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APPLICATION OF SYSTEMS ANALYSIS TO INDUSTRIAL PROJECT IMPLEMENTATION IN DEVELOPING COUNTRIES [1]

by

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TABLE OF CONTENTS

Chapter Page

5 (Cont'd)

6 CRITICAL RESOURCE ALLOCATION AND SCHEDULING

7 DECISIONS IN SYSTEMS

8 SYSTEM CONTROL

9 SYSTEMS IMPROVEMENT

10 SYSTEM EVALUATION

11 RECOMMENDATIONS

APPENDICES

B Bibliographies

1. INTRODUCTION

1.1 Background

The implementation of an industrial project is a very complex undertaking which involves a multitude of inter-acting functions. Some of these are planning the sequence of activities in the project, setting up the schedule of their implementation, making an appropriate distribution of the load on resources, assuring that the capacity of the resources is not exceeded by the demand on them, appraising alternative courses of action for implementation, and co-ordinating the efforts of many people and agencies. All these functions are directed toward the goal of completing the project within the limits of the specifications set for it and under the most optimum combination of time and cost.

This undertaking is even rendered more difficult in developing countries, where resources are more scarce, efficiency is lower and delivery times of goods and sources are longer than those in industrially advanced countries. All this is coupled with a lack of managerial experience, a scarcity of technical skills, and an absence of the required industrial base. This poses tremendous problems for the managers in developing countries who are responsible for the construction and putting into operation of industrial projects. They are required to make decisions on a large number of questions arising during the implementation process, taking into consideration all the facets of the projects. In such situations, systems analysis would be of great benefit. Systems analysis assists the manager in looking at the project as one whole to which each activity fits as a part, and making decisions with reference to the total project.

1.2 Organisation of the Study

After the introduction, the second chapter attempts a definition of the areas related to the study of systems, namely, operations research, systems analysis, systems engineering and the theory of decision.

In the third chapter a system definition is given to industrial project implementation, both at the project level and at the organisation level. Several methods of system description are explained and applied to project implementation, in the fourth chapter.

An application of the systems analysis approach to a specific problem in project implementation is presented in Chapter 5. This is a new approach based on intensive research conducted at the University of Illinois in collaboration with E. J. Dunne.

The problem of critical resource scheduling is presented in Chapter 6. Decision making in systems is treated in Chapter 7, and is followed in Chapter 8 by a discussion of the control system needed for implementing decisions, together with its associated information feedback system.

In Chapter 9 some suggestions for systems improvement have been given, with particular reference to the problems of the study.

Chapter 10 focusses on the question of evaluation, that of the system and also of the system approach. Finally, some recommendations are proposed in Chapter 11.

2. SCIENTIFIC DISCIPLINES RELATED TO SYSTEMS

2.1 Operations Research

It is very difficult to define a field of scientific or professional specialisation in one paragraph. However, it will be of great help in outlining the scope of the area of specialization dealing with the study of systems and the making of decisions, to point out some characterisations of each. Our starting point is operations research, which is the best known among these fields.

Ackoff[1] one of the pioneers of O.R., asserted that Operations Research could be considered as being:

(a) The application of scientific method

(b) by inter-disciplinary teams

(c) to problems involving the control of organised (man-machine) systems so as to provide solutions which best serve the purpose of the organisation as a whole.

Richmond[2] described it as an approach to problem solving

Ackoff and Rivett[3] pointed out that the essential characteristics of O.R. were:

(a) Systems orientation (the study of whole integrated systems as contrasted to the analysis of localised problems)*

(b) The use of inter-disciplinary teams (in order to assist in formulating an integrated description of the system)*

(c) The application of O.R. methodology.

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[1] Ackoff, R.L. and M. Sasieni, "Fundamentals of Operations Research", Wiley, New York, 1968.

[2] Richmond, S.B., "Operations Research for Management Decisions", The Ronald Press, New York, 1968.

[3] Ackoff, R.L. and P. Rivett, "A Manager's Guide to Operations Research", Wiley, New York, 1963.

* The phrases between parenthisis are due to the author.

Wagner[4/] however, stated that the distinguishing characteristics of O.R. were.

(a) A primary focus on decision-making

(b) An appraisal resting on economic effectiveness criteria

(c) Reliance on a formal mathematical model

(d) Dependence on an electronic computer.

The credit for the whole system (or holistic) approach to studying system problems, goes to the pioneers of O.R. Nevertheless, the emphasis on whole systems has tempered in O.R. studies since the inception of this discipline due to the limitations of the techniques used. Also, the need for, and the appointment of, inter-disciplinary teams has been reduced by the emergence of a large number of O.R. specialists. Actually, inter-disciplinary teams now act as a support, and not a substitute, to the O.R. specialist who brings to the problems under study his knowledge and skills in O.R. methodology.

Although economic effectiveness remains to be the most important single criterion, it is by no means the sole objective a manager or an engineer tries to achieve.

O.R. applications abound in examples in which other important criteria, such as reliability, were pursued. Perhaps the second characteristic mentioned by Wagner could better be stated as "an appraisal resting on quantitative criteria".

The electronic computer is, of course, most useful in large-scale problems, but it can hardly be considered as an integral part of every O.R. study.

In essence, the primary characteristic of O.R. is its methodology, which relies heavily on a certain approach and a body of concepts and mathematical models, in which optimisation plays an important role.

Again, Ackoff[5/] described the phases of an application of O.R. methodology to problem solving as:

(a) Formulating the problem

(b) Constructing a mathematical model

[4/] Wagner, H.M., "Principles of Operations Research", Prentice-Hall Incorporated, Englewood Cliffs, New Jersey, 1969.

[5/] Churchman, C.W., R.L. Ackoff and E.L. Arnoff, "Introduction to Operations Research", Wiley, New York, 1957.

(c) Deriving a solution from the model

(d) Testing the model and the solution derived from it

(e) Establishing controls over the solution

(f) Putting the solution to work. Implementation.

2.2 System Analysis and Systems Engineering

A "System" is any collection of inter-acting elements that operate to achieve a goal.6/ The systems which O.R. and related fields are applied for their study have the following characteristics in common:

(a) They are at least partially controlled by man.

(b) The major variables can be expressed quantitatively.

(c) There is some degree of man-machine inter-action; the machine is to be viewed here broadly as any hardware or physical facility.

Organisations of all sorts represent a special class of such systems. Examples are industrial, service, commercial and financial firms, educational institutions and military organizations. Other types of systems of interest to O.R. men are complex engineering systems such as transportation, utility and electric networks, and weapon systems.* Lately, large scale projects have been viewed as systems which are subject to the same methods of study. Examples are space and construction projects. Sub-systems of these systems may constitute identifiable (but not independent) entities; for example, an industrial organisation embodies production, inventory, accounting, control and other systems. Sub-systems of this kind may also be amenable to the application of O.R. methodology.

Industrial engineers have contributed to the solution of many problems pretaining to all types of systems, with the application of the methods of O.R. and related fields.

6/ Elmaghraby, S.E., "The Analysis of Production Systems", Reinhold, New York, 1966.

* It is to be noted that the field of Systems Analysis started with Weapon Systems Analysis.

One of the important fields allied to O.R. is "Systems Analysis" (sometimes known as Systems Evaluation). Quade[1] approached an explanation of systems analysis in the following words.

> "In the absence of a good brief definition, Systems Analysis, ... , can be characterized as "a systematic approach to helping a decision-maker choose a course of action by investigating his full problem, searching out objectives and alternatives, and comparing them in the light of their consequences, using an appropriate framework - insofar as possible analytic - to bring expert judgement and intuition to bear upon the problem"".

This characterisation of system analysis makes it look very similar to O.R., which it is; after all the two areas emerged from the same origin, namely, the improvement in the design and utilisation of weapons systems. However, there are some significant differences between the two areas of endeavour.

It has been pointed out by specialists in systems analysis and O.R. that the former discipline undertakes strategic problems while the latter tackles tactical ones. This implies the following:

(a) In scope: strategy studies tend to involve a larger segment of the organisation, and consequently they address themselves to answering the needs of decision-makers of higher rank.

(b) In range: strategy studies tend to evolve long-range plans. They generally have as end products decisions or designs which have long-range implications.

(c) In end-orientation: strategy studies tend to be more involved in problems of formulating organisational objectives and policies rather than of finding means of reaching the objectives and making operational decisions.

(d) In weight: the impact of strategy studies on the system as a whole is generally more pronounced (as well as more durable). This can be measured by the amount of money involved in the decisions, the risks faced, the extent of change to be introduced and similar indices.

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[1] Quade, E.S. and W.I. Boucher, (Eds.), "Systems Analysis and Policy Planning - Applications in Defense", Ch. 1, Elsevier, New York, 1968.

Also, systems approached by systems analysis studies are generally more complex, in terms of the number of components they contain and the degree of complexity of inter-relationships among the components. When this is the case, methods of O.R. may be used to tackle sub-system problems.

Another aspect sometimes used to distinguish between O.R. and systems analysis is that the former area attempts to optimise the use of existing facilities while the latter aims at proposing new facilities. This is not always true since some O.R. studies end by a recommendation of new facilities and some systems analyses propose fundamental changes that do not involve the acquisition of any hardware.

Due to the complexity of the systems they study, and their strategy orientation, system analyses tend to be less formal in the construction of the mathematical models they use, and less concerned about the application of optimization techniques. Instead, they rely more heavily on graphical methods, simulation, heuristics, and approximate solutions, and use as inputs more qualitative (as contrasted to quatitative) statements than are generally observable in O.R. studies. Consequently, the judgemental element in systems analyses play a more important role than in O.R. work.

It should be pointed out here that these qualifications do not make systems analysis any less important than O.R. Systems analysis, as a discipline, should be evaluated in terms of its only possible existing alternative, the absolute reliance on judgement in the solution of extremely important systems problems. It is also to be realised that it is a very recent field whose tools are still in the process of being sharpened.

An expression which emerged along with 'Systems Analysis' is "Systems Engineering". Sometimes the two expressions are used inter-changeably. However, systems engineers asserted that their main emphasis was on the design of systems as contrasted to improving their utilization. Although systems engineering had the same origin as both O.R. and systems analysis, it has been mainly advanced by electrical engineers who drew heavily on feedback, control, and servo theories and on information theory.

The characteristics of the class of systems which are studies through systems engineering have been described by Machol[8] as:

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[8] Machol, R.E. (Ed.), "Systems Engineering Handbook", Cha. 1, McGraw-Hill, New York, 1965.

(a) The system is man-made, from equipment, or "hardware".

(b) The system has integrity - all components are contributing to a common purpose, the production of a set of optimum outputs from the given inputs.

(c) The system is large - in a number of different parts, in replication of identical parts, perhaps in functions performed, and certainly in cost.

(d) The system is complex - here it is taken to mean that a change in one variable will affect many other variables in the system, rarely in linear fashion; in other words, the mathematical model of the system will be complicated.

(e) The system is semi-automatic, which means that computers always perform some of the functions of the systems and human beings always perform some of the functions of the system.

(f) The system inputs are stochastic.

(g) Most systems, and especially the most difficult systems, are competitive.

Although a few systems, such as weapon systems, are approached by both systems analysis and systems engineering, there are some areas of differences. Systems analysis is more interested in "management systems", those in which the allocation of human and material resources is an important aspect, and decision-making plays a vital role. Organisation studies fall into that category. On the other hand, systems engineering is mainly concerned with "engineering systems", those in which the design of physical facilities (in relation to certain human uses) is the most important outcome of a study.

A field of specialisation which bears close resemblance to O.R. systems analysis and systems engineering is known as "cybernetics", and was introduced by Norbert Wiener[9] The term "cybernetics" is an adaptation of the Latin word gubernator which is derived from a Greek word meaning "steersman", The subject is concerned with the notion of feedback, information and control as applied in automation. It draws parallels between the functions of man and machine and thus borrows heavily from biophysics. Much of the ground covered by cybernetics is already now integrated in our three areas of interest.

9/ Wiener, Norbert, "Cybernetics", Wiley, New York, 1948.

2.3 Decision Theory

The process of decision making has been the subject of study by two different, but converging groups: the behavioral scientists and the mathematicians. Roughly speaking, the behavioral scientists take a "descriptive" approach, in which they seek to learn about how decisions "are actually" being made by individuals and groups, while the mathematicians look at decisions from a normative point of view, attempting to reccomend rules for how decisions "ought to be" made. Naturally, the mathematicians' emphasis is on optimization, drawing heavily upon probability theory and statistics.

The two approaches are converging as a result of the interest of members of each group in the other group's approach. In fact, a good deal of the latest developments in statistical decision theory has been contributed by social scientists, and conversely, it is due to mathematicians that the first attempts at measuring utility and preferences were made.

The interest of statistical decision theory in mathematical models and optimisation in relation to decision-making makes it almost synonymous with O.R. However, research conducted under decision theory puts a greater emphasis on utility as a measure of preferences, and takes an approach based on subjective probability, modern utility theory and the new methods of Bayesian statistics. In spite of the fact that decision theory started to blossom in the early fifties, based on earlier developments in the theory of games, the literature of O.R. did not include significant discussions of it until the middle sixties. Apparently, O.R. methodology could benefit from decision theory specifically in the areas of competitive models and sequential decision-making under risk.

On the other hand, it was vividly demonstrated by behavioral scientists that normative decision theory, in the process of structuring rules for "rational" decision making, based its arguments on assumptions that are not always valid. Foremost among these is the assumption that an individual, or a group, will behave, or at least will like to behave, rationally in a decision situation. A great deal of light has been recently shed on the dynamics of inter-personal inter-action, and its relationship to decision-making and problem solving, which is of extreme importance to the development of a realistic decision theory.

2.4 Applications

It should be clear that the four areas - operations research, systems analysis, systems engineering and decision theory - can be very powerful tools in the hands of the engineers and managers. For example, techniques of O.R. (also known as operations analysis, operations evaluation, systems research and management science) are being used in mechanical engineering for the solution of problems of heat transfer and design. The most important of the techniques applied are those of optimisation such as linear programming and dynamic programming. Chemical engineers also use dynamic programming to optimise multi-stage chemical processes. Civil engineers apply systems analysis in the study of construction projects and use network theory in the analysis and design of transportation and utility networks. Also, electrical engineers use systems engineering as one of their powerful tools.

Outside engineering disciplines, business schools have been staunch advocates of the introduction and application of O.R. methodology, often going under the name "quantitative methods" or "quantitative analysis". Besides, they were pioneers in the teaching of decision theory and the application of its concepts and techniques to management problems. Also, schools of economics have included O.R. in their curricula. In addition, some mathematical techniques such as linear programming have constituted central theories in the subjects of mathematical economics and econometrics. Indeed, it is due to the efforts of a renowned economist (Leontief), that input-output analysis, the forerunner of linear programming, has been introduced. Last but not least, the subject of decision theory is of interest to behavioral scientists, especially psychologists, sociologists and social psychologists.

There is no need to emphasise that there is much to be gained from an interaction among these areas of specialisation in activities related to systems. Indeed, it is the objective of this study to explore areas of application of the systems approach to industrial project implementation in developing countries.

For further clarification of the definitions of areas related to systems, a list of the topics normally considered to belong to each one of the form areas is listed in Appendix A.

3. SYSTEM DEFINITION OF PROJECT IMPLEMENTATION

3.1 Definition of the System

Regardless of the approach used in a systems study, the starting point must be a proper definition of the system. In general, a system is: -

(a) a set of elements (components)
(b) which are interrelated,
(c) serving from function(s),
(d) and seeking some objective(s).

The first three attributes of a system would equally describe a respiratory system, the solar system, and an industrial project. The stipulation of the last attribute specifies the kind of systems we are interested in, those which are purposeful. They are man-machine systems in which man plays the dominant part.

Churchman[10] stated that five basic considerations must be kept in mind when thinking about the meaning of a system:

(a) The total system objectives and, more specifically, the performance measures of the total system.
(b) The system's environment - the fixed constraints.
(c) The resources of the system.
(d) The components of the system, their activities, goals and measures of performance.
(e) The management of the system.

It is appropriate at this stage to raise the question, "In industrial project implementation in developing countries, what is to be defined as a system?" An answer to this question is a prerequisite to applying the previous thinking. Nevertheless, there can be no unique answer to this question. Instead there are many possibilities, of which the following three seem to be the most meaningful:

(a) An industrial project.
(b) A set of related projects.
(c) An organization in charge of industrial project implementation.

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[10] Churchman, C.W., "The Systems Approach", Delacorte Press, New York, 1968.

The broader the system is defined, the more complex it is and the more difficult to study, but, at the same time, expanding the definition of the system offers an opportunity for co-ordinating the utilization of resources for maximum benefit.

The definition of the boundaries of the system under study has always been one of the most nagging problems facing system analysts. To be sure, the proponents of the "whole system" or "holistic" approach insist that no problem can be meaningfully solved unless the "total system" in which the problem is embedded is taken into consideration. But this approach is limited by the fact that every system is embedded in a larger system and so on until the whole universe is contained, and there will always be an argument that some variable in the larger system will have an influence on the operation of the specific problem in question.

The systems analyst, however, looks for a practical guide for the delineation of the boundaries of his system, and perhaps the following considerations might be of help to him in this respect, as they provide the factors which should influence the scope of the system under study.

(a) The position of the client (the person, or persons, who requests, or request, consultant help for analysing problems of project implementation). The limit in this case is suggested by the scope of the organization (or sub-organisation), which is headed by the client.

(b) The degree of interaction between the factors directly influencing the project (or organization), and other factors outside the project (or organisation) headed by the client.

If, for example, a project uses resources which are not competed for by other projects except minimally, then it may be considered as a separate system.

(c) The degree to which the attainment of the objectives of the project is affected by outside factors, in other words, the sensitivity of the objective function to such factors.

(d) The controllability of outside factors by the client. There is no meaning in considering a variable as subject to manipulation, when it falls completely outside the domain of the people using the recommendations of the study.

(c) The ability of the systems analyst himself, whether he is a member of the organization or an outside consultant. For a beginning analyst, it may be expedient to practice his knowledge on a limited problem, and as he gathers experience, he may expand the scope of his studies.

The set of elements apparently related to a study of the implementation of an industrial project or a set of projects can be so large as to prohibit the establishment of meaningful relationships among them. A primary classification of such elements into the following categories is often helpful.

(a) The system proper - those elements affecting the study and within the scope of complete or partial control by the client.

(b) The environment - those elements affecting the study but which are beyond the control of the client.

(c) The irrelevant elements - those which are poorly related to other relevant elements or for which the objectives of the system are not sensitive. A procedure for identifying these elements is outlined in the next chapter.

There are some arguments which favour the expansion of the definition of the system under study in a developing country.

(a) A developing nation generally lacks the industrial base required for the flourishing of industry. This implies that the completion of a project is often required before one or more other projects can be made use of. For example, power plants are required before factories can run, and steel mills are required before an automobile plant can produce, if such an industry is not to rely entirely on imports of raw materials. This necessitates co-ordination in the implementation of projects which are part of a plan.

(b) Resources are more scarce in a developing country than they are in an industrialized one. Thus the need for co-ordinating the implementation of several projects, which call upon the use of scarce resources, becomes imperative.

(c) The urgency with which many emerging nations are pursuing accelerated industrial development prompted them to create organizations which undertake the task of planning for industrial development, co-ordinating the implementation of plans, and providing facilities and services to the units in charge of implementation. This means that in these cases not only is co-ordination needed, but is is possible as well. Whenever such an organization exists, systems analysts should attempt to address its efforts to the solution of the total organization's problems.

After this general exposition of the "systems approach" as applied to industrial project implementation in developing countries, the details of the approach can be better explained in terms of more specific examples.

3.2. The Project

Suppose that is has been decided that the system actually consists of one project. The five considerations mentioned in the previous section can now be related to the project as a system.

(a) The project's objectives:

Given the design of any particular project, the objectives of its implementation may be analysed into four basic components: quality, time, cost and social value. Although the four are interconnected, an order of priority could be set on them. "Quality" is generally regarded as a constraint, a set of specifications which have to be satisfied, although it may be advantageous to reconsider the given quality standards occasionally, in order to explore the possibility of relaxing them or improving them as opportunities arise. In a developing country the attention that "time" receives is variable and is dependent on a number of factors. Social and national security pressure as well as the interest of stockholders may tend to accelerate the implementation of a project. On the other hand, the precise cost of delay is rarely estimated and hardly influences the completion time of a project. Naturally, "cost" is an important objective. Every project manager has a keen interest in minimizing it. However, very few managers install systematic procedures for cost estimation, evaluation and control. "Social values" play a particularly important role when the project represents a national symbol such as an iron and steel plant, or when it plays a particular role in the nation's security. However, social values can be over-emphasized. The role of the systems analyst in these cases is not to question these values, but rather to evaluate and point out their economic costs. In fact, one of the analyst's first jobs should be to try to establish the order of priority of the objectives, making sure that this order does reflect the real system's objectives, and not just impressions, feelings and opinions of some individuals.

(b) The project's environment:

As mentioned before, the environment consists of those factors influencing the project but which are beyond the control of its managers. They are deadlines, limits on resource acquisitions, minimum specifications and other project constraints. However, there may be a tendency to over-estimate the environment, in other words, to consider some factors as being beyond control while, with some effort, they may be within control. For example, a project manager may feel that he has acquired all the resources he can master, while with some extra effort he can obtain additional financing or manpower. At the same time, there is an obvious danger of overlooking the existence of constraints on the system.

(c) The resources of the project:

These may be classified into: manpower (managerial, technical, clerical and manual), materials (equipment, raw materials, component parts, supplies), information (blueprints, utilisation and availability of resources, stage of completion of project, financial situation) and money.

(d) The components of the project:

Those are the basic elements which when put together they constitute the project. They are generally mainly the activities of the project. As in any other system, there is no unique way of defining the components (activities) of the project. As the project is broken down into finer components, more interrelationships can be taken into consideration, but the system will become more complex. It will also be more difficult to collect data for the finer components. However, a useful definition of an activity is that it is a collection of tasks that are highly interrelated but which are related to other tasks only as a group. In most of the literature on project implementation, activities are taken to be the sole components of the project. A broader point of view would consider resources, products and functions as component parts of the project.

(e) The management of the project:

It is the management of the project which is being advised by the systems analyst. The basic functions of management are planning, controlling, supervising, and evaluating. It is the task of this report to show how the systems analyst can help project managers to improve their system's performance.

3.3 The Organization

If systems analysis is applied to serve the goals of an organization charged with the implementation of several projects, the definition of the system will be different.

(a) The organization's objectives:

Basically, the objectives will be the same as those of the project, except that they have to be sought for the set of projects as a whole, and not for a single one by itself. Also, the implementation of a project is a process which has definite starting and ending points, whereas an ongoing organization has no limit on the time horizon. This makes a difference, not only in the physical breadth of the system, but also in its time depth.

(b) The organization's environment:

As the system enlarges, the variables under its control increase, and what is considered to be an environment from the point of view of one project, may be a controllable variable from the organization's point of view. This is because an ongoing organisation would have command over more resources than a temporary project.

(c) The organization's resources:

Foremost among the resources which are more accessible to an ongoing organization is manpower with skill in implementation of industrial projects. Another is construction equipment which can be deployed directly by the organisation rather than having to subcontract for their use.

(d) The organization's components:

The components of the organization are not to be taken, as in the traditional view, as its divisions and departments. Rather, they are to be described in terms of the basic activities of the organization. From this point of view, an implementation plan for a large set of projects may consider a single project as a component of the system.

(e) The management of the organisation:

In addition to managing the implementation of one project, the management of the organisation faces the task of co-ordinating among the various projects in a plan.

4. SYSTEM DESCRIPTION

1 Basic Consideration in System Description

Given a definition of the boundary of the system and its objectives, one can proceed with the system description. As previously mentioned, there is no unique way of describing a system, and the way it is to be described hinges upon the system goals and the objective of the study. Any study starts with a set of questions which are in need of an answer. For example, "What is the minimum completion time for the project?", or "What are the additional resources which might be needed if the project is to be completed in so many weeks ahead of schedule?", or "What is the best schedule for the starting dates of each project in a set of projects?" The answer to each one of the previous questions requires a different set of data and a different organization of the data. The systems analyst is often given a number of questions, for which he is required to provide answers. A skillful analyst would start by questioning the questions themselves. For example, if the question is, "How much would it cost to reduce the project duration by so many weeks?", he may build up a case against restricting the choice for that specified amount of reduction. He may argue for leaving the question of the desired reduction open to optimization together with that of cost.

With the determination of the scope, objectives and questions to be answered, the problem under study is now formulated. The next step is to identify the variables relevant to the study. A list of such variables is possible to construct. However, t is important at the onset to decide upon the pattern of organization of data. gain, this should be oriented toward both the system objectives and the way the data re going to be used. In principle, all the requirements of a project should be isted according to their ultimate use rather than their common function. Therefore, f carpenters are needed to construct a shack as a temporary office for the project upervisor and later to construct doors and windows for the office buildings after hey are finished, the prime classification of the carpenters would be their use in he project, and a secondary classification could be their belonging to the carpentry epartment or carpentry sub-contractor. Taking this approach, it may be only ecessary to identify a team consisting of carpenters, masons and electricians as a eam performing a particular job rather than by the professions of its members, which ay come as a secondary classification.

[illegible].2 Data Organization

Components of any system are contained within larger components and so on. When the component is complex enough it is called a sub-system. In fact a complete system may be a component in another larger system, such as, a project may be a component in a plan of a set of projects.

Going back to the basic components of a project, the data about these components (men, material, activities, etc.) are formed into records, and records are formed into files. Some ordering method is necessary so that information can be easily obtained when needed. File organization has particular importance when data must be collected for system definition, or for the design of information systems with storage points for data in the information flow sequence. As can be seen, industrial project implementation is an activity where this is needed. The need becomes more urgent if electronic data processing facilities are used, and such facilities may be easy to justify for a permanent organization in charge of the implementation of industrial projects.

The ordering method as used in file organization implies a hierarchy of classifications, that is, broader classifications, then less broad and so on down to the specific. The following is an example of hierarchies of classification of workers:

I. Personal Data

A. Name

1. Last

2. First

3. Middle

B. Address

1. City

2. Street

3. Street Number

C. Marital Status

D. Number of Dependents

II. Skill Data

A. Craft Type

B. Skill Level

C. Educational Level

III. Job Data

A. Job Name
B. Rate of Pay
C. Seniority

IV. Task Assignment

A. Task Name
B. Location
C. Duration

According to this order, the last name assumes more importance than the first, and craft type precedes skill level. It is clear that any hierarchy is artibrary, but it must be geared to the way data are to be used. The grouping of data most frequently demanded in data retrieval should be the one assuming the top level in the hierarchy.

Van Court Hare 11/ specifies a systematic method of system definition as follows:

"1. List, with appropriate name, each element to be defined.

2. Number, or otherwise code, each element to be listed. A simple serial listing is often satisfactory here, but if later grouping of elements is contemplated, a partially blocked code* may be used to identify similar elements.

3. Develop categories for each transaction that may be encountered, and develop a code or check list for these attributes. Such a code will certainly contain a space for the "From" and "To" element codes and will also contain additional information that may be useful in later analyses. It may be desirable to include some space for a transaction (or report).

4. Construct, for each element, an element sheet whose physical form can range from simple cards to extensive dossiers, but regardless of the form, the element sheet should show the element name and number, and should

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* The block code is one in which character, position and choice have meaning, and the serial code is one in which characters are applied arbitrarily in sequence.

11/ Hare, Van Court, "Systems Analysis: A Diagnostic Approach", Harcourt, Brace and World, New York, 1967.

provide space for the specified transaction data, which is arranged in a uniform format. The element sheet is usually divided into two parts: one records the structural information that relates incoming and outgoing transactions to the given elements; the other shows the detailed information on transformation procedures at the element and detail of any files, storage or delay that occurs at the element. An instruction sheet, or manual, containing the method of data collection and the instructions for filling out the element sheets can then be provided to a team of investigators, together with assignments to investigate specific elements. The investigators will also need to have the coded element dictionary or cross reference to fill out the transaction code correctly.

5. Collect the information required on the element sheets (for hardware systems, the required forms may be completed by several design groups or a team of engineers familiar with component specifications and connections)."

Resources and activities of a project could be identified as the basic elements of the project. The items to be included at this stage may be selected arbitrarily, bearing in mind the ultimate use to be made of them. Therefore, if only the project duration and the critical path are to be determined, the only information of relevance would be activities, their durations and precedence relationships, assuming no resource to be really critical. On the other hand, if a cost-duration analysis is to be conducted, cost data for different durations of certain activities would be required. It is safer at this stage to collect more information than would be normally required, as long as further investigation will screen out the irrelevant elements.

Once the elements have been organized in this form, their assembly, on the basis of any desired grouping, can be done by simply sorting them according to the proper selection of the transaction code category.

2.3 Model Building

The description of the system entails a description of the relationships among its elements. This description may simply be in the form of a specification of a simple type of relationship between different elements. For example, element (activity) 'A' precedes element (activity) 'B', or element '[illegible]' uses resource 'S' and element 'B' uses resource 'A' at given levels. Such information can be easily recorded on the element sheet, and is very easy to extract and use.

More complex relationships, in the form of mathematical equations or transfer functions, require additional effort and additional recording procedure. Some forms of relationships are hypothesized at this stage to be later tested for validity. The initial model, describing the system's objectives and the inter-relationship among its components can serve as a basis for the sensitivity analysis to be conducted on the elements of the system. In the sensitivity analysis, effects of variations in the levels of doubtful elements are observed on the objective function or on any performance indices in the system which are of interest. If the objective function or index is shown to be unaffected, or insignificantly affected, by these variations, the elements can be discarded from the study.

Also, the sensitivity of the objective function or the performance indices are to be tested against whatever simplifying assumptions have been made. For example, if a slightly non-linear relationship, describing the behaviour of the cost of an activity as its duration is reduced, is approximated by a linear function, it will be desired to test the effect of such approximation on the value of the criterion function.

A model is refined as fresh data are fed into it and as the assumptions made in it are either validated or invalidated.

2.4 Qualitative and Quantitative Information

The previous discussion may have conveyed the notion that the only information usable in systems analysis is quantitative data. This is not true, because there are several aspects in any system which can never be put in numbers. People's attitudes, biases, interpersonal relations, organizational limitations, behavioral uncertainties and social goals are all phenomena which are very difficult to express mathematically, but nevertheless are often very influential on the system's performance.

Several approaches may be taken in order to incorporate the unquantifiable aspects of the system in the description. One of them is to compute the economic cost of a decision which is largely influenced by social considerations. Another is to translate human attitudes into constraints on the system's performance or into uncertainties in the expected outcomes. A third approach is to assume the worst possibility and act accordingly, that is, to minimax. For example, if there is some chance of a workers' strike that would affect the progress of the project drastically and that would entail enormous costs, the action would be to assume that the strike will actually happen and to take the necessary precautions to prevent or at least alleviate its consequences.

4.5 Basic System Presentations

The function of any system is to transform inputs into outputs, an industrial project transforms given resources into a final construction of a plant, and a company transforms capital, material and manpower into products. It is possible to restrict the system description to the relationships between the outputs and the inputs of the system as a whole. In this case, the system is treated as a "black box", about whose internal operation we know nothing, but we know what we should expect as outputs, once certain inputs are fed into the system. Although such an approach can sometimes be of value, it is often desired to take a closer look at the system, and observe some of its detail. In this case the inputs and outputs are not only observed for the total system but also for some of its sub-systems and even components. But still at these levels, once we focus on the input and output of an entity (a component or a sub-system), the entity is treated as a black box. Most systems can be treated in terms of the flows taking place in and out of them, and according to this approach, a certain degree of detail is reached when analyzing *how* a certain input is transformed into a certain output becomes too costly, and instead an emphasis is given on *what* inputs produce certain outputs. In other words, what is of interest is the "transformation functions" which describe the relationships between outputs and inputs.

There are several ways in which transformation functions are expressed, and the following are the basic methods:

(a) Mathematical expression:

The relationships between inputs and outputs are described by mathematical equations or inequalities in a deterministic or stochastic fashion. This is the most formal method, and when an explicit analytical solution is available for the model, it becomes the most precise and convenient. However, very few mathematical models of systems lend themselves to analytic solutions. An example is the network in Figure (5.1), which may be taken to be an activity network representing a project. It has nodes (V_0, V_1, V_2, V_3) and arcs, activities, $(a_1, a_2, a_3, a_4, a_5)$. A mathematical expression describing the relationship among a_2, a_3 and a_5 is

$$t_2 = \max. \{(t_0 + t_{02}), (t_1 + t_{12})\}$$

where t_0, t_1 and t_2 are the earliest start of nodes o,1 and 2 respectively and t_{02} and t_{12} are the durations of activities a_2 and a_3 respectively. There are also other ways of expressing the paths lengths mathematically.

(b) Matrix representation:

Many ways of representing the above network in matrix form exist. Some of these are: arc-arc adjacency matrix (Table 4.1), node-arc adjacency matrix Table (4.2), node-node adjacency matrix (Table 4.3) and path-arc matrix (Table 4.4).

Table (4.1)

Arc \ Arc	a_1	a_2	a_3	a_4	a_5
a_1	0	0	1	1	0
a_2	0	0	0	0	1
a_3	-1	0	0	0	1
a_4	-1	0	0	0	0
a_5	0	-1	-1	0	0

Table (4.2)

Node \ Arc	a_1	a_2	a_3	a_4	a_5
v_0	1	1	0	0	0
v_1	-1	0	1	1	0
v_2	0	-1	-1	0	1
v_3	0	0	0	-1	-1

Table (4.3)

	v_o	v_1	v_2	v_3
v_o	0	1	1	0
v_1	-1	0	1	1
v_2	-1	-1	0	1
v_3	0	-1	-1	0

Table (1.4)

Arc / Path	a_1	a_2	a_3	a_4	a_5
P_1	1	0	0	1	0
P_2	1	0	1	0	1
P_3	0	1	0	0	1

Matrix representation of systems can be very useful in numerical solutions to system problems. Each type of presentation is more suited for the solution of specific problems.

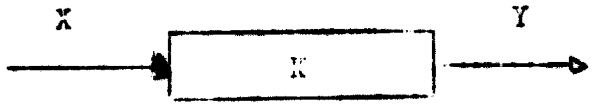
Another type of presentation closely allied to this is that of the language of sets. Table (5.3) shows an alternative way of describing the relationship between paths and arcs.

Other matrix presentations of projects are also possible and are quite suited for specific uses. For example, a matrix could be formed with activities as rows and resources as columns, so that, for any particular period, the activities calling upon a certain critical resource may be identified and perhaps rescheduled.

(c) Graphical presentations:

The most common type of presentation for projects is the flow diagram, in this case better known by the activity network (Figure (5.1)). In addition to the flow of activities, flow of materials, labour, cash, orders, equipment and information can be represented on a flow diagram. Quite often, a representation of storage points, at which levels of these flows accumulate and influence flows at following stages and so on. In these cases, the study of interactions between flows and levels provides a great deal of insight into the system. Industrial Dynamics[12] is a technique which relies heavily on this approach.

Other graphical presentations which show the relationships between inputs and outputs are the block diagram, Figure (4.1), and the flow graph, Figure (4.2).



The Block Diagram

Figure (4.1)

Flow Graph

Figure (4.2)

The two types of presentations express basically the same thing; that an input X is operated upon by a transfer function K to produce an output Y such that Y = KX. The difference is that in block diagrams inputs and outputs are arrows and the transfer function is a block, whereas in flow graphs inputs and outputs are nodes and the transfer function is an arrow.

Graphical methods serve as a good initial approach to the description of the system, providing a vivid illustration of its complex inter-relationships. Besides, they are very useful when a graphical solution is available (as in CPM, the critical path method).

12/ Forrester, J., "Industrial Dynamics", M.I.T. Press, Cambridge, Massachusetts, 1962.

4.6 Determination of System Parameters

Parameters are the quantities describing the system which assume constant values at least during given time intervals. Some of these quantities are part of the environment (constraints) and some are within the system (decisions). For example, if demand (on a product or a service) is at a constant value within a given time period, it is taken as a parameter. If it is constantly increasing, it may be expressed as a variable which is a function of time with two parameters, a constant initial level and a constant rate of increase. If demand is seasonal, a periodic function such as trigonometric function could be defined with given constants. For stochastic demand, a probability distribution could be defined which again has constant parameters. Availability of agricultural workers for construction work may follow a pattern similar to that described above for demand.

An environmental factor which often has a great deal of influence on industrial project implementation is weather. Rain, snow, sand storms and extreme heat could stop the progress of a project. Such weather phenomena generally occur with a seasonality, but they are also subject to random fluctuations.

In general, where the constraints are dynamic, they are defined as a function of time, and sometimes even the parameters determining their values are themselves variable with time.

Productivity is another constraint, which may be constant, increasing as a resul of learning or technological developments, or fluctuating with seasons.

Internal system parameters are those dictated by the policies of the organization, such as the policy toward overtime hours, hiring of seasonal workers, use of sub-contractors, etc. Also, upper bounds on capacity and other sources form natural system constraints.

In summary, information concerning parameters should cover requirements, upper bounds, costs, technical co-efficients and probability and time constants. It shoul take into account the dynamic and stochastic nature of the parameters.

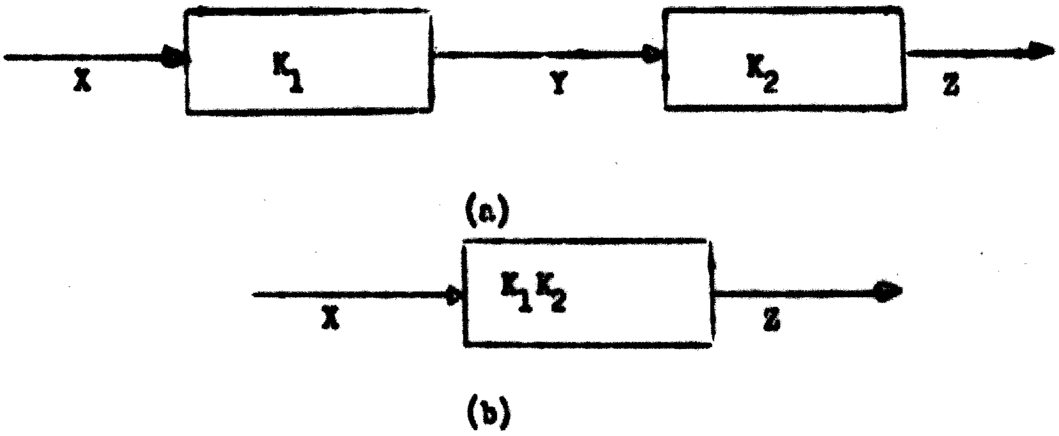
4.7 System Simplification

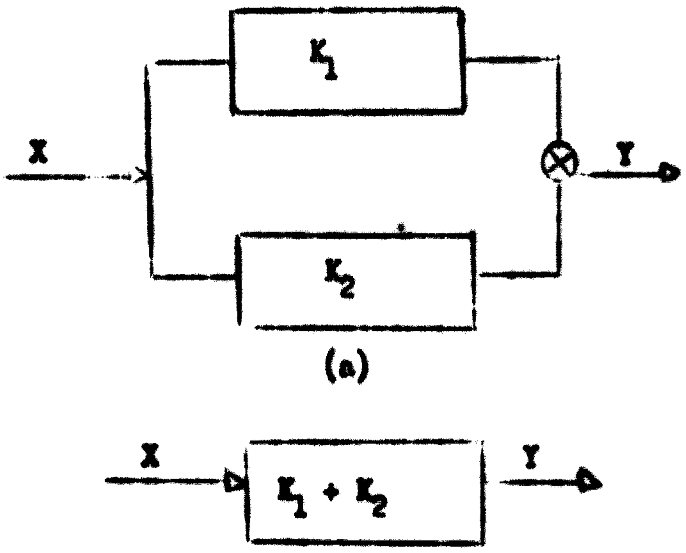
Systems can be simplified in a number of ways. An obvious approach is the reduction of the number of variable to be handled simultaneously. This can be accomplished either by elimination or by grouping. The method of elimination is followed when irrelevant variables, or variables with little influence, are excluded from the model. Grouping can be accomplished when the elements to be grouped are connected with elements outside the group through common channels. This is the case when elements are interconnected strictly in series or strictly in parallel, with no connection to outside elements except at the two terminals. This is the property of separability of the sub-system consisting the group of elements, and this is why grouping of elements in a system is synonymous with partitioning of the whole system into sub-systems.

An application of the methods of elimination and grouping to activity networks is shown in the next chapter on cost-duration analysis.

Combination of Blocks in Series

Figure (4.3)





Combination of Block in Parallel

Figure (4.[illegible])

Figures (4.3) and (4.4) show how transfer functions in series and in parallel may be combined to form one transfer function.

Other approaches to simplifications are possible. Most common among these are simplifying assumptions. An example is the assumption that future behavior in the system is an extension of its past behavior. According to this, figures of future productivity would be extrapolated from those of past productivity, perhaps after modification, based again on past experience.

Another example is that regarding a relationship between two or more variables. Two variables, such as cost and duration, may be assumed to be linear, for the sake of simplifying the determination of parameters and conducting other computations, while in reality they may not be strictly so.

Variables or relationships among variables may be taken to be independent, assuming that whatever correlation exists to be insignificant. A quantity may be defined as constant, while it is variable, or as deterministic, when it is actually stochastic.

Simplifying assumptions, though often needed and sometimes desirable, have to be tested for validity, otherwise erroneous results may be obtained by their use.

5. PROJECT COST DURATION ANALYSIS

5.1. Formulation of the Problem

In this chapter, the systems approach is applied to answer a specific question related to project implementation. The question is, "What is the minimum total cost to reduce the total duration of a project from a specified amount to another specified amount?" The question is often formulated so that the answer covers a range of possible reductions.

Let us try to formulate the problem more formally. Suppose that a project is represented by a network N, for which the arrows stand for the activities of the project. Let $A = \{a_j\}$, $j = 1,2,\ldots,n$, be the set of activities. The duration of activity a_j may be denoted by Y_j. Let $Y = \{Y_j\}$, $j = 1,2,\ldots,n$.

The total project duration (length of the project) L, is a function of Y and may be written L (Y). If $\{Y_j\}$ are viewed as variables, that is, activities may be controlled as to duration, then it may be observed that, given N, for every Y there is only one L, but the same L may be obtained from more than one Y.

Let Y_j be defined over the region $Y_{jL} \leq Y_j \leq Y_{ju}$. The upper limit of this range, Y_{ju}, is commonly called the normal duration of activity Y_j, and represents the "minimum" time an activity takes at a minimum of expenditure. It is presumably the initial estimate of an activity duration before any consideration is given to reducing it in time at a higher cost. It is not to be confused with the most pessimistic estimate of time which is used in "PERT"-type activity networks referred to in Section 4.2. If a resort to PERT networks is made, then the most pessimistic, the most optimistic and the most likely estimates of an activity duration at the minimum cost are combined to give Y_{ju}.

The lower limit of the range of Y_j, Y_{jL}, is called the crash duration and it is that value beyond which it is impossible to reduce the activity duration at any "acceptable" cost.

It is conceivable that at least some of the $\{Y_j\}$ may be reduced by putting more expenditure into the project. What is particularly of interest is the direct cost of reducing Y_j; that is, the cost directly chargeable to Y_j. If an increment in cost resulting from a reduction in the total project duration is not chargeable to particular activities, then a different choice of activities to be reduced will result in the incurrence of the same expenditures, and these costs should not affect the decision on how to reduce the project duration, but may influence that on <u>whether</u> to reduce the project duration. Since our immediate concern is with the first questi only direct costs will be considered.

Let $c_j (Y_j)$ be the direct cost of activity a_j when its duration is Y_j. The relationship between c_j and Y_j is termed the (direct) cost-duration relationship of activity a_j and is defined over the region $Y_{jL} \leq Y_j \leq Y_{ju}$. The total project cost C is a function of Y.

$$C(Y) = \sum_{j=1}^{n} c_j (Y_j)$$

Suppose that the total project duration is required to be a specific L. It has been observed that this L may be obtained from any one of different possible Y's. It is required to find the vector Y which will give a minimum value of $C(Y)$. The ob in cost-duration analysis is then to find

$$C^*(L) = \min C \left\{ L(Y) \right\} \qquad L_L \leq L \leq L_u.$$

where L_L and L_u are the lower and upper limits on L, determined by the limits on Y_j and by the structure of the network. The solution to this problem is often given in the form of a curve for C^* against L.

5.2 <u>Previous Approaches</u>

The previous approaches to solving the problem of cost-duration analysis in activity networks may be summarized under two broad categories:

1. <u>Numerical Approaches</u>

These base their computations on a linear programming formulation of the dual of a parametric linear programming problem, describing the cost-duration relationship over the range of L (L or some function of it being the parameter). Th algorithm is then expressed as flow computations on the original network N.

The main shortcomings of this approach are its difficulty to explain, a seriou limitation especially in a developing country, and its restriction to linear cost relationships. That is, $c_j(Y_j)$ must be a linear function. However, computer programmes have been developed for these approaches.

2. Heuristic Approaches:

Which are trial and error approaches depending on intuition and skill. They use hand methods to select individual activities for reduction. The obvious shortcomings of these approaches are that they lack a systematic procedure and that they do not guarantee that the solution obtained is optimal.

5.3 The Proposed Approach

The approach to cost-duration analysis suggested in this chapter is based on extensive theoretical work in graph theory conducted at the University of Illinois by E.J. Dunne and the author, and which will be submitted for publication, and also on a procedure developed by the two collaborators as an application of the theoretical work.

Suppose that a network N has only one critical path P_1 (P_1 is actually the ordered set of critical activities in the project). It is obvious that in order to reduce the total project duration, L, from its normal value (upper limit) L_u by one time unit, it is sufficient to reduce the length of <u>any</u> activity on P_1 by one time unit. If it is desired to reduce L_u one time unit at a minimal cost, this may be done by looking into the unit reduction costs of the activities on P_1, and selecting that one which has the minimum such cost. For a reduction of L by two time units, two conditions will have to be observed: (1) whether the first reduced activity a_1 has reached its reduction limit, and (2) whether another sub-critical path P_2 becomes critical after the first step. If none of the two above conditions materialise, then depending upon the cost functions $c_j(Y_j)$, Y_j being the duration of a_j, the minimum cost reduction of two time units may be obtained by a reduction of:

i) a_1 by two time units
ii) a_1 by one unit and some other activity a_2 by one unit
iii) some a_2 by two time units

If the cost functions $c_j(a_j)$ are all linear, that is, they are of the form

$$c_j = \alpha_j - \beta_j a_j \qquad \text{for all } j$$

where α_j and β_j are positive constants, then when conditions (1) and (2) above do not exist, only outcome (i) can occur; that is, the optimum reduction is through reducing a_1 by two time units.

If a_1 reaches its reduction limit after one unit, then only solution (ii) or (iii) is possible, and in the linear case, only (ii).

If another sub-critical path P_2 becomes critical, the new set of activities to be reduced must include at least one from P_2. This problem is more complex because the number of combinations of activities from all critical paths increases rapidly with the number of critical paths. In fact, if there are two critical paths, each with p activities and with no common activities, then the number of combinations becomes 2^p.

Suppose that all paths in the network N are critical. There is no loss of generality in this assumption because the cost of reducing an activity on a slack path (a slack activity) can then be considered zero for an amount of reduction in the total project duration at least equal to the total slack of the activity.

If $\underset{\sim}{p}$ is the set of m paths in the network; i.e., $\underset{\sim}{p} = p_i$, $i = 1,2,\ldots,m$, then it is obvious from the previous discussion that in order to produce a unit reduction in L from $L = L_u$, that a set of activities one from each p_i in $\underset{\sim}{p}$ should be reduced by one unit each. (An activity may be on more than one path). Such asset may be called a reduction set.

Again, it is also clear that in order to reduce L from $L = L_u$ one or more reduction sets have to be reduced so that the sum of reductions of all sets is equal to the total reduction desired. This is the main idea in the proposed approach.

The procedure outlined in this paper is applied to the case of linear costs, but can be applied identically to piecewise linear but convex cost functions. It may very well be adapted to any convex cost function, and perhaps any cost function.

Starting with the assumption of linearity of activity cost-duration relationshi

$$(5.1) \qquad c_j(Y_j) = \alpha_j - \beta_j Y_j \qquad\qquad Y_{jL} \leq Y_j \leq Y_{ju}$$

where β_j is the cost slope of the activity, the initial step in the approach is to find the "normal" project duration L_u corresponding to the maximum durations $\{Y_{ju}\} = Y_u$. The total direct cost of the project at this point is

$$(5.2) \quad C(L_u) = \sum_{j=1}^{n} c_j(Y_{ju}) = \sum_{j=1}^{n} (\alpha_j - \beta_j Y_{ju}) =$$

$$\sum_{j=1}^{n} \alpha_j - \sum_{j=1}^{n} \beta_j Y_{ju}$$

This is at the same time $C^*(L_u)$, the optimum cost corresponding to a project duration of L_u.

It has been observed that the length of the project is a function of the duration of its activities, that is, $L = L(Y) = L(\{Y_j\})$. If the reduction in activity a_j from its maximum duration is r_j, that is

$$(5.3) \quad r_j = Y_{ju} - Y_j \qquad \text{all } j$$

then the total direct cost of the project at length L is given by:

$$(5.4) \quad C(L) = \sum_{j=1}^{n} c_j(Y_j) = \sum_{j=1}^{n} \alpha_j - \sum_{j=1}^{n} \beta_j (Y_{ju} - r_j)$$

$$= \sum_{j=1}^{n} (\alpha_j - \beta_j Y_{ju}) + \sum_{j=1}^{n} \beta_j r_j$$

$$= c(L_u) + \sum_{j=1}^{n} \beta_j r_j$$

It is obvious that the expression $\sum_{j=1}^{n} \beta_j r_j$ will include only those activities which are reduced to produce the desired L, since other activities have a value of r_j equal to zero. These activities in this set which are slack will have a value of β_j equal to zero.

Once L_u and $C^*(L)$ are determined, it is possible to focus on the reductions in, rather than the lengths of, the activities and the project. Therefore if

$$(5.5) \quad R = L_u - L, \text{ then}$$

$$(5.6) \quad C(L) = C(L_u - R) = C(R),$$

since L_u is a constant. Also,

$$(5.7) \quad C^*(R) = \min C(R) = \min C(L)$$

$$= \min \left[C(L_u) \right] + \sum_{j=1}^{n} \beta_j r_j$$

$$= C^*(L_u) + \min \sum_{j=1}^{n} \beta_j r_j$$

Since $C^*(L_u)$ is constant, the minimization of $C^*(R)$ is equivalent to the maximization of $\sum_{j=1}^{n} \beta_j r_j$. If

$$(5.8) \quad B(R) = \sum_{j=1}^{n} \beta_j r_j$$

which is the marginal cost of a reduction R, and $B^*(R) = \min B(R)$, then the problem becomes that of finding the appropriate $B^*(R)$ for every reduction R within the range $0 \leq R \leq L_u - L_L$, where L_L is the project crash duration, which is the duration resulting from crashing all activities down to their minimum durations.

The first step is to find a reduction set, Q_1, such that the sum of all unit reduction costs (cost slopes β_j) of the activities a_j in the set is minimum. Call this set Q_1^*, and the sum of the cost slopes of its activities b_1.

$$(5.9) \quad b_1 = \sum_j \beta_j \quad \text{for all } a_j \text{ members of } Q_1^*.$$

The marginal cost of a reduction R within this range is equal to

$$(5.10) \quad B^*(R) = \sum_{j=1}^{n} \beta_j R = R \sum_{j=1}^{n} \beta_j = Rb \qquad 0 \leq R \leq R_1$$

where R_1 is the maximum reduction in the set Q_1^*.

The maximum simultaneous reduction of a set of activities is the smallest of the maximum reductions of all the members in the set. The maximum reduction of any activity at any particular step is dictated by either the physical limit on any further reduction in it, or by a point where any further reduction will be at a higher cost of reduction per unit reduction time. This happens when a slack activity stops being slack, and any further reduction will be at a positive cost. The maximum reduction for a slack activity is therefore the amount of its slack. There are also other cases which will become apparent with further treatment of the problem.

From equation (5.10) it is apparent that the curve for $B^*(R)$ against R, which can evidently be interpreted as that of $C^*(L)$ against L, is linear within the range $0 \leq R \leq R_1$.

Step (2) is to find a set of activities Q_2, which consists of one or more reduction sets, that can be simultaneously reduced to produce a total reduction in the project R, within the range $R_1 \leq R \leq R_2$, where R_2 is maximum reduction in Q_2. This Q_2 must be chosen such that B(R) is minimum, that is, the sum of the cost slopes of all activities in Q_2 is minimum within the ranges of their durations corresponding to the given range of R. Denote this Q_2 by Q_2^*, and the sum of its activities cost slopes by b_2.

In general, at any step (k) the problem is to find a Q_k^*, which when reduced gives the minimum B(R) for values of R within the range $R_{k-1} \leq R \leq R_k$. This means that the sum b_k of the cost slopes of activities in Q_k^* at their corresponding level of reduction must be minimum.

It is obvious that, as in the range $0 \leq R \leq R_1$, the optimum cost of reduction $B^*(R)$ is linear with respect to R within any range $R_{k-1} \leq R \leq R_k$, with a cost slope b_k. Any b_k should be greater than b_{k-1}, otherwise Q_{k-1}^* would have been replaced by Q_k^*. Also, $B^*(R)$ at the end of the range $R_{k-1} \leq R \leq R_k$ is equal to that at the beginning of the range $R_k \leq R \leq R_{k+1}$. This all means that the $B^*(R)$ against R curve is piece-wise linear (broken line), and convex (the open end of the curve looks upwards).

It is not always the case that Q_k^* may consist of Q_{k-1}^* plus one or more reduction sets, since Q_k^* may consist of Q_{k-1}^* plus activities that do not constitute by themselves one or more reduction sets. This happens when Q_{k-1}^* contains more than one activity from the same path, and the path is over-reduced by reductions in Q_{k-1}^*, in which case no activity will have to be especially reduced to shorten this path beyond a reduction of R_{k-1}. It may also be that a reduction in some of the activities in Q_k^* requires an increase in an activity in both Q_k^* and Q_{k-1}^*, which means that some of the new set of activities make some of those in Q_{k-1}^*

unnecessary to produce a reduction beyond Q_{k-1}. This occurs when more than one activity in Q_k^* and not in Q_{k-1}^* lie on the same path, and thus over-reducing it by their simultaneous reduction. These cases will be observed in the examples following.

What is needed then is a procedure to find Q_1^*, to determine which activities to add to Q_1^*, to form Q_2^*, and in general, to determine which activities to add to Q_{k-1}^* to form Q_k^*, until the maximum reduction possible for the network is reached.

This procedure is the subject of the following sections in this chapter.

5.4 Reduction Sets and Proper Oriented Cut-Sets

A formal definition of a reduction set can now be given: "A reduction set is a minimal set of activities in a project such that when simultaneously reduced by one time unit, the total project will be reduced by one time unit".

The concept is defined minimally because there will be no need to reduce an activity beyond a minimal set, as this will only add to the cost without accompanying benefit.

If all paths in the network are considered critical, that is, if it is required to reduce all paths in the network, in which case non-critical paths will be reduced by zero time, the concept of a reduction set becomes identical with the concept of a proper oriented cut-set (POCS), which is defined and explored in a work by E.J. Dunne and the author[13].

Suppose that in the network of Figure (5.1) it is required to disconnect the start node (source), v_0, from the finish node (sink), v_3. This is equivalent to finding a set of arrows (arcs) which disconnects a set of nodes, W, which includes v_0 from the remaining set of nodes in the network, $\overline{W}$, which includes v_3 (the complementary set). Such a set of arcs is called a cut-set. Once we define W, we have defined this set, and it is to be remembered that the direction of the arrows in this definition is not important, so it does not matter whether an arrow is

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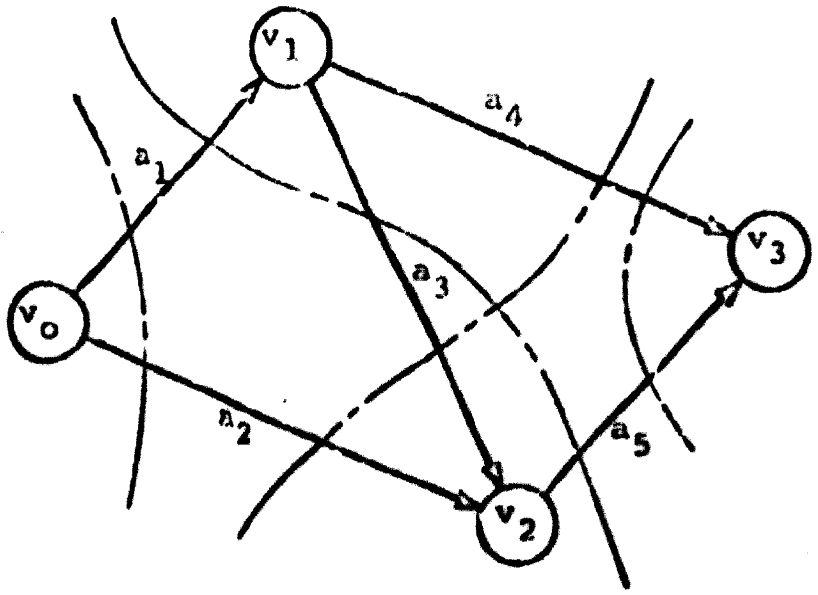
[13] Dessouky, M.I., and E.J. Dunne, "Proper Oriented Cut-Sets and their Properties" Unpublished research. University of Illinois, Urbana, 1970



Networks and Cuts

Figure (5.1)

directed from N to $\bar{N}$ or from $\bar{N}$ to N. The cut-sets of the network in Figure (1) are given in Table (5.1) below.

Table (5.1)

N	$\bar{N}$	Cut-set
v_o	v_1, v_2, v_3	a_1, a_2
v_o, v_1	v_2, v_3	a_2, a_3, a_4
v_o, v_2	v_1, v_3	a_1, a_3, a_5
v_o, v_1, v_2	v_3	a_4, a_5

A proper cut-set is a cut-set such that no proper subset of it is also a cut-set. That is, no arc in it can be removed and we are still left with a cut-set. Actually, all cut-sets in Table (5.1) are proper.

If the objective is to interrupt every path (flow) from v_o to v_3, then the direction (orientation) of the arcs should be taken into consideration. An oriented cut-set in a network is the set of all arcs directed from a set of nodes, N, including the source to its complementary set. The oriented cut-sets of the network in Figure (5.1) is given in Table (5.2) below.

Table (5.2)

N	$\bar{N}$	Oriented Cut-set
v_o	v_1, v_2, v_3	$K_1 = a_1, a_2$
v_o, v_1	v_2, v_3	$K_2 = a_2, a_3, a_4$
v_o, v_2	v_1, v_3	$K_3 = a_1, a_5$
v_o, v_1, v_2	v_3	$K_4 = a_4, a_5$

The concept of an oriented cut-set is the same as the concept of "cut" advanced by Ford and Fulkerson [14]. A proper oriented cut-set (POCS) is an oriented cut-set such that no proper sub-set of it is an oriented cut-set. All oriented cut-sets in Table (5.2) are POCS's.

It will be noticed that each one of the four sets in Table (5.2) has at

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14/ Ford, L.R., Jr. and D.R. Fulkerson, "Flows in Networks", Princeton University Press, Princeton, 1962.

least one arc (sometimes two) on each path in the network, listed in Table (5.3). This is an important property of POCS's.

Table (5.3)

Path	Arcs
P_1	(a_1, a_4)
P_2	(a_1, a_3, a_5)
P_3	(a_2, a_5)

The property can be stated as follows:

"A proper oriented cut-set is a minimal set of arcs which contains at least one arc on each path in the network; minimal in the sense that if an arc is removed from the set, it will not have the same property. Conversely, a minimal set of arcs which includes at least one arc on each path in the network is a proper oriented cut-set". [15]

This property shows that if we consider all paths in the network as critical, a reduction set will be equivalent to a POCS. If we have a method for displaying all arcs in a network N, on an associated network N', such that a POCS in N is a path in N', then when reduction cost slopes are attached to the arcs of both networks the minimum reduction set (POCS) in N becomes the minimum cost path (shortest path) in N'. This associated network is called the cut network.

5.5 The Cut Network

The definition and construction of the network has been developed by Dunne and the author [16]. Given a network N with a source v_0 and a sink v_n, it is required to construct a network N' with the following properties:

1. All arcs in N are represented in N'.
2. Every POCS in N is a path in N'.
3. No path in N' is less than a POCS in N.

Attaching the same costs to the same arcs in the two networks, the last two

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[15] Dessouky and Dunne, Op. Cit.

[16] Ibid

properties guarantee that the minimum cost POCS in N is a minimum cost path in N′, often referred to as shortest path or shortest route, giving the cost the interpretation of the length of an arc. Since shortest route computations are easier, finding the minimum POCS becomes a simple task, once the cut network is constructed.

The steps in constructing the cut network will be explained, first in connexion with planar networks, and later in connection with non-planar networks.

In simple terms, a planar network is one which can be drawn such that no two arcs intersect except at a node. In this study if a network is planar, it will be assumed that the drawing will contain no arcs intersecting at points which are not nodes. It will also be assumed that neither the source nor the sink is inside the network.

In a planar network, every POCS may be obtained by drawing a construction line from one side of the network S, cutting across the network, and ending at the other side T. The arcs intersected by a construction line thus drawn and which are oriented from the source side of the line to its sink side (the oriented arcs) form an oriented cut-set. It can be shown that for every POCS in a planar network there is a construction line whose oriented arcs are solely the members of this set. 17/

Define a region in a network as a space enclosed by arcs on all sides and which is not intersected by any arc. A procedure for drawing the cut network of a planar network is to place a node in the middle of every region, and one on each side of the network. In Figure (5.2), nodes G_1, G_2, S and T represent those nodes as drawn on the network of Figure (5.1). A line is then drawn between every two nodes representing two adjacent regions, including S and T. The resulting network is the <u>dual</u> network of the original network N. Identify every line in the new network with the arc it intersects.

The orientation of the new lines can be determined as follows: Lines connected to S should be directed <u>away</u> from it and those connected to T should be directed toward it. If an arc in N is oriented <u>clockwise</u> with respect to the node in the middle of its region, the corresponding arc in the dual network should be oriented <u>toward</u> that node, and if an arc in N is oriented <u>counterclockwise</u> with respect to th node in the middle of its region, the corresponding arc in the dual should be

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17/ Ibid

oriented away from the node. Every arc in N lies between two regions, but it will be seen that regardless of the region used to determine the orientation of its dual arc, the orientation will be the same.

The resulting network is called the directed dual network*. It may be noticed that some of the POCS's of N, listed in Table (5.2) are represented as paths in this network. They are (a_1, a_2), (a_4, a_3, a_2) and (a_4, a_5). But the new network does not contain (a_1, a_5) as a path. If a dashed-line, a'_3, is drawn parallel to arc a_3 on the oriented dual network, and opposite in orientation to a_3 (Figure 5.3), a path (a_1, a'_3, a_5) is formed, and considering a'_3 to be a dummy arc (activity) with no significance except to indicate the existence of paths, this path represents the POCS (a_1, a_5).

The procedure for a planar network is then to introduce a parallel arc with opposite orientation to every arc in N, except those arcs starting from v_0 or ending at v_n, and arcs lying on the boundary of the network. The resulting network is the cut network N'.

In larger networks, N' will satisfy the three conditions metnioned above, but it will often contain as paths some which are not POCS's. This does not negate the statement that the shortest path in N' is the minimum-cost POCS in N, since any path in N' is either a POCS in N or contains one, and all POCS's in N are paths in N'.

5.6 Cost-Duration Analysis

Based upon the relationship between an activity network N and its cut network N', the problem of finding a minimum reduction set in N, becomes equivalent to the problem of finding the minimum-cost path (shortest path) in N'. This latter problem may again be interpreted as that of finding the path which carries a unit of flow at minimum cost, assuming that the reduction cost slope of each activity is the unit cost flow on each arc. The algorithm for finding the minimum cost unit flow is the same as that for determining the shortest route, and will be described shortly, but the flow interpretation is important. Suppose now that the flow rate in the cut netowrk is to be increased at the same cost rate and through the same initial path. The maximum flow that could be attained this way is equivalent to the maximum

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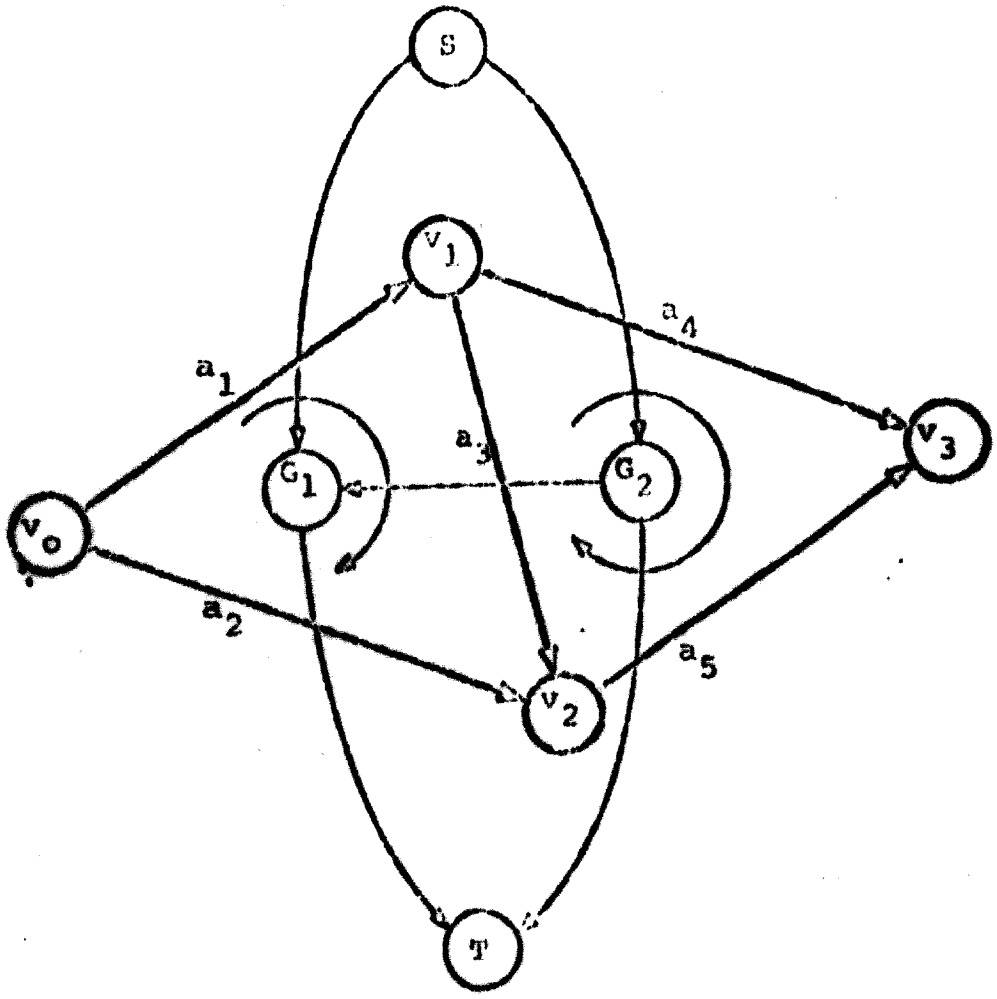
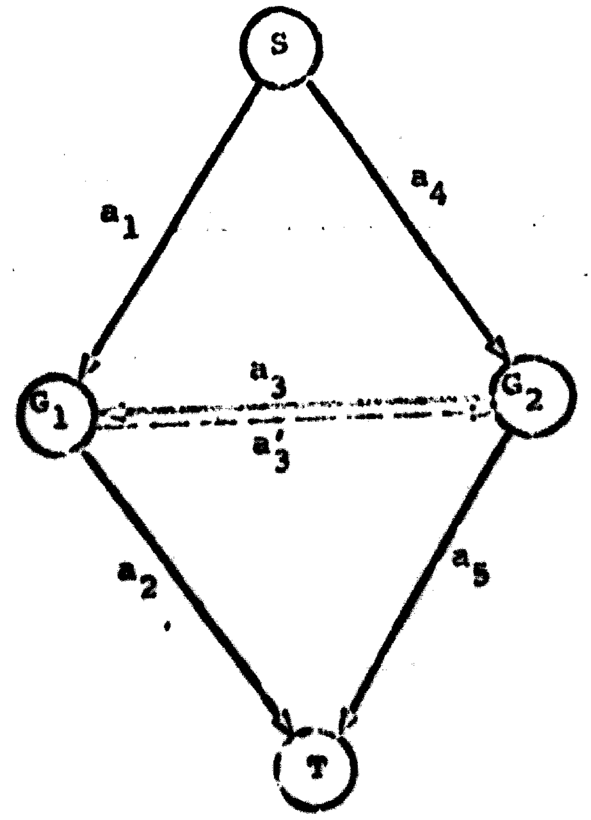
* Zimmerman, L.S. "A Network Approach to Resource Scheduling", Master's Thesis, University of Illinois, Urbana, Illinois, 1967.



The Oriented Dual Network

Figure (5.2)



<u>The Cut Network</u>

<u>Figure (5.3)</u>

reduction (R_1) in the first minimum-cost reduction set (POCS) chosen Q_1^*, if the capacity of flow on each arc in N′ is taken as the maximum reduction in the corresponding activity in N.

The problem of finding the minimum-cost combination of reduction sets Q_2^* which is necessary for a reduction greater than R_1 in network N is equivalent to finding the minimum-cost flow of a value greater than R_1 in network N′, which will have a solution consisting of a set of paths each corresponding to a reduction set in N.

In general, the problem of finding a set of reduction sets for a reduction in the total project represented by a network N of any value within the feasible range, becomes equivalent to the problem of finding the minimum-cost flow of a value equal to that reduction in the cut network N′[*]. The cost slopes of activities in N become the unit costs of flow in their corresponding arcs in N′, and the maximum reduction in the activities in N become the flow capacities of the corresponding arcs in N′.

The minimum-cost flow algorithm is based on successive shortest route computations. Therefore, we will begin by explaining the shortest route algorithm.

5.7 Shortest Route Problems[**]

Given a network with one starting and one ending node, two types of shortest route problems exist:

(a) When the network is directed and acyclic. That is, if there is a path from arc a_1 to arc a_2, there can be no path from arc a_2 to arc a_1. Activity networks are directed and acyclic.

(b) When the network is either undirected or directed and cyclic. Cut networks are often of this sort.

The algorithm for the two cases will be explained in connexion with two examples.

The first example is the directed network in Figure (5.4), where the numbers on the arcs represent distances (costs). Due to the network's acyclicity, nodes can

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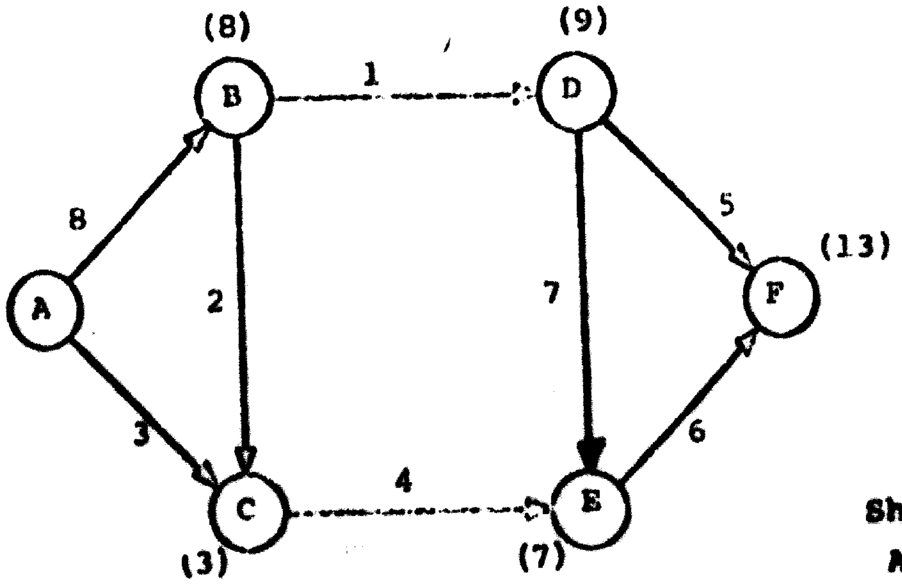
[*] This concept is due to Dessouky and Dunne.

[**] Hillier, F.S., and G.J. Lieberman, "Introduction to Operations Research", Chapter 7, Holden-Day, San Francisco, 1967.



Shortest Route
A-C-E-F
Length = 13

Shortest Route in an Acyclic Network

Figure (5.4)

be arranged according to their precedence relationships, and the shortest distance to all preceding nodes should be computed before that of any node. This is similar to the computations of the critical path, except that in the latter case the largest route is sought. The number between parentheses at each node represents the shortest distance to it. It is obtained by comparing the sum of the shortest distance to a preceding node and the distance between the two nodes, for all preceding nodes, and selecting the smallest sum. The shortes route in this case is A-C-E-F, with a length of 13 units.

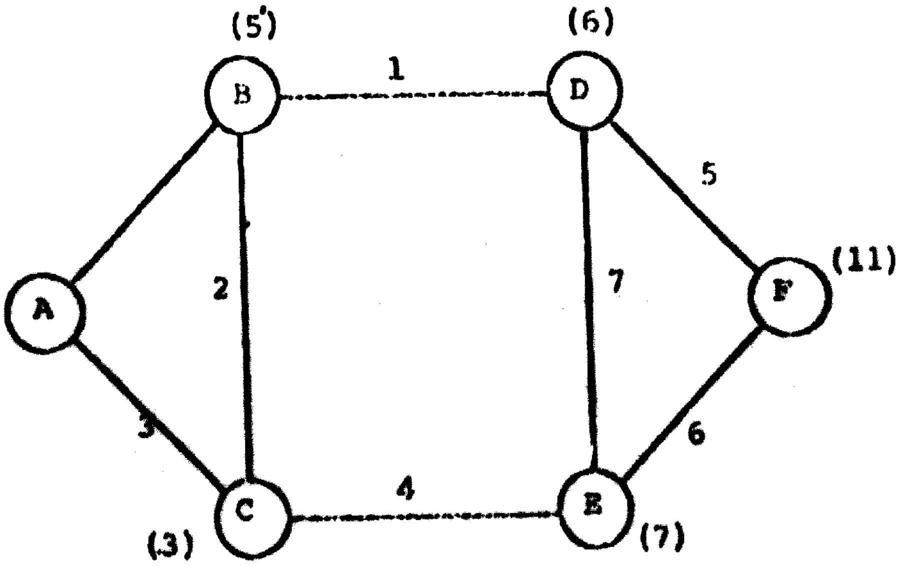
The second example is the undirected network in Figure (5.5). Since it is undirected, it can be considered as symmetrical, the distance from a node to another is equal to the distance from the second to the first. This is not always the case, as in cyclic directed networks such as cut networks. The computational procedure for both cases are, however, the same. One simple and direct procedure for determining shortest routes in these cases is to order the nodes in the network according to thei proximity to the starting node. A systematic procedure to do that is to construct a table such as Table (5.4) below. At the top of the table are listed the nodes of the network starting from the "start" (A) and down to the "finish" (F). Under each node, a list is made of all the links (edges) branching from it, in an ascending order of their lengths, that is, with the shortest edge on the top of the list. The length of each edge is written by its side. It is now required to order the nodes of the network, n = 1,2,...,5, excluding "A", which may be labelled n = o, in an ascending order of distance from A. Write (o) on top of column A, to indicate its distance from itself.

Table (5.4)

(0)	(5)	(3)	(6)	(7)	(11)
A	B	C	D	E	F
x	x	x	x	x	
✓ AC 3	✓ BD 1	✓ CB 2	x DB 1	x EC 4	
x AB 8	x BC 2	x CE 4	✓ DF 5	x EF 6	
			✓ DE 7	x ED 7	

n = 1:

Starting with the column representing node A (n = o), the first link on the top of the list (AC) is chosen. Node C is the closest to A (=1) with a shortest distanc



Shortest Route:
A-C-B-D-F
Length = 11

Shortest Route in an Undirected Network

Figure (5.5)

of 3. This is so because it is certain that no other indirect route to C is shorter than the direct one from A. Write (3) on top of column C. Check link (AC and cross out all other links ending with C, namely (BC) and (EC), since it will never be desired to reach C via any route other than the shortest.

n = 2:

The candidate to the second closest node to A must have a direct link to one of the ordered nodes, otherwise, a node intervening between it and an ordered node is closer to A than the candidate itself. Therefore, the search for n = 2 must be among nodes with direct links to either A or C. Besides, if more than one node is directly connected to either A or C, only the closest to each is considered. Therefore, the topmost link in both columns A and C which have not been checked or crossed out are considered. They are AB and CB, both leading to node B. The shortest distance from A to any "new" node is obtained by adding the number on the top of the colum representing the ordered node (or nodes) connecting it to A to the number representing its link. Therefore for B, two distances are compared: (a) from A directly = (0+8) = 8, and (b) via C = (3+2) = 5, with 5 being the smallest. Therefore, write (5) on top of column B, check (CB) and cross out (AB) and (DB). Also cross out (BC)* since a shortest route can never contain a loop or traverse an edge in opposite directions. Place "X" under A at the top of its columns in order to indicate that the links in that column have either checked or crossed out and thus are not subject to further consideration for selection of new nodes.

n = 3:

Now the only links to be considered are (BD) and (CE). For node D, shortest distance = (5+1) = 6. For node E it is (3+4) = 7. Therefore D is n = 3. Write (6) on top of column D, check (BD) and cross out (ED). Place "X" under B.

n = 4:

Consider columns C and D. Compare E with (3+4) = 7 to F with (6+5) = 11. Write 7 on top of column E. Check (CE) and cross out (DE).

n = 5:

Finally, consider columns D and E, comparing the two routes to F, via D = (6+5) = 11, and via E = (7+6) = 13, with 11 being the smallest. Write (11) on top of column F, check (DF) and cross out (EF). Place "X" under both D and E.

The shortest route from A to F is then equal to 11 and may be determined by going backward from F through checked links. It is A-C-B-D-E.

In summary, at any particular step, for each column with a number on its top and no X below its name, add the number on the top to the number at the topmost link in the same column which is not checked or crossed. Compare the sum for all such columns to determine the next closest node to the start, until the finish node is reached. Begin with the start node and place (0) on the top of its column.

It should be noted that, even though the networks of Figures (5.4) and (5.5), and the numbers on them are the same, the shortest route in (5.4) is larger than that in (5.5) because of the restriction placed on the direction of movement.

If the network is asymmetrical, that is, if the distance between two nodes moving in one direction is not equal to that moving the opposite one, the numbers in the table will reflect this fact, but the procedure will remain the same. It may be pointed out that once the initial table is constructed, all computations can be performed on it, and there is no need to refer to the graph.

5.8 Minimum-Cost Flow*

The algorithm for minimum-cost flow will be explained in connexion with the flow network in Figure (5.6a). To each arc two numbers are attached; the arc's flow capacity in the numerator and the cost per unit of flow in the denominator. The numbers are attached closer to the start node of each arc. It is required to find the minimum cost for every feasible level of flow in the network, and to identify the paths that carry the flow at each level.

The first step is to find the minimum-cost path for one unit of flow. It has been mentioned before that this is equivalent to the shortest route, when the costs are interpreted as lengths of arcs. In this case it is path (A-C-B-D-E-F) with a total cost per unit of 14 (the cost slope). The maximum flow along this path is limited by the minimum capacity of the arcs on it, which is 2 and is determined by arcs (DE) and (EF). In other words, a flow at a level between zero and 2 carries a minimum cost of 14 per unit.

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* Busacker, R.G., and P.J. Gowen, "A Procedure for Determining a Family of Minimal-Cost Network Flow Patterns", ORO Technical Report 15, Operations Research Office, Johns Hopkins University, 1961.

Any increase in flow beyond 2 will require a "flow-augmenting path". For flow-augmenting computations, flow may be introduced in an arc in a direction opposite to that of an existing flow in it. This amounts to the reduction of the existin flow by an amount equal to the opposite flow. It is obvious that the flow carrying arc does not have to have an "initial" capacity in the opposite direction in order to allow for the opposite flow; the mere fact of the existence of its presence flow creates a potential for its reduction by an equal amount. Therefore, as soon as flow is introduced in an arc, a capacity for flow in the opposite direction equal to the amount of flow is created. The unit cost of such a flow is naturally the negativ of the unit cost of the flow in the original direction, since by introducing the opposite flow we are actually reducing the original one. This opposite capacity is established whether the arc originally has a flow capacity in that opposite direction or not. If this is the case, the new opposite capacity will be utilized completely before the original one is used, since it will generally carry a lower unit cost. It will be remembered that it is not necessary to install an opposite capacity in arcs which can never carry flow in the opposite direction to their flows, for example, arc emerging from the source node, those converging on the sink node, and boundary arcs in planar networks. In the network in Figure (5.6a), these will be (AB), (AC), (DF), (EF), (BD) and (CE).

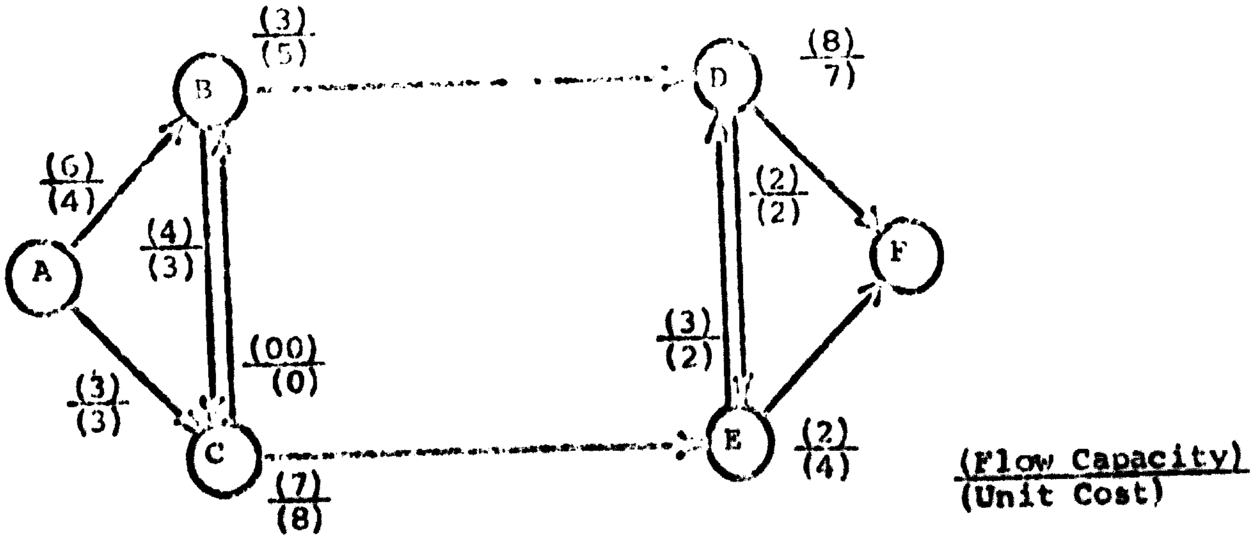
The only opposite capacities to be installed as a result of flow in the path (A-C-B-D-E-F) are a capacity of 2 in both arcs (CB), with a unit cost of zero, and arc (DE), with a unit cost of (-2). The capacities in the original directions of al arcs in this path will have to be adjusted by a reduction of 2 units.

A new lowest-cost flow-augmenting path is then found in the adjusted network, by shortest route computations. This path (A-C-B-D-F) with a cost slope of 15 and a maximum flow augmention of one unit dictated by the capacities of arcs (AC) and (BD).

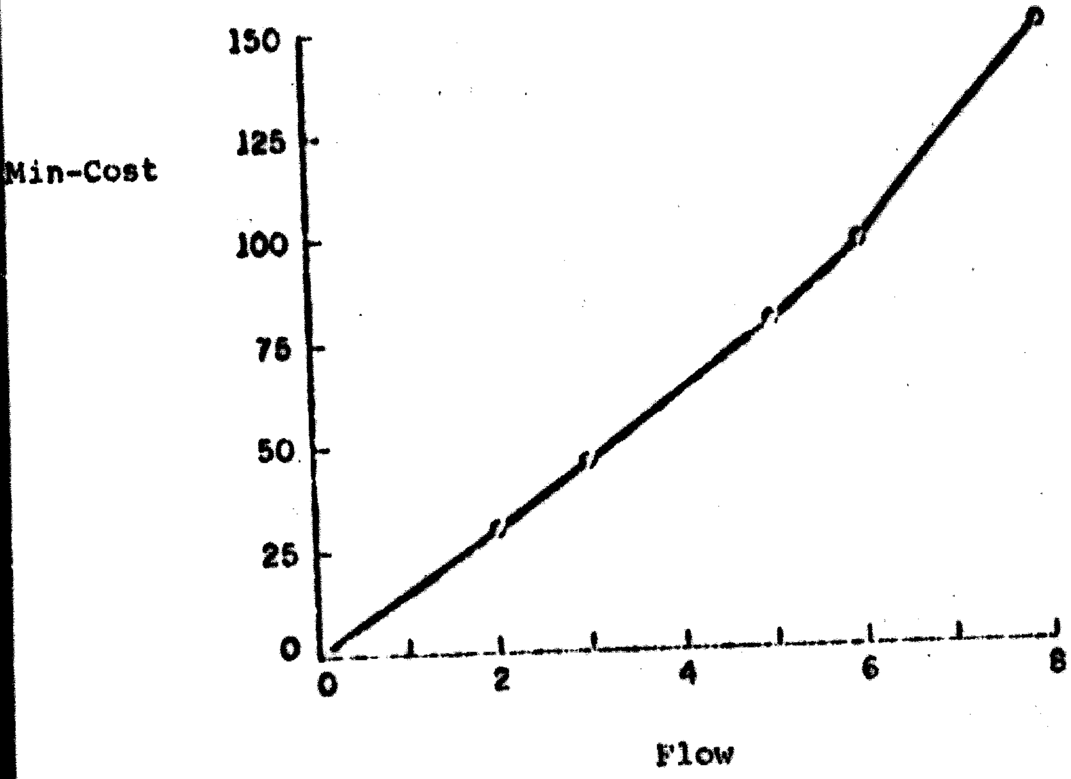
A summary of the five flow-augmenting paths is given in Table (5.5) below.

Table (5.5)

Path No.	Path	Cost Slope	Max. Flow	Cum. Flow	Cum. Cost
1	(A-C-B-D-E-F)	14	2	2	28
2	(A-C-B-D-F)	15	1	3	43
3	(A-B-C-E-D-F)	17	2	5	77
4	(A-B-C-E-D-F)	21	1	6	98
5	(A-B-C-E-D-F)	24	2	8	146



(a) The Flow Network



(b) Min-Cost Flow Graph

Minimum-Cost Flow

Figure (5.6)

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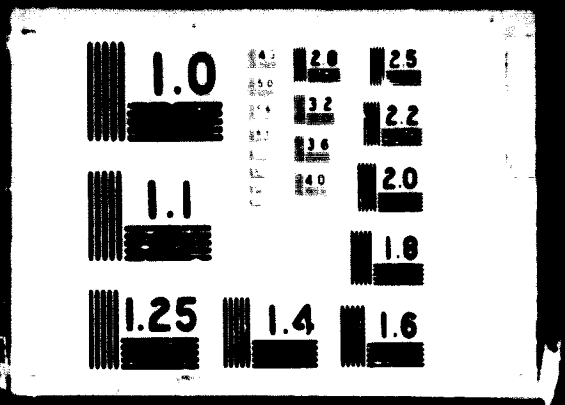

The maximum flow in any path is the maximum amount of augmenting flow which could be passed through the path at the given cost slope. The cumulative flow is the sum of the maximum flows over all previous paths inclusive of the current one, and the cumulative cost is the sum of the product of the cost slope with the maximum flow.

Path No. 3 takes advantage of the created capacities in arc (BC) at zero cost and arc (ED) at a cost of (-2), up to 2 units when the new capacity in the latter arc is absorbed. Its cost slope is 17. In path No. 4, which is the same as path No. 3, arc (ED) assumes its original capacity of (3) at a unit cost of (2) instead of (-2), which results in an increase of 4 in the cost slope of the path to reach 21. The maximum flow in path No. 4 is 1 and is restricted by the acquired capacity in arc (BC). In path No. 5 arc (BC) uses 2 units of its original capacity of (4) at a unit cost of (3) instead of zero, which raises the cost slope of the path to 24. The capacity of flow in path No. 5 is limited by arc (ED), and no more flow can be allowed in the network. The maximum possible flow is 8 units at a total cost of 146.

The computations could all be performed on the network by continually adjusting the figures for the capacities and costs. A curve for minimum-cost against flow is given in Figure (5.6b), which shows that the relationship is piecewise linear.

It is interesting to note that saturating paths numbers 1 and 2 and introducing a unit of flow in path No. 3 is equivalent to passing one unit in path 1, one unit in path 2, one unit in path (A-B-D-E), and one unit in path (A-C-E-F), cancelling out one unit of flow in (BC) against one in (CE), and one unit in (ED) against one in (DE) at a total cost of 61. Similarly, if paths 1, 2 and 3 are saturated, the result will be equivalent to passing one unit in path 2, two units in path (A-C-D-E) and two units in path (A-C-E-F) at a total cost of 77. This shows that the summation of augmenting paths is equivalent to summing original paths at their original, rather than adjusted costs. This fact is to be retained for future reference in cost-duration analysis.

5.9 Cost-Duration Algorithm

The new project cost-duration algorithm* will be explained in connection with

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* Developed jointly by the author with the support of UNIDO and E.J. Dunne in partial fulfillment of his Ph.D. requirements at the University of Illinois.

the simple project network, N, in Figure (5.7). Activities are $(a_1, a_2, \ldots, a_5)$ and nodes are $(v_0, v_1, v_2$ and $v_3)$. The relevant data for cost-duration analysis about the project are given in Table (5.6) below.

Table (5.6)

Activity	Predecessor	Maximum Duration	Minimum Duration	Cost Slope
a_1	–	–	3	3
a_2	–	9	5	6
a_3	a_1	4	2	2
a_4	a_1	16	10	5
a_5	a_2, a_3	12	7	4

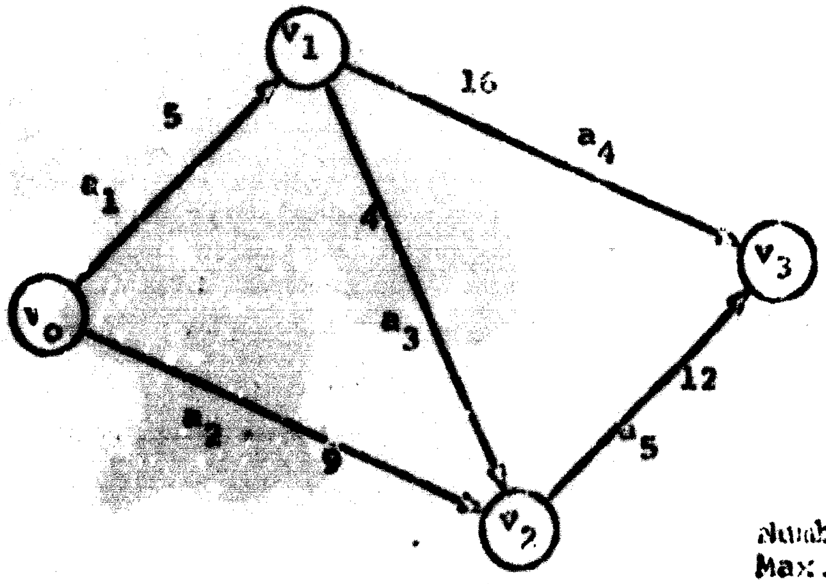
Critical path computations will show that the total project duration is 21 and that all paths are critical. The next step is to construct a table showing the maximum reduction in each activity (its maximum duration less its minimum duration), its cost slope and its slack. Table (5.7) below exhibits this information.

Table (5.7)

Activity	Maximum Reduction	Cost Slope (β_j)	Slack
a_1	2	3	0
a_2	4	6	0
a_3	2	2	0
a_4	6	5	0
a_5	5	4	0

Slack is shown in order to determine the amount an activity can be reduced at zero cost.

The cut network, N', of the activity network is shown in Figure (5.8), with the information in Table (5.7) indicated on each arc, the maximum reduction being in the numerator, and the cost slope in the denominator. If an activity has any slack, its amount is written in the numerator and a zero indicating the unit cost of its reduction is written in the denominator right below. It will be noted that dummy activities such as a_3' have an infinite capacity for reduction at zero cost.



Numbers Represent
Max. Activity Duratio

Activity Network (N)

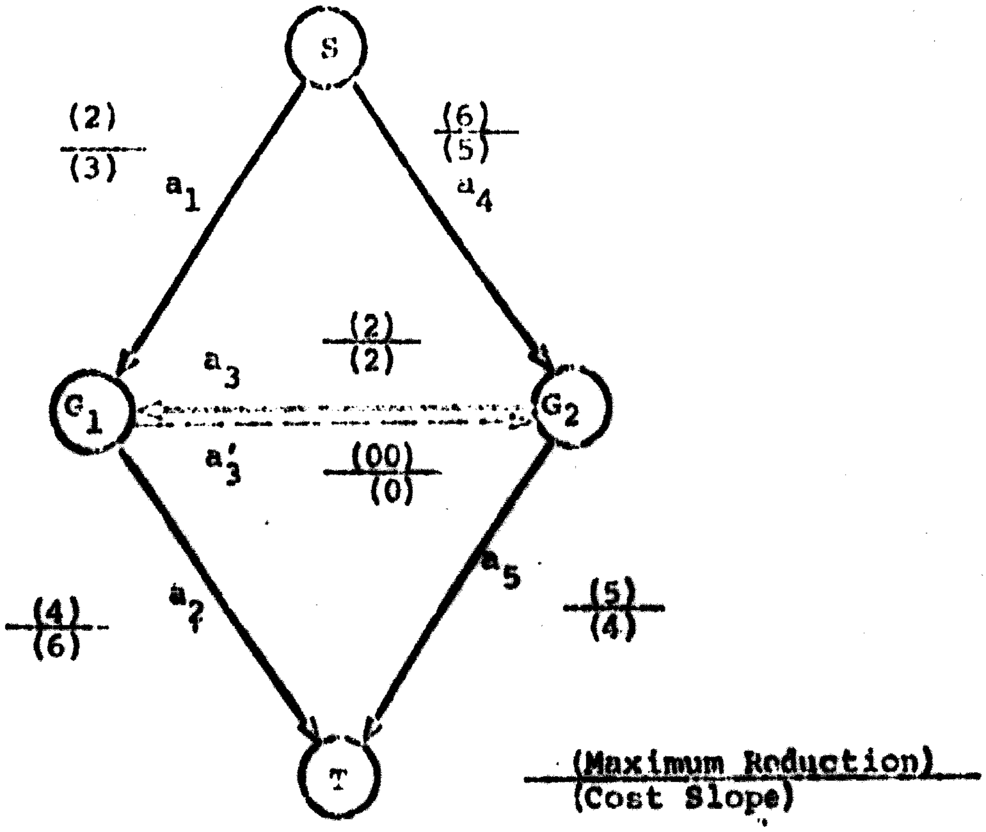
Figure (5.7)

As demonstrated in section (5.5), the cost-duration problem can be interpreted s a minimum-cost flow problem when the numbers in the numerators are taken to be the low capacities of the arcs and those in the denominator as their unit costs of flow.

Table (5.8) shows the summary of the computations for the cost-duration problem sing the minimum-cost flow algorithm. Each flow-augmenting path represents the dditions to and subtractions from the previous set of reduction sets.

The set Q_k of reduction sets under column (3) represents the net reduction sets f N (paths of N' without dummy arcs), after increases are cancelled out with eductions in the same arcs (that is, flows in opposite directions are cancelled out). t will be noticed that although in step (3) the flow augmenting path does not orrespond to a complete reduction set, the set Q_3 consists of 3 complete ones. This mphasizes the argument that the reduction at any step is the result of the reduction n the members of a set of one or more reduction sets.

As in minimum-cost flow analysis, computations could be largely conducted on he network in Figure (5.8). The results shown in Table (5.8) may be displayed on graph such as Figure (5.9). The maximum reduction in the project is 8 time units, hich makes its minimum duration 13 units, at a minimum additional cost of 76 units.



Cut Network (N')
With Cost-Duration Information

Figure (5.8)

Table (5.8)

(1) Step (k)	(2) Path (P_k)	(3) Q_k	(4) Limiting Arc	(5) Maximum Reduction	(6) Cost Slope (λ_k)	(7) Cumulative Reduction(R_k)	(8) Cum. Cost B (R_k)
1	$(a_1-a_3{}'-a_5)$	$(a_1-a_5=2)$	a_1	2	7	2	14
2	(a_4-a_5)	$(a_1-a_5=2)$ $(a_4-a_5=3)$	a_5	3	9	5	41
3	$(a_4-a_3{}', a_2)$	$(a_1-a_5=0)$ $(a_4-a_5=5)$ $(a_1-a_2=2)$	$-a_3{}'$	2	11	7	63
4	$(a_4-a_3-a_2)$	$(a_4-a_5=5)$ $(a_1-a_2=2)$ $(a_4-a_3-a_2=1)$	a_4	1	13	8	76

Table (5.8) Continued

Explanation of Columns

(1) Step (k) = reduction step.

(2) Path (P_k). = flow-augmenting path.

(3) Q_k = set of reduction sets, sum of all flow-augmenting paths to step k. The number on the right of each reduction set is the maximum reduction in the set at end of step k.

(4) Limiting arc = arc limiting the capacity of path P_k.

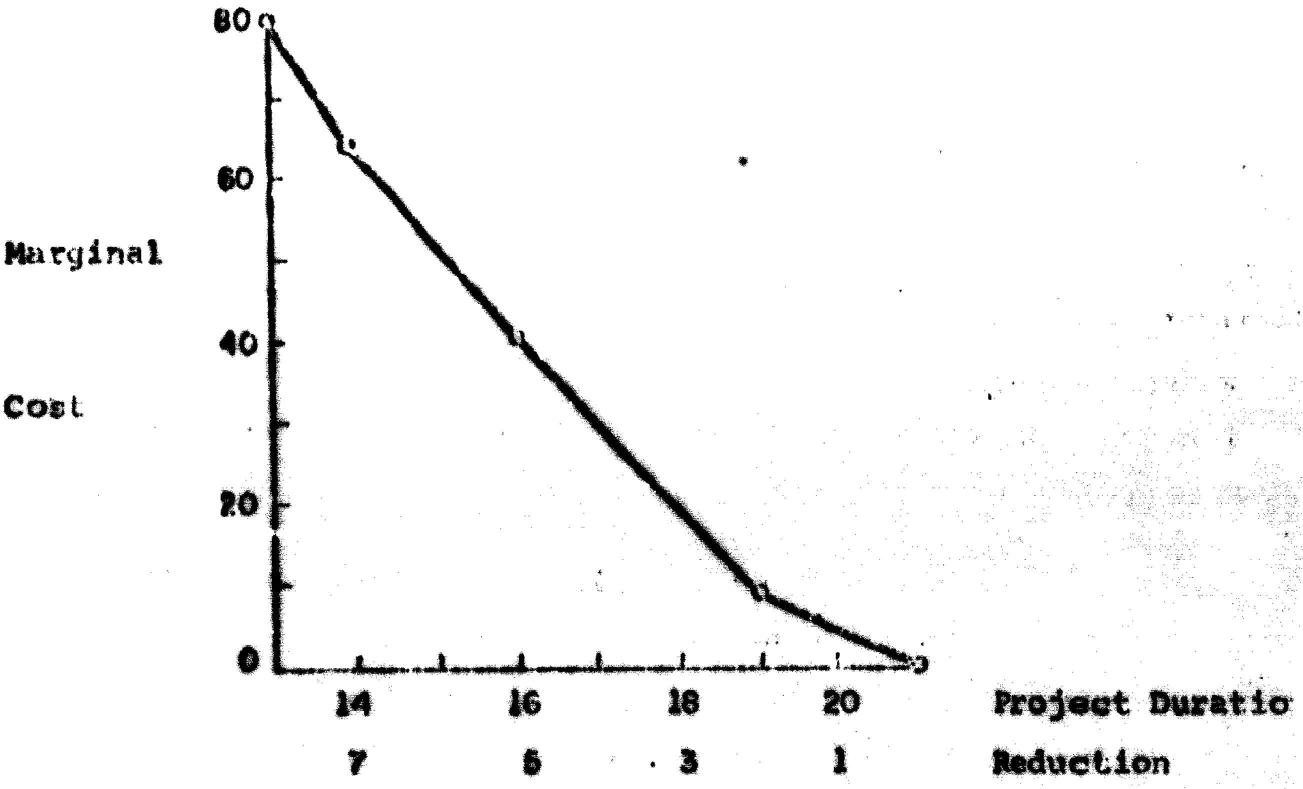
(5) Maximum reduction = the maximum reduction at step k, equal to maximum flow in Path P_k. equal to $R_k - R_k - 1$.

(6) Cost slope (b_k) = of the set $Q_k = \sum_{j=1}^{n} \theta_j$ for all a_j in P_k.

(7) Cumulative reduction (R_k) = the maximum reduction at the end of step k.

(8) Cumulative cost ((R_k)) = minimum total marginal cost to achieve reduction

$$R_k \cdot B(R_k) = \sum_{h=1}^{k} b_h(R_h - R_{h-1}).$$



Project Cost-Duration Curve

Figure (5.9)

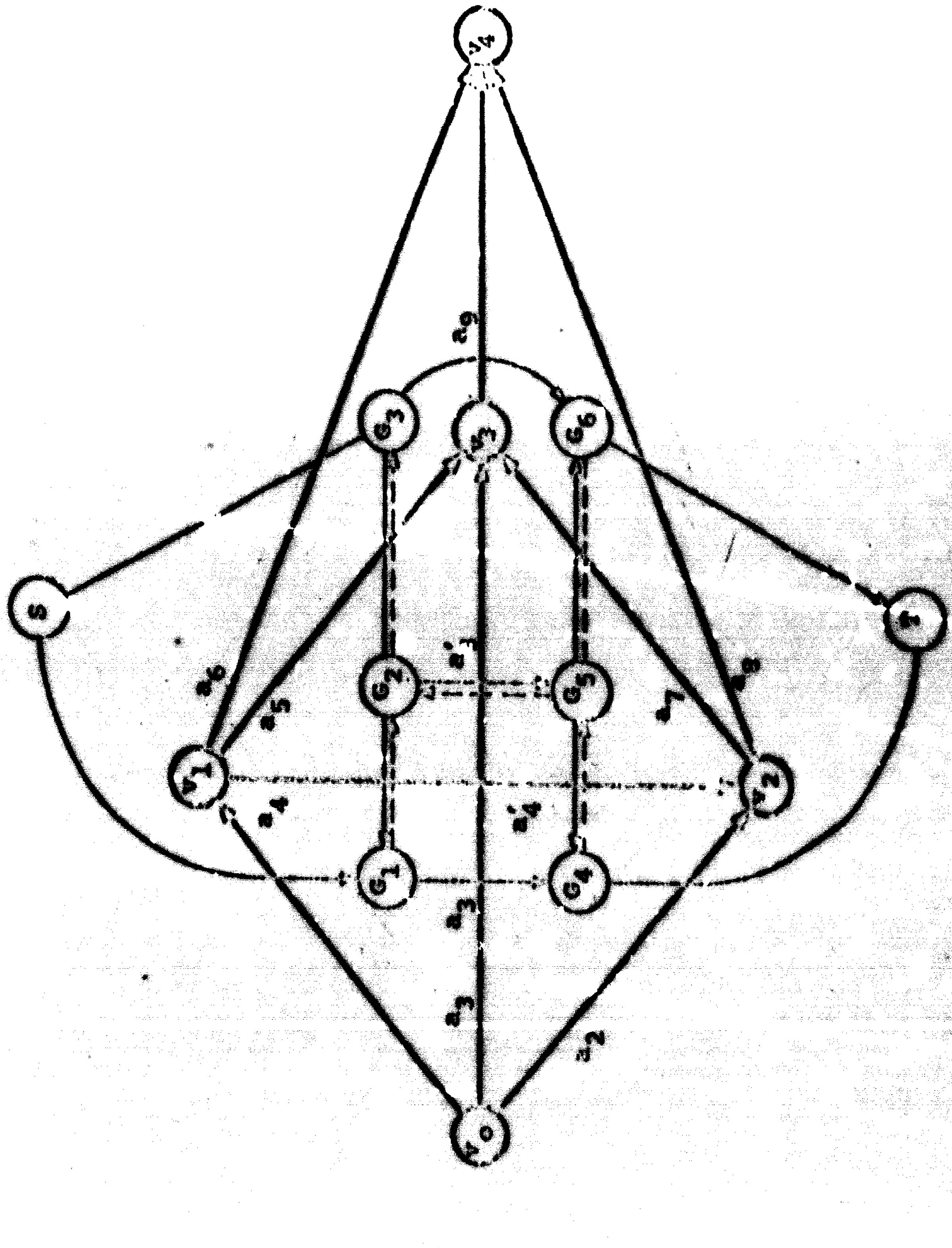
5.10 Nonplanar Networks

Nonplanar networks, such as the network N in heavy lines in Figure (5.10), pose special problems in trying to construct the cut network. If the procedure for constructing the cut network of a planar network is followed, nodes are placed in all regions, nodes in adjacent regions are joined, proper orientation is given to the links according to the procedure outlined before, and oppositely-oriented dashed-line arcs are drawn parallel to the appropriate arcs. The resulting network (the light-lined network in Figure (5.10) will contain as a path every POCS which consists of al the oriented arcs intersected by a partition line going from one side of the network to the other; for example, the sets (a_1, a_3, a_2) and $(a_6, a_5, a_4, a_3, a_2)$. It should be noted that in this case the arcs involved in nonplanarity, that is, the arcs intersecting at a point which is not a node, namely, arcs a_3 and a_4, are represented in this network by two arcs each (a_3, a_3' and a_4, a_4').

The new network, however, does not contain any POCS which does not constitute all oriented arcs intersected by any partition line. The POCS (a_1, a_9, a_2), which is sufficient to interrupt all paths from v_0 to v_4 in a minimal way, cannot be obtained by any partition line. However, if arc a_4 is stretched around node v_3 as in Figure (5.11) to avoid intersecting a_3, a partition line could be drawn which starts from region S outside the network, and intersects arcs a_1, a_5, a_9, a_7 and a_2 in this order. Of these, only arcs a_1, a_9 and a_2 are oriented, and they constitute the POCS in questi

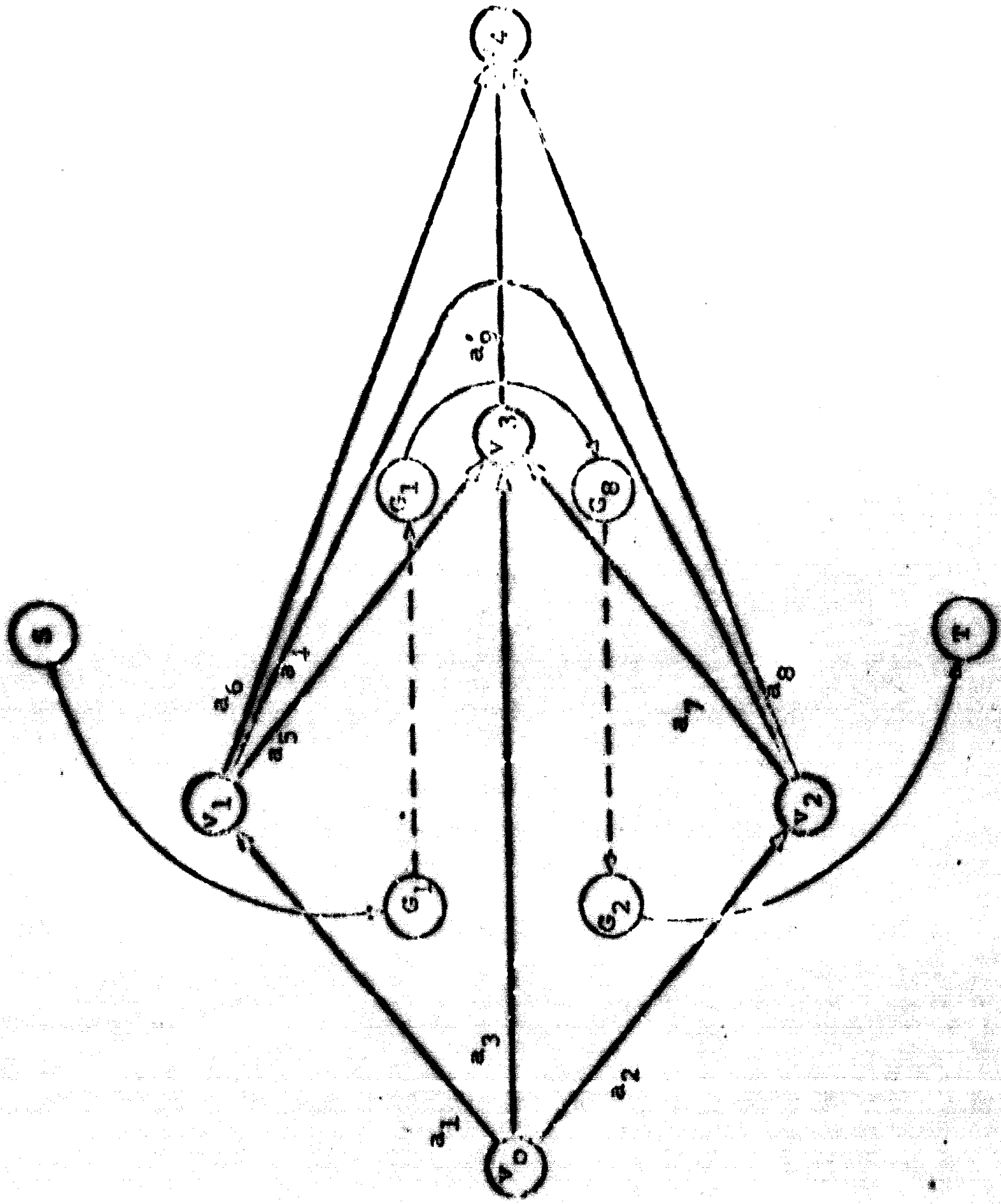
This POCS may be obtained in the network by placing two additional nodes G_7 and G_8 (Figure 5.11), joining nodes G_1 and G_7, and nodes G_8 and G_4 by dashed lines in the orientation shown in the figure, to represent the opposites of arcs a_5 and a_7, and joining G_7 and G_8 by a solid line representing a_9, to be identified as a_9' in order to distinguish it from the previous presentation of a_9 in the cut network. Figure (5.11) shows the only path representing a POCS not existing in Figure (5.10). Superimposing the two we obtain the cut network in Figure (5.12).

The procedure is then to introduce additional nodes for every nonplanarity, by stretching the arcs involved in the nonplanarity so as to avoid the present intersection, and joining the new nodes together and with old ones with solid and dashed arcs, in order to create paths in the cut network representing the POCS's otherwise impossible to represent.



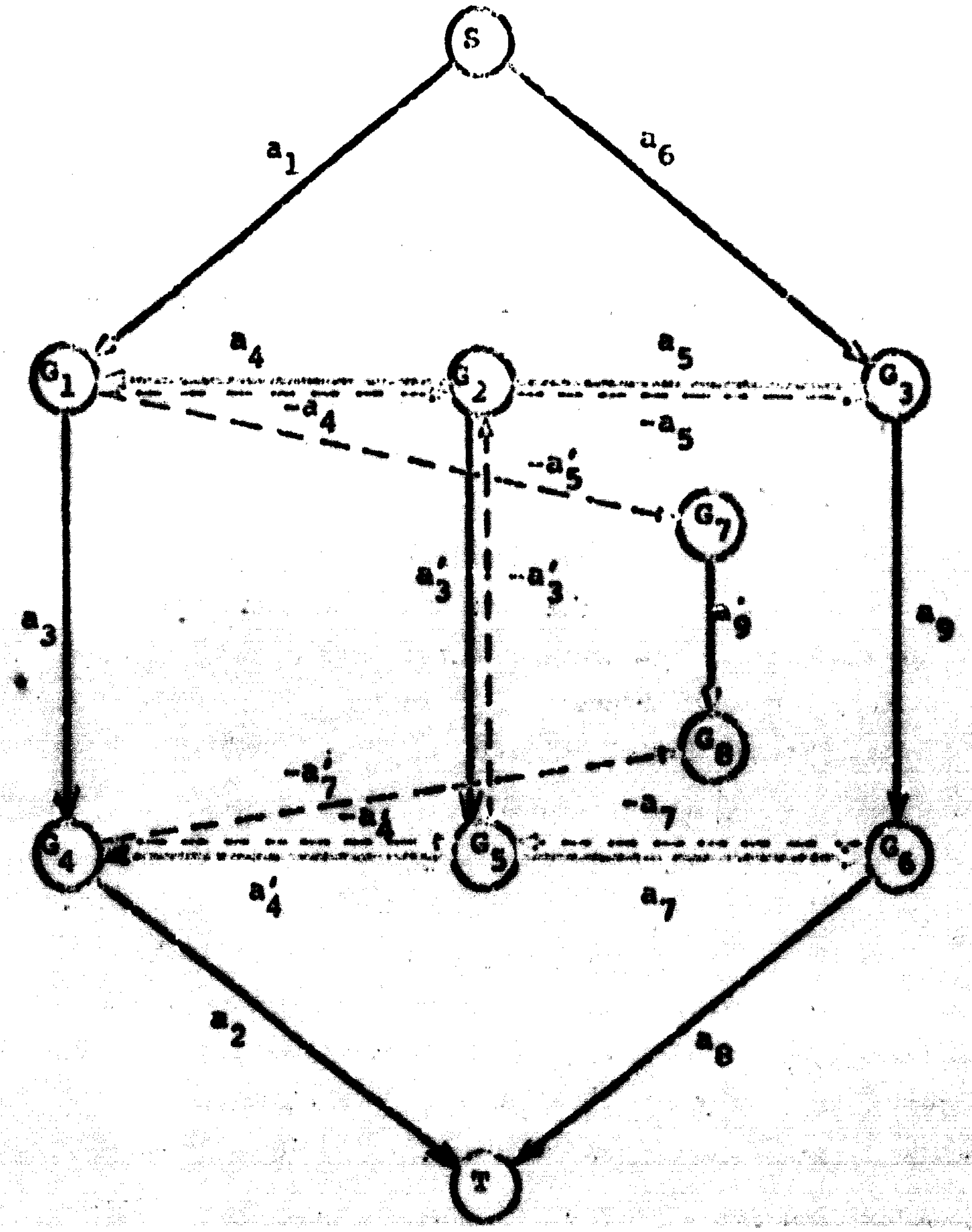
A Nonplanar Network

Figure (5.10)



Nonplanarity

Figure (5.11)



The Cut Network
of a Nonplaner Network

Figure (5.12)

5.11 Network Simplification

Simplification may be effected in two ways:

(a) By combination:

A set of activities strictly in parallel, that is, all having the same starting node and the same terminating node, can be combined to form one activity, with one cost-duration function. This can be done by adding the cost slopes of the activities at each level of reduction within the total range of reduction for this set, which is the smallest maximum reduction of all its activities, including their slacks.

It is obvious that if the slack of an activity is greater than the maximum reduction of a parallel activity, it will never have an opportunity for reduction, and it could be excluded from cost-duration calculations. This will be taken care of automatically in the combination process by the fact that the combined activity will not include the cost slope of that slack activity as part of its cost slope.

A set of activities strictly in series, that is, a set of activities forming a subpath in the network, such that any path including an activity in the set will include all activities in the set, may also be subjected to combination. The combine cost slope will be defined, at any level of reduction, by the minimum of the sum of cost-slopes of the activities in the series producing that reduction. For the linear case under consideration, the first range of reduction is effected through the minimu cost slope activity, the second range by the next to minimum and so on. For non-lin cases dynamic programming could be used to find the combined cost-duration function.

If a separable part of the network consists of sets of activities in series and in parallel, a succession of combination steps can result in the combination of all into one activity.

(b) By elimination:

Some slack activities are such that even when the project is reduced to its bare minimum duration, no reduction in them will be necessary. If such activitie can be identified before cost-duration analysis is conducted, a lot-off effort could be saved. The procedure which will be described here can identify all such slack activities except anyone which lies on a path, or a set of paths, strictly parallel to some other path whose madimum reduction is less than the slack of the given activity. If such parallel activities have been treated as suggested before, the proposed procedure will eliminate all activities not relevant to cost-duration analysis.

The procedure is simple and consist of finding the total project duration under complete crash of activities, and then running forward critical path computations using normal activity durations up to the last node (finish node). The earliest finish of that node will be the project duration under normal activity durations. Now force the crash duration of the project as the latest finish time of the last node, and compute the latest finish of all activities in the network. Some of these slacks will naturally be negative, the most negative being, of course, the critical activities. The activities with positive slack can be easily eliminated, as they will never be reduced. This will take care of eliminating all unnecessary activities, unless some are strictly parallel to ones which are relevant.

It is quite conceivable that after eliminating all irrelevant activities we end up with a planar network, or at least one which has a minimum of non-planarities.

5.12 Treatment of Slack

As the length of the project is reduced, slack is reduced, not only on activities included in the flow-augmenting path in question, but on other activities in the project as well. It is possible to identify these slack activities which are to be reduced with reference to the cut network, but it is easiest to do that by going back to the original network after each reduction step and to compute the new slack on it.

5.13 Summary

The proposed procedure for conducting cost-duration analysis, as related to linear or price-wise linear convex-shaped activity cost-duration functions may be summarised in the following steps:

(a) Simplify the network by combination, elimination or both.

(b) For each activity in the modified network, find the slack, maximum reduction and cost slope. If the activity is slack or price-wise linear, then for each range in the cost-duration relationship, specify the slope of the line segment of the cost curve, and the maximum durations as numerators in a fraction and the corresponding costs underneath. For example, an activity with these numbers $\frac{(3),(2),(5)}{(0),(4),(6)}$ has a slack (zero cost) of 3, a cost slope of 4 for a maximum reduction of 2 and a cost slope of 6 for a maximum reduction of 5.

(c) Construct the cut network for the modified network. Place the information developed in step (b) on the respective arcs.

(d) Conduct minimum-cost flow calculations.

(e) Draw the cost-duration curve.

The new procedure has distinct advantages over all old procedures, especially for use in developing countries. Among these are:

(a) Due to the scarcity of skills in solving network problems in developing countries, a new procedure will have to be simple, direct, easy to explain and easy to compute.

(b) As a result of the lack of computing facilities, the method should preferably be a hand method, which it basically is.

(c) It is possible to expand the use of this procedure to include cases of random cost functions. These cases are of specific interest in developing nations. Further work in this area is needed.

(d) The method has demonstrated its adaptability to price-wise linear convex-shaped cost functions over and above the simple linear case, which is something beyong most available procedures. Furthermore, the method has a great deal of promise for solving the discrete case when only two durations are possible either normal or crash, and nothing in between. This case, and the general non-linear case, need further research.

(e) The method not only gives the optimum reduction sets, but also any alternative optima, giving the decision-maker a latitude for choice.

(f) Sensitivity analysis, to test the effect of unexpected variations in the parameters on the total cost function, and parametric analysis, to explore the potential benefit in changing some parameters (resources) or costs, may be easily performed using this method. An interesting test is that of finding the effects of alternative reductions in various activitie at different costs on the total project cost-duration curve.

5.14 Comments

Why is cost-duration analysis considered as one system's approach to industrial project implementation? The answer lies in the fact that rather than providing one single programme for implementing a certain project, it gives a range of alternatives for project duration at different costs. The decision maker can then choose the duration that best suits his conditions. There are four possible situations:

(a) That cost is the primary factor, in which case the normal duration is used unless with very slight additional cost the project may be accelerated appreciably.

(b) That time is the primary factor, in which case the crash duration is used unless with a very slight sacrifice in time a great deal of cost saving is gained.

(c) That given the project cost-duration curve, the decision-maker can make a subjective choice of the optimum duration.

(d) That given the function of savings versus time reduced, or costs versus delays (if a deadline is to be met), the optimum duration will be that which minimizes the sum of the costs of reduction and delay, or maximises the savings less the cost of reduction.

It is this last approach that is worth further reflection. It takes explicitly into consideration the cost of delay, which is an important and often forgotten cost. It consists of the overhead cost tied up with the project during the period of delay, any additional and unnecessary direct costs incurred on activities and the lost production of the project (or penalties to be paid to owners). On the other hand, early completion of project may yield added production (or a premium by owners).

The curve for the cost of delay against project duration will have an upward trend, while that for the cost of acceleration versus duration will have a downward trend. Summing the two, a combined curve will be obtained with a minimum point at the optimum project duration.

6. CRITICAL RESOURCE ALLOCATION AND SCHEDULING

6.1 Critical Resources

The problem of critical resources is a central problem in developing countries Therefore, it requires special attention by those in charge of project implementati A critical resource is a resource whose level of availability at a given point in time (or within a period of time) may pose a constraint on the operation of the system. Resources are men, equipment, material and money, and any of these can be critical at any point of time. The problem of critical resources may belong to any one of the following categories:

(a) The resource is adequate for all demands on it within a given period of time, but it is required to control the rate at which the resource is used by the different activities, either to avoid exceeding the limit on the resource, or to maintain a constant rate of usage or any other desired pattern for that rate. This is the problem of "resource levelling", and normally a feasible schedule of the critical resource to satisfy the required conditions is needed.

(b) The resource is inadequate for all demands on it within a given period of time, and a distribution of the resource over the uses must fall short of the requests for it. This is possible when parts of the system can operate at lower levels of the resource than is normally expected to. This is the "resource allocation problem". It is normally faced when a cutback in the investment budget is enforced and a retrenchment programme becomes necessary. In these cases, an activity may be reduced in level or quality, and a project may be decreased in volume or quality or completely eliminated. The objective is usually to allocate resources over activities for maximum benefit from the project or set of projects.

(c) The resource is inadequate for all demands on it within a given period of time, and a feasible programme requires the scheduling of the resource beyond that period. This is the "resource scheduling problem". In such problems, the objective is generally to schedule the use of the resource to minimize the amount of extension in time beyond the given period.

(d) The resources of the project are adequate for all demands on them within the time period of the project, but additional levels of some resources are available at additional costs, so that a reduction in the time period of the projec is possible. Decisions concerning these situations require the "cost-duration analysis" discussed in Chapter 5 of this study. The objective is mainly to determine the optimum duration and the minimum cost corresponding to it.

Approaches to solving problems of type (a) and type (c) are more or less similar. Most of them depend on an initial scheduling of resources with no regard to capacity and then successive adjustments taking the limits on capacity into consideration. The procedures are mostly heuristic, and some are programmed on computers. Other methods depend on implicit or explicit enumeration of all possible schedules.

Appendix P-4 * is a list of many of the articles written about critical resource analysis.

In critical resource problems, especially those of the cost-duration type, planning for resource acquisition is essential, and should go hand-in-hand with programming the use of the resources.

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* Compiled by E.J. Dunne, University of Illinois, Urbana, Illinois, 1970.

7. DECISIONS IN SYSTEMS

7.1 Optimization

The ultimate purpose in systems analysis is to reach better decisions, effect better control, and improve system performance, whether the system is a project or an organization. Two approaches to decision-making are outlined here, the first being optimization and the second being experimentation.

If an explicit criterion function can be developed which gives a measure of effectiveness in reaching system objectives, then it may be possible, through some computational procedure, to find the solution (decision or policy), which attains the best level of the criterion function. This is optimization. When the computational procedure for optimization through analytic or numerical methods are prohibitive, near-optimum or suboptimum solutions are sought through approximations or through heuristic methods. Heuristic methods seek solutions to a problem throug trial and error procedures, relying heavily on the problem-solver's experience in finding clues to a proper solution. Computers have been programmed to use heuristic methods in solving problems.

In Chapter 5 of this study, a procedure for finding the optimum cost-duration relationship in activity networks has been described. In Chapter 6, it was shown how optimization and heuristic methods may be used to solve the critical resource allocation problem. Indeed, the literature still contains very little on the subject of optimization in project planning and implementation.

7.2 Experimentation

If the qualitative aspects of the objectives of a system are predominant, or if the diverse objectives are in conflict, then the expression of an explicit criterion function may not be possible. Also, if the system is so complex that the search for the optimum or even near-optimum can be futile, other methods will have to be resorted to. In these cases, it is possible to construct a model of the system, usually in the form of a set of mathematical equations, introduce inputs int the model, impose certain policies or decision rules, and observe the system's outputs. Several policies could then be tested in order to choose the one which gives the most desirable outputs. Inputs should represent the real inputs the actual system is expected to receive, and outputs may be judged on the basis of the complex set of criteria of the system.

Sometimes even when an optimization procedure is available, it may be more economical to reach a solution through experimentation.

Experimentation in systems is generally referred to as simulation. Several approaches to simulation of managerial systems have been followed, with associated computer programmes such as SIMSCRIPT[18] and GPSS[19]. An approach with particular interest is "industrial dynamics" [20], with its computer language, DYNAMO. It seems that such an approach may be of promising potential for applications to problems of managing the implementation of several industrial projects.

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[18] Markowitz, Harry M., Bernard Hausner, and Herbert W. Karr, "SIMSCRIPT: A Simulation Programming Language", Prentice-Hall, Englewood Cliffs, N.J., 1963

[19] "General Purpose Simulation System/360 GPSS/360", IBM Application Programmes H20-0304-3, Introductory User's Manual and H20-0326-2, User's Manual-International Business Machines, White Plains, N.Y., 1968.

[20] Forrester, J., "Industrial Dynamics", M.I.T. Press, Cambridge, Massachusetts, 1962.

8. SYSTEM CONTROL

8.1 Elements of Control

The control of a system means the assurance that the system is pursuing its objectives according to plan.

Control involves the following elements:

(a) Performance criteria.

(b) Information feedback.

(c) Corrective decisions.

(d) Corrective actions.

The absence of any one of these elements would result in the ineffectiveness of the control system.

8.2 Performance Criteria

No control is possible without some reference datum, against which it is judged whether the system is under control or out of it. Criteria are to be maintained for the system as a whole, as well as for its components and sub-systems. They should exist for the final product of the system as well as for the processes yielding the final product. Without effective control over the components and processes, it may be too late to establish any control over the total system, or its final output.

Component performance measures should branch out from total system performance measures, and process criteria should be derived from final product criteria.

Performance criteria may be in the form of fixed standards or as minimum standards with some incentive to exceed them. These standards may refer to quality, quantity, cost, or time. Quality standards are expressed with reference to specifications, but also with reference to the proportion of items which are allowed to fall outside specifications. Quantities produced of items to be used in construction, such as doors and windows, measurable construction items, such as miles of roads, and worker productivity are often important standards to maintain. Cost standards can be developed for activities or cost centres. Also, target dates are set for the completion of activities so that the target date for the total project is met.

All of this means that standards for all those aspects of system performance should be stored in proper files for each component, sub-system and process. These standards may be modified, but they should always be realistic and accepted by all people concerned.

8.3 Information Feedback

The information system supporting the control function is of central importance. Without up-to-date information about the actual - as contrasted to desired - performance of the system, control would be impossible. Feedback information should emphasise deviation from standards or plans. The most efficient type of feedback control is that which depends on information about anticipated deviations, so that action could be taken before duration actually occurs. This requires an effective forecasting and prediction mechanism. For example, if a shortage of a certain item used in project implementation is sensed in the market, steps could be taken to overcome this problem before the shortage in the market becomes a shortage in the company's own warehouse.

Up-to-date reports on the actual progress of work, from procurement of materia and recruitment of personnel to actual completion of activities, should be prepared and summarized in a form usable by the decision-makers.

Most management systems in charge of construction operations, especially in developing countries, suffer from the lack of an appropriate cost accounting procedure. Three accounting systems are needed in any such organisation:

(a) Financial accounting.
(b) Payroll accounting
(c) Cost accounting.

The first two are classical and they exist in almost all companies. It is the third system that poses a problem, especially when a modern system is desired, which maintains records about standard costs.

The data for a typical cost account on a project are:

account ID
account description
estimated quantity needed
estimated cost of material
estimated cost of labour
actual quantity purchased .

actual cost of material purchased
actual quantity used
actual labour hours
actual labour cost

An example of the data for a single activity of a CPM network is the following

activity ID
cost account number
activity description
activity duration
cost of activity
immediate predecessors
resource types and quantities
earliest scheduled start date
earliest scheduled finish date
latest scheduled start date
latest scheduled finish date
special remarks

Cross references should tie the individual data in a data network within the system. With data appropriately organized, computer programming could be resorted to for data processing.

8.4 Corrective Decisions

Decision-making in systems was discussed in Chapter 7. However, corrective decisions are at an operational level, and should be made at the lowest management level at which all the information needed for decisions can be assembled, and which has the required decision-making skills. Unless co-ordination is necessary among corrective decisions in several places in the system, decentralisation should be adhered to, in order to reduce the lead time in reacting to deviations. What makes corrective decisions easy to decentralise is the presence of clear performance standards.

8.5 Corrective Actions

Needless to say, corrective decisions should be coupled with corrective actions. Again, the delay in communicating the decision to the implementors could be reduced if the decision is made at a level close to the executors.

8.6 Delay in Feedback

Two aspects of control are worth mentioning here. The first is that a feedback loop may be contained in another and so on. For example, when material is needed, orders are made for withdrawal from a storeroom. If this is out of material, another feedback loop takes the order to a general warehouse and another perhaps to the manufacturer or the importer.

The second aspect is the delay nature of feedback. It should be noted that the delay consists of the sum of the delays in information collection and reporting, decision-making, communication of decision, action and response to action. The longer each one of these elements takes, the longer the delay is, and the worse the deviation from plan becomes, with the result that correction assumes a higher cost. The situation is more critical when more than one feedback loop has to be travelled.

9. SYSTEMS IMPROVEMENT

9.1 Methods of Improvement

One of the most important qualities of successful organization is their consistent pursuit of self-improvement. In organizations in charge of construction operations the following are simple directions for improvement of project implementation:

(a) Modular construction:

If an organization is in charge of implementing projects of similar nature. One of the possible ways to cut costs, speed construction and increase reliability is to design and construct standard modules (for example of doors, windows, attachments, patterns, etc.) which could be used on a broad range of projects.

(b) Data bank:

The use of improved information collection and handling systems can provide significant improvements in system performance. The idea of a data bank is that of a master file, containing information about the operations and activities of completed projects and projects to be implemented, resources, productivity, costs, availability of material and their sources, and all information which could be used in future planning and implementation of industrial projects. Co-operative figures from other industries and other countries are often stored. The mechanization of the data bank through electronic computers makes information storage and processing much easier.

9.2 Goal and Constraint Refinement

An organization lives in a changing environment, abundant materials become scarce, and other material become abundant. Prices and wages increase, and technolog changes, A viable organization is one which adapts itself to environment.

Adaptation involves modifying the perceived constraints, and perhaps changing the goals, with the result that the decision rules change.

Management of a project or an organization should keep aware of these changes and adapt to them as they occur. Better still, they should anticipate their occurrence and prepare themselves ahead of time.

10. SYSTEM EVALUATION

10.1 The Project

The most obvious criterion for the success of the implementation of a project is whether it has been completed on or before the scheduled date, according to the specifications set on it, and within the cost limits assigned to it. However, sophisticated evaluation should go beyond that, since the initial costs may have been exaggerated or underestimated.

There is no easy answer to this question, but it is at least clear that the existence of performance criteria and standards is essential for the development of a sound evaluation procedure.

Evaluation should also take into consideration the ability of the people in charge of implementation to deal with contingencies as they arise. It is this ability that quite often decides whether the project will be completed on time, or completed at all.

10.2 The Organization

The organization in charge of project implementation, as an on-going concern, can accumulate information and experience about the implementation of industrial projects, which can be used in implementation planning, control and evaluation. In fact, the performance of the organization as a whole could be judged in terms of its ability to improve on past performance. Costs should consistently become lower as experience is gained, occurrences of missed deadlines and penalties for delay should become less, and complaints about deviations from quality standards should diminish.

Another dimension for evaluation is the ability of the organization to co-ordinate the implementation of several projects, schedule the use of scarce resources, and gear the implementation of projects to other industrial plans in the country. The criterion here is not the success of implementation of one single project, but that of an industrial plan.

A third dimension is that of the success with which it develops its own resources, men, equipment, information system and organization. Without a proper development of its own resources, an organization will not be capable of carrying out the implementation of projects, whose demands become increasingly complex as the process of industrialization becomes more extensive.

10.3 The System Approach

A very significant question to be raised at the end of this study on the application of systems analysis to industrial project implementation in developing countries, is whether such an approach is of any use to these countries.

It could be safely stated that a systematic approach to project implementation, even in a crude form, could be of great use in:

(a) Describing the needs of the project in precise terms, and relating the components of the project in a meaningful and accurate way.

(b) Making realistic estimates of completion dates and avoiding over ambitious promises.

(c) Focusing attention on critical activities and bottleneck operations.

(d) Computing demands on critical resources and programming the supply of such resources.

(e) Exploration of alternative plans or policies.

(f) Providing a structure which helps in determining the data needed to work out a plan.

(g) Furnishing a conceptual framework which guides thinking in planning and decision-making, and which may serve as a training tool for those who are working in the area.

However, a number of objections and criticisms have been levelled against the systems approach, especially as it relates to the use of mathematical models, in the study of complex systems. The following are examples:

(a) Lack of adequate and accurate data, this being even more so in developing countries. Although this statement is largely true, accepting it as face value would inhibit the development of meaningful data in the future, since there should always be a theoretical structure around which data is collected.

(b) Inadequacy of the model. In the author's opinion, with the use of some model, even if it were crude, more accurate estimates of the consequences of a plan are likely to be produced than when no model is used at all.

(c) Inaccuracy of simplifying assumption. A test of the validity of an assumption, or the sensitivity of the system's output to it, can answer this question.

(d) The presence of untested assumptions. These are more dangerous than simplifying assumptions because there is generally no awareness of their existence. The systems analyst should keep his eyes open to avoid such traps.

(e) Lack of adequate computing facilities. This is an argument for creating organisations to take charge of implementation.

(f) Emphasis on the quantitative, rather than the qualitative, aspects of systems. A good systems analyst tries to avoid just that by taking social, political and human factors into consideration implicitly or explicitly. The interaction between the quantitative and qualitative aspects of systems could be the subject of the study of the system, for example, determining the economic cost of a social or political decision.

11 RECOMMENDATIONS

11.1 Requirement for Successful Application of Systems Analysis

In the light of the study, the following are the elements which would contribute to the success of a systems analysis study of industrial project implementation in developing countries;

(a) The existence of an adequate data collection system.

(b) The existence of an adequate data processing system.

(c) The existence of personnel specialized in systems analysis with a good knowledge of its philosophy and techniques They should also be knowledgeable in the areas of operations research and computer science. Besides, they should be familiar with the managerial and technical problems of industrial project implementation.

(d) The support of top management of the project or the organisation.

11.2 Areas for Further Research

The success of systems analysis cannot continue without supporting research. The areas which badly need research effort are;

(a) Critical resource analysis

(b) Application of simulation techniques to industrial project implementation.

(c) Resource scheduling over a number of projects

(d) Information handling and storage. The data bank.

(e) Cost estimating, accounting and control of industrial project implementation.

Indeed, one of the uses of systems analysis for industrial project implementation in developing countries is to determine the areas which need further research and investigation.

A. THE SCOPE OF THE GENERAL AREA

A.1 The purpose

In this appendix, a list of the major topics under each one of the four main areas referred to in Chapter 2 will be developed. The list will be neither detailed not comprehensive, it will only represent the main subjects that can be candidates to a programme in O.R.

It will be recognized that a great deal of overlap exists between the four areas. However, a topic will be listed only under one area, the one which draws upon it more frequently.

A.2 Operations research

a. Linear Programming

- i. The general linear programming model
- ii. The simplex procedure
- iii. Resolution of degeneracy
- iv. The transportation problem
- v. The assignment problem
- vi. The dual problem
- vii. Sensitivity analysis
- viii. Parametric linear programming
- ix. Upper bounds
- x. Secondary constraints
- xi. Decomposition techniques
- xii. Advanced linear programming computing techniques
- xiii. The travelling salesman problem
- xiv. The caterer problem

b. Mathematical Programming

(Linear programming is a special case which has been presented separately)

- i. Quadratic programming
- ii. Non-linear programming
- iii. Integer programming (including the zero-one case)
- iv. Stochastic programming
- v. Geometric programming

c. Dynamic Programming

- i. Problems of sequential decisions
- ii. Deterministic processes - limited horizon
- iii. Deterministic processes - unlimited horizon
- iv. Stochastic processes - limited horison
- v. Stochastic processes - unlimited horison
- vi. Adaptive processes
- vii. Dynamic programming and finite Markov chains

d. Network Analysis

- i. Networks, definition, interpretations and basic relationships
- ii. The shortest route problem
- iii. Flow networks, - maximum flow (in non-directed and directed networks), minimum cost.
- iv.
- iv. Activity networks - CPM and PERT, the critical path, cost duration relationships, resource allocation.
- v. The minimal spanning tree problem.

e. Queuing, or Waiting-Line Theory

- i. Single-channel queues - Poisson (infinite and finite)
- ii. Single-channel queues - Erlang
- iii. Multiple-channel queues
- iv. Sequential queues
- v. The transient state
- vi. Simulation in queues
- vii. Networks of queues
- viii. Optimization in Markov chains

f. Inventory Models

- i. The nature of inventory problems
- ii. Economic lot size models (without and with shortages)
- iii. Other static deterministic models - price breaks, step functions for holding cost, price-dependent demand, consideration for slow-moving items.
- iv. Static probabilistic models (without and with set-up cost)
- v. Inventory control systems and evaluation

- vi. Dynamic models (multi-period problems)
- vii. Parallel stations
- viii. Stations in series
- ix. Multi-echelon (multi-stage) inventory problems

g. Replacement Models

- i. Replacement of items which deteriorate gradually
- ii. Replacement of items which fail suddenly
- iii. Group replacement
- iv. Maintenance and inspection
- v. Reliability

h. Scheduling Problems

- i. The nature of scheduling problems and evaluation criteria
- ii. Finite sequencing for a single machine
- iii. One-operation per job problems
- iv. Flow-shop scheduling
- v. General n/m job-shop problem
- vi. Assembly-line balancing problems
- vii. Application of queuing systems
- viii. Continuous job-shop processes

i. Other Optimisation Techniques

- i. Gradient methods
- ii. Branch-and-bound techniques
- iii. Optimum search methods
- iv. Pontryagin maximum principle

A.3 Systems Analysis

a. System Description

- i. Graphical
- ii. Matrix

b. Graphical Presentation

- i. The block diagram
- ii. Networks and decision trees
- iii. Flow graphs

c. Information Systems
   - i. Information requirements
   - ii. Information systems design
   - iii. Selecting the information processing equipment

d. Control Systems
   - i. First-order prediction and control
   - ii. Second-order prediction and control
   - iii. Feedback and adaptive control
   - iv. System classification

e. System Complexity
   - i. Complexity and variety
   - ii. Requisite variety
   - iii. Memory capacity and speed of processing
   - iv. System size and Ashby's law

f. System Simplification
   - i. Methods of simplification
   - ii. Economic analysis of simplification

g. Symbolic Logic in Systems Analysis
   - i. Applications of Boolean Algebra and propositional calculus
   - ii. Truth tables
   - iii. Symptom-cause complex tables

h. Economic Aspects of Systems
   - i. Cost-effectiveness or cost-benefit analysis
   - ii. Economic analysis
   - iii. Financial planning

i. Managerial Aspects of Systems
   - i. The system environment
   - ii. Long-range planning
   - iii. Structuring the system's organisation
   - iv. Tactical planning and control

j. System Simulation

- i. Simulation as a technique when everything else fails
- ii. Conducting the simulation study
- iii. Industrial dynamics
- iv. Testing the results of simulation
- v. Limitations of simulation

A.4 Systems Engineering

a. Signal Flow Graphs

- i. Rules of signal-flow graphs
- ii. The single-loop feedback graph
- iii. Graph reduction - Mason's rule

b. Information Theory

- i. Models of communication systems
- ii. Definition of information - properties of average information (entropy)
- iii. The compatability problem
- iv. Information content of messages and signals
- v. Statistical encoding and translator properties
- vi. The properties of messages and signals
- vii. Channel properties

c. Feedback Control Theory

- i. Definition of feedback systems
- ii. The Laplace transform
- iii. Frequency response
- iv. System stability
- v. Sensitivity

d. Adaptive and Learning Control Systems

- i. Adaptive control
- ii. Identification, decision, modification
- iii. Learning systems
- iv. Pattern recognition

e. System Design

  i. The economic aspects of design
  ii. The psychological aspects of synthesis - creativity
  iii. Automated and computer-aided design
  iv. Evaluating the system design

f. Computer and Systems

  i. The role of computers in systems analysis, design and operations
  ii. Uses for information handling (data processing)
  iii. Uses in system design - automated and computer-aided design, heuristic design, etc.
  iv. Uses in decision-making and problem-solving - simulation, processing of large-scale numerical problems, heuristic problem solving, etc.
  v. Uses in system control.

A.5 Decision Theory

a. a. General Concepts

  i. Elements of a decision
  ii. Classifications of decisions
  iii. Criteria and decision rules
  iv. Behavioral and statistical decision theories

b. Utility and Value Theory

  i. Expected values and utility
  ii. Measurement of utility-simple gambles
  iii. Properties of utility
  iv. Utility and subjective probability
  v. Inconsistency of preference

c. Riskless Choice

  i. Models of riskless choice
  ii. Man-computer co-operation

d. Decision-Making Under Uncertainty (complete Ignorance)

  i. The criteria
  ii. Techniques of choice

e. Decision-Making Under Risk

  i. Bayes theorem and Bayesian statistics in decision-making
  ii. A *priori* probabilities
  iii. A *posteriori* probabilities (revised probabilities)
  iv. Sufficient statistics and non-informative stopping
  v. Opportunity loss
  vi. The value of information
  vii. Optimal sample-size in decision problems

f. Decision-Making Under Conflict (Game Theory)

  i. The characteristic of conflict situations - conflict and co-operation and intermediate situations
  ii. Two-person zero sum games - with and without saddle points, game value, mixed strategies.
  iii. Dominant strategies
  iv. Two-person non-zero sum games
  v. n-person games (zero sum and non-zero sum)
  vi. Methods of solution - graphical, algebraic, linear programming.
  vii. Bidding theory— open bids, closed bids, collections
  viii. Group decision-making (an axiomatic treatment)

g. Psychological and Sociological Aspects in Decision-Making

  i. Rationality - man as a rational animal, optimising and satisficing, rationality and ethics, limits on rationality, psychological needs and rational decision
  ii. Group decisions - autocratic, majority coersion, minority coersion, unanimity, group manipulation, interpersonal relations
  iii. Decision-making under pressure - time limit, distress, very limited choice, one-shot decisions
  iv. Attitude toward risk - personal characteristics, environmental factors
  v. Contributions of behavioral science to decision theory.

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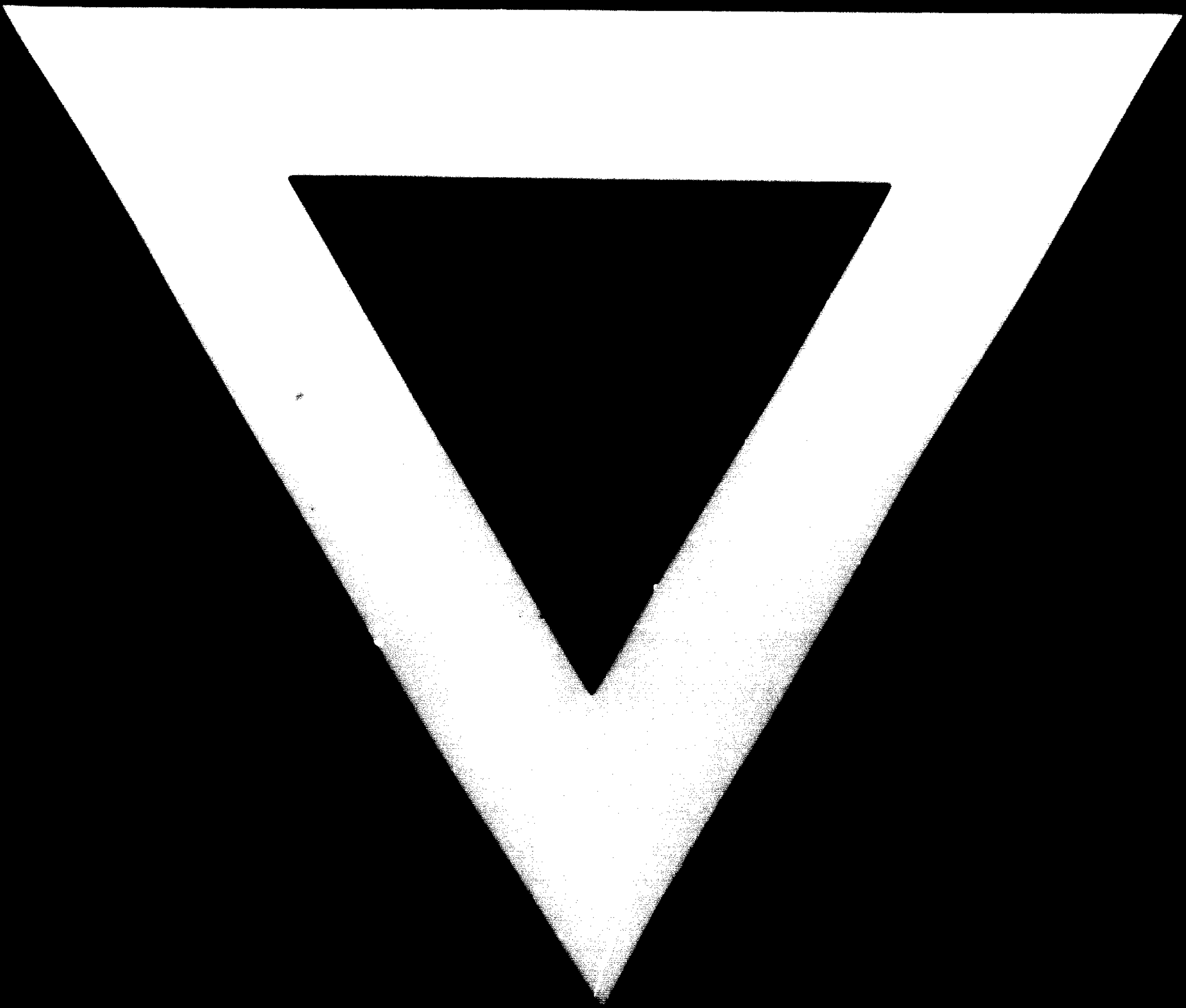

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