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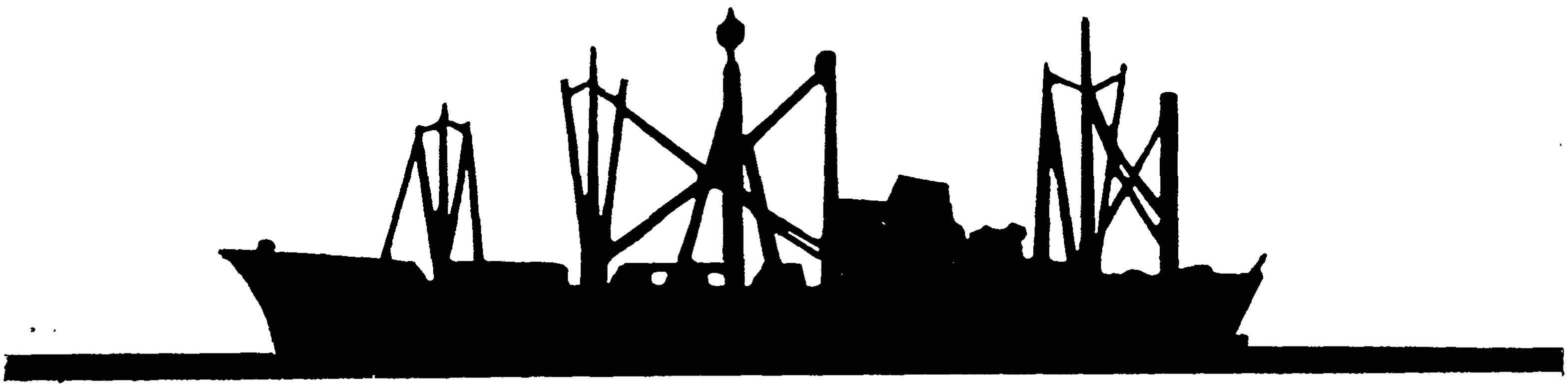


INSTITUTE FOR RESEARCH AND ENGINEERING FOR AUTOMATION AND PRODUCTIVITY IN SHIPBUILDING

I R E A P S

# SHIPBUILDING PROJECT MANAGEMENT

Ernst G. Frankel
Professor, Shipbuilding Analysis, Ship Design, Management
Massachusetts Institute of Technology
Cambridge, Massachusetts

Professor Frankel's areas of expertise are naval ship design and procurement, program management, shipbuilding and shipping management, maritime policy, manpower planning and control, cost control and analysis, ship specifications, strategic planning, and management information systems.

## ABSTRACT

Uncertainties in material and component delivery as well as fabrication,, assembly, and erection process times make it difficult to effectively use traditional CPM, PERT, and similar methods for shipbuilding project management. A conditional probabilistic project management and control method is proposed which allows incorporation and updating of times and their uncertainties by the use of feedback, to improve real time decision making, project control, and adaptive planning.

## Introduction

American shipbuilding management and planning has become a topic of increasing discussion in recent years and various proposals for change have been advanced. Many of these propose adoption-of certain techniques and approaches successfully used --in other major shipbuilding countries such as Japan and Korea, where shipbuilding management is based on organizational, decision making, and operating structures and procedures founded on quite different cultural backgrounds, human relations, and traditions than those found in the U.S. While some of the techniques and approaches found successful in those countries may be transferrable, it must be recognized that the environment in the U.S. cannot be changed in the short run. This makes successful application of some of these methods difficult.

Factors which make Japanese and Korean shipbuilding competitive include value engineering, quality circles, labor incentives, high productivity manufacturing processes; rationalized ship design and production, effective organization, labor relations and flexibility, good supplier and customer relations, and effective production planning management and control. There are some factors which are distinctly different, such as the lack of adversity between shipbuilder and client on one hand and management and labor on the other hand. There **is** a general recognition and acceptance in these countries that adversary relations and potential litigous actions hinder achievement of ship production efficiency and on schedule low cost (and therefore price) delivery. Similarly most supplier, client, and labor issues with shipbuilding management are resolved by various informal approaches with little if any delay. This is quite different from the generally formal approach used in the U.S.A., where procedure, documentation, and even conflict resolution methods are often defined.

While supplier, subcontractor, and shipyard work performance is highly predictable in foreign shipbuilding countries such as Japan and Korea, U.S. supplier and subcontractor delivery times, as well as shipyard work center performance times are subject to many more uncertainties. There is also a much higher risk that supplies or work delivered are not acceptable or require rework because acceptability checks are usually made only on delivery.

Planning of shipbuilding in the U.S. therefore requires consideration of more significant uncertainties in the performance of the various task activities involved in a shipbuilding project, as well as the consideration of alternative activities,to correct for unexpected development.

## Critique of CPM/PERT Project Planning

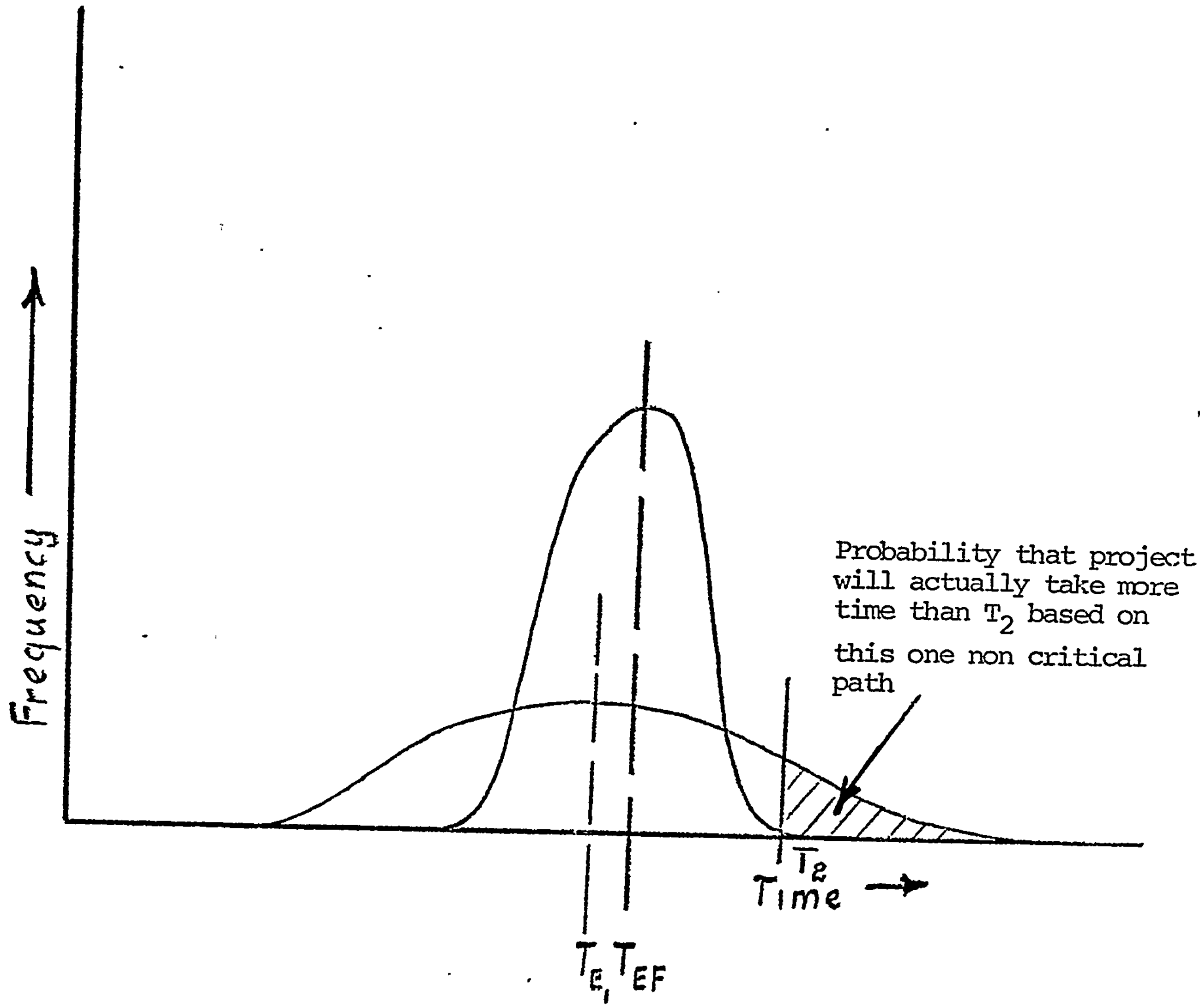
Planning of shipbuilding projects, from planning of complete ship production projects to that of subsystems or block construction, is often performed using either deterministic task and event planning methods such as CPM, or similarly structured probabilistic network planning techniques such as PERT.

-Either or both methods are simply additive networks which allow computation of the expected time and cost of realization of the various events including the completion event. PERT also permits determination of the statistical distribution of time and/or cost of realization of events in terms of the standard deviation of event time and cost. It must be recognized though that these statistical deviations consider only deviations in cost and time of chains of critical activities leading to the event under consideration. In many cases though the event time and cost of critical-activity chain may have a substantially lower deviation than that of non critical activity chains interphasing with the event under consideratior (Figure 1).

The errors introduced by the statistical assumptions of the PERT model (PERT Time, PERT Cost), such as the abovementioned errors in the expected variance of the critical path or path with the largest sum of expected activity times is discussed by Wiest (Ref. 1) l The Beta and Pierson distribution assumption in PERT is ***also*** criticised by Maccrimmon and Ryavez (Ref. 2) as are other statistical shortcomings of the method questioned by authors such as H.O. Hartley and A.W. Wortham (Ref. 3), Dr. J.A. Welsh (Ref. 4) and J. Lukaszewicz (Ref. 5).

The PERT-CPM precedence relationship is extremely rigid since it allows only one interpretation of the timing of activity (i,j) in that event i precedes event j and activity (i,j) must be completed before event j is realized for all activities-interfacing with event j. Furthermore CPM/PERT methods do not permit consideration of alternative activities, feedback, or learning, and consideration of completely alternate project performance structures.

The appropriateness of such a fixed network planning structure has been questioned for R & D projects by researchers such as Eyring (Ref. 6), but the arguments raised are equally valid to applications of PERT/CPM in U.S. shipbuilding which is usually subjected to equally if not larger uncertainties in supply, performance, client demands, and more. One problem not met in the planning of projects in most other industries is frequent delays caused by the unavailability of drawings and plans, which are generally generated while the lead ship is being built.




$T_2$ = Latest time of completion of last activity on critical path

$T_{E_1}$ = Expected time of completion of last activity on non critical path

$T_{EF}$ = Expected time of completion of last activity on critical path - expected completion time of project

FIGURE 1

CPM/PERT COMPLETION TIME DISTRIBUTION

A common occurrence in the use of PERT/CPM is that whenever a serious overrun in time or cost occurs, efforts are made to tighten up on the remaining activities to return the project to planned schedule and budget using the preestablished structure or CPM/PERT network of project performance. A major reason for the problem though may be the structure of the **CPM/PERT** network itself and alternate activity scopes and sequences may offer much better opportunities for performance of the project from this point on. A CPM/PERT network does not allow for alternate network structures to be considered.

While CPM/PERT originated in the U.S. and **PERT** was in fact developed for the specific reason of providing an effective schedule and cost control method for the 'Polaris' program, the most ardent use of the approach to design, plan, and control shipbuilding projects was in Japan starting nearly 20 years ago. For example, the use of an integrated procurement control system based on PERT is credited with the drastic reduction in steel and other storage stock ratios. For example, between 1964 and 1966 the amount of steel stocked in the average Japanese yard as a percentage of the amount of steel supplied to the fabrication shop per month fell from 1.5 to 0.3. In other words from 45 days to 10 days, average demand (Ref. 7). Similar savings were attained not only in the stocking of other materials and components, but also in productivity in design, fabrication, subassembly, assembly, erection, and outfitting. Although U.S. government requirements for use of network procedures have been greatly relaxed or eliminated altogether, **PERT/CPM** appear still to be used in shipbuilding project planning (at least in cost and schedule estimating) and to a lasser degree in shipbuilding project control.

While PERT/CPM are simple methods, with which most shipbuilding managers are familiar, they must recognize the limitations of these methods particularly in the U.S. shipbuilding environment with all its uncertainties, and changes in direction.

Among the reasons for the consideration of different network techniques for shipbuilding project planning and control is that PERT/CPM assumes that each job has a unique, definable beginning and ending and that all other jobs which must be completed before the job can be started are similarly uniquely defined. Similarly all jobs whose starts are triggered by the completion of the job are uniquely defined. The PERT/CPM network describing the shipbuilding project is therefore directed, unidirectional, acyclic, and-does not allow for updating, feedback, or adaption, This unfortunately introduces severe restrictions which make the approach impractical when jobs and their sequence must often be changed, and job or activity performance including the allocation of resources for its performance are conditioned on the performance of other jobs, including jobs which do not interface or are not in sequence with the job or activity under consideration. Yet this is precisely the condition under which shipbuilding projects operate.

## Project Planning Network Developments

Recent developments in network project planning and control methodology concentrated to a large extent on:

1) Incorporation of Resource Scheduling (Ref. 8)
2) Introducing Effect Precedence Methods
3) Consideration of Decision Alternatives in a Network Project Plan
4) Use of Probabilistic Condition of Precedence Sensitive Network Techniques

In resource scheduling we incorporate the use of one or more! resources in the performance of each of the required developments. Precedence methods such as PDM (Procedure Diagram Method) introduce precedence (lead/lag) relationships, eliminate the need for dummy activities, and permit easier changes in the structure of the network, such as the addition or change in sequence of activities. 'Decision Critical Path Methods developed by W. B. Crawston et al (Refs. 9 and 10), allow for the conditional choice among alternative decisions with trade-off of resources used to implement these decisions.

Conditional probabilistic project management and control network techniques permit consideration of-the uncertainties involved in the performance of shipbuilding activities and of alternative activities designed to 'correct for activities which caused time and/or budget distortions. It also incorporates continuous feedback of information to permit reevaluation and updating of the shipbuilding project plan. This method which combines many of the characteristics of the other project planning network techniques was largely developed by A.A.B. Pritsker (Refs. 11 and **12).**

It is generally referred to as GERT (Graphical Evaluation and Review Technique). Detailed description of the method as applied to Queueing-Job-Shop systems are presented in Ref. 13, and a brief summary of the GERT network rationale is given in the Appendix of this paper.

## Proposed Shipbuilding Project Management Method

The method presented here is an application of GERT, by representing shipbuilding projects as **conditional, stochastic networks.** The **shipbuilding process is by its very nature a job-shop queueing system in which most jobs or activities are unique and there is usually a need for some storage of the output of one or a series of jobs before another job or series of jobs can be** performed. While some **jobs are repetitive and others can be** performed by sequential in-line production, most are discontinuous and batch production **or jobs which** if **involved, are usually** of **small** batch size. Furthermore most jobs performed are stationary and often require a specific facility and location for their performance. As a result we have many work centers which draw upon a pool of resources and perform their activities in prescribed sequences in relation to jobs performed at or by other work centers. In general we can describe the shipbuilding process as a multi-resource constraint activity system with job shop type activities which can be represented as a conditional queueing network.

To represent probabilistic resource constraint job shop type or queueing networks, each job or activity can be defined by the statistical distribution of its resource requirements. GERT networks can be constructed with Exclusive-or, Inclusive-or, and And events or a mixture of different events. Many aggregate project planning models can be designed as Exclusive-o;: network such as a simple ship repair project.

Ship Repair' Project Management

Assuming that ship repair project management requires the determination of the average utilization of facilities, time to repair and other information, a simple Exclusive-or model may be constructed as shown in Figure 2. Here we present a greatly simplified tanker repair planning model for a shipyard with one floating and one dry dock, which regularly performs survey repairs on a fleet of tankers-. The network indicates in a very aggregate form some of the major activities and events from the receipt of the ETA to ship departure. Each activity has an associated probability of realization and an equivalent function which represents the statistical distribution of time, cost; etc. required to perform the activity, given the activity is realized. For example, after the receipt of the ETA, there is a probability $P_{12}$ that the ship will actually arrive at the repair port and $P_{1a}$ = (1-P ) that it is diverted to another port or shipyard, The time from receipt to actual arrival, given the ship arrives, similarly can be expressed by the statistical distribution of time from the receipt of the ETA.

Given the ship arrived, it may be able to proceed to preparation for docking with probability $P_{24}$, may have to be berthed first with probability $P_{23}=(1-P_{24}-P_{2.13})$ or may be prepared for departure again with probability $P_{2.13}$. Once berthed it may have to be unberthed. Given the ship is unberthed it may then proceed to preparation for docking, or departure. Given it is prepared for docking, it may have to wait for an empty dock with probability P44, be docked in the available floating dock with probability P45, or in the available dry dock with probability P46. Again each of these activities has an associated time, cost, etc. distribution. Subsequent activities include shaft and propeller drawing and other jobs until a ship is ready and proceeding for departure again.

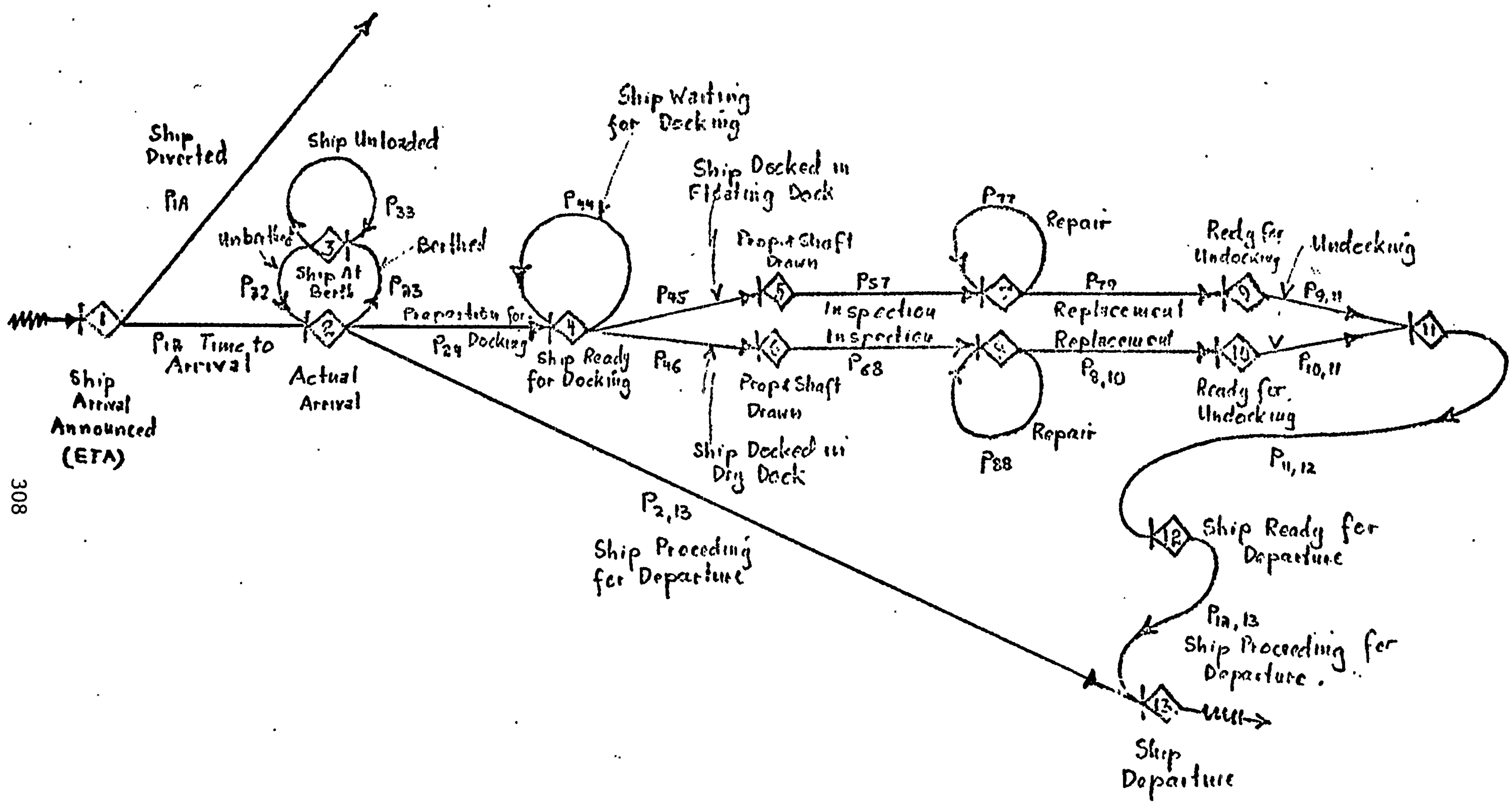



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FIG. 2 SHIP REPAIR AGGREGATE PLANNING MODEL

The diagram is usually expressed in matrix form, from which a computational algorithm can readily be formulated. Assuming that the times required for the different activities described by this simplified model each have their particular statistical distribution as obtained from historic data and that the product of the conditional probabilities of realization of the respective activities and their Moment Generating Functions can be expressed in terms of an equivalent function $W_{ij}(s)=P_{ij}MGF_{ij}(S)$, than using Mason's reduction from flowgraph theory we can obtain the equivalent function expressing the relationship between any pair of events or nodes. For example the equivalent function between ship arrival announcement (node 1) and ship departure (node 13)

$$W_{1,13}(s) = W_{1,2}(s)[W'_{2,13}(s) + W''_{2,13}(s)]$$

$$= W_{1,2}(s)\left[\frac{G'_{2,13}(s)\Delta'_{2,13}+G''_{2,13}(s)\Delta''_{2,13}+G'''_{2,13}(s)\Delta'''_{2,13}}{\Delta}\right]$$

where

$G'_{2,13}(s)$ = Path 2-13 via nodes 4, 5, 7, 9, 11, and 12

$$= W_{2,4}(s)W_{4,5}(s)W_{5,7}(s)W_{7,9}(s)W_{9,11}(s)W_{11,12}(s)W_{12,13}(s)$$

$\Delta_{2,13}$ = Path Factor of this Path = $\Delta$ in which all loops touching above nodes are zero

$$= 1-W_{33}(s)-W_{88}(s)+W_{33}(s)W_{88}(s)$$

$G''_{2,13}$ = Path 2-13 via nodes 4, 6, 8, 10, 11, and 12

$$= W_{2,4}(s)W_{4,6}(s)W_{6,8}(s)W_{8,10}(s)W_{10,11}(s)W_{10,12}(s)W_{12,13}(s)$$

and

$$\Delta''_{2,13} = 1-W_{33}(s)-W_{77}(s)+W_{33}(s)W_{77}(s)$$

Finally,

$G'''_{2,13}$ = Path 2-13 direct

$$= W_{2,13}(s)$$

and

$\Delta'''_{2,13}$ = $\Delta$ with all $W_{22}(s) = 0$

where

$\Delta$, the Graph Determinant is

$$\Delta = 1-[W_{33}(s)+W_{22}(s)+W_{44}(s)+W_{77}(s)+W_{88}(s)]$$

$$+[W_{22}(s)W_{44}(s)+W_{22}(s)W_{77}(s)+W_{22}(s)W_{88}(s)$$

$$+W_{33}(s)W_{44}(s)+W_{33}(s)W_{77}(s)+W_{33}(s)W_{88}(s)$$

$$+W_{44}(s)W_{77}(s)+W_{44}(s)W_{77}(s)+W_{44}(s)W_{88}(s)+W_{77}(s)W_{88}(s)]$$

$$-[W_{33}(s)W_{44}(s)W_{77}(s)+W_{33}(s)W_{44}(s)W_{88}(s)+W_{22}(s)W_{44}(s)W_{77}(s)$$

$$+W_{22}(s)W_{44}(s)W_{88}(s)+W_{44}(s)W_{77}(s)W_{88}(s)] + [W_{33}(s)W_{44}(s)W_{77}(s)$$

$$W_{88}(s)+W_{22}(s)W_{44}(s)W_{77}(s)W_{88}(s)]$$

Once the graph determinant is determined the derivation of all kinds of relations within the model becomes easy. For example, average time between arrival of a ship for repair and departure is

$$\bar{T}(E)_{1,13} = \frac{\partial W_{1,13}(s)}{\partial s}\Big|_{s=0}$$

Probability that an arriving ship will be repaired in the floating dock

$$P_{4,11} = W_{4,11}(s)/[W'_{2,13}(s)+W_{2,13}''(s)]\big|_{s=0}$$

We could similarly find the probability that an arriving ship will require shaft or propeller repair while being docked in the floating dock, or the average time a ship requires in port for (survey) repairs given it has to discharge cargo in the port as well, or we may want to compute the probability that a ship has to wait in excess of say 3 days before a specific dock is available, given it had to be unloaded before preparation for docking. A real world planning problem of this type would obviously have many more activities and events, with each activity expressed by its conditional probability of realization or use as well as the statistical distribution of its resource requirements, given it is used.

Analysis of larger, real world models is obviously done using computers. The model is then developed as a matrix in which each square contains either a zero or the product of the conditional probability that the activity is realized and the Moment Generating function of the statical distribution of the resource requirements. Table 1 is a listing of distributions acceptable to such a GERT program. A GERT project planning model can also be used to determine the sensitivity of a project outcome or performance to changes in the probability or resource requirements of one or more activities which form part of the project.

## TABLE 1

## DISTRIBUTIONS ACCEPTABLE TO GERT PROGRAM

| Type of Distribution | $M_E(s)$ | Mean | Second Moment | Input Variables |
|---|---|---|---|---|
| Binomial (B) | $(pe^s+1-p)^n$ | $np$ | $np(np+1-p)$ | $w_E(o);n,p$ |
| Discrete (D) | $\frac{p_1e^{st_1}+p_2e^{st_2}+\ldots}{p_1+p_2+\ldots}$ | $\frac{p_1T_1+p_2T_2+\ldots}{p_1+p_2+\ldots}$ | $\frac{p_1T_1^2+p_2T_2^2+\ldots}{p_1+p_2+\ldots}$ | $w_E(o);p_1,T_1,p_2,T_2;$ |
| Exponential (E) | $(1-s/a)^{-1}$ | $1/a$ | $2/a^2$ | $w_E(o);\ 1/a$ |
| Gamma (GA) | $(1-s/a)^{-b}$ | $b/a$ | $\frac{b(b+1)}{a^2}$ | $w_E(o);1/a,b$ |
| Geometric (GE) | $\frac{pe^s}{1-e^s+pe^s}$ | $1/p$ | $\frac{2-p}{p^2}$ | $w_E(o);p$ |
| Negative Binomial (NB) | $\left(\frac{p}{1-e^s+pe^s}\right)^r$ | $\frac{r(1-p)}{p}$ | $\frac{r(1-p)(1+r-rp)}{p^2}$ | $w_E(o);r,p$ |
| Normal (NØ) | $e^{(sm+\frac{1}{2}s^2\sigma^2)}$ | $m$ | $m^2+\sigma^2$ | $w_E(o);m,\sigma$ |
| Poisson (P) | $e^{\lambda(e^s-1)}$ | $\lambda$ | $\lambda(1+\lambda)$ | $w_E(o);\lambda$ |
| Uniform (U) | $\frac{e^{sa}-e^{sb}}{(a-b)s}$ | $\frac{a+b}{2}$ | $\frac{a^2+ab+b^2}{3}$ | $w_E(o);a,b$ |

Similarly we can determine the variance and other statistical measures of the time or other resource use for the whole project or any subnetwork of activities relating any set of two events or nodes. GERT networks similarly permit multiple inputs and outputs and multiple feedback loops which can be used to simulate repetitive performance of activities.

## GERT Simulation in Shipbuilding Project Management

A basic GERT Exclusive-or or similarly structured network model, as discussed, is useful for the analysis of aggregate or small-scale shipbuilding planning problems. When the number of activities becomes large and when the network representing the project and its alternatives is represented by a large resource constrained queueing network, then a simulation approach is usually the only effective approach. GERT Simulation or GERTS was developed by Pritsker (Ref. 13) and later expanded by Hogg, Phillips, Maggard, and Lesso (Ref. 17 and 18). Cochran and Rowe studied the sources of disruption to project cost and delivery performance (Ref. 15) while Cochran added the impact of design uncertainty and delivery urgency in a later paper (Ref. 16). A shipbuilding project was used by Wolfe, Cochran, and Thompson as an example for a GERTS-based interactive computer system for analyzing project networks incorporating improvement curve concepts (Ref. 14).

Since then several applications of GERTS to manufacturing, including shipbuilding project planning, have been made. The results have shown the great advantage of this approach as compared to the use of CPM/PERT, Precedence Diagram and other project network planning methods. A number of extensions to GERTS have been developed in recent years. These are found in GERTS III, GERTS III Q, GERTS III C, and **GERTS III** R {where Q, C, R stand for Queue, Cost, Resource, etc.) There are also versions of GERTS (Fortran) which combine Q and R consideration.

To model a shipbuilding project we prepare a network diagram representing the structure of activities and events comprising or judged necessary for the performance of the project. Alternative activities (not necessarily leading to the same event) which may be introduced to use alternate processes, make more effective use of resources; or for other reasons, are next Identified. We similarly define the number of 'incoming activities required to realize a node or event for the first time, as well as the number of completed incoming activities required to realize it even after the first time. For example position one events on a flat panel line may require five edge prepared plates to be positioned. Next queue disciplines, at the start of the various activities at which queueing is allowed, must be defined.

To control resource use, resource levels and resource use costs are set for each activity and resource allocation rules are determined. GERTS simulation programs define six node types:

Source, Statistics, Mark, Queue, ***Sink,*** and Standard. Some versions (Ref. 15) include storage, generator, and distinguisher nodes. (For description of GERT node characteristics see Appendix.) The basic GERTS programs require each unit in a queue to require the same storage. Wolfe, Cochran, and Thompson (Ref. 14) recognized that this may be unrealistic in ship production analysis, and therefore introduced a storage node, which permits the amount of space required before or by an activity to be specified in terms 0'- area, volume, weight, etc. In GERTS, when storage or queue capacity is exhausted blocking occurs, yet resource utilization may, In part, continue at the blocked activity. Blocking does not require a queue or storage node, as activities may be blocked as a result of delayed arrival of the input, when the activity is discrete,

When an activity is blocked or when the waiting line exceeds a certain number (or expected waiting time), then GERTS permits ordered balking. Here the program channels the arrival to another activity or other resource use. How, Phillips, Maggard, and Lesso (Refs.117 and 18) assumed that resources are homogeneous, or in other words a unit of resource used is applied equally effectively at any activity. This constraint used in GERTS QR can be relaxed without too much complication. Wolfe, Cochran, and Thompson (Ref. 14) expanded the GERTS QR node concepts by introducing a distinguisher node, which is realized when particular defined characteristics of the preceding activities are realized, and a storage node, which defines the primary and secondary storage resources used, as well as the resources of incident activities that can be blocked, and the node number to which incident activities can balk. A generator node is similarly defined which enables simulation of irregular arrivals, or the time between arrivals specified by a particular statistical distribution. As noted GERTS has become a very versatile project simulation method which permits effective and realistic evaluation of project performance with computational efficiency.

**A** very simple shipbuilding project example is next presented to show the application of GERTS. Figure 3 is a simplified flQw diagram of the flat stiffened panel construction part of a tanker shipbuilding project. The distribution of time and other resources required (labor, machine time) was established for each activity from existing data. Several of the activities (such as edge preparation, plate stripping, etc.) could be performed by more than one alternative machine (or activity) with its associated resource requirements. To assure optimum resource use in the simulation, activities were at the start ranked by efficiency of performance in terms of resource use. When queue lengths before such activity exceeded the amount which would affect the effective and more discrete progress of work on the panel line, the next arrival would balk and divert to the next best alternative activity (say gas stripper).. Activity costs were expressed in terms of both fixed and variable costs to permit consideration of idle time costs. The simulation provides:

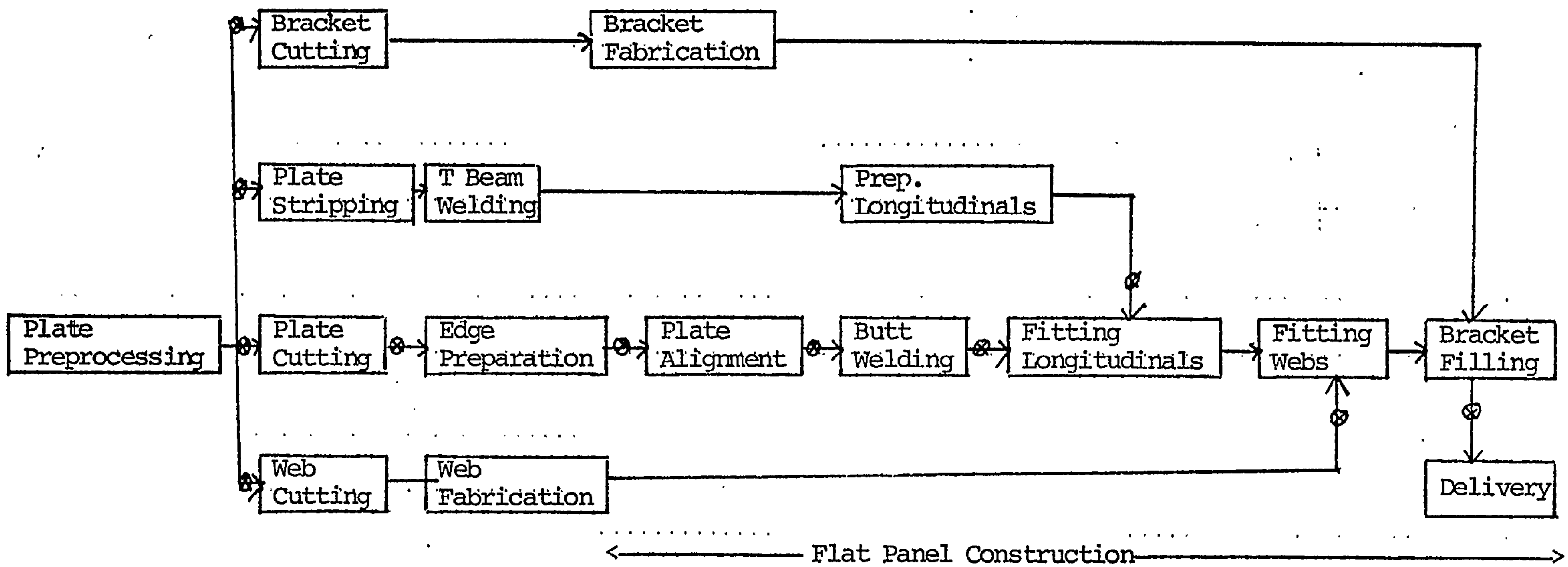



FIGURE 3 - FLOW DIAGRAM OF SIMPLIFIED FLAT STIFFENED PANEL CONSTRUCTION

1. Start and Finish Time of all jobs performed by the various activities.

2. Utilization of all activities and use of resources for **their** performance..

3. Time of waiting before each activity and variation of queue length at each buffer

4. Number of and time of occurrence of balking

5. Average distribution of time between the passage of a job between any two events (say between start of stripping and fitting of jongitudinals)

6. Throughput per unit time of the various activities and the total time.

The simulation was used to study various allocations of machine or activity capacities and the potential for reassignment of some machines to other projects. Methods of use of various machines or activities (and alternative manning) was similarly evaluated as was the effectiveness of existing or proposed buffer storage and interprocess handling. The approach was found to be an effective tool for the planning of shipbuilding projects. It is now proposed to study the use of this type of simulation for project management and control as well.

## Conclusions

After gaining experience with some limited applications of GERTS in the study of critical elements of the shipbuilding project such as flat stiffened panel construction, machinery (open sky) outfit (only major modules considered) and structural block or module assembly, it is now proposed to attempt the simulation of a complete shipbuilding project from the ordering of materials and equipment to the delivery and acceptance of a ship. While this will be done in the aggregate at the start, with most subnetworks of activities lumped into aggregate activities, it is hoped that it will show the way towards the development of a general approach to shipbuilding project planning under uncertainty and resource constraints.

# APPENDIX

## GERT (GRAPHICAL EVALUATION AND REVIEW TECHNIQUES)

(Extracted from RefJ. 11)

This network technique introduces conditional probability **of** activity use in addition to making the activity variable (time, cost, and other resources) random variables, which can be associated with most appropriate statistical distributions. In other words, in a GERT network, there are probabilities associated with each job or activity which represent the relative frequency of the occurrence of the activity within the network or the probability that the job will be performed. When an activity is used or a job is performed, it is said to be realized. This concept of Deslization obviously applies similarly to events connecting the activities.

In the simplest case we assume that each activity of the project network has two parameters associated with it:

1. $t_i$ - time or cost required for the performance of activity, i, a random variable with associated statistical measures
2. $p_i$ - the probability that activity i is performed, given that the starting event for the activity is realized
3. $P_j$ - the probability that event j is realized
4. $T_j$ - time of realization of event j. ($T_j$. = expected time of realization of event j)

**To** apply GERT we go through the following steps:

1. Convert qualitative information of jobs, their relations, and alternative jobs.
2. Collect the data on activities comprising the network
3. Develop statistical distributions or averages for the resources required for the performance of each job. (In our case, only time.)
4. Obtain equivalent single line function between any two events (nodes) of the network.
5. Convert equivalent single line function into performance measures comprised of the probability that a specific event is realized and the moment generating function of the time or cost associated with the equivalent network.
6. Make inferences concerning the system response.

GERT defines events or nodes by different types of input and output characteristics:

a. Exclusive-or Input - only one of the branches leading into the node can be realized.

b. Inclusive-or Input - any branch leading into the node realizes it, but time or cost of realization is always the smallest of the completion times of the activities leading into the node.

C. And Input - only realized if all activities (branched) leading into the node are realized. Time or cost of realization is always largest of incoming activity times. This is therefore equivalent to a PERT node.

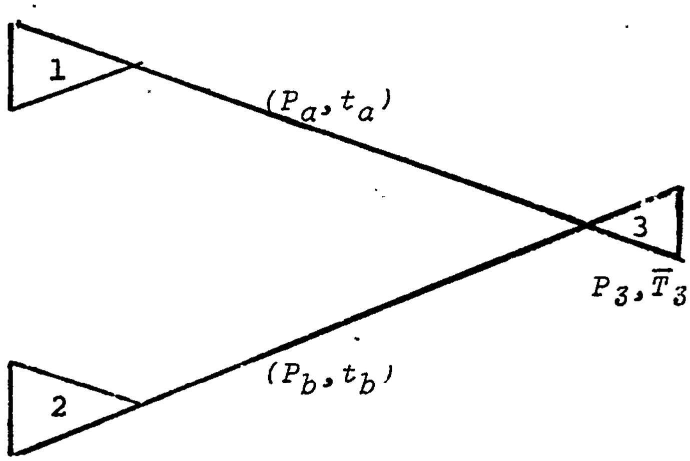
d. Deterministic Output - all activities leading from the node must be performed if probability of realization equal to one.

e. Probabilistic Output - exactly one and only one activity emanating from the node can be performed if the node is realized.

Each node of event is represented by one of the input and one of the output characteristics.

In Exclusive-or Node Networks or subsets of networks feedback is possible. If all the inputs or events of a network are Exclusive-or, then either all node outputs are probabilistic, or the activities following a deterministic output are independent (nontouching, disjoint).

In some networks And and Inclusive-or Nodes can be converted to Exclusive-or Nodes. Considering an Exclusive-or Mode with two_ inputs where P. is the probability that node i is realized, and $T_i$ is the expected time that node i is realized,.given it is realized,



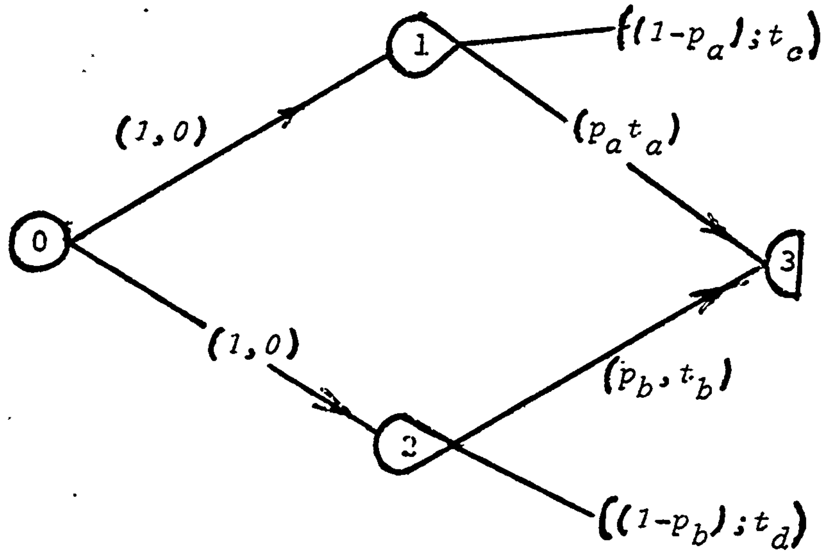

$$P_3 = P_1 p_a + P_2 p_b$$

$$\bar{T}_3 = \frac{P_1 p_a (\bar{T}_1 + t_a) + P_2 p_b (\bar{T}_2 + t_b)}{P_1 p_a + P_2 p_b}$$

If $P_1 = P_2$, then $\bar{T}_1 = \bar{T}_2$ and $P_3 = P_1(p_a+p_b)$ and $\bar{T}_3 = T_1$

$$+ \frac{p_a t_a + p_b t_b}{p_a + p_b}$$

Considering next an And Node Network,



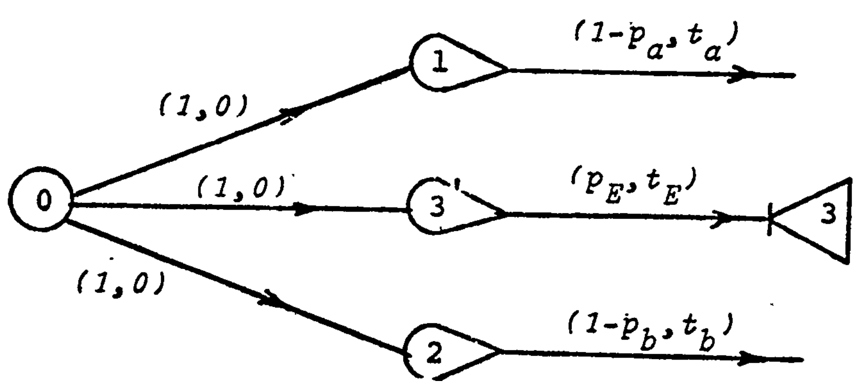

As node 3 is only realized if a and blare realized and the probability of a and b being realized is $P_1P_a$ and $P_2P_b$ respectively, the probability that both are realized is the intersected or joint event of both being realized.

$$P_3 = P_{1\cap 2}\, p_a\, p_b$$

$$\bar{T}_3 = max\ (T_1 + t_a,\ ;\ T_2 + t_b)$$

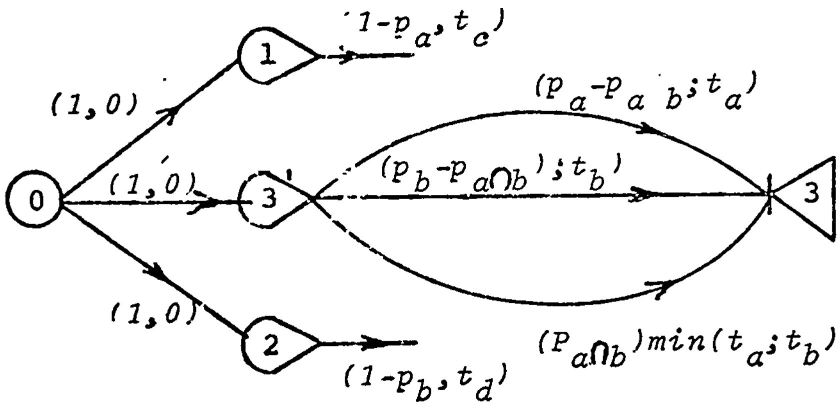
It should be noted that the expected value of the maximum is not always the maximum of the expected value.

An Exclusive-or relation can replace the And node at node 3 as shown.



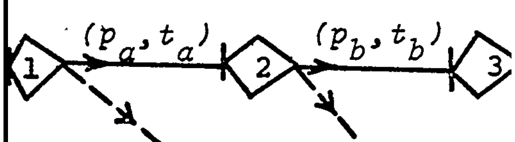
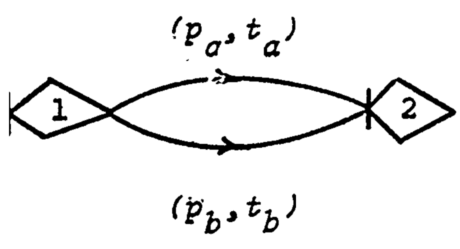
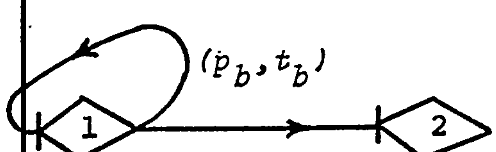
where $P_E = p_a p_b$ and $t_E = max\ (t_a, t_b)$

For an Inclusive-or relation the analysis is as in the And case and we get for the previous network now,




The reduction basically involves enumeration of all mutually exclusive alternative methods of realizing node *3* from node 0.

<u>Simple Exclusive-Or Networks</u>

| Network Type | Representation With Constant Times | Equivalent Probability | Equivalent Expected Time |
|---|---|---|---|
| **a) Serles** |  | $P_a P_b$ | $t_a + t_b$ |
| **lb) Parallel** |  | $P_a + P_b$ | $\frac{P_a t_a + P_b t_b}{P_a + P_b}$ |
| **c) Self Loop** |  $(P_a t_a)$ | $\frac{P_a}{1 - p_b}$ | $t_a + \left(\frac{p_b}{1-p_b}\right) t_b$ |

The relation between GERT networks, PERT, flowgraphs, and stochastic networks can be stated as:

PERT networks are equal to GERT networks with all And deterministic nodes, in which case all activities must be performed.

FLOWGRAPHS are stochastic networks with a single multiplicative parameter (all additive parameters such as time are set zero) and the probabilistic interpretation for the multiplicative parameter is removed.

To facilitate operation with a general conditional stochastic network (GERT) which permits simultaneous handling of multiplicative and additional parameters (such as probabilities and times or costs in a series network) we use a transformation of p and t into a single function such as $w(s) = pe^{st}$ when, for instance, for two activities in series w(s) function will be multiplied and for 2 activities in parallel with w(s) functions would be added. If we then differentiate with respect to s and set s=O we will get an expression proportional to the expected times. The function w(s) is normally called the moment generating function, MGF.

If $w_E(8)$ is the equivalent MGF for a complete network, then

$$p_E = \text{equivalent probability} = w_E(0)$$

For instance, for two activities in series,

$$W_E(8) = w_1(8)\,w_2(8) = \left(p_1 e^{st_1}\right)\left(p_2 e^{st_2}\right)$$

and

$$p_E = w_E(0) = p_1 p_2$$

as desired.

For two parallel activities,

$$w_E(8) = W_1(8) + W_2(8) = p_1 e^{st_1} + p_2 e^{st_2}$$

$$P_E(0) = P_1 + P_2$$

To find the expected equivalent **time** for **two activities in series,**

$$p_E \cdot E(t) = \left.\frac{\partial w_E(s)}{\partial s}\right| = P_1 P_2 (t_1 + t_2)$$

and for two activities in parallel,

$$P_E \cdot E(t) = \left.\frac{\partial w_E(s)}{\partial s}\right|_{s=0} = P_1 t_1 + P_2 t_2$$

Therefore, by dividing the derivative set to s=O by the equivalent probability we obtain the equivalent expected time E(t).

To employ the w(s) function effectively we use flow graph theory. The $w_E(s)$ or equivalent MGF of a complex network is obtained by Mason's rule or a similar flow graph reduction approach.

## Fundamental GERTS Concepts

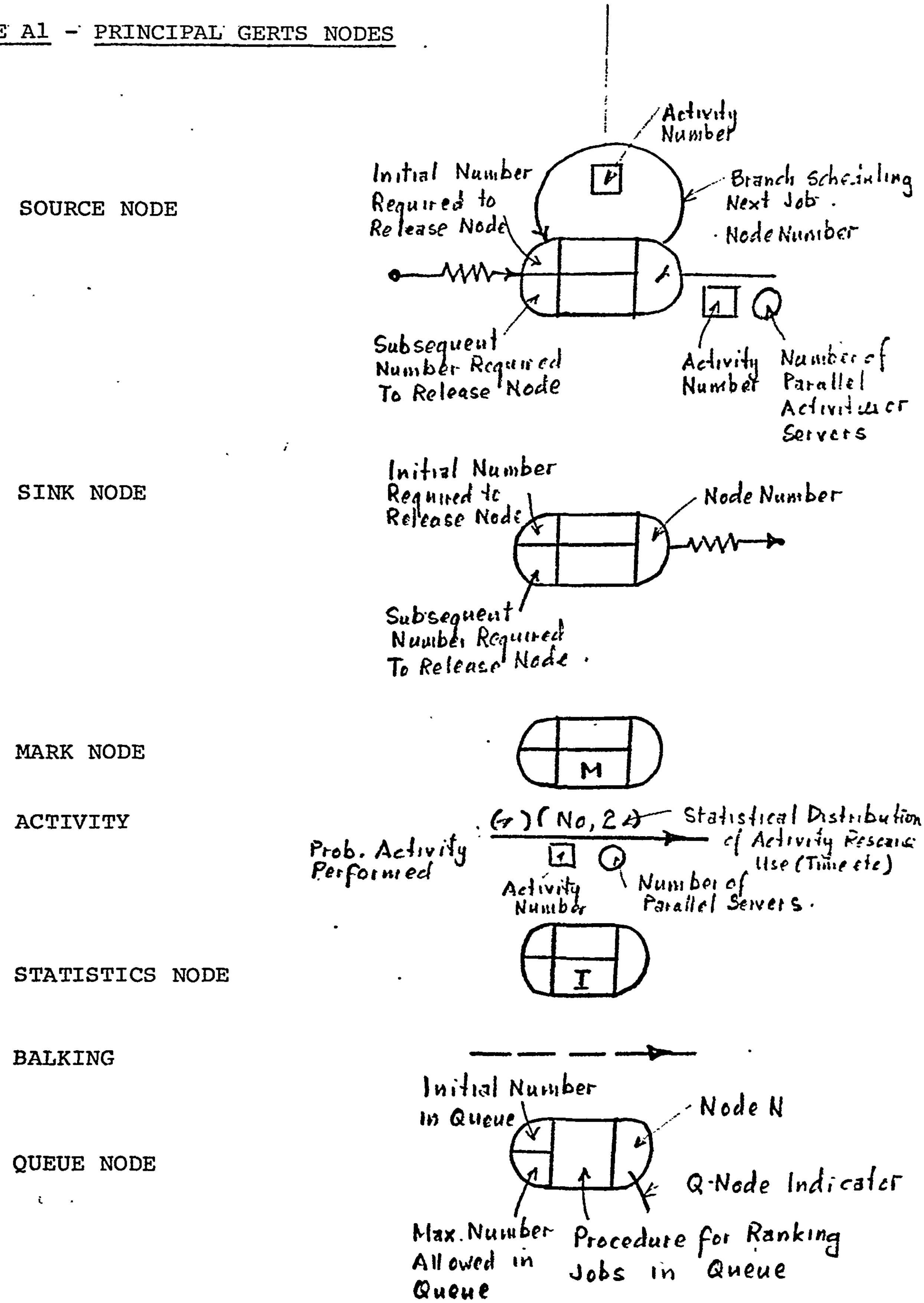
GERTS or GERT Simulation and their derivatives use a number of imaginative node definitions which provide a large amount of flexibility in analyzing and evaluating shipbuilding project performance, resource use, schedules, and more. GERTS nodes can have probabilities or stochastic output and input. The basic node characteristics are shown in Figure Al. It should be noted that nodes can have a deterministic (semi-circular) or probabilistic (triangular) input or output, in which case not all incoming activities are required to realize the node nor do all outgoing activities have to be performed.

In addition to the nodes shown there are regular or standard nodes, which only perform the function of receiving and routing jobs. Statistical Distributions are designated by codes such as:

| | |
|---|---|
| BE | Beta Distribution |
| BP | Beta Distribution fitted to three parameters |
| co | Constant Distribution |
| ER | Erlang Distribution |
| EX | Exponential Distribution |
| GA | Gamma Distribution |
| LO | Log normal Distribution |
| NO | Normal Distribution |
| PO | Poisson Distribution |
| TR | Triangular Distribution |
| UN | Uniform Distribution |

It is noted that GERTS permits use of most practical distributions in simulating a project.

FIGURE A1 - PRINCIPAL GERTS NODES



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