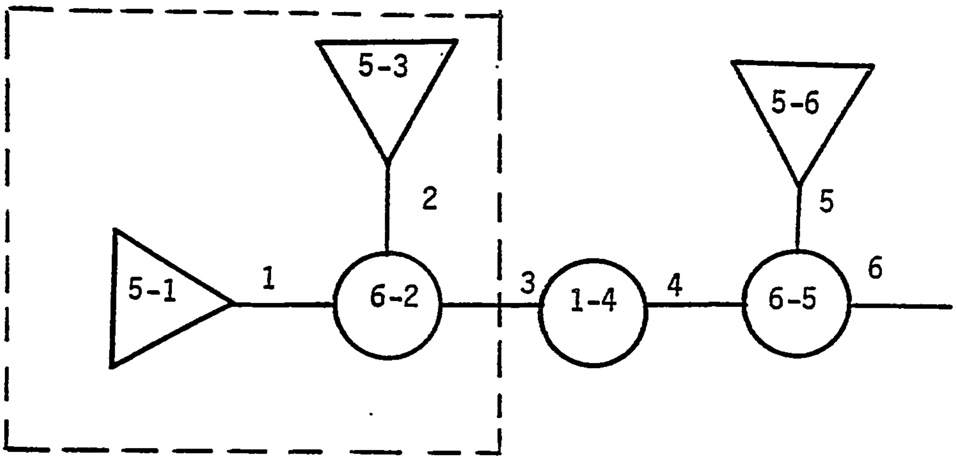


Figure 5.2 Formation of equivalent component A

The equivalent failure rate of component A, λ_A can be calculated using Equation 4.12 and the equivalent repair rate, μ_A can be calculated using Equation 4.14. The equivalent availability A_{eq1} at point 3 can be calculated using λ_A and μ_A. The next step involves combining component A with component 1-4. This results in an equivalent component B as shown in Figure 5.3.

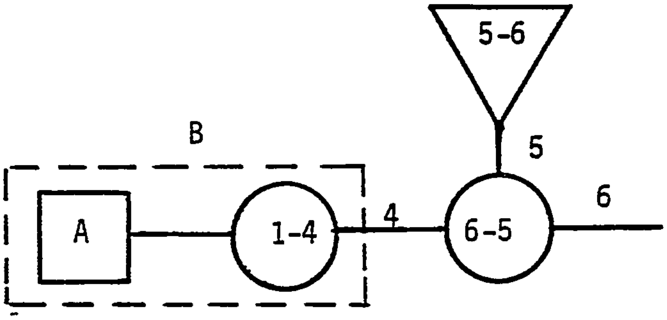


Figure 5.3 Formation of equivalent component B

The failure rate λ_A of equivalent component A and the repair rate μ_A of the equivalent component A are combined with the failure and repair rates of component 1-4 using Eqn. 4.12 and Eqn. 4.14 to produce an equivalent failure rate λ_B and equivalent repair rate μ_B which can be used to calculate the availability A_{eq2} of component B. This is the index at signal point 4. Figure 5.4 shows how the remaining components in the chain can be combined to produce the final equivalent component C.

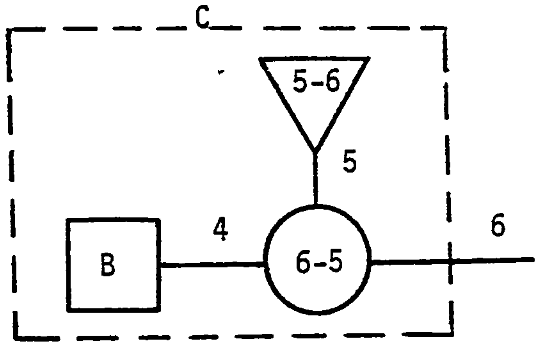


Figure 5.4 Formation of equivalent component C

The failure and repair rates, λ_B and μ_B, of equivalent component B can now be combined with the failure and repair rates of components 5-6 and 6-5 to produce the equivalent failure rate λ_c and equivalent repair rate μ_c of equivalent component C. The availability of this component and the availability at signal point 6, A_{eq3} can be calculated using λ_c and μ_c.

Table 5.1 shows the successive formation of equivalent components which leads to the availability at signal point 6 in the example shown in Figure 5.1.

Table 5.1 Formation of equivalent components

Sig No.	Comps Involved	Eq. Comp.	Eq. Rates f/yr	r/yr	Availability
1	5-1	-	3	62	0.9538462
3	5-1,5-3,6-2	Aeq	8	62.247	0.8861162
4	Aeq,1-4	Beq	10	61.3485	0.859843
6	Beq,5-6,6-5	Ceq	15	61.6937	0.804417

Table 5.2 shows the difference in the signal point availabilities using the original and the modified method.

Table 5.2 Compared signal point availabilities

Sig. No.	Availability Original Method	Modified Method
1	0.95384616	0.95384616
3	0.88182790	0.88611620
4	0.85243300	0.85984300
6	0.78807241	0.80441700

5.3 Conclusion

This chapter described the basic procedure by which the GO calculational routine can be modified to consider dependence of series elements in a series system. The use of equivalents, as discussed in Chapter Four, has been incorporated into the calculational routine where the probabilities of successive individual components are simply multiplied together in the original approach. Instead of just being multiplied together, successive equivalents are now formed and the availability of the equivalents is calculated. The modeling procedure, however, remains the same as in the original approach. The modified approach leads to a more accurate value of availability for those systems in which when one component fails no further failures can occur.

Chapter 6

APPLICATIONS AND COMPARISON OF THE TWO METHODS

6.1 Introduction

The modifications incorporated into the basic GO method were described in Chapter 5. The improvement in the calculated availability index using the modified approach was shown using a simple series system. This chapter illustrates the application of the two methods to a more practical situation. A propulsion subsystem of a ship [6] has been selected to provide a practical framework for assessing the difference in availability as determined by the two methods. The impact on the calculated availability using the modified method is a function of the number of components in the series system. This situation can be illustrated using a simple series example.

The number of components in a series system affects the calculated availability index. The two methods were applied to a simple series system in which the number of components in series were steadily increased. Identical components with λ=0.002 f/hr and μ=0.2 r/hr were considered. The availability of a single component is 0.990099. The variation in the difference between the calculated values with the number of series components is shown in Table 6.1.

Table 6.1 Difference in values with increase in complexity

No. of Components	Original Method	Modified Method	Difference
2	0.98029608	0.98039222	0.00009614
3	0.97059017	0.97087377	0.00028360
4	0.96098036	0.96153843	0.00055808
5	0.95146573	0.95238096	0.00091523
6	0.94204527	0.94339627	0.00135100
7	0.93271810	0.93457943	0.00186133
8	0.92348325	0.92592591	0.00244266
9	0.91433984	0.91743118	0.00309134
10	0.90528697	0.90909094	0.00380397
11	0.89632374	0.90090090	0.00457716
12	0.88744926	0.89285713	0.00540787
13	0.87866265	0.88495570	0.00629306
14	0.86996299	0.87719297	0.00722998
15	0.86134952	0.86956525	0.00821573
16	0.85282129	0.86206895	0.00924766

Figure 6.1 shows the increase in the difference as the number of components in this series system is increased.

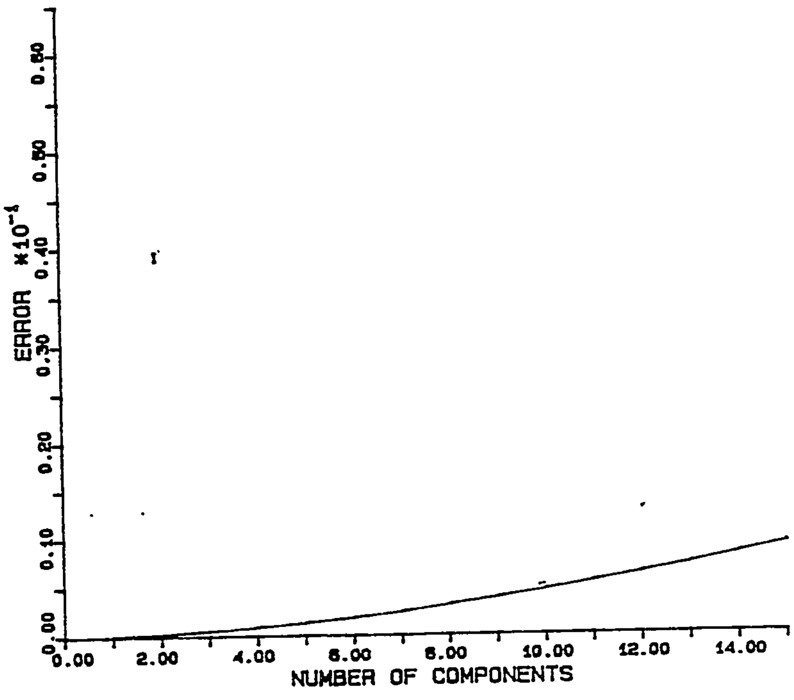


Figure 6.1 Variation in the difference with number of series components

Figure 6.2 shows the decrease in the availability as the number of series components in the system increases.

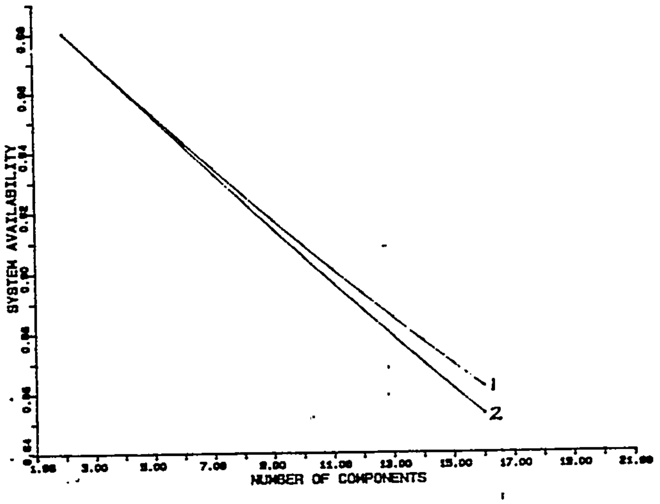


Figure 6.2 Variation of availability with number of series components

In Figure 6.2, Curve 1 shows the decrease in the availability when the modified method is used and Curve 2 when the original method is used. The availability of the system depends on the availability of the individual components making up the system. Table 6.2 shows the variation in the availability of a series system containing sixteen components when the availability of the individual components is varied.

Table 6.2 Variation of System availability with component availability

Component Availability	System Availability		Difference
	Original	Modified	
0.990099	0.852821	0.862069	0.009248
0.980392	0.728446	0.757575	0.029129
0.970873	0.623167	0.675675	0.052508
0.961538	0.533908	0.609756	0.075848
0.952381	0.458112	0.555556	0.097444

6.2 Practical System Application

The two methods were applied to a practical system. Figure 6.3 shows the component level block diagram of the propulsion subsystem of a ship. The complete system component data and description of the system components are shown in Table 6.3.

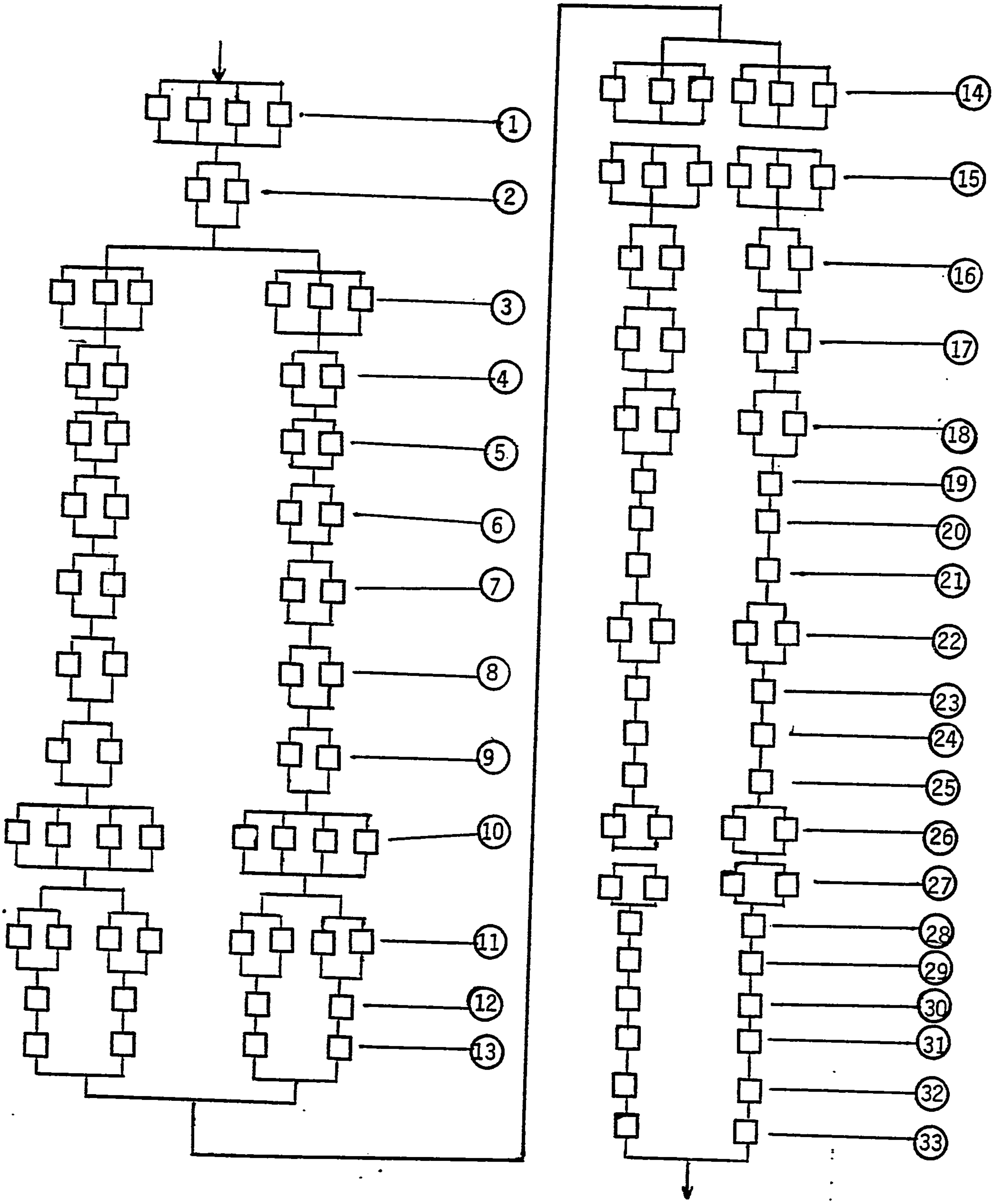


Figure 6.3 Propulsion Subsystem Block Diagram

Table 6.3 Component Data of System

Block No.	Item	Failure Rate f/yr	Repair Rate r/yr
1	Drain Pump	0.000038	0.04
2	Deaerating Pump	0.000044	0.05
3	Main Feed Booster Pump	0.000352	0.10
4	Main Feed Pump	0.000239	0.29
5	Main Feed Control	0.000048	0.31
6	Main Feed Lines and Fittings	0.000019	0.36
7	F.O. Service Tanks	0.000057	0.45
8	F.O. Service Pumps and Strainer	0.000045	0.24
9	F.O. Lines and Fittings	0.000019	0.36
10	F.O. Heaters	0.000013	0.17
11	Forced Draft Blower	0.000057	0.25
12	Main Boiler	0.000285	0.06
13	Steam Piping and Fittings	0.000127	0.22
14	L.O. Pumps	0.000041	0.36
15	L.O. Storage Tanks	0.000045	0.32
16	L.O. Setting Tanks and Heaters	0.000006	1.00
17	L.O. Cooler	0.000009	1.00
18	L.O. Strainer	0.000012	0.50
19	L.O. Heater, Pump and Coales	0.000016	0.17
20	L.O. Purifier	0.000066	0.19
21	L.O. Piping and Valves	0.000018	0.22
22	Condensate Pumps	0.000050	0.22
23	Turbine Set and Controls	0.000072	0.21
24	Gland Fan	0.000044	0.20
25	Main Condenser	0.000062	0.27
26	Circulating Water Lines	0.000111	0.36
27	Circulator Pump	0.000121	0.35
28	Main Air Ejector	0.000010	0.26
29	Ejector Condenser	0.000009	0.11
30	Reduction Gear	0.000060	0.45
31	Thrust Block and Bearings	0.000008	0.59
32	Shafts and Bearing Assemblies	0.000061	0.37
33	Propeller	0.000061	0.37

The simplified block diagram of the system is shown in Figure 6.4. Block A represents the drain pumps and the deaerating feed tanks (items 1 and 2 in Table 6.3). The water and fuel oil pumps and equipment (items 3 through 10) are represented by Block B. The steam generation (boilers) equipment (items 11,12 and 13) makes up Block C and the turbine drive train (items 14 through 33) is shown by Block D.

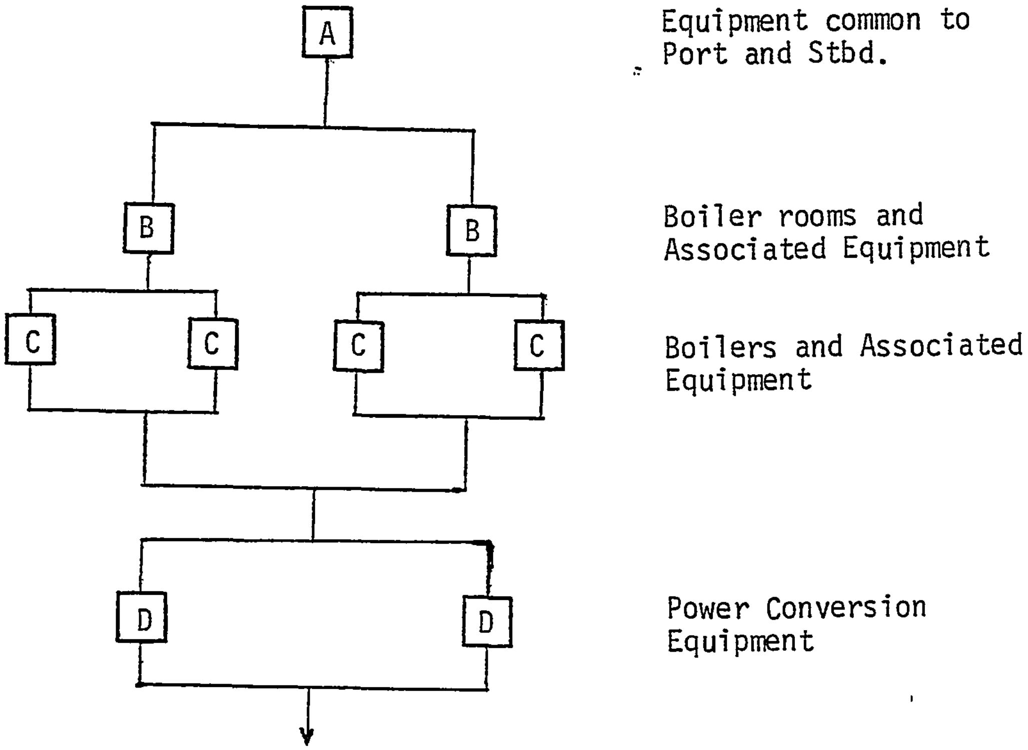


Figure 6.4 Simplified Block Diagram for the propulsion subsystem.

The complete GO chart of the system in Figure 6.3 is shown in Figure 6.5.

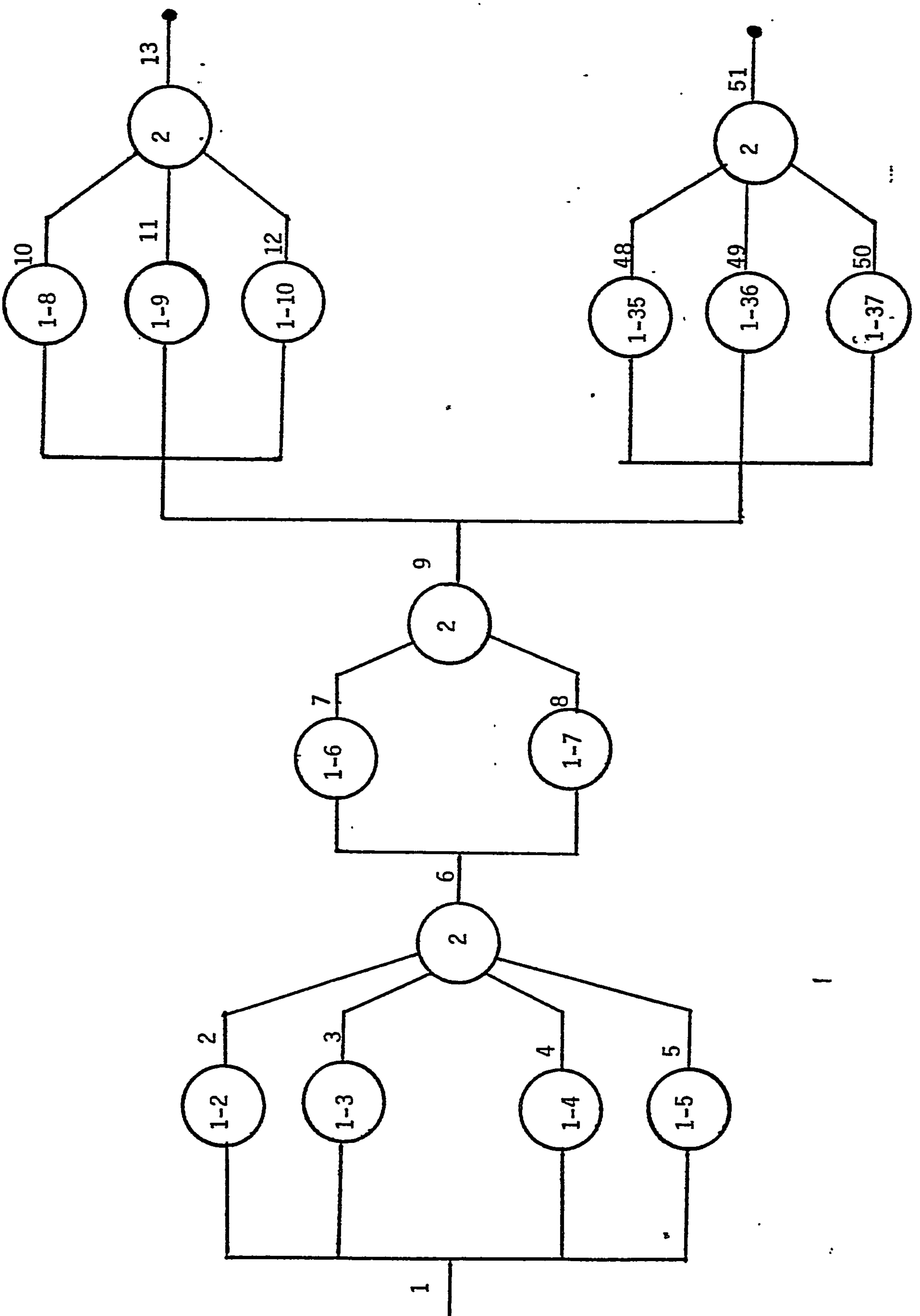


Figure 6.5 Complete GO Chart of Propulsion Subsystem

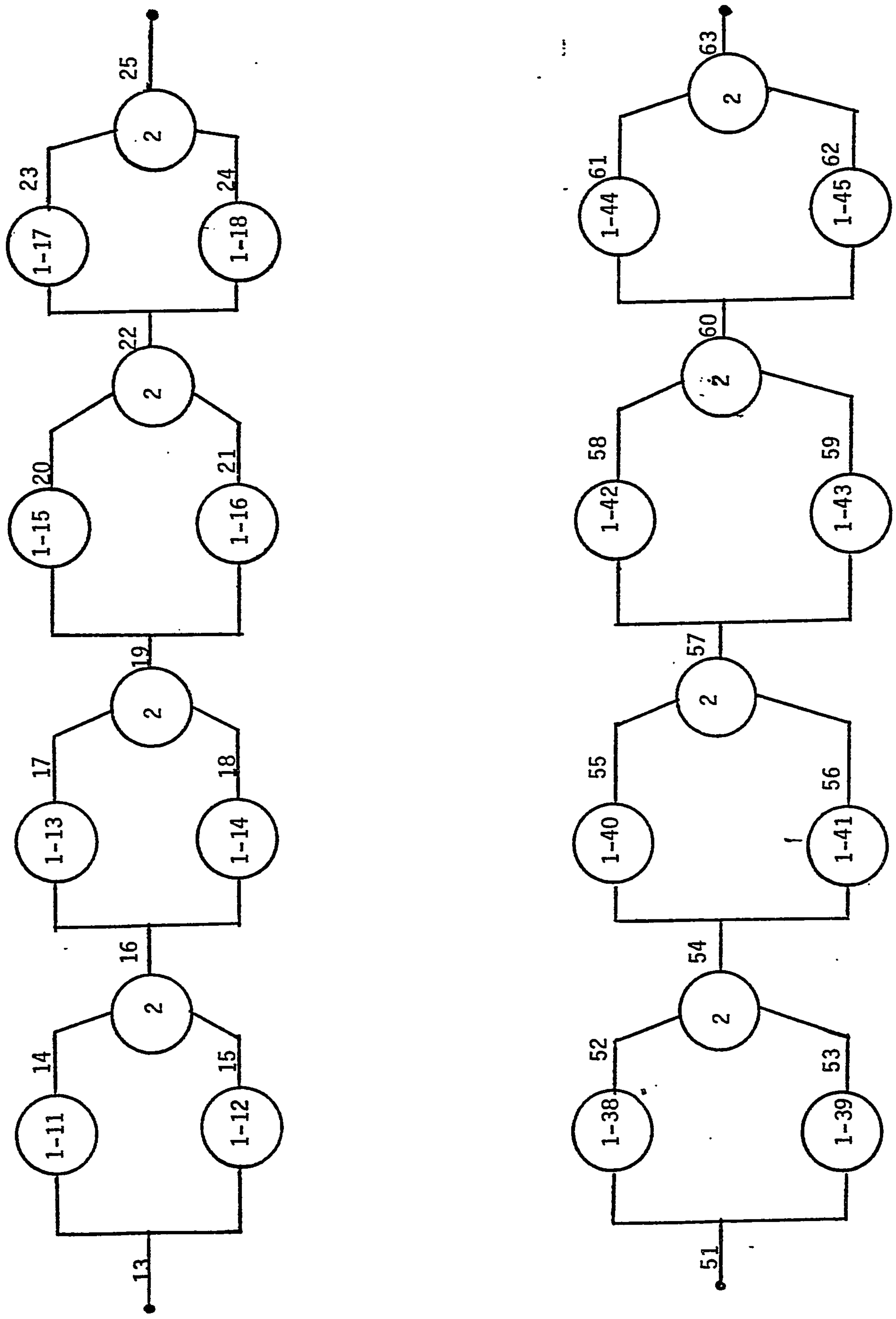


Figure 6.5 (contd.)

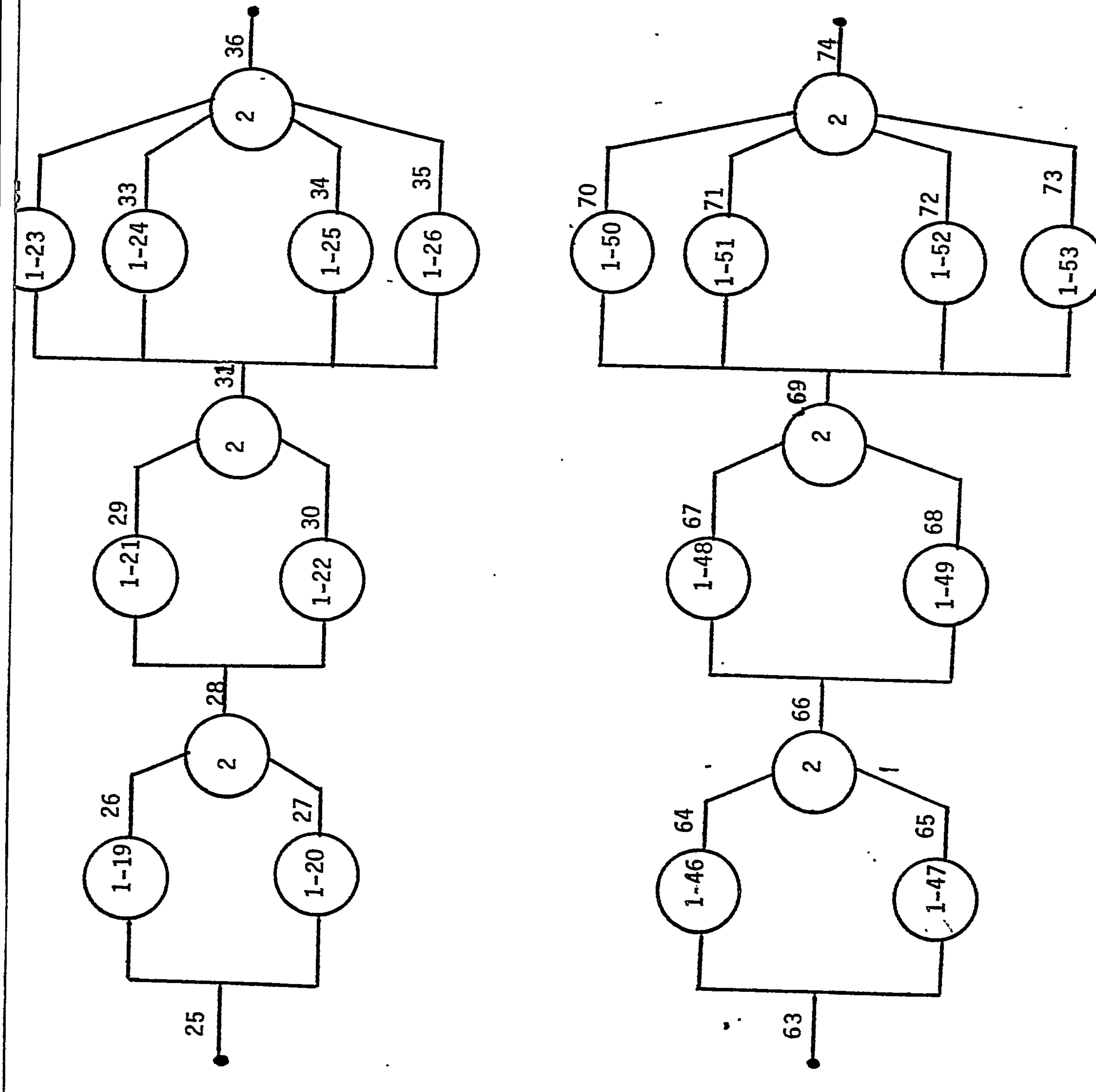
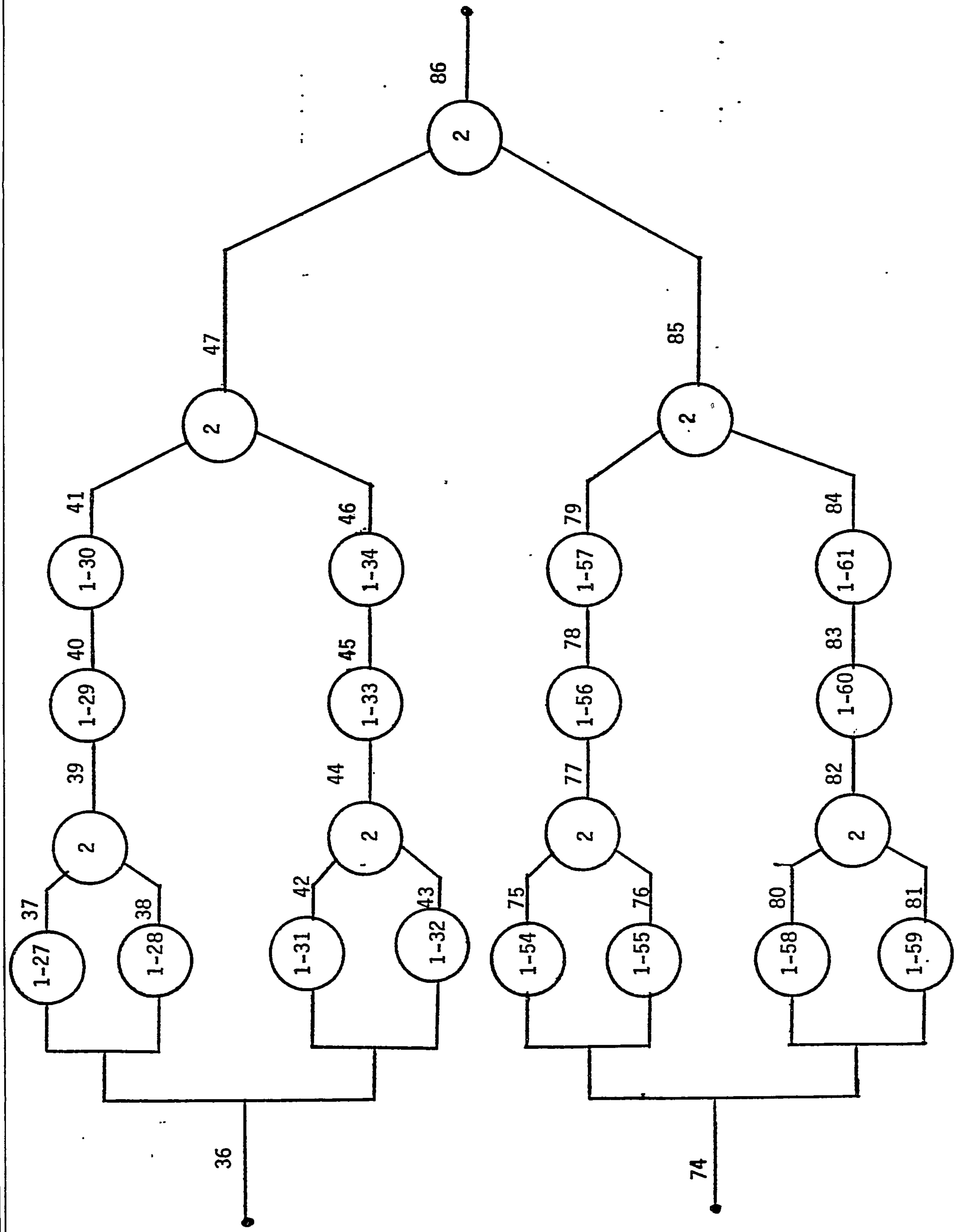


Figure 6.5 (contd.)



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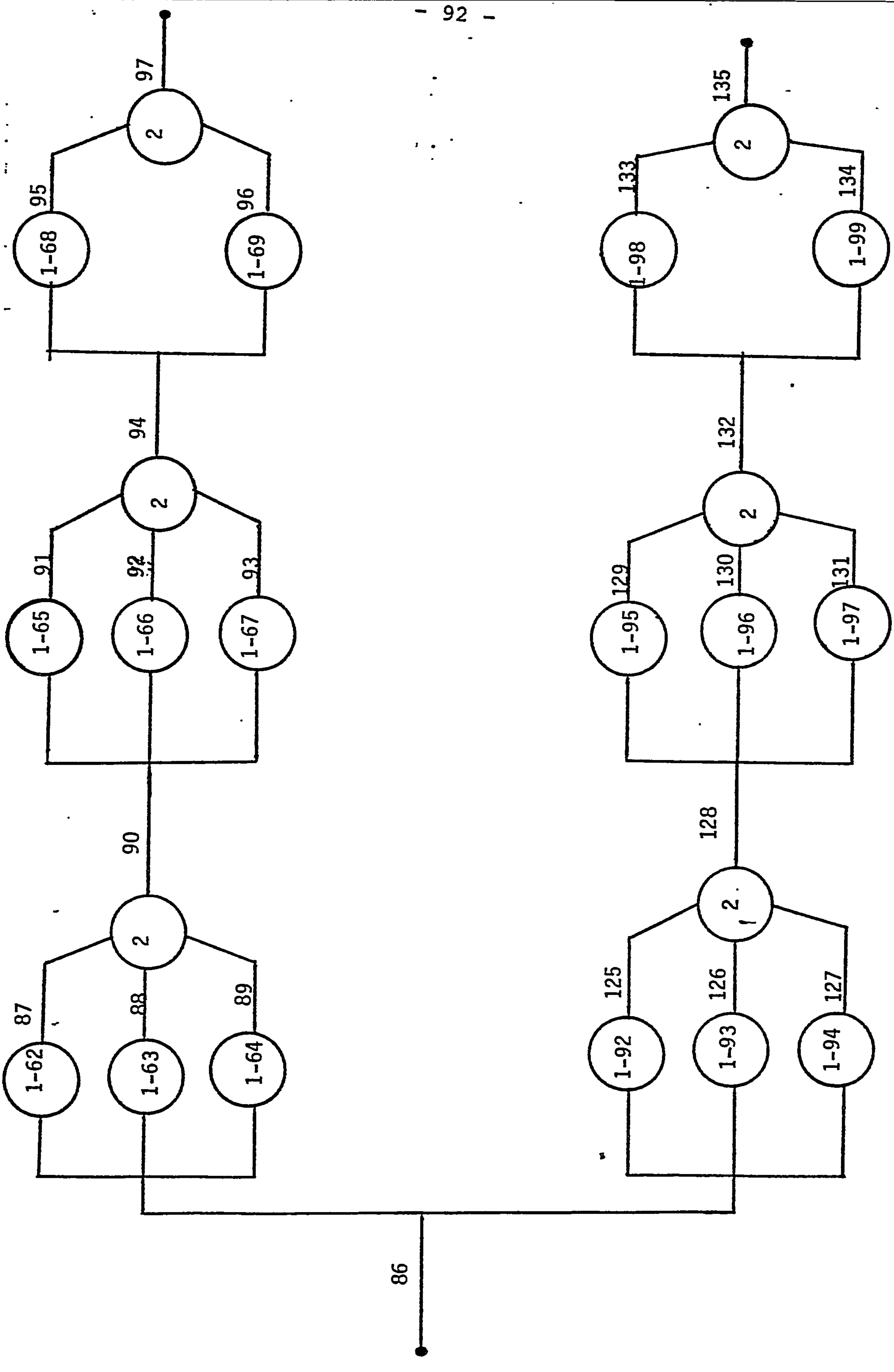

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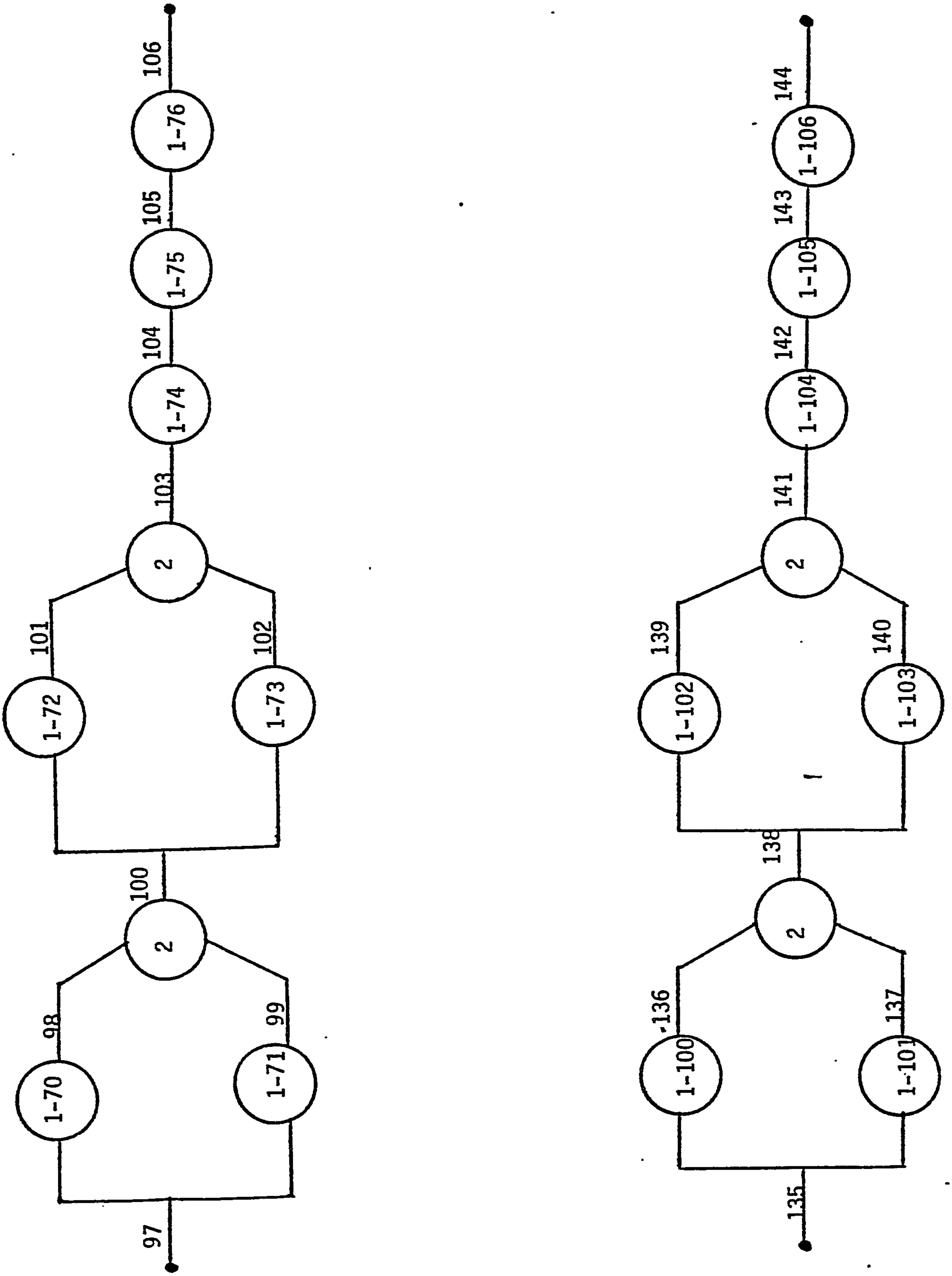

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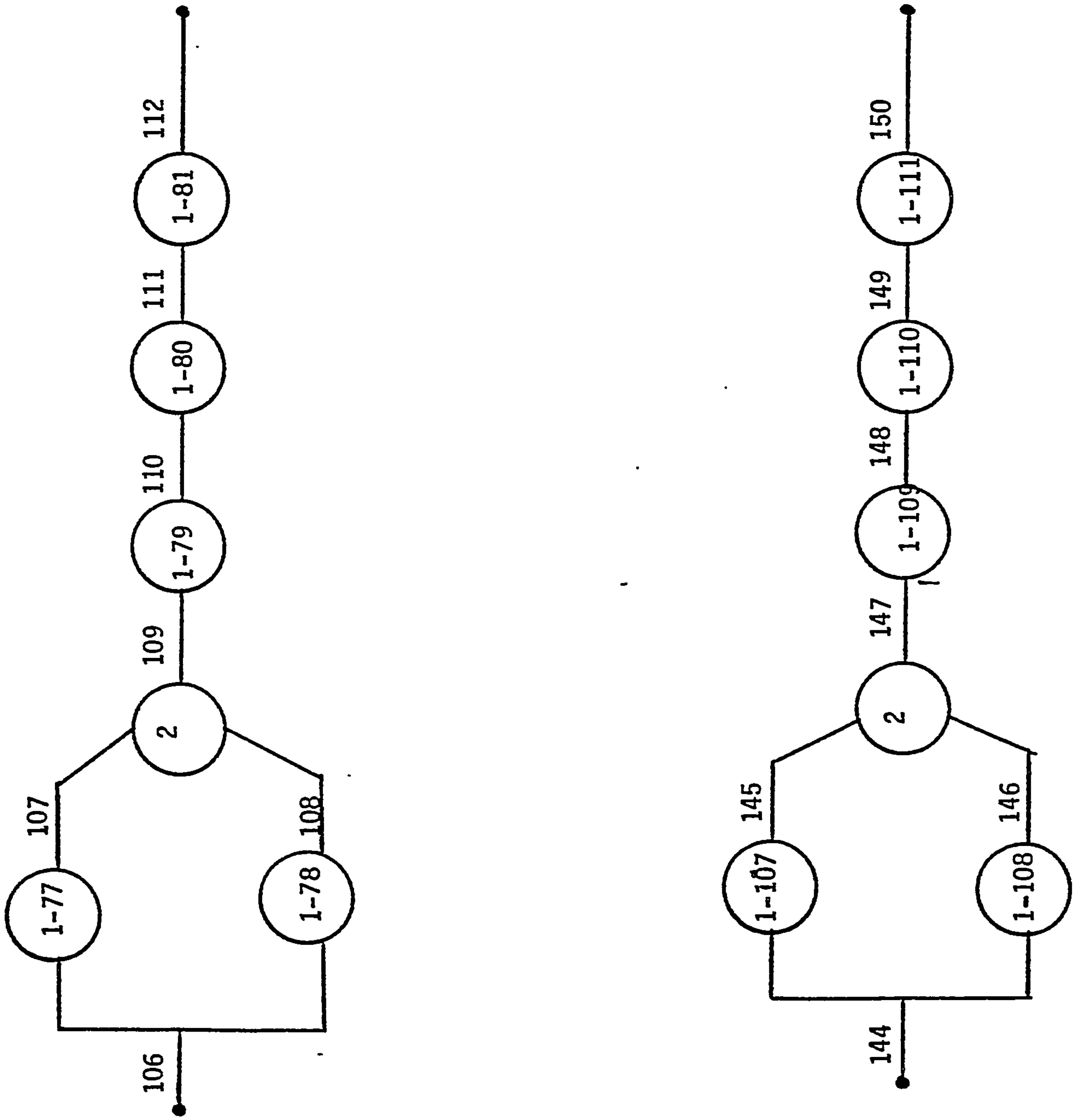
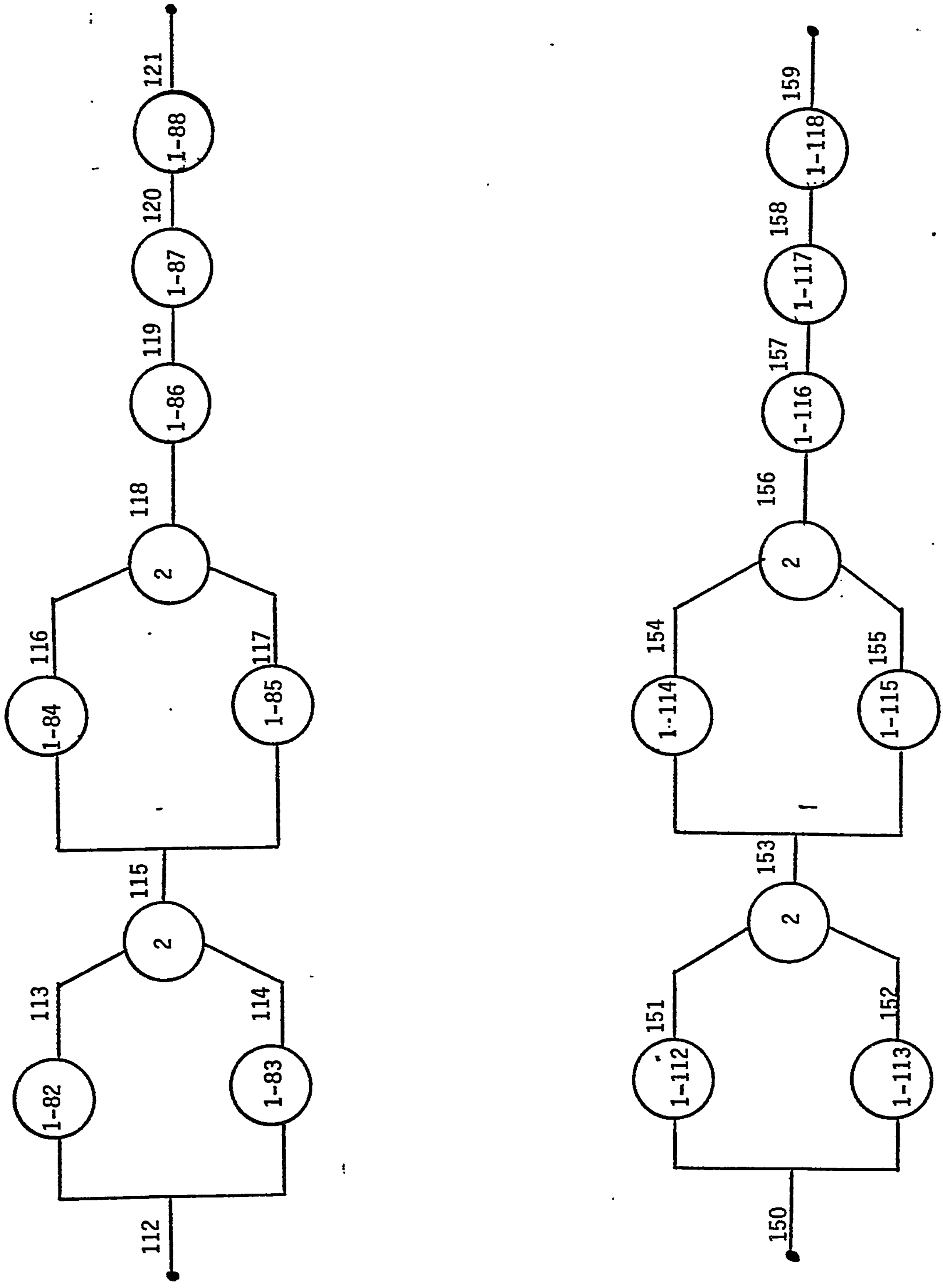


Figure 6.5 (contd.)



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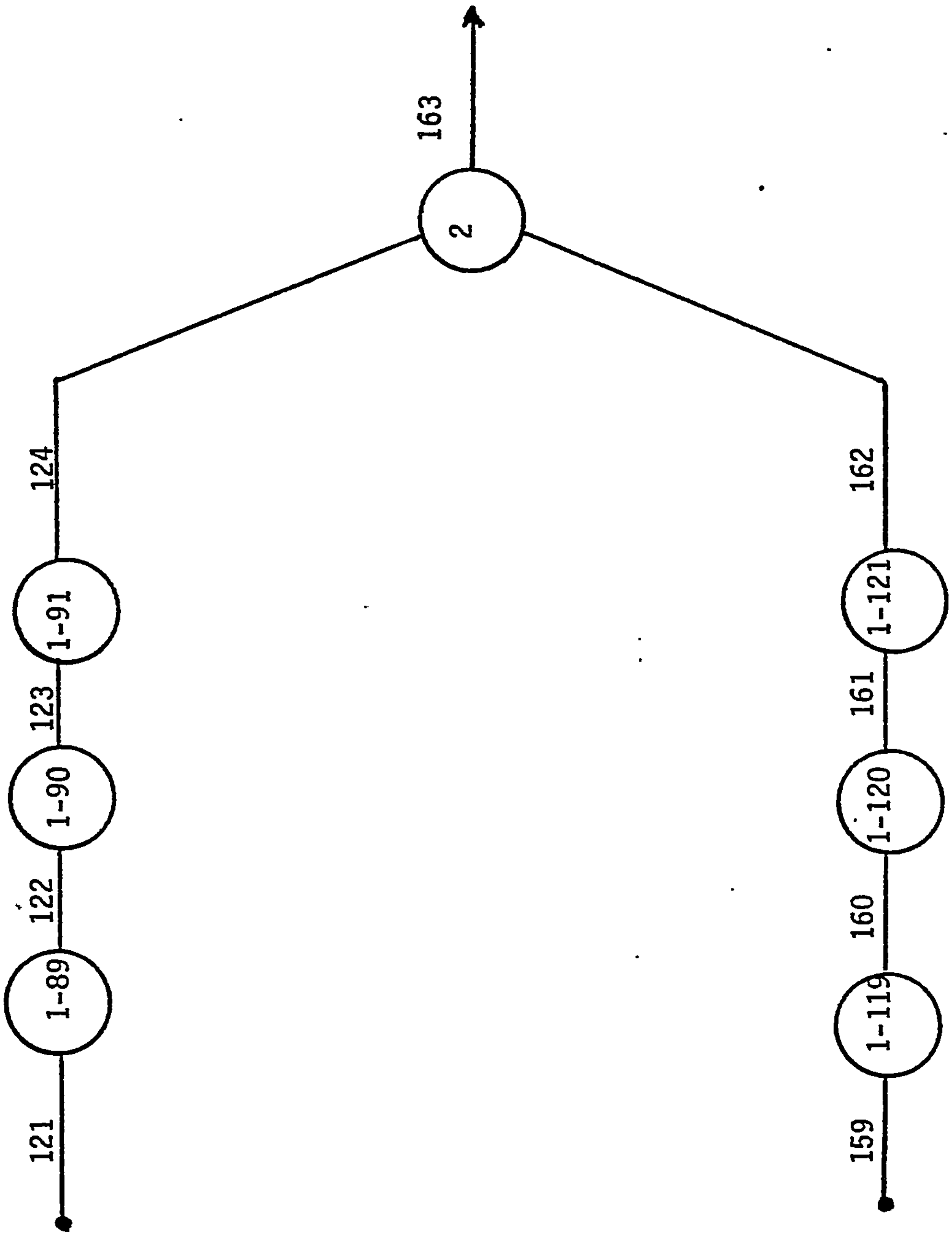

Figure 6.5 (contd.)

6.3 Comparison Study

The system was analyzed using both the original and the modified GO methods. Table 6.4 presents the availability values obtained using the two methods. The first set of readings were obtained using the original data. The availability of the components were then changed by factors shown in Table 6.4.

Table 6.4 Comparison of System Availability using the two methods

Factor	Availability		Difference
	Original Method	Modified Method	
1	0.99999458	0.99999869	0.00000411
2	0.99992520	0.99998295	0.00005775
3	0.99962997	0.99992132	0.00029134
4	0.99882048	0.99972624	0.00090575
5	0.99702096	0.99917716	0.00215619
6	0.99345732	0.99779779	0.00434047
7	0.98693055	0.99474436	0.00781381
8	0.97573227	0.98877537	0.01304310
9	0.95769006	0.97835517	0.02066511
10	0.93039894	0.96188325	0.03148431

The results presented in Table 6.4 show the improvement in the calculated index when the modified method is used. The values obtained when the original data are used are very similar as the individual component availabilities are very high. The difference in the values gradually increases as the individual component values are modified. Table 6.4 clearly shows the variation in the system availability with individual component availability. The number of series blocks or components is a factor which affects the availability. The high order of redundancy in this system keeps the availability of the system quite high.

6.3 Conclusion

This chapter has presented the application of the two methods to a practical system. The system used was the propulsion subsystem of a ship [6]. The difference in the calculated values when the two methods are used is clearly illustrated. The value calculated by the modified method which is based on the concept of equivalent components is higher than that calculated using the original method based on the assumption of independence of series components. The improvement in the calculated index has been illustrated for a range of individual component availability values.

Chapter 7

CONCLUSION

System availability evaluation can be conducted using a wide range of techniques. One of the more popular approaches is the GO Methodology which was developed by the Kaman Sciences Corporation. This thesis presents a general study of the GO methodology and the concepts involved. A computer program was also developed based on the GO modeling technique. The basic GO approach assumes independence of series elements and this assumption can lead to an underestimation of the system availability. The effect on the system availability of the assumption of independence of series elements has been examined. A modification has been developed which uses equivalent components in place of the individual components in a series system and incorporates the concept of dependence into the calculation process. This modification has been incorporated into the computer program using the GO Methodology.

The first phase of the work involved the study of the existing method and the development of a basic computer program based on the GO modeling approach. Chapters 2 and 3 describe the GO Methodology, the modeling procedure and the operators used in the process. The program which was developed based on the GO technique is described in detail and the analytical procedure illustrated using an example system.

The basic concept of independence in series systems was examined and it was shown that the assumption of independence in systems, where once a failure has occurred no further failures can occur, leads to an underestimation of system availability. This effect was shown using Markov modeling concepts and examples. The conceptual modification which recognizes dependence in series systems was achieved by using equivalent components to replace individual components. The modified procedure shows an improvement in the calculated availability index. The study of the effect of the assumption of independence in series systems and the resulting modification based on the concept of dependence is described in Chapter 4 and comprises the second phase of the overall project.

The concept of dependence was incorporated into the GO technique as described in Chapter 5. The computer program which was developed to consider the concept of dependence in series systems utilizes routines which form equivalents to replace individual components in the analysis of the system. The practical application of the developed package is illustrated using a practical example. A comparative study of the system was made using the original program and the modified program. The results of the analysis presented in Chapter 6 clearly show that a higher value of availability is obtained when the modified approach is used. The difference in the calculated values is illustrated for a range of individual component availabilities.

The concepts described in this work and the program developed incorporating these concepts will assist in analysing maintainable systems. Series systems and subsystems in which no further failures can occur once a failure has occurred can be evaluated with greater accuracy than previously obtainable using basic concepts. The modified method should be used in those systems for which it is applicable. If independence does exist then the basic approach should be used. System reliability and availability are important aspects of overall system evaluation and the modeling techniques used should be as realistic as possible. The concept of dependence as incorporated into the GO method can be extended to other analysis techniques where the concept of independence in series systems and elements is involved.

REFERENCES

1. Billinton, Roy and Allan, Ronald N., "Reliability Evaluation of Engineering Systems: Concepts and Techniques", Plenum Press, New York, 1983

2. "GO Methodology",Volume 1: Overview Manual NP-3123-CCM, Volume 1, June 1983

3. "GO Methodology",Volume 2: Application and Comparison of the GO Methodology and Fault Tree Analysis NP-3123-CCM, Volume 2, June 1983

4. "GO Methodology",Volume 3: GO Modeling Manual NP-3123-CCM, Volume 3, November 1983

5. Billinton, R. and Hosain, K.L., "Reliability Equivalents - Basic Concepts", Reliability Engineering, Vol. 5, No. 4, 1983, pp 223-237

6. Absher Jr, George W.,"Reliability Approach to Ship Systems", Proceedings, Symposium on Reliability, Washington D.C, January 1971