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OPERATIONS RESEARCH: APPLICATION TO THE MANAGEMENT OF THE CONSTRUCTION PROCESS

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF ARCHITECTURE

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Houston, Texas

MAY 1971

ACKNOWLEDGMENT

My primary debit is to the School of Architecture at Rice University for enabling me to undertake graduate studies through the granting of a Graduate Fellowship.

I would like to express my deepest gratitude to my Thesis Director, Professor Chalmers G. Long, Jr., for his thoughtful guidance and advice in the preparation of this Thesis.

My Thesis Advisors were: Professor Anderson Todd, Director of the School of Architecture, Doctor Jerome D. Wiest, Professor in Management Science, and Mr. Jonathan King, Vice President of Educational Facilities Laboratories, Inc., of New York. I would like to express to them my appreciation for their criticism and suggestions in the process of this Study.

ABSTRACT

OPERATIONS RESEARCH: APPLICATION TO THE MANAGEMENT OF THE CONSTRUCTION PROCESS. BY PATRICE DALIX.

New and better solutions to management problems in the construction industry are essential if demands of contemporary society for habitat are to be met.

Operations Research is defined and presented as uniquely successful in providing such solutions.

Eight basic forms of O.R. are defined, examples are given from other industries and from Construction of their use, and applicable mathematical techniques are listed for each.

Sequencing, one of the eight forms, is given in depth study because of its particular applicability to construction management problems. A single construction management example is used as a base for describing Critical Path, PERT, CPM, and CPM cost control.

The utility of O.R. techniques in obtaining optimal problem solutions is concluded to the whole range of the Construction process, including programming and design.

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I. INTRODUCTION

Our expanding urban society demands that its habitat be built faster, cheaper, and better. Such demands suggest that new, or more efficient, production processes are necessary. A new or more efficient production process requires:

- New design.
- New technological ideas.
- New organizational ideas.

There is no shortage of good ideas at the design and technological levels in the construction industry. But how many of these good ideas go unfulfilled for lack of organization to implement them, and how many are badly warped by poor management?

Ideas for industrialized construction systems are many, for instance, but only a very few have been realized. And from this small number, there is not one which could not be criticized for at least: its price, its delay, or its quality. It is obvious that good design and technology (Research domain) require good management (Operational domain) for realization.

The purpose of this study is to help answer these questions:

- How to go from theory to practice.
- How to narrow the odds that a project which is successful in the laboratory will be successful in the field.
- How to pass from the research domain to the operational domain.

We know that in Construction these passages are extremely complex. This thesis will be a study of management tools which could be, or have already proven to be efficient in smoothing these complex passages from theory to practice, from design to finished building.

- We will describe some basic techniques of "Operations Research" (O.R.).
- We will then show from a general viewpoint how these techniques, already applied with success in other fields, are, or could be useful to the construction industry.
- We will describe in some depth, Sequencing techniques that have already obtained remarkable results in Construction.

From complete descriptions of these techniques, it will become obvious that they can be applied to many problems arising at all levels of the construction process, from Planning to Maintenance, as well as Management. The final part of this study will deal with new prospects from this base.

II. OPERATIONS RESEARCH

II.1 HISTORY

II.2 THE THREE ESSENTIAL CHARACTERISTICS OF O.R.

II.2.1 Systems Approach

II.2.2 Interdisciplinary Team

II.2.3 Scientific Method

II.2.31 Representation and Simulation

II.2.32 The Basic Form of O.R. Models

II.2.33 Controlled and Uncontrolled Variables

II.2.34 O.R. Methodology

II.1 HISTORY

"Radar apparatus that worked perfectly in the testing laboratory often failed to work properly on the site where it was erected. Thus, the traditional method of proofing equipment did not completely apply to the new apparatus." To solve this problem, in September, 1940, a British physicist, P.M.S. Blackett, decided to "bring together a number of men with good scientific training but without specialist radio knowledge, to study the new problems from a more general point of view . . . The first two members of the group were physiologists, the next two were mathematical physicists, then an astrophysicist, followed by an army officer . . ."[1]

This type of scientific activity came to be known in Britain as Operational Research because the first studies were devoted to the operational use of radar and were carried out by scientists known to be working in radar research.

After the war, scientists who had spent years in military O.R. were quick to take the opportunities opening up in industry for them. The opportunities are still there; today almost all of the five hundred largest corporations in the United States are using O.R.

II.2 THE THREE ESSENTIAL CHARACTERISTICS OF O.R.

II.2.1 Systems Approach

- The activity of any part of an organized system has some effect on the activity of every other part of the system.
- To evaluate any decision or action in an organized system, it is necessary to identify all the significant interactions and to evaluate their combined impact on the performance of the organized system as a whole.[2]
- The statement of problems is deliberately expanded and complicated until all the significantly interacting components are contained within it.
- The entire area under control is covered; no region is singled out for special concentration.

This approach is an integrated control system. It is quite contrary to the usual inclination which eliminates the hard parts of a problem, reducing the problem to one that can be handled by standard techniques, or by judgment based on experience.

II.2.2 Interdisciplinary Team

In a simple system it is clear which of the alternative ways of viewing a phenomenon is best relative to the viewer's purpose. When a situation becomes complex, however, it is

increasingly unclear as to how a phenomenon should be approached. It becomes necessary to look at the problem in many different ways in order to determine which one or which combination of disciplinary approaches is the best. In complex systems, it is difficult to predict in advance which of the possible viewpoints is likely to be the most profitable. It is necessary to try as many approaches as possible so that one may be selected which best fits the circumstances. This can only be done by a team of researchers who come from different disciplines, or who are familiar with and know how to use disciplines other than their own. No team can feasibly contain every point of view. It is important to use researchers who will subject their work to as wide a critical review by representatives of other disciplines as is possible.

II.2.3 Scientific Methods

II.2.31 Representation and Simulation

The kinds of systems for which O.R. is most applicable do not lend themselves to laboratory study; experimental methods cannot be used. Furthermore, those systems are generally difficult and frequently impossible to manipulate and control in their environment for experimental purposes.

Since manipulation of the system under study is difficult at best, it is necessary to build a representation of it, a mathematical model. The model represents the structure of

the real system in quantitative terms; it can be manipulated and analyzed more easily than the real system. Some properties of the system can be varied systematically, while holding others constant to determine how the system as a whole would be affected if changes actually did occur. The real life alteration is simulated in abstract terms.

In some cases the way of experimenting must be in an abstract form, when the mathematical model breaks down under the sheer complexity of the real life situation. Doing so,there is a close relationship between the makeup of the experiment and the real life situation such that the real life situation is not affected by the experiment. This method is called simulation.

II.2.32 The basic form of O.R. models

All O.R. models take the form of an equation in which a measure of the system's overall performance (P) is equated to some relationship (f) between a set of controlled aspects of the system (Ci) and a set of uncontrolled aspects (Uj). Thus expressed symbolically, the basic form of all O.R. Models is:
$P=f(Ci,Uj)$

Performance depends upon significant controlled and uncontrolled aspects of the system. In order to obtain a solution one seeks those values of the controllable variables (Ci) that maximize the measure of performance (P).

The solution may be accomplished either by conducting experiments on the model or by mathematical analysis. In either case the solution yield consists of one equation for each controllable variable in the form:

$$C=f(U)$$

The optimizing value of the controlled variables are expressed as functions of the values of the uncontrolled variables. These equations are called "decision rules."

II.2.33 Controlled and Uncontrolled variables

In formulating the model, it is necessary to state explicitly what is under control and what is not. Often it is found that:

- Variables considered to be uncontrollable can be brought under control.
- Restrictions on controlled variables can be lifted.

In so doing, a better solution is often possible. But the values of uncontrolled variables in organized systems are subject to change over time. As these values change, so must the optimizing values of the controlled variables. A procedure is necessary which is capable of providing the optimal solution under any specific set of feasible conditions. Therefore, the output of O.R. is not only a solution relative to an existing set of circumstances, but also a procedure for:

- Determining when significant changes have occurred in the system.

- And adjusting the solution to take these changes into account.

II.2.34 O.R. Methodology

O.R. methodology is concerned with and involved in the implementation of its results: O.R. can only partially test its results against the past or in the laboratory. Consequently, the real test of results must come in their application in the real world: results must be translated into instructions for management and operating personnel.

Despite the most thorough advanced planning, something almost always comes up during implementation which is not anticipated. O.R. must be involved in the implementation of the findings. O.R. is action research. Its objective is not to turn out reports but to improve operations. This cannot be done without direct involvement in the operations.

O.R. phases are:

1 - Formulate the problem.
2 - Construct a mathematical model to represent the system under study.
3 - Derive a solution with the model.
4 - Test the model and the solution derived with it.
5 - Establish controls over the solution.
6 - Put the solution to work: Implementation.

III. OPERATIONS RESEARCH AND THE CONSTRUCTION SECTOR

III.1 THE CONTROLLED AND UNCONTROLLED VARIABLES IN THE CONSTRUCTION SECTOR

III.2 THE EIGHT BASIC FORMS OF PROBLEMS WHICH CAN BE RESOLVED WITH O.R.

III.21 Inventory Problems

III.22 Allocation Problems

III.23 Queuing Problems

III.24 Routing Problems

III.25 Replacement Problems

III.26 Competitive Problems

III.27 Search Problems

III.28 Sequencing Problems

III.1 THE CONTROLLED AND UNCONTROLLED VARIABLES IN THE CONSTRUCTION SECTOR

In the last chapter O.R. was defined as:

- the application of scientific methods
- by interdisciplinary teams
- to the problem-solving process so as to provide the best or optimal solution to the problems being considered.

For the construction sector the concepts of "Interdisciplinary team"[3] and "Integrated control system"[4] are already accepted, but these do not necessarily include the application of scientific methods.

The basic form of O.R. problems was given as:

$$P=f(Ci,Uj)$$

Where: P = the system's overall performance.

Ci = the set of controlled aspects of the system.

Uj = the set of uncontrolled aspects of the system.

The problem for consideration was a matter of <u>form</u>.

In this chapter problems are considered in terms of their <u>content</u>.

As with all other industry, the construction industry has its controlled (Ci) and uncontrolled (Uj) variables:

- Ci: The emphasis will not be upon the description of the controlled variables, for they are common to all

industries; Raw materials, manpower, equipment, time, price, and product performances.

- Uj: But the construction sector has some specific characteristics which engender many uncontrolled variables.

These specific characteristics are:

- Hazards of weather at the construction site. (Even if prefabrication is used)
- Hazards of subsurface conditions for foundations. (Even if tests are well executed.)
- Hazards of time: Beginning of the construction is never reliable because of administrative formalities. (Construction permit, site condemnation, dedication, etc. . . . .)
- Difficulties and delays involving the fee schedule.
- The traditional product is a unique building which is difficult to define with accuracy. (Even if specifications are competently written.)

III.2 THE EIGHT BASIC FORMS OF PROBLEMS WHICH CAN BE RESOLVED WITH O.R.

According to Ackoff and Rivett[5], there are eight different forms which account for almost all the problems which can be resolved with O.R.:

- Inventory problems
- Allocation problems
- Queuing problems
- Routing problems
- Replacement problems
- Competitive problems
- Search problems
- Sequencing problems

For each form, we will:

A - Give its definition.

B - Give an idea of its possible content by examples taken from sectors other than the construction sector.

C - Refer to mathematical techniques which can be used to solve the problem.

D - Consider when and how the form of the problem under study is used within the construction sector.

Sequencing problems will be the subject of the next chapter because of their special importance to the construction sector.

III.21 Inventory Problems

A - These problems arise when it is necessary to select the quantity or the frequency of acquisition, or both, so that the sum of the relevant costs is minimized.

- "Inventory" is an idle resource, and "resource" is anything which can be used to obtain something else (men, material, machines, money and time)
- Two quite different types of cost associated with idle resources must be distinguished: A cost which <u>increases</u> as inventory increases (storage cost, spoilage cost, obsolescence.) A cost which <u>decreases</u> as inventory increases. (The cost of lost sales, the cost of labor stabilization, etc. . . .)

B - Inventory problems appear in a wide variety of contexts. For example:

- When and how much operating capital should a company keep available?[6]
- How many retail establishments should a company have?[7]
- At what point in a production process should inventory be held, and of what should they consist?

C - Mathematical techniques for handling inventory problems are highly developed:

- Calculus and probability theory.
- Linear programming (used for determining the minimum of a

linear function given linear constraints on the function variables.)[8]

- Simulation techniques ("to obtain the essence of somethings without reality.")[9]

D - The use which the construction industry can make of inventory analysis at the programming, designing, construction, and maintenance levels is evident and manifold:

- How often and how large should a production run of concrete wall panels be?
- When and how much raw material should be transported to the construction site?
- When should an electric generator be added to a system, and how large should it be?

To generalize: The solution of inventory problems is the answer to the questions: "How much of an item to order, and when?"

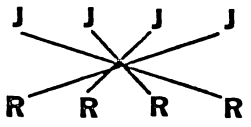
III.22 Allocation Problems

A - These problems arise with any one of the three following sets of conditions:

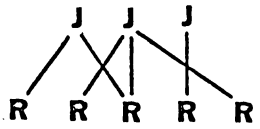
- First type

  There are several jobs to be done. Enough resources are available for doing all of them. At least some of the jobs can be done in different ways by using different accounts and combinations of resources. Some of the ways of doing these jobs are better than others. There are seldom enough resources available, however, to do each job in the best way.

- The problem is to allocate resources to jobs in such a way that overall efficiency is maximized. When each type of job requires one resource and when there are the same number of jobs and resources, it is an assignment problem.



When some jobs require more than one resource and when the resource can be used for more than one job, it is a distribution problem (including the transportation problem.



- Second type

There are more jobs to be done than available resources permit. Hence, a selection of jobs must be made, as well as a determination of how they are to be done.

- Third type

There is control of the amount of resources and it must be determined what resources should be added, and where, or what resources should be disposed of.

B - Example of utilization from the first type:

- To assign N trucks of different sizes to N different routes of differing characteristics.
- To distribute the coal from eight hundred collieries to two hundred power stations with the least expense. 10

From the second type:

- To decide which research and development projects available to a company to carry out when resources are

insufficient to do all of them.[11]

From the third type:

- To decide how many salesmen should be carried by a company and how their territories should be selected.[12]

C - Most of the techniques used to solve allocation problems are of the mathematical programming type (linear and dynamic.)[13]

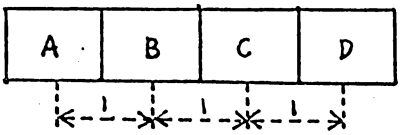
D - In the construction sector, allocation problems are used:

- To assign activities to spaces (this problem is given in appendix I.)
- To find the best location for a machine shop in a new plant design.
- To find the best location for activities in various buildings of a multibuilding complex. The CRAFT program, designed for these purposes, is described in Appendix II.

A space allocation problem:[15]
The planner must decide the placement of activities on spaces which are already fixed.

In order to determine the constraint equations necessary to attain a physically feasible solution, a sample problem was studied in great depth. After making some preliminary tests to determine the optimal number of spaces and activities to examine, four spaces and four activities were chosen. This assignment problem is more difficult than the trivial problem of three spaces and three activities and does not involve as many possible constraints as the five space, five activity problem.

The configuration chosen is illustrated below.



The distance between entrances was assumed to be one. The space distance matrix appears as follows:

	A	B	C	D
A	0	1	2	3
B	1	0	1	2
C	2	1	0	1
D	3	2	1	0

SPACE DISTANCE MATRIX

The activities were numbered from one to four. A set of arbitrary values was chosen for the trip matrix. This is shown below with the activity distance matrix.

	1	2	3	4
1	0	6	7	5
2	6	0	5	1
3	7	5	0	9
4	5	1	9	0

TRIP MATRIX

	1	2	3	4
1	0	X_{12}	X_{13}	X_{14}
2	X_{21}	0	X_{23}	X_{24}
3	X_{31}	X_{32}	0	X_{34}
4	X_{41}	X_{42}	X_{43}	0

ACTIVITY DISTANCE MATRIX

The trips and distance between two activities were considered equal in both directions to reduce the number of unknowns. This left X(1,2), X(1,3), X(1,4), X(2,3), X(2,4) and X(3,4) as the basic variables.

By multiplying the elements of the trip matrix by the elements in the corresponding rows and columns of the activity distance matrix, the objective function was formed:

$$6X(1,2)+ 7X(1,3)+ 5X(1,4)+ 5X(2,3)+ X(2,4)+ 9x(3,4) = \min.$$

The necessary constraint equations for this case appear as follows:

$X(1,2)\geq 1$
$X(1,3)\geq 1$
$X(1,4)\geq 1$
$X(2,3)\geq 1$
$X(2,4)\geq 1$
$X(3,4)\geq 1$

(The distance between any two activities must be greater than or equal to the minimum distance between two spaces.)

$X(1,2)\leq 3$
$X(1,3)\leq 3$
$X(1,4)\leq 3$
$X(2,3)\leq 3$
$X(2,4)\leq 3$
$X(3,4)\leq 3$

(The distance between any two activities must be less than or equal to the maximum distance between two spaces)

$X(1,2)+X(1,3)+X(1,4)\geq 4$
$X(1,2)+X(2,3)+X(2,4)\geq 4$
$X(1,3)+X(2,3)+X(3,4)\geq 4$
$X(1,4)+X(2,4)+X(3,4)\geq 4$

(The total distance from any one activity to all other activities must be greater than or equal to the minimum total distance be tween one space and all other spaces)

$$X(1,2)+X(1,3)+X(1,4)+X(2,3)+X(2,4)+X(3,4)=10$$

(The total sum of the distances between activities must equal the total sum of distances between spaces.)

With these constraint equations and the given objective function, a simplex tableau was set up and used as input to a computer program to solve for the values of X(1,2), X(1,3), X(1,4), X(2,4), X(3,4) that would give the minimum travel between activities. The computer programs used in testing the sample problem together with the input/output are shown in the Appendix.

The output arranged in the activity distance matrix appears as follows:

	1	2	3	4
1	0	1	1	2
2	1	0	2	3
3	1	2	0	1
4	2	3	1	0

By observation, the assignment of spaces was made:

2	1	3	4

This arrangement yields a total minimum travel of ninety distance unites per unit of time.

APPENDIX II:

Allocating facilities with "CRAFT"[16]

The CRAFT program described in this article is in the SHARE Library of computer programs (#SDA3391) and is freely available for use by companies, consultants, or individuals.* In less than one minute of computer time CRAFT can:

Determine for a new plant design the best relative location of departments for a machine shop.

Evaluate the re-layout of existing facilities where management is committed to certain department locations because of foundation investments, the location of rail spurs, roads, other buildings, and so forth.

Help determine what activities should be located in various buildings of a huge integrated multibuilding complex, where new possible buildings should be located, and what activities should be centered in those buildings. An application of CRAFT in a large integrated movie studio indicated a fantastic cost reduction of nearly $240,000 per year in material-handling savings alone through the relocation of many of the major functional departments.

Evaluate whether to centralize or decentralize such activities as:

1. Maintenance.
2. Medical services.
3. Shipping.
4. Receiving.
5. Raw-materials storage.
6. Special laboratory testing services.

For instance, an application of the CRAFT program in the location study of a special laboratory testing service department resulted in a cost reduction of 14 per cent by showing that the location should be centralized. Another study of a maintenance department resulted in a cost reduction in material handling of almost 27 per cent.

Help management deal with other nonmanufacturing problems—for instance:

1. Determining the best relative location of such functional units in a hospital as x-ray rooms, laboratories, and operating rooms.
2. Choosing the most economical location of warehouses.
3. Planning the relative location of storage units within a warehouse so that order-picking labor is minimized.
4. Analyzing layout and re-layout questions in department stores from the viewpoint of material handling and other costs.

The use of the CRAFT program, a case study:

Questions and Needs

The company was a precision manufacturer in the aerospace industry, and the plant involved was a general machine shop with about 42,000 square feet of floor area. The majority of shop orders were for small precision parts in low quantities, so that most material handling was accomplished by the machinists themselves carrying orders to and from a central holding and dispatch area (Department K) in tote pans.

The current layout had grown around the central holding and dispatch department. One of the important questions which management wished to evaluate, in addition to the layout itself, was the validity of having material flow through the central holding area.

For purposes of analysis, there were 22 plant areas designated as department centers. Table A (Figure 18-3) shows the department name, the letter code used for that department, and the approximate area requirement for each department.

TABLE A LIST OF DEPARTMENTS WITH LETTER CODES AND AREA REQUIREMENTS

Letter code	Department name	Area (in square feet)
A	Electrical maintenance	1,200
B	Drill presses	1,800
C	Degrease	500
D	Milling machines	3,800
E	Turret lathes & automatic screw machines	1,300
F	Jig borers	2,500
G	Boring mills	800
H	Hardinge and hand screw machines	400
I	Lathes	1,600
J	Slabbing mills	700
K	Central holding and dispatching	1,700
L	Grinding machines	2,000
M	Saws	100
N	Gear hobbing machines	1,700
O	Tool room	7,500
P	Numerically controlled Fosdick jig borers	1,600
Q	Numerically controlled Burgmasters	800
R	Deburring	200
S	Pantograph	1,200
T	Inspection	3,000
U	Washrooms (fixed location)	2,400
V	Vacuous area not in building (fixed location)	5,000
	Total area	42,000

TABLE A

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	T	T	T	T	T	V	V	V	V	V	V	V	V	V	V
2	T				T	V									V
3	T				T	V									V
4	T				T	V									V
5	T				T	V	V	V	V	V	V	V	V	V	V
6	T	T	T	T	T	N	N	N	N	N	B	B	B	A	A
7	S	S	S	S	S	N				N	B		B	A	A
8	S				S	N	N	N		N	B		B	A	A
9	S	S	S	S	P	M	L	L	N	N	B		B	A	A
10	R	R	R	P	P	L			L	L	B		B	A	A
11	R	R	R	P	P	L				L	B	B	B	A	A
12	Q	Q	P		P	L			L	L	D	D	D	C	C
13	Q	Q	P		P	L	L	L	K	K	D		D	C	C
14	Q	Q	P	P	P	K	K	K		K	D		D	C	D
15	O	O	O	O	O	K				K	D			D	D
16	O				O	K	K	K	K	K	D				D
17	O			O	U	U	U	U	U	U	D				D
18	O			O	U					U	D				D
19	O			O	U					U	D				D
20	O				O	U	U	U	U	U	U	D	D	D	D
21	O					O	E	E	E	E	E	E	E	E	E
22	O					O	E	E	E	E	E	E	E		E
23	O					O	I	I	I	I	I	J	J	E	E
24	O					O	I				I	J	J	J	J
25	O					O	I	I	I	I	I	F	F	F	F
26	O					O	H	H	H	H	F				F
27	O					O	G	G	G	G	F				F
28	O	O	O	O	O	O	G	G	G	G	F	F	F	F	F

TOTAL COST 3296.98 EST. COST REDUCTION 0.
MOVEA MOVEB MOVEC

TABLE B

Input Data

Flow data—In order to determine interdepartmental flow it was necessary to analyze approximately 1600 shop orders (approximately an eight-week sample) on which the routing required to fabricate the part was indicated. Fortunately, these data were available on punched cards, so that it was relatively simple to develop a matrix which showed the number of loads flowing between all combinations of departments. Table B (Figure 18-3) shows an example of the interdepartmental-flow matrix

INTERDEPARTMENT PRODUCT FLOW

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
A	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
B	-0.	-0.	57.0	20.0	4.0	12.0	12.0	-0.	16.0	-0.	10.0	20.0	5.0	2.0	-0.
C	-0.	57.0	-0.	67.0	11.0	17.0	19.0	17.0	50.0	2.0	3.0	63.0	1.0	13.0	-0.
D	-0.	20.0	67.0	-0.	10.0	8.0	19.0	3.0	12.0	1.0	10.0	20.0	16.0	2.0	-0.
E	-0.	4.0	11.0	10.0	-0.	4.0	1.0	4.0	26.0	-0.	10.0	15.0	-0.	-0.	-0.
F	-0.	12.0	17.0	8.0	4.0	-0.	3.0	-0.	6.0	2.0	10.0	3.0	-0.	-0.	-0.
G	-0.	12.0	19.0	19.0	1.0	3.0	-0.	-0.	4.0	-0.	-0.	5.0	1.0	-0.	-0.
H	-0.	-0.	17.0	5.0	4.0	-0.	-0.	-0.	8.0	-0.	10.0	20.0	-0.	1.0	-0.
I	-0.	16.0	50.0	12.0	26.0	6.0	4.0	8.0	-0.	-0.	10.0	23.0	1.0	11.0	-0.
J	-0.	-0.	2.0	1.0	-0.	2.0	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
K	-0.	10.0	3.0	10.0	10.0	10.0	-0.	10.0	10.0	-0.	-0.	10.0	10.0	3.0	-0.
L	-0.	20.0	63.0	20.0	15.0	3.0	5.0	20.0	23.0	-0.	10.0	-0.	10.0	15.0	-0.
M	-0.	5.0	1.0	16.0	-0.	-0.	1.0	-0.	1.0	-0.	10.0	10.0	-0.	-0.	-0.

TABLE B

Material-handling cost data—Table C shows the material-handling costs in dollars per 100 feet of movement for combinations of departments for which flow occurred.

INTERDEPARTMENT MOVE COST
PER UNIT LOAD PER UNIT DISTANCE

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
A	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
B	-0.	-0.	0.033	0.033	0.027	0.033	0.033	-0.	0.033	-0.	0.027	0.033	0.027	0.027	-0.	0.027
C	-0.	0.033	-0.	0.033	0.033	0.033	0.033	0.033	0.033	0.027	0.027	0.033	0.027	0.033	-0.	0.027
D	-0.	0.033	0.033	-0.	0.033	0.027	0.033	0.027	0.033	0.027	0.033	0.033	0.033	0.027	-0.	0.027
E	-0.	0.027	0.033	0.033	-0.	0.027	0.027	0.033	0.033	-0.	0.033	0.033	-0.	-0.	-0.	-0.
F	-0.	0.033	0.033	0.027	0.027	-0.	0.027	-0.	0.027	0.027	0.027	0.027	-0.	-0.	-0.	-0.
G	-0.	0.033	0.033	0.033	0.027	0.027	-0.	-0.	0.027	-0.	-0.	0.027	-0.	-0.	-0.	-0.
H	-0.	-0.	0.033	0.027	0.033	-0.	-0.	-0.	0.027	-0.	0.027	0.033	-0.	0.027	-0.	-0.
I	-0.	0.033	0.033	0.033	0.033	0.027	0.027	0.027	-0.	-0.	0.033	0.033	0.027	0.027	-0.	-0.
J	-0.	-0.	0.027	0.027	-0.	0.027	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
K	-0.	0.027	0.027	0.033	0.033	0.027	-0.	0.027	0.033	-0.	-0.	0.027	0.033	0.027	-0.	-0.

TABLE C

Existing block layout—The existing block layout for the plant was reduced for input to the computer in the form shown by Table D, where the scale is 10 feet per character.

The program, proceeded as described, and it was found that the best first exchange involved Departments P and S, which reduced material-handling costs by $168.74, as shown in Table E.

In Table F, this particular layout was the best one possible under *existing* policies and practices in the company.

```
   1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
 1 T T T T T V V V V V V V V V V V V
 2 T         T V                     V
 3 T         T V                     V
 4 T         T V                     V
 5 T         T V V V V V V V V V V V V
 6 T T T T T T N N N N N B B B A A A
 7 P P P P P P N           N B     B A A
 8 P         P N N N       N B     B A A
 9 P P P P P S M L L N N B     B A A
10 R A A R S S L       L L B     B A A
11 R R R S S L         L B B B A A
12 Q Q Q S   S L     L L O D D C C
13 Q Q Q S   S L L L K K O     D C C
14 Q Q S S S S K K K   K O     O C O
15 O O O O O O K       K O         D O
16 O         O K K K K K D           O
17 O       O U U U U U U D           O
18 O       O U           U D         O
19 O       O U           U O         O
20 O         O U U U U U U U O O D D
21 O           O E E E E E E E E E E
22 O           O E E E E E E E     E
23 O           O I I I I I I J J E E
24 O           O I             I J J J J
25 O           O I I I I I I F F F F
26 O           O N N N N N F         F
27 O           O G G G G G F         F
28 O O O O O O O G G G G G F F F F F F
TOTAL COST 3126.24 EST. COST REDUCTION 168.74
MOVEA P MOVEB S MOVEC
```

TABLE E

```
   1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
 1 P P P P P V V V V V V V V V V V V
 2 P         P V                     V
 3 T P P P P P V                     V
 4 T T T T T T V                     V
 5 T         T V V V V V V V V V V V V
 6 T         T B B B B B B B D D N N
 7 T         T B       B O       D N N
 8 T         T B   B B B O         D D
 9 T T T T T M B B K K K O           D
10 S S S S L L L L K     K O           O
11 S   S L     L K     K O           D
12 S   S L     L K     K O           D
13 S   S L     L K     K O           D
14 R S S L L L L I K K O D D B N
15 R R R C I I I   I I I I N N N N
16 R R C C I I I I I I I I N         N
17 Q Q Q C U U U U U U N N           N
18 Q Q Q C U           U G G N N N
19 F F F F U           U G   G J J
20 F     F U U U U U U G G G J J
21 F     F E E E E E E A A A J J
22 F     F E         E A       A A
23 F F F E E E E E E E E A A A A
24 O O O O O O O O O O O O O O O O
25 O                             O
26 O                             O
27 O                             O
28 O O O O O O O O O O O O O O O O
TOTAL COST 2645.08 EST. COST REDUCTION 39.17
MOVEA R MOVEB S MOVEC
```

TABLE F

III.23 Queuing Problems

A - These problems arise when service must be provided to meet some demand which is in any way irregular: Costs are connected with the length of the waiting line and the time lost in waiting. There are also costs associated with increasing the capacity of the servicing unit (both capital costs and labor costs). Since arrivals are random, there may be times when there are waiting lines, and other times when there is idle servicing capacity. As the mean arrival rate approaches capacity, the length of the waiting line will tend to approach infinity. Obviously, capacity must be at least a little greater than the mean arrival rate. The optimum solution for this class of problem will provide a processing capacity just sufficiently in excess of the mean arrival rate to minimize the total of the cost of the added processing capacity, plus the cost of waiting.

B - The optimal balance between excess capacity and time lost in waiting is an important consideration in many problems:

- The extent of docking facilities for unloading ships in ports.[17]
- The optimal speed for an industrial production line.[18]
- The optimal switch at the exchange of service channels in a telephone company.

C - A single set of mathematical formulas is not used for queuing, rather an expanding collection of methods and techniques based on the variety of assumptions. In most cases practical results derive from:

- The use of tables which give general solutions to various waiting line situations.[19]
- A process for developing data through the use of random number generators: the Monte Carlo technique.[20]

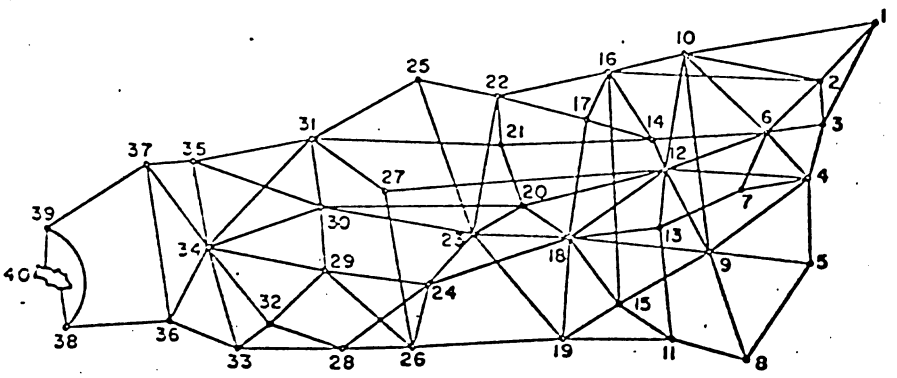
D - The following titles show the usefulness of queuing problems for programming, designing and maintenance:

- "Analysis of congestion in an out patient clinic."[21]
- "Studies in the function and design of hospitals."[22]
- "Customer behavior as a Markow process."[23]
- "Three queuing problems in designing an Air-terminal."[24]
- "Problems d'attente dans une compagnie aerienne."[25]

III.24 Routing Problems

A - These problems arise when trying to route movement among points with a minimum of time or travel, or cost; each point must be visited but once; the optimal routing must have the shortest distance (or use the least time, or involve the least expense).

B - A vacation problem: How to drive from Chicago to the Grand Canyon using the shortest path? Which, for example, is the shortest path between points "1" and "40"?



1= Chicago

40= The Grand Caynon

C - The techniques involved in solving routing problems are:

- Algorithms (like the "Tree building").
- Matrix methods.
- Linear programming techniques.
- Heuristic methods.

D - The following problem description demonstrates the usefulness of regarding certain design problems as routing problems:[30]

Design of Electric Power Stations

Electric generating stations contain large systems of cables for the distribution of power within the station. These cables are run through "cable trays," which are tubes, ordinarily of rectangular cross-section, which provide a common housing for a number of cables. The tray system is composed of horizontal runs, usually hung just beneath each floor, and vertical runs between floors. In Fig. 6, we illustrate a possible tray layout. The building outlines are shown by straight lines and the cable trays by dotted areas. Several terminals are indicated by the letters A, B, C, etc.

It is clear that a cable from A to E, for example, can be laid through the trays along several different routes. One of the problems facing the engineer is to select a route for each cable, given the list of all connections which are to be made and given the locations of all trays and the lengths of these trays between branch points. In order to minimize cost, it is desirable to select a path for each cable which minimizes the length of cable used.

By assigning a vertex number to each terminal and to each point where trays intersect, we can replace the physical diagram by a graph of the type we have been discussing. We have done this for Fig. 6, the result being Fig. 7. The lengths assigned to the various edges in the latter graph are the physical lengths of the cable trays from Fig. 6, and are not shown to scale on the graph. These could be entered in a matrix t_{ij} just as before. The problem of determining the shortest route for a cable from terminal A to terminal E now becomes the problem of determining a shortest path from vertex 1 to vertex 10 on the graph.

In practice, this problem becomes very complicated since it is necessary to take into account different sizes of cable and of cable trays, and various other factors. Nevertheless, a successful computer program has been designed and used for this purpose.

The problem of determining the shortest route for a cable from terminal A to terminal E becomes the problem of determining the shortest path from vertex 1 to vertex 10 on the graph:

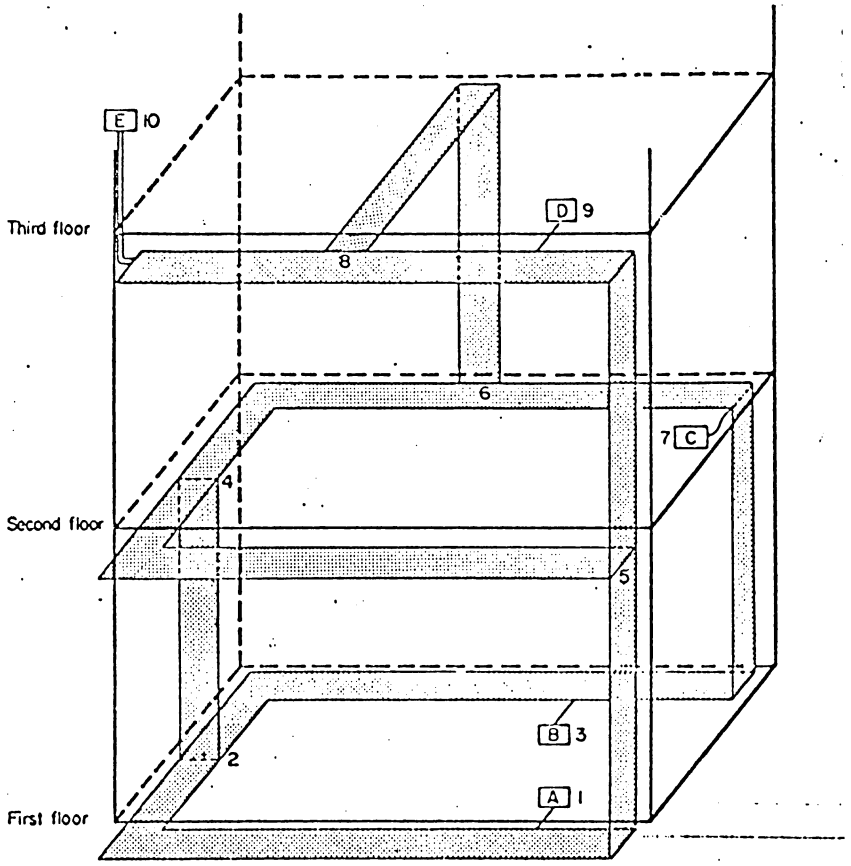


Fig. 6

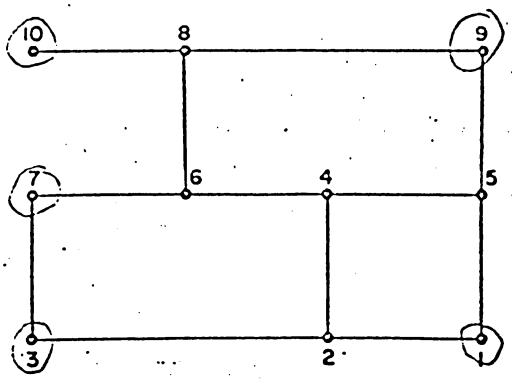


Fig. 7

III.25 Replacement Problems

A - These problems involve decisions as to equipment renewal or replacement in such a manner as to minimize operating and investment costs.

The basic principle is that the value of equipment depreciates with time. This depreciation phenomenon affects practically all machinery, industrial or domestic.

The corollaries of this first principle are:

- The longer equipment is "kept on the job," the higher becomes the cost of maintaining this equipment, and the greater becomes the loss owing to a decrease in relative and absolute operating efficiency.
- The more frequently the machinery involved is replaced, the greater becomes the investment costs.

The problem applies equally in cases where it is desirable to establish a "group-replacement" policy which seeks to minimize the total replacement costs involving the cost of the items of machinery themselves, the cost of equipment failure, and the replacement cost of a given piece or pieces of machinery. This "group replacement policy" generally deals with those items which regularly "fail" after a certain amount of use (light bulbs, tires, cigarette lighters, automobiles, etc.). Two corollaries to this "group replacement" policy are:

- To replace items only after they fail maximizes costs associated with waiting, or "down time."
- On the other hand, to regularly replace these items before they fail minimizes "down time" but tends to maximize replacement costs due to the fact that the items have not seen full use. Example: to replace all the lamps on a city street on a regularly scheduled basis according to the average lifetime of a typical bulb means that a certain percentage of these lamps will be withdrawn from service before their real lifetime has been expended.

B - The resolution of this type of replacement problem (group or individual) is of primary importance to industry[31] and business. The determination of optimum service life is intimately connected with the theory of optimal replacement policy since the service life of an asset is terminated by retirement or replacement of that asset.[32]

C - The mathematical procedures used for the first type of replacement problems are: - calculus and dynamic programming. For the second type: - analysis and simulation.

The essential input is: a statistical distribution allowing one to predict with relative accuracy the approximate moment of failure of the item involved (failure time).

D - This type of problem solving methodology is useful for measuring or predicting the quality of obsolescence in

construction. This ability will enable maximum savings with routine service procedures (lights; floor finishes; soap dispensers, etc.). Especially benefitted by these procedures are: building mechanical plant operations involving valve, seal, belt, and bearing replacement.

III.26 Competitive Problems

A - Competitive problems involve more than one decision-maker, and presume that a decision made by one decision-maker is changed, altered or affected by the decisions made by one or more of the other decision-makers.

The relationship between the interacting decision-makers may be either cooperative or competitive. The problem is to positively increase the effectiveness of the competitive situation.

Basically, there are two types of competitive situations:

- when a definite terminal point is involved (ie., a discontinuous situation with a definite "end," such as bidding for a specific contract).
- when there is a continuous state of competition involved (ie., advertising a commodity).

B - Examples of Utilization:

- in advertising campaign strategies[33]
- in determining if, how, and when a new product should be marketed[34]
- in planning for a future war against an unknown enemy at an unknown time and place.

C - The mathematical technique most familiar to this type of problem situation is game theory. Gaming as a technique is used in those situations where all the alternatives

cannot be explicitly formulated, except through the interaction of the parties concerned.

D - There is little current application of this problem solving methodology in Construction, but it may be used:

- To draw out more competitive bids.
- To estimate the chance and the strategy of winning a bid.
- To demonstrate the predictability of competitive behavior.

III.27 Search Problems

A - These problems apply in those cases in which an appropriate choice must be made among several alternatives. The procedure is basically the following: the quantity of resources (time, money, etc.) must be fixed; the coverage (sample size or quantitative aspect of alternative) must be selected and the type (sample design) must be taken into account. It must be borne in mind at the same time that if more resources are employed, the cost of the search is greater, but the expected margin of error (cost of error) is decreased.

B - All problems dealing with estimating, predicting, or forecasting may be classified as search problems. A variant of this type of problem is the exploration problem (what to explore, or investigate, and how).

C - The mathematical procedure used in this type of problem involves estimation theory and statistical sampling.[35]

D - The range of usefulness of this problem-solving technique applies to all phases of the industry:
- To determine the layout of department stores as a function of typical customer search patterns.
- To determine where to make soil test borings on a building site; and to design spot checking for a final inspection.

IV. SEQUENCING PROBLEMS

IV.1 DESCRIPTION

IV.2 THE CASE STUDY

IV.3 THE NETWORK

IV.4 THE CRITICAL PATH

IV.41 An Algorithmic Method

IV.42 A Computer Program

IV.43 A Linear Programming Formulation

IV.5 PERT MODEL

IV.6 CPM MODEL

IV.7 NETWORK COST SYSTEM

IV.8 USERS OPINIONS

IV.9 FAST TRACK

IV.1 DESCRIPTION

These problems arise when it is necessary to lay out activities of a project in the time order in which they must be performed. From a managerial viewpoint, these problems can be called Scheduling problems according to the basic managerial functions of Planning, Scheduling, and Control. Sequencing is concerned with processes which are unique and which are performed only once (Research and Development programs, Construction projects). Some steps of the process must precede others; some may be done simultaneously. Sequencing problems establish starting dates and due dates within known

This chapter will explain techniques to solve sequencing problems with a small fictitious case study:

- Description of the case study: a small construction project.
- Another way to describe the project:
  The network drawing.
- How to predict project completion time:
  The network Critical-Path.
- How to account for timing uncertainties:
  The PERT model.
- How to minimize job cost:
  The CPM model.
- How to prevent and control the time-cost trade-off: The Network-Cost System.

IV.2 THE CASE STUDY

The project is a steel frame industrial building on a slope. The foundations are concrete footings and grade beams; the heating is suspended space apparatus.

The list of jobs (or activities) necessary to complete the project can be set up by subcontractors:

SUB CONTRACTOR	JOB DESCRIPTION	JOB IDENTIFICA.	JOB DURATION
EARTHWORK	SCRAPING, LEVELING, COMPACTING	4	15
EXCAVATIONS	DIGGING FOR FOOTING	6	30
	DIGGING FOR GROUND BEAMS	8	4
	DIGGING FOR DRAINAGE	14	5
CONCRETING	DESIGN	3	10
	SETTING OUT	5	5
	FOOTING	7	20
	GROUND BEAMS	9	18
	DRAINAGE	15	20
	FLOORING	22	35
	FINISHING	22	55
FRAME	DESIGN	2	15
	FABRICATION	10	60
	TRANSPORT	12	5
	ERECTION	13	25
ROOFING	DESIGN	1	3
	INSULATION	20	20
HEATING	DESIGN	1	10
	TRANSPORT	16	45
	INSTALLATION	17	35
ELECTRICITY	DESIGN	19	2
	INSTALLATION	21	20
PAINTING	FACTORY	11	20
	SITE	18	40

Fig. 1

Section of the industrial building:

P: Footing

B: Grade beam

F: Flooring

W: Walls

G: Frame

I: Insulation

H: Heating

E: Electricity

Q: Painting

D: Drainage

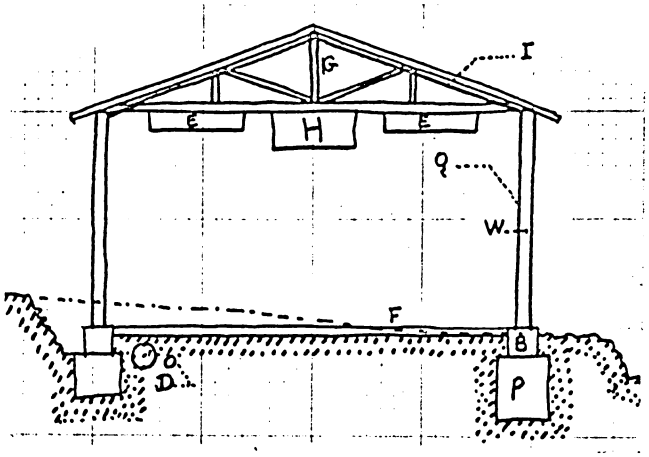


Fig. 2

NOTE: The following figure is the estimating form used in a construction firm (Zachrie Corp., San Antonio, Texas):

DATE

JOB 65023 — 20 ITEM NO. — 8in Conc. Pmt ITEM DESCRIPTION — 100818 QUANTITY

ESTIMATED BY — WORK WEEK 10 HRS 1 SHFTS 6

Op No	No. Req.	Descrip Code	Operation Quantity	Unit	O/T Labor	MATERIALS	Days/Mo Equip. Owner	Outside Rental Prod/Hr	EQUPT. OPER.	SUB-CONTRACT	SUPPLIES
1		Form Set	22,500	C.Y	18 %		12	60 C.Y			
	1	Hydro									
	4	Lab									
	1	FG00									
	2	AC125									
	4	AIRTO									
	1	FMSTP									
	3	FMSTPH									
	10	Lab									
	1	WEMCH									
2											
2		Foreman	3	Mo.							
	1	PEORE	3	Mo.	950.00						
	1	PU	3	Mo.			166.00				

Fig. 3

Each line, which represents one item, can be punched on a card for computations.

IV.3 THE NETWORK

The following diagram is set up so that "jobs" are arranged in the manner in which the construction is to be performed:

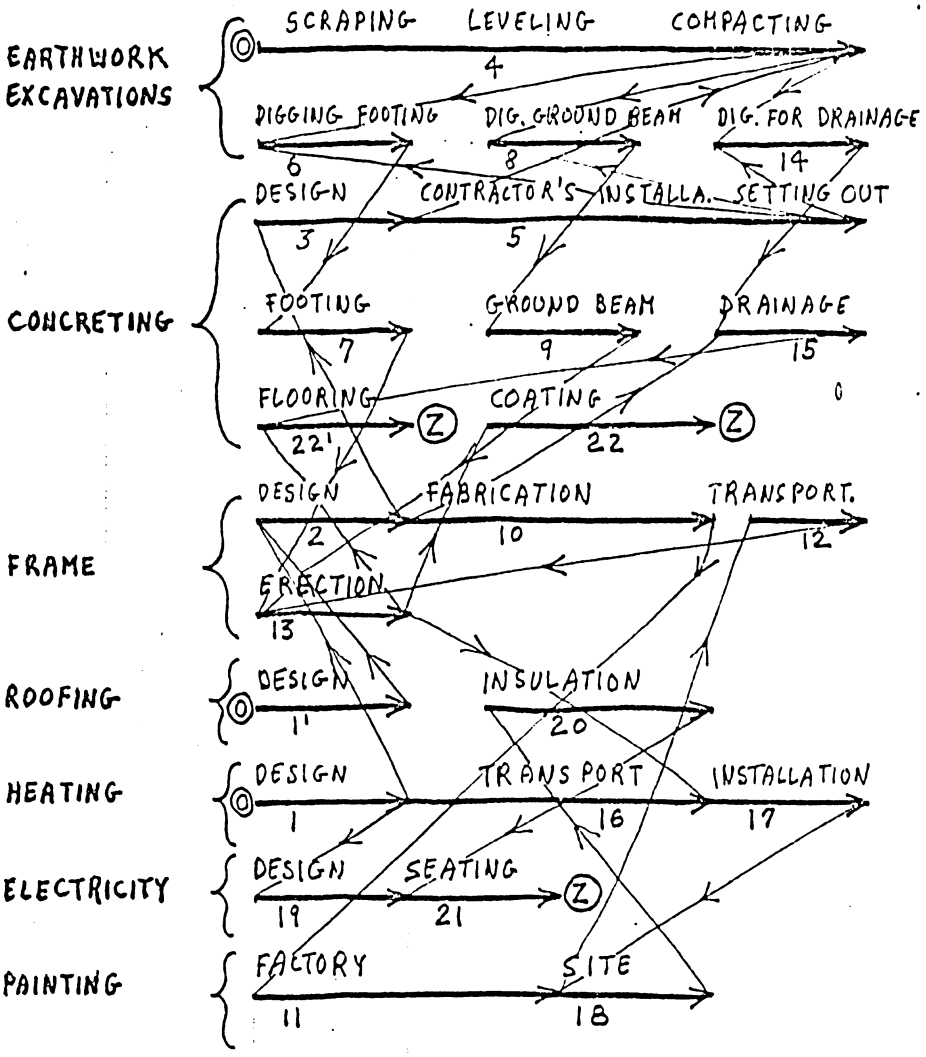


Fig. 4

REMARKS: - There is no relationship intended between the time to perform a job and the length of the arrow which represents the job.

- "0" means the beginning and "Z" the end of the project.

Another way to represent the last diagram is the following network:

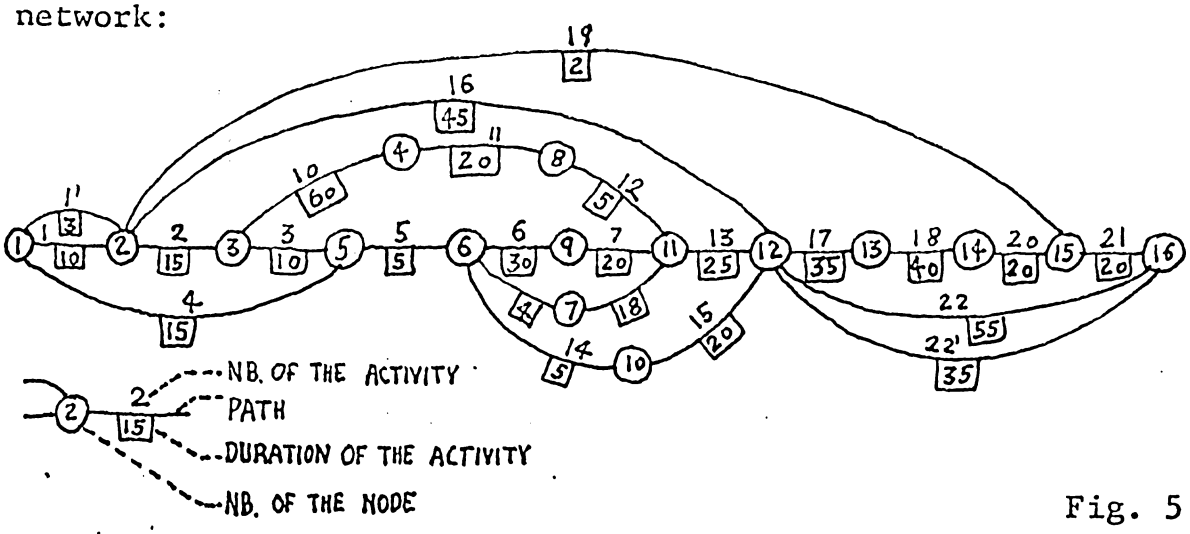


Fig. 5

REMARKS: The shape of an arrow which represents an "activity" does not matter. More important are the connections of the jobs: The "events" which are represented by nodes.

NOTES: There are many ways to draw a network. The following one is called "Precedence Network":

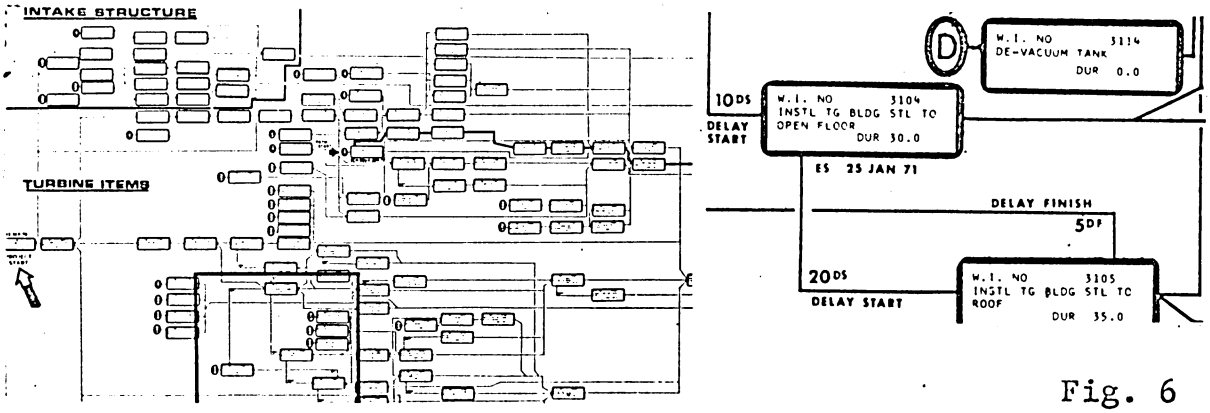


Fig. 6

This network is event oriented: calculations are not done for activities but for events. In contrast, the network of Fig. 5 is activity oriented. Computer calculations are easier with event oriented networks.

IV.4 TECHNIQUES TO FIND THE CRITICAL PATH OF A NETWORK

- We have analyzed the jobs to be done for our project.
- We have arranged jobs in the manner in which the project is to be performed.
- We have reduced the project to a network of activities and events.

Now the question could be:

- What is the minimum time required for completion of the whole project? (or will the project be done at the due date?)

To answer these questions, it is necessary to find the longest path (= sequence of connected activities) through the network. This is called the Critical Path of the network; its length determines the duration of the project.

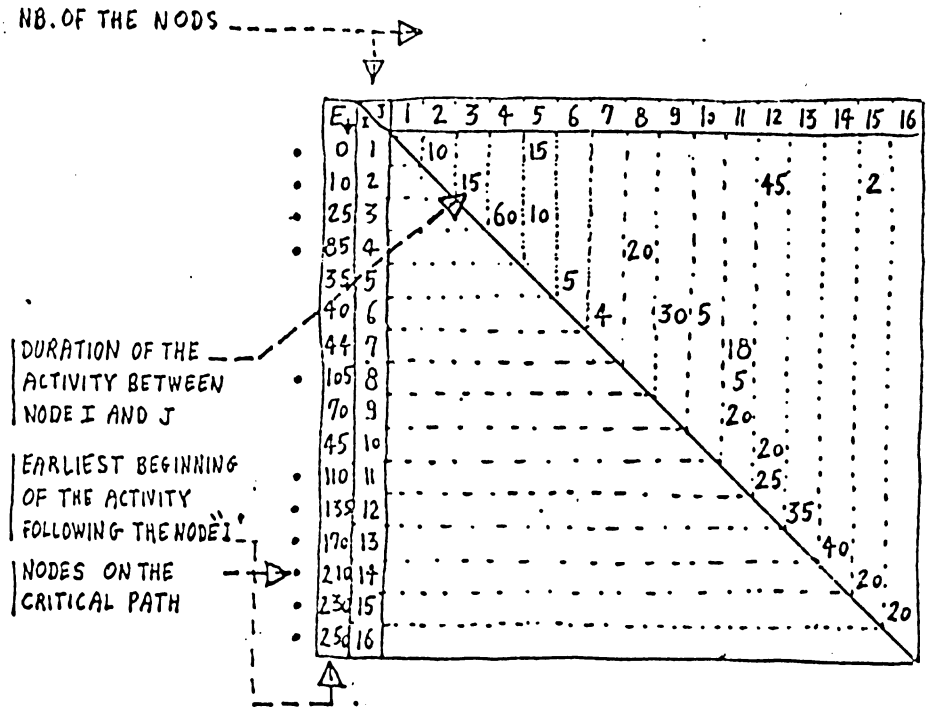
- The first technique shown is fast for small projects, because it uses an algorithmic method with calculations by hand.

- The emphasis will be on the second technique: a computer program written in Fortran IV, mainly used for big projects, but used here for the twenty-two activities of the sample project.

- The third technique, a linear programming method, is useful for trade-offs in cost-time.

IV.41 The Critical Path: An Algorithmic Method

For the sample project the following matrix is set up:



The activity between nodes "1" and "2" has "10" for a duration time: this value is written into the cell which is at the intersection of row 1 and column 2. The same is done for the activity between nodes 2 and 3, etc...

Column "E" records the earliest nodal event time. To determine "E" for a corresponding node, we start at the node in column "I" and move right along the row until the diagonal is reached. Set in column "E" the figure found above the diagonal, plus the "E" in that figure's row. If there are several numbers above the diagonal, the "E" entered is the

largest combination possible of each number above the diagonal plus its corresponding "E" number.

The Critical Path is noted with dots in figure 7.

IV.42 A Computer Program

The following program is written to determine if a project will be done on a due date, or how long before or after this date the project will be accomplished.

Input: For the case study "0" is the project starting date and "300" the due date.

The data deck is punched in the following manner:

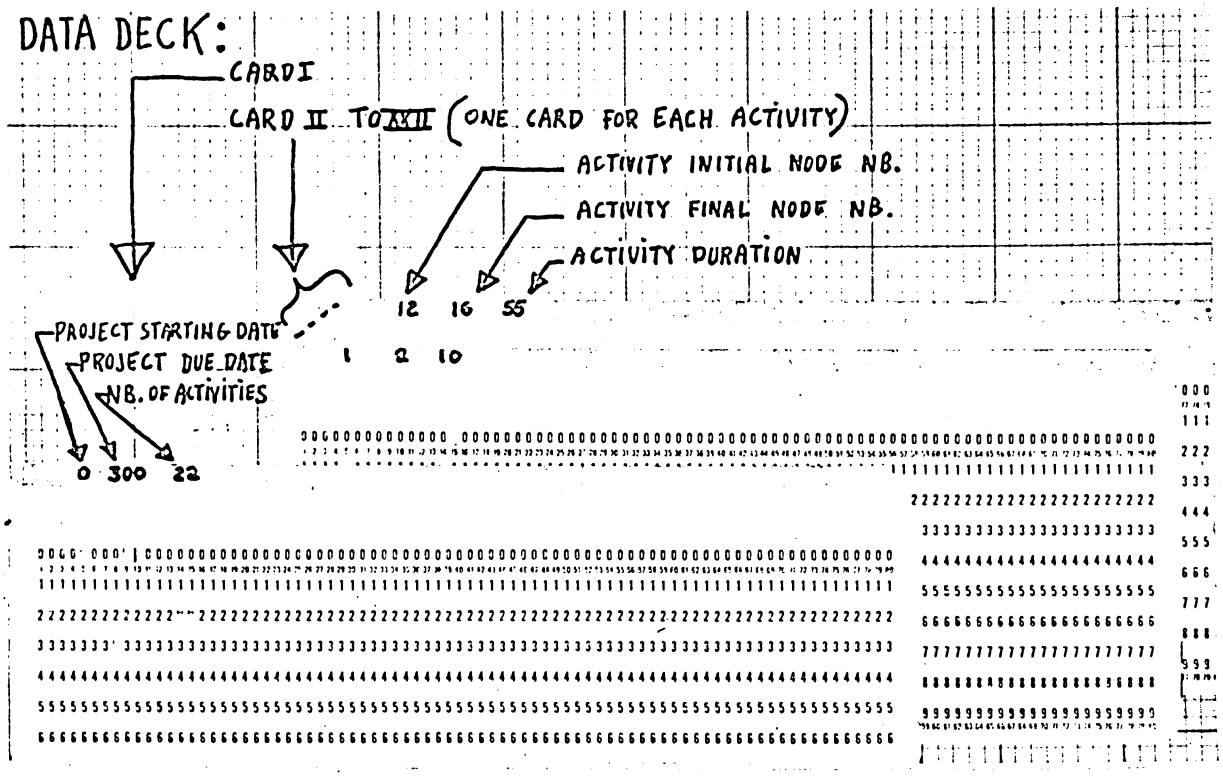


Fig. 8

Program:

Node numbers and activity duration are all whole numbers; all variables are specified as integers in the program.

LS$_n$ Latest start of activity n.

LF$_n$ Latest finish of activity n.

ESn: Earliest start of activity n.

EFn: Earliest finish of activity n.

TSn: Total slack of activity n (the difference between late finish and early finish times).

FSn: Free slack of activity n (the difference between the early start time of activity (n-1) and the early finish time of activity n).

ETn: Earliest occurrence time of node n.

S: Start date

D: Due date

N: Number of activities

In and Jn: I and J node numbers of activity n.

Tn: Duration time of activity n.

PROGRAM FOR CRITICAL PATH CALCULATIONS:

```
      R 5 5 0 0   F O R T R A N   C O M P I L A T I O N     X.15,    TUESDAY,  1/ 5/71, 12:44 H.

FILE  5= NAMEB,UNIT=READER                                                    R  0000
FILE  6=PRINT,UNIT=PRINT                                                      R  0000
                                                          START OF SEGMENT **********   1
      DIMENSION I(2500),J(2500), LS(2500),LF(2500)                            R  0000
      INTEGER T(2500), ES(2500), EF(2500), TS(2500), FS(2500), ET(2000),       R  0000
     XLT(2000),S,D,TMIN                                                       R  0000
      READ 1, S, D, N                                                         R  0000
    1 FORMAT (3I5)                                                            R  0014
      DO 2 K=1,N                                                              R  0014
    2 READ 3,I(K), J(K), T(K)                                                 R  0020
    3 FORMAT (3I5)                                                            R  0046
      DO 4 K=1,2000                                                           R  0046
      ET(K)=S                                                                 R  0054
    4 LT(K)=D                                                                 R  0059
      TMIN=C                                                                  R  0063
      DO 5 K=1,N                                                              R  0064
      INODE=I(K)                                                              R  0069
      JNODE=J(K)                                                              R  0073
      ES(K)=ET(INODE)                                                         R  0077
      EF(K)=ES(K)+T(K)                                                        R  0085
      IF(EF(K)-ET(JNODE))6,6,7                                                R  0096
    7 ET(JNODE)=EF(K)                                                         R  0106
    6 IF (EF(K)-TMIN)5,5,8                                                    R  0114
    8 TMIN=EF(K)                                                              R  0120
    5 CONTINUE                                                                R  0124
      DO 9 K=1,N                                                              R  0124
      L=N+1-K                                                                 R  0129
      INODE=I(L)                                                              R  0131
      JNODE=J(L)                                                              R  0135
      LF(L)=LT(JNODE)                                                         R  0139
      LS(L)=LF(L)-T(L)                                                        R  0147
      IF(LS(L)-LT(INODE))10,11,11                                             R  0158
   10 LT(INODE)=LS(L)                                                         R  0168
   11 TS(L)=LS(L)-ES(L)                                                       R  0176
    9 CONTINUE                                                                R  0188
      DO 12K=1,N                                                              R  0188
      JNODE=J(K)                                                              R  0193
   12 FS(K)=TS(K)-LT(JNODE)+ET(JNODE)                                         R  0198
      DO 13 K=1,N                                                             R  0213
   13 WRITE(6,100)K,LS(K),LF(K),ES(K),EF(K),TS(K),FS(K),ET(K)                 R  0219
  100 FORMAT(8I10)                                                            R  0271
      STOP                                                                    R  0271
      END                                                                     R  0272
                                                                  SEGMENT    1 TS  305 LONG
```

Fig. 9

Output:

N	LS	LF	ES	EF	TS	FS	ET
1	50	60	0	10	50	0	0
2	60	75	10	25	50	0	10
3	95	105	25	35	70	0	25
4	90	105	0	15	90	20	85
5	105	110	35	40	70	0	35
6	110	140	40	70	70	0	40
7	140	160	70	90	70	20	44
8	138	142	40	44	98	0	105
9	142	160	44	62	98	48	70
10	75	135	25	85	50	0	45
11	135	155	85	105	50	0	110
12	155	160	105	110	50	0	135
13	160	185	110	135	50	0	170
14	160	185	40	45	120	0	210
15	185	185	45	65	120	70	230
16	140	185	10	55	130	80	250
17	185	220	135	170	50	0	0
18	220	260	170	210	50	0	0
19	278	280	10	12	268	218	0
20	260	280	210	230	50	0	0
21	280	300	230	250	50	0	0
22	245	300	135	190	110	60	0

ACTIVITY NB.	LATEST START LS	LATEST FINISH LF=LS+D	EARLIEST START ES=E	EARLIEST FINISH EF=ES+D	TOTAL SLACK TS=LS-ES	FREE SLACK $FS_N=ES_{N+1}-EF_N$	EARLIEST COMPLETION TIME OF NODE N.

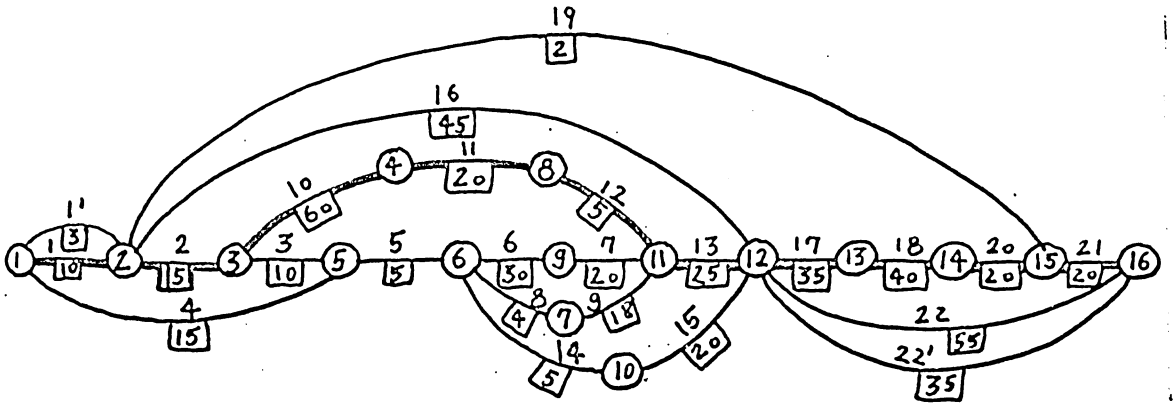


Fig.10

Interpretation of the output:

On the "ET" line is the earliest completion time of the whole project: 250 days.

The "TS" line shows which jobs are critical; they are jobs which do not have total slack.

There are many ways to present the output:

- The schedule in job sequence:

JOB NO. 1345, PROJECT NO. 0760 *** EARLY START *** 27 SEP 196 PAGE 2

WORK ITEM	DESCRIPTION	DURATN	REMAIN DURATN	PC	CAL HR	S	FC D	EARLY START	LATE START	EARLY FINISH	LATE FINISH	TOTAL SLACK	FREE SLACK
00134003	EXCAV + 36 IN. RCP N F	3.0	3.0		10	1	5	6OCT64	7FEB66	9OCT64	11FEB66	265.9	LAG
00132003	EXCAV 18 + 24 IN. RCP N FRO	3.0	2.9	5	10	1	5	A	11SEP64	9OCT64	14FEB66	266.2	LAG
00127001	LOAD + HAUL BROKEN CONC NFRD + MEDIAN	30.0	11.4	62	10	1	5	7OCT64	25JAN66	23OCT64	14FEB66	257.5	LAG
00126301	REMOVE RD CONC N FR RD	20.0	7.4	63	10	1	5	A	29JUN64	19OCT64	7FEB66	257.5	LAG
00163015	FG FORM + MESH RIPRAP CHANNEL LINING-760	3.0	3.0		10	1	5	7OCT64	7DEC64	13OCT64	15DEC64	31.1	LAG
00133003	LAY 18 + 24 IN. RCP N F	2.0	1.9	5	10	1	5	A	11SEP64	12OCT64	14FEB66	266.2	LAG
00135003	LAY + 36 RCP N F	1.0	1.0		10	1	5	12OCT64	11FEB66	12OCT64	14FEB66	265.9	LAG
00170015	P F + C RIPRAP CHANNEL LINING-760	2.0	2.0		10	1	5	12OCT64	11DEC64	14OCT64	16DEC64	31.1	LAG
00104002	CHANNEL EXCAV N FR RD + ML	3.0	3.0		10	1	5	13OCT64	16OCT64	15OCT64	21OCT64	3.6	LAG
00506002	CONST SEWER OUTFALL AT 1960	140.0	67.2	52	10	1	5	A	20JUL64	19FEB65	7DEC65	162.6	LAG
00103003	RD EXCAV N FR RD + ML	60.0	60.0		10	1	5	13OCT64	1DEC65	3FEB65	21MAR66	225.9	LAG

Fig. 11

Real calendar dates are written by the computer itself (a sub-routine can do it). When activity has already started, there is a column for "Remain duration." This form of schedule is useful, for example, for the subcontractor who reads the row which interests him.

- The schedule in bar-chart form:

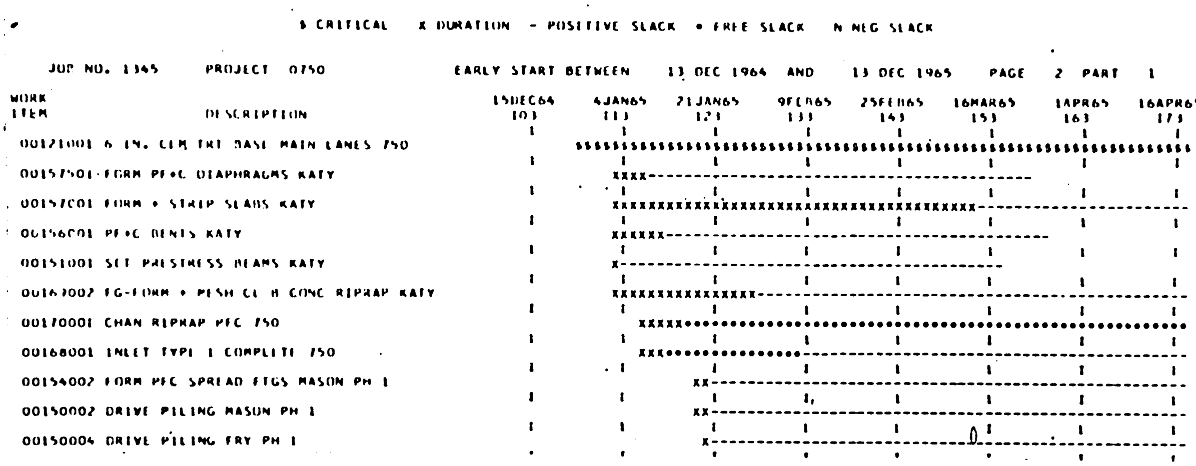


Fig. 12

This form is helpful to the foreman in planning his work; to the owner in keeping informed of project status.

IV.43 The Critical Path: A Linear Programming Formulation

To find the Critical Path, it is necessary to know the earliest occurrence time for each node. Let "Xi" represent the early occurrence time of node "i" (i=1,2,..,16). In this case, the function objective is to minimize: $X_{16}-X_1$

subject to: $X_j-X_i \geq t_{ij}$.

(t_{ij} is the duration of the activity connecting nodes "i" and "j"). Calculations can be handily done, as follows:

X_i = EARLY OCCURENCE TIME OF NODE "i"
(OR THE EARLIEST BEGINNING OF THE ACTIVITY FOLLOWING NODE "i")

FUNCTION OBJECTIVE: MINIMIZE $X_{16}-X_1$

SUBJECT TO:

$X_2-X_1 \geq 10$
$X_5-X_1 \geq 15$
$X_3-X_2 \geq 15$
$X_5-X_3 \geq 10$
$X_6-X_5 \geq 5$
$X_9-X_6 \geq 30$
$X_{11}-X_9 \geq 20$
$X_{12}-X_{11} \geq 25$
$X_{13}-X_{12} \geq 35$
$X_{14}-X_{13} \geq 40$
$X_{15}-X_{14} \geq 20$
$X_{16}-X_{15} \geq 20$
$X_{15}-X_2 \geq 2$
$X_{12}-X_2 \geq 45$
$X_4-X_3 \geq 60$
$X_8-X_4 \geq 20$
$X_{11}-X_8 \geq 5$
$X_7-X_6 \geq 4$
$X_{11}-X_7 \geq 18$
$X_{10}-X_6 \geq 5$
$X_{12}-X_{10} \geq 20$
$X_{16}-X_{12} \geq 55$

IF $X_1=0$:

THE SMALLEST VALUE PERMITTED BY CONSTRAINTS IS:

$X_2 \geq 10$	→	$X_2 = 10$
$X_5 \geq 15$		
$X_3 \geq 15$	→	$X_3 = 25$
$X_5 \geq 10$	→	$X_5 = 35$
$X_6 \geq 5$	→	$X_6 = 40$
$X_9 \geq 30$	→	$X_9 = 70$
$X_{11} \geq 20$		
$X_{12} \geq 25$	→	$X_{12} = 135$
$X_{13} \geq 35$	→	$X_{13} = 170$
$X_{14} \geq 40$	→	$X_{14} = 210$
$X_{15} \geq 20$	→	$X_{15} = 230$
$X_{16} \geq 20$	→	$X_{16} = 250$
$X_{15} \geq 2$		
$X_{12} \geq 45$		
$X_4 \geq 60$	→	$X_4 = 85$
$X_8 \geq 20$	→	$X_8 = 105$
$X_{11} \geq 5$	→	$X_{11} = 110$
$X_7 \geq 4$	→	$X_7 = 44$
$X_{11} \geq 18$		
$X_{10} \geq 5$	→	$X_{10} = 45$
$X_{12} \geq 20$		
$X_{16} \geq 55$		

△
EARLY OCCURENCE TIME FOR EACH NODE.

Fig. 13

IV.5 PERT MODEL

The Critical Path determines the minimum time required for the completion of a project represented by a network. This is no small task; there is a large amount of uncertainty in the time required for each activity, and so in the completion time of the project.

PERT takes some of these uncertainties into specific account. It assumes that the activities and their network relationship have been well defined, but it allows for uncertainties in activity times.

An example from the case study: At what date must frame erection specialists start work? What is the uncertainty of this date? From the network, Figure 4:

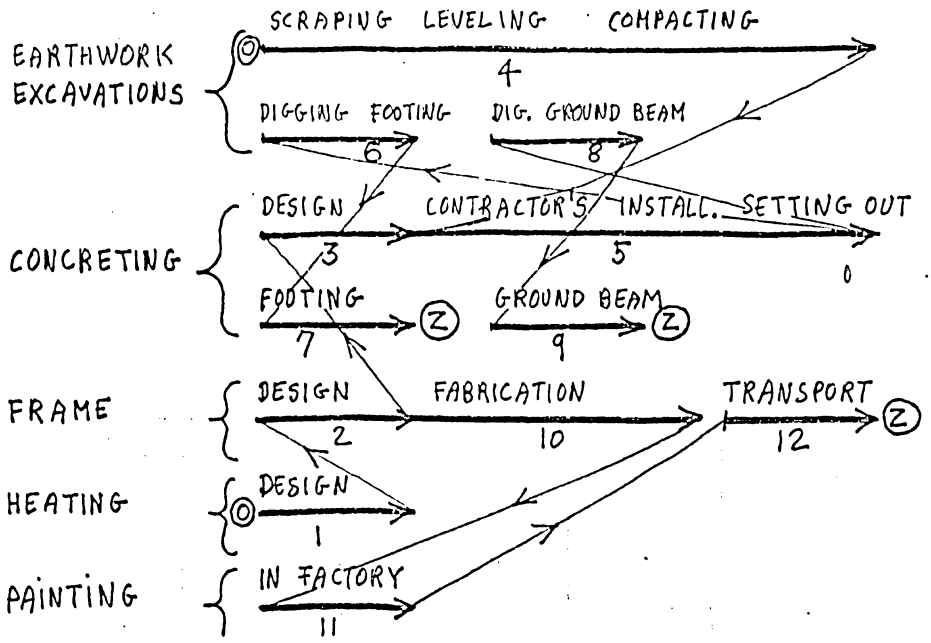


Fig. 14

Another way to represent the last diagram is the following network:

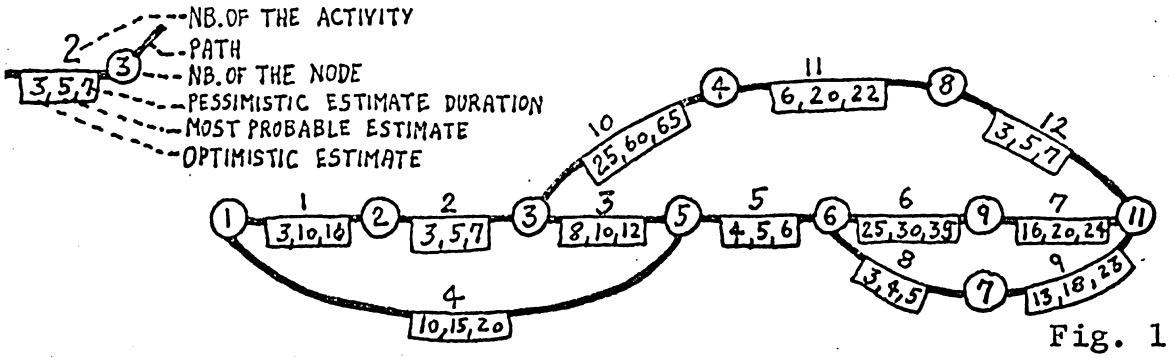


Fig. 15

The PERT procedure is:

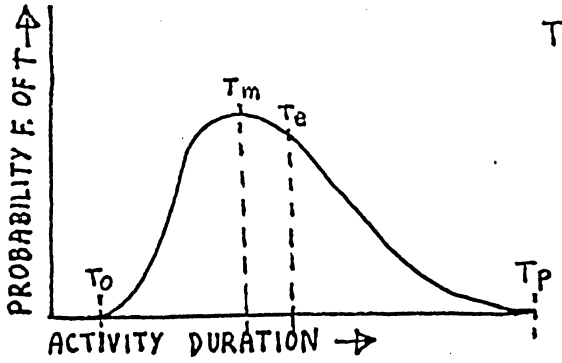
- To calculate the expected time.
- To calculate the standard deviation.
- To interpret these calculations.

PERT requires for operation not only the most probable estimated time to complete each activity, but also the pessimistic estimate and the optimistic estimate.

	NB.OF NODE	OPTIMISTIC ESTIMATE	MOST PROBABLE ESTIMATE	PESSIMISTIC ESTIMATE	EXPECTED TIME
DESIGN HEATER	1-2	3	10	11	9
DESIGN FRAM	2-3	3	5	7	5
DESIGN CONCRETE	3-5	8	10	12	10
INSTALLATION	5-6	4	5	6	5
DIGGING FOOTING	6-9	25	30	35	30
CONCRETE FOOTING	9-11	16	20	24	20
FABRIC. FRAM	3-4	25	60	65	55
PAINTING FRAM	4-8	6	20	22	18
TRANSPORT.FRAM	8-11	3	5	7	5
EARTH WORK	1-5	10	25	20	15
DIGGING BEAM	6-7	3	4	5	4
CONCRETE BEAM	7-11	13	18	23	18

Fig. 16

The expected duration for each activity is calculated according to the following statistical formulation:



$$Te = \frac{To + 4Tm + Te}{6}$$

T_o = OPTIMISTIC ESTIMATE
T_m = MOST PROBABLE ESTIMATE
T_e = EXPECTED TIME
T_p = PESSIMISTIC ESTIMATE

Fig. 17

The Critical Path, calculated from the expected time of each activity is: 1-2-3-4-8-11. The expected time of the "Critical Path" is the sum of the expected time of each activity on the Critical Path. This is then the expected time for the project. The standard deviation calculation is: $S_d = \frac{t_p - t_o}{6}$

with: t_p = Pessimistic estimate

t_o = Optimistic estimate

For the case study expected time and standard deviation are shown in the following figure:

	OPTIMISTIC ESTIMATE	MOST PROBABLE ESTIMATE	PESSIMISTIC ESTIMATE	EXPECTED TIME	STANDARD DEVIATION	VARIANCE
DESIGN HEATER	3	10	11	9	≃1	≃1
DESIGN FRAM	3	5	7	5	≃1	≃1
FABRICATION FRAM	25	60	65	55	7	49
PAINTING FRAM	6	20	22	18	3	9
TRANSPORT. FRAM	3	5	7	5	0	0
				92	≃8	60

EXPECTED LENGTH OF THE CRITICAL PATH

S.D. OF THE CRITICAL PATH

Fig. 18

The date at which the frame erection specialists must start work is found as follows:

- The most probable date: 100 days
- The expected date : 92 days
- The standard deviation: 8 days

Which means there is a 68% probability[36] for the project to be done between 84 and 100 days (84=92-2 and 100=92-8), and a 95% probability for the project to be done between 76 and 108 days (76=92-(8x2) and 108=92-(8x2))

IV.6 CPM MODEL

Critical Path gives the minimum time required for the completion of a project, and PERT gives the probability. CPM evaluates the job cost/job-time trade off. CPM measures the relationship between more resources to shorten a job and the increased cost of these additional resources.

Concerning costs:

- Direct costs are associated with jobs: Jobs can be reduced in duration if extra resources are assigned to them. (When duration cannot be further reduced, it is called "crash time").
- Indirect costs are: managerial services, equipment rentals, indirect supplies, and so forth. They are affected by the length of a project; when the project is reduced in duration, these expenses are lower. The following figure gives a simplified idea of the relationship between direct and indirect cost of a project:

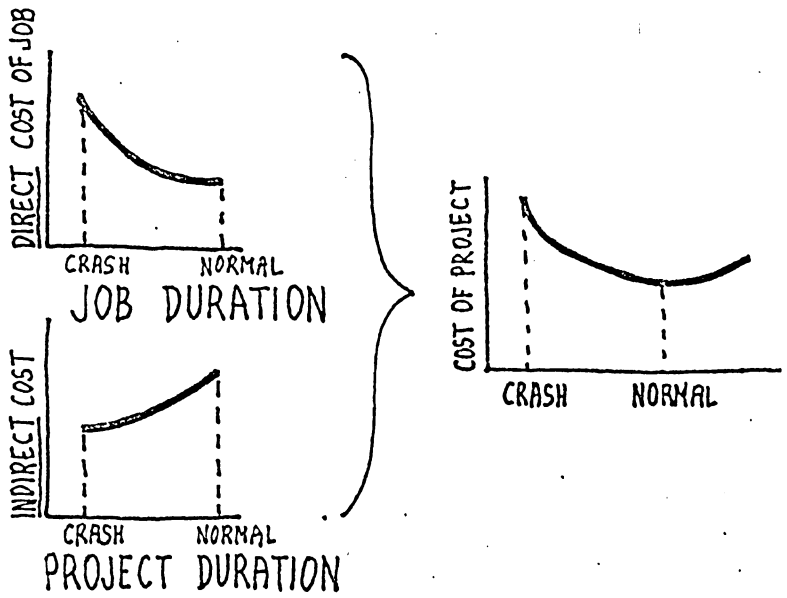


Fig. 19

From the case study: At what date should the yard shed be erected so that all activities to be accomplished before will be done in the cheapest way?

According to the diagram of Fig. 5:

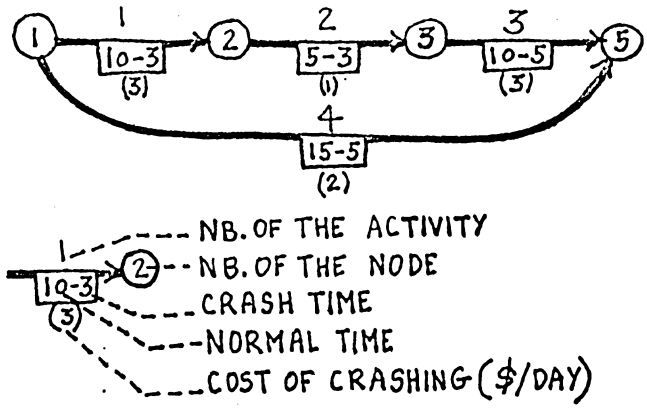


Fig. 20

To simplify the problem, functions are assumed to be linear (Curves of the graphs may be approximated with straight lines). The trade off between direct costs and the time for activities is as follows:

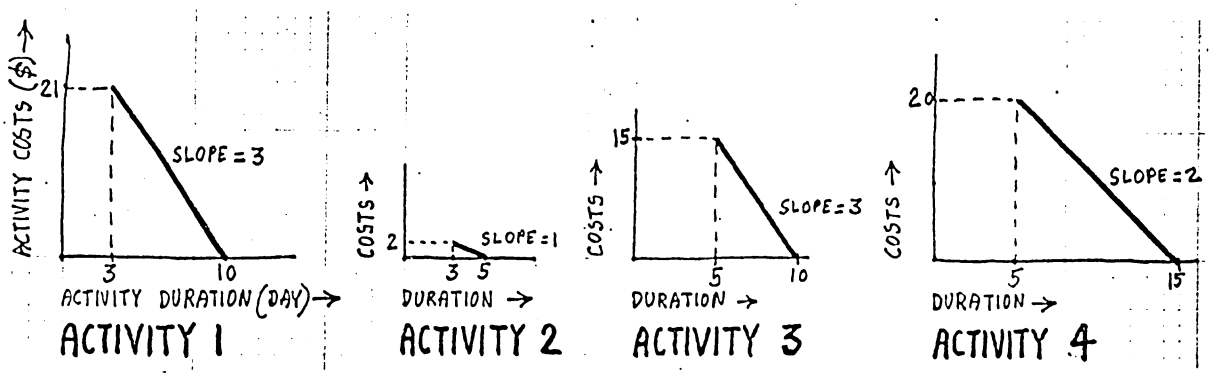
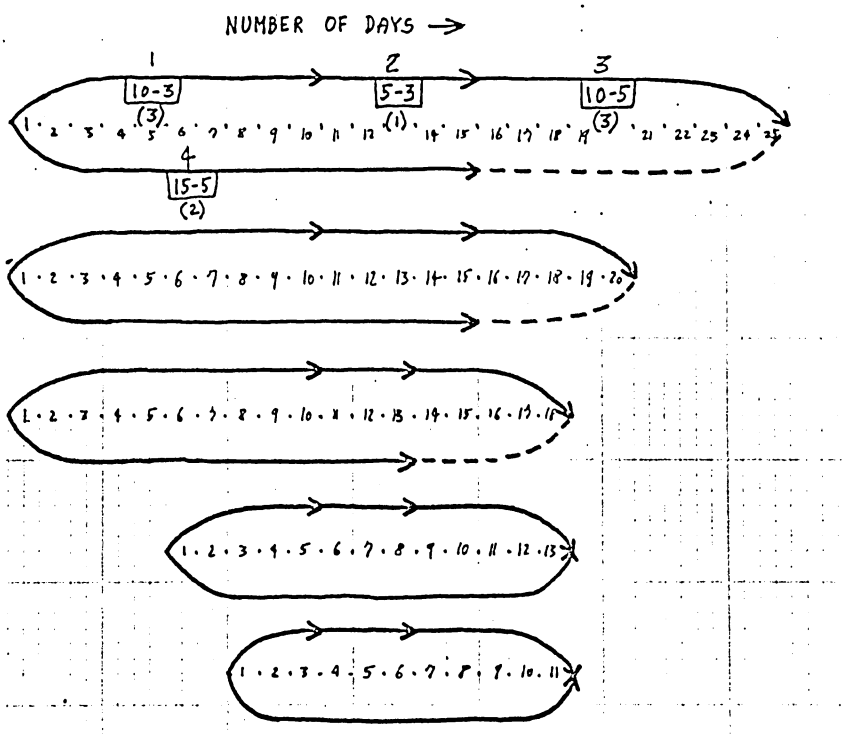


Fig. 21

We assume that indirect overhead costs of the project are increasing at "4" unit costs every day.

To find the optimum schedule, the step-by-step method of CPM starts with all activity at normal duration time. The Critical Path then is: 1-2-3, which is 25 days long. If the base cost of the activities is ignored, the cost of this schedule is 100 units (100=25X4).

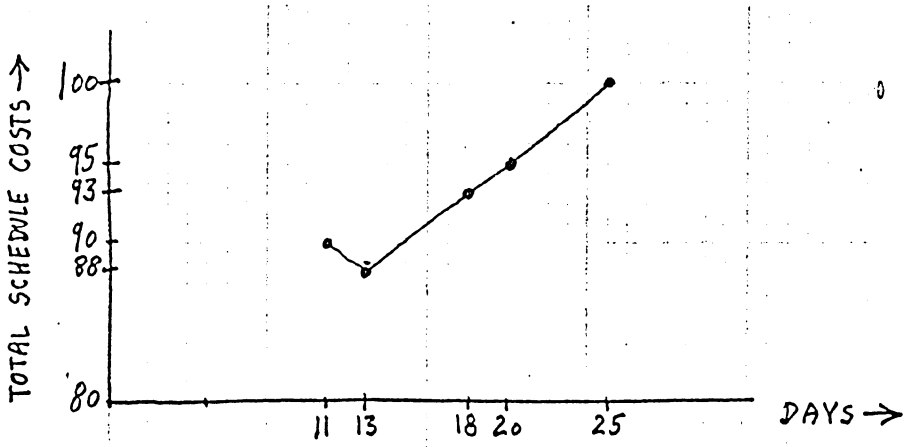
To shorten the schedule, activity 3 can be crashed for five days at three units-cost-day. Because the path is now only twenty days, the schedule now is 95 units. As duration is decreased, total cost decreases, then bottoms, then increases. The following diagram describes these steps:



COST OF CRASHING	OVERHEAD COSTS	TOTAL COST
0 +	25x4 =	100
5x3 +	20x4 =	95
(5x3)+(2x2) +(2x1)+	18x4 =	93
(5x3)+(2x2) +(2x1)+(5x3)	13x4 =	88
(7x3)+(4x2) +(2+1)+(5x3)	11x4 =	90

Fig. 22

Combining all of the results of Figure 22 in a graph showing how project length affects total schedule costs, the following curve is obtained:



PROJECT COST-TIME CURVE

Fig. 23

The yard shed should be erected by the 88th day from the beginning of the project, if all the previous activities are to be accomplished in the cheapest way.

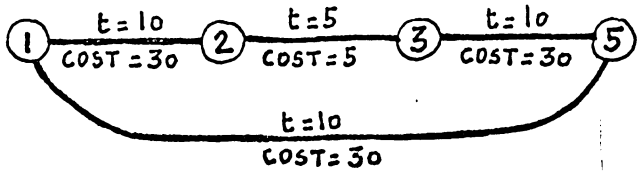
A project with several hundred activities would present an impossible task for this manual technique, so more sophisticated techniques must be used, combined with the computational power of the modern electric computer.
According to J. J. Moder,[37] more than sixty CPM programs are existant, and most of them are using a linear programming model.

IV.7 NETWORK COST SYSTEM (or PERT/cost Control)

The techniques described in previous pages are essentially time oriented. With these techniques, if the cost of jobs is taken into account, it is only to find the duration of the project so that costs will be minimized.

But decision makers are concerned with activity costs as well as with elapsed activity times. "Network Cost System" has this purpose: it shows what the time pattern of expenditures will be for a project.

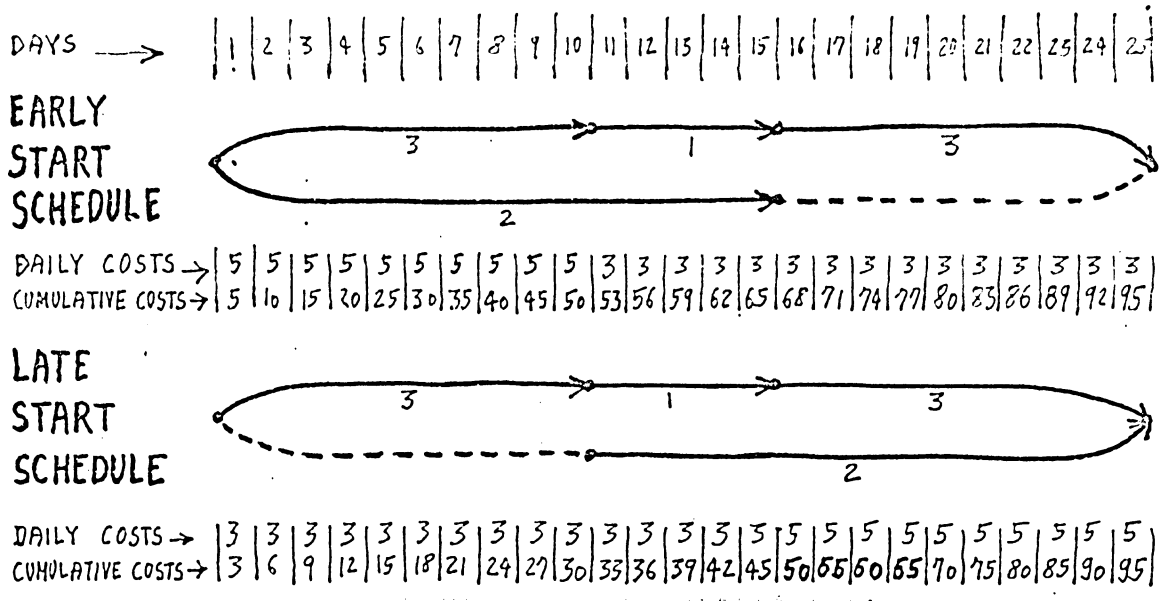
Again from the case study: The assumption is made that expenditures for an activity are incurred at a constant rate over the duration of the activity:



ACTIVITY	DURATION (DAY)	EARLY START	LATE START	TOTAL COST	COST PER DAY
1,2	10	0	0	30	3
2,3	5	10	10	5	1
3,5	10	15	15	30	3
1,5	15	0	10	30	2

Fig. 24

A day-by-day summary of cost requirements is calculated for both early and late start schedules from the following network which is a schedule graph plotted on a time scale:



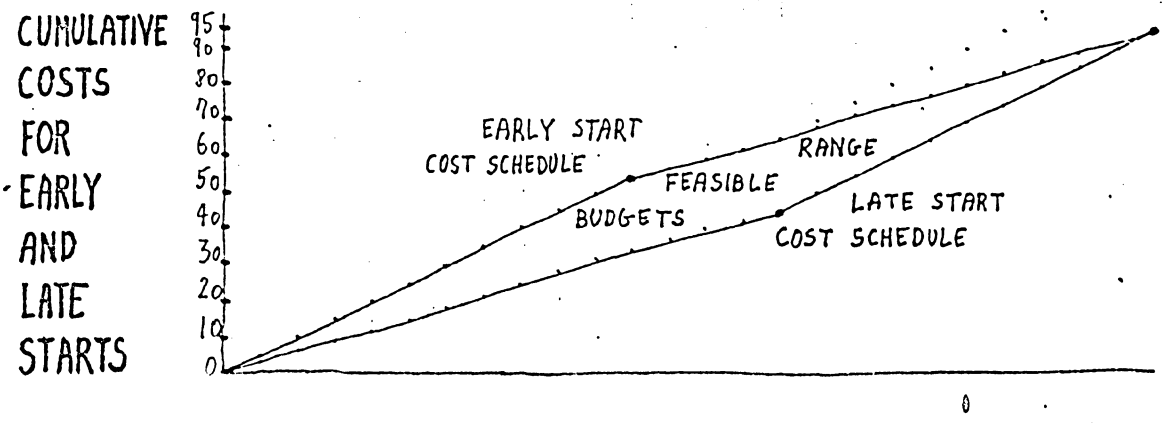


Fig. 25

The last graph illustrates graphically the budget implications of the early and late start schedule. The area between the two curves represents a range of feasible budgets.

This technique can be used not only for budgets, but also for resource and equipment requirements. The following example shows the cumulative number of barrels of cement required for a project on a weekly basis.[38]

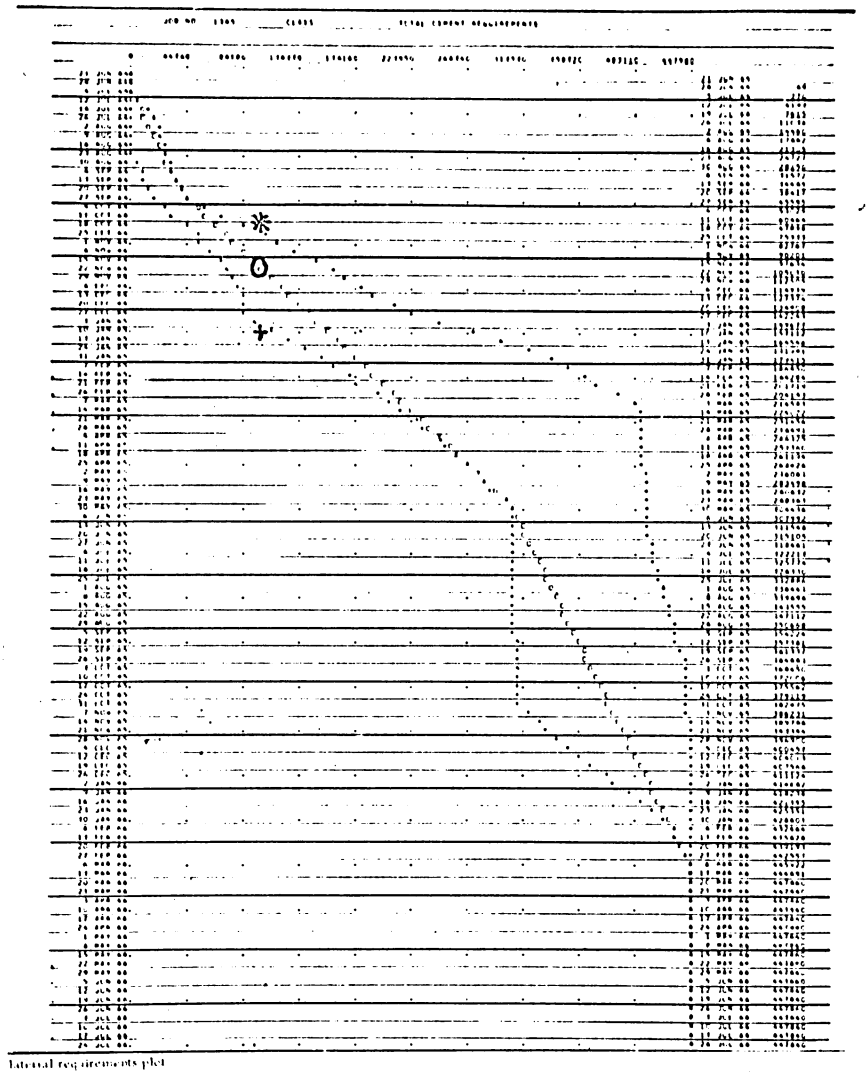


Fig. 26

The plot represented by the symbol "+" is indicative of the effect of all items starting at the earliest start time. The plot using the symbol "*" represents the effect of items starting at the latest start time. The plot using the letter "o" represents the target, based upon the application of a

mathematical smoothing technique. With this technique, it is not difficult to:

- Compare actual costs with budgeted costs.
- Compare work scheduled with work accomplished.

Hence useful graphic reports can answer three questions:

- Is the project on schedule?
- When is the expected completion time?
- How far over budget are present costs?
- What are the sources of delay and cost overruns?
- Is a particular activity in trouble, or is some departmental problem affecting several activities?

M.B. ZACHRY COMPANY — MONTHLY JOB COST SUMMARY — 30 JUNE 196 — JOB 2400 BROOME COUNTY HWY.

DESCRIPTION	PERCENT ACTUAL TO ESTIMATED COST	TOTAL COST STATUS ESTIMATE	ACTUAL	VARIANCE	DIRECT COST STATUS ESTIMATE	ACTUAL	VARIANCE	INDIRECT COST STATUS ESTIMATE	ACTUAL	VARIANCE	MAN HOURS ACTUAL	AVERAGE HOURLY COST
CURRENT MONTH												
LABOR	86 %	21566	18414	3152	15216	13764	1452	6350	4650	1700	5670	3.25
EQUIP.	119	38482	45660	7278-	28617	29875	1258-	9865	15785	5920-		
MATL.	114	17500	20076	2576-	17125	20076	2951-	375		375		
SUB-CON.	75	6000	4500	1500	6000	4500	1500					
SUP-SUN.	102	14695	15070	375-	13995	14520	525-	700	550	150		
TOTAL	105 %	98243	103720	5477-	80953	82735	1782-	17290	20985	3695-		
JOB TO-DATE												
LABOR	110 %	151382	166822	15440-	121134	132062	10929-	30248	34760	4512-	44705	3.97
EQUIP.	121	177783	215447	37664-	147764	157871	10107-	30019	57575	27556-		
MATL.	90	90500	81916	8584	85500	80266	5234	5000	1650	3350		
SUB-CON.	83	12000	10000	2000	12000	10000	2000					
SUP-SUN.	98	67000	65750	1250	59000	59750	750-	8000	6000	2000		
TOTAL	108 %	498655	539935	41270-	425398	449949	14552-	73267	99985	26718-		
PLUS WORK DONE FOR OTHERS			9675									
INVENTORIES			716									
GRAND TOTAL EXPENDITURES			550326									

COST TRENDS	LABOR	EQUIP.	MATL.	SUB-CON.	SUP-SUN.	TOTAL	CUMULATIVE TO-DATE
THIS MONTH	86 %	119 %	114 %	75 %	102 %	105 %	108 %
LAST MONTH	110	119	85	83	111	108	106
TWO MONTHS	106	117	87	85	96	109	107
THREE MONTHS	109	140	50	87	87	107	105
FOUR MONTHS	107	112	65	90	87	101	102

TOT. CRITICAL PATH CALENDAR DAYS	490
TOT. C.P. CALENDAR DAYS TO-DATE	140
PERCENT C.P. CALENDAR DAYS USED	29%
TOT. WORKING DAYS TO-DATE	120
PERCENT COMPLETE	26%

ORIG. EST. COMPL. DATE 03 JUN 196
REV. EST. COMPL. DATE 22 JUN 196

Fig. 27

IV.8 THE USER'S OPINIONS

The following is a sample of comments made by construction men who have used sequencing techniques with various degrees of sophistication in a wide range of projects:[39]

- I made up the arrow diagram on the job.
  I don't consider it as "law," only as a tool.
  It is a very good tool, but only as good as the man who makes it up, in that it is a direct reflection of his knowledge, experience and familiarity with the work at hand.
  It is very useful scheduling materials.
- Controllability of a job is a very important consideration. If a job can't be fully controlled because of its inherent characteristics, a lot of detailed scheduling is a waste of time.
  CPM is a big help in showing the owner how an impediment affects your work.
- Acceptance by field personnel is a big problem. They are afraid of change.
- Using CPM with time cost data has helped us, but our major saving came from building the model. We have found that ideas derived from seeing how the project fits together are our major saving. We saved forty days on one project via a single idea brought out during modelling.
- Accurate estimates are important. CPM programs are

dumb, just like a slide rule. It just knows what you tell it.

- We spent a lot of time making up a diagram with only time estimates. We spent a terrific amount of time revising our diagram until we finally quit using CPM altogether.

From the preceding opinions, the practice of "Sequencing techniques" shows us the need for: education, judicious application, easier access to date required to use the full CPM or PERT package, computer assistance, participation at appropriate levels, and overall flexibility.

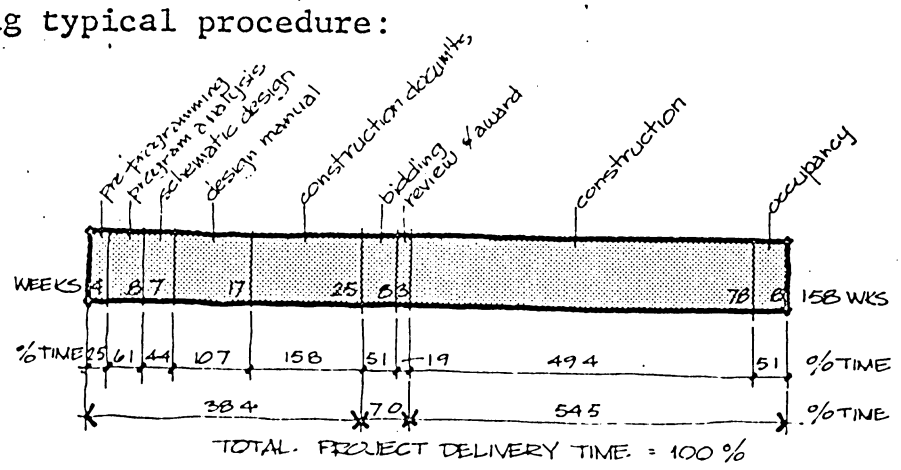
The more these conditions are met, the more powerful will be these techniques as tools for decision making. We know that the basic functions of management decision making are Planning, Scheduling and Control. These techniques are useful at all stages: Scheduling and Control, but also Planning.

Planners must specify not only all activities to complete a project, but also their technological dependencies. Network calculations lay out clearly the implications of these interdependencies and help the planners find problems that might otherwise be overlooked in large projects.

IV.9 FAST TRACK

Prior examples are from construction scheduling. "Fast Track," however, is an interesting example of an attempt at sequencing the whole building activity, including design.

Traditional tasks and relationship among the participants involved in construction are distributed according to the following typical procedure:



Health & Physical Education Building
Brockport Campus. SUNY

Fig. 28

Sequencing techniques can be used to program, schedule and control this traditional procedure, but a new network can be set up according to the following scheme:

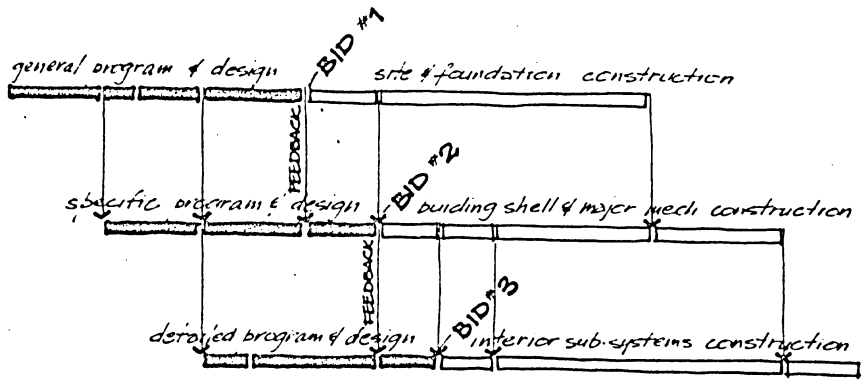


Fig. 29

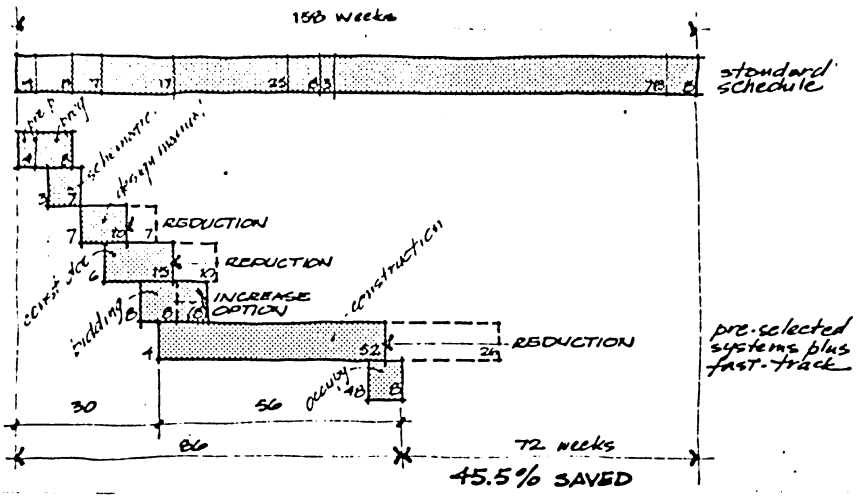


Fig. 30

The following explanations are from the brochure: "Fast Track and Other Procedures."[40]

The key is in dividing the overall project into several categories or hierarchies of detail. Basic design decisions are made from general criteria; more detailed design decisions are made from more detailed information. These levels of decisions generate a phased construction sequence and bidding. If bidding on separate parts of a project can be implemented, construction can begin at a date well ahead of the traditional one. By developing a procedure which permits more men to work on different phases of a project concurrently, the overall time to accomplish the task is shortened. Because there are obviously minimum limits to which any single schedule can be compressed, overall time expended can be reduced sharply by overlapping tasks.

In the conclusion, it is said that a 25% reduction can be achieved in project delivery time with fast track scheduling, and even 45% if activities duration can be reduced.

In addition to an appreciable saving of time, there are a number of important benefits from overlapping the phases of a project:

Design

Most projects suffer an unfortunate break between design and working drawing when the project passes from one team to another. As specialization within the profession increases, this characteristic will be amplified. However, in an overlapping process, it is possible for both the design and the construction documents teams to work together in a continuous and integrated manner, rather than in separately staged pieces of work. More importantly, in this process, the design team continues to work on the project after construction begins. There is continuous opportunity for important feedback from design decisions.

Cost Control

Since bids can be done independently over a period of time, it is possible to do some fine tuning, adjusting the design to available funds.

Manpower Leveling

With overlapping processes, projects need not have extreme peaks and valleys of manpower demands within architects' offices. It is possible to put together smaller teams to do bigger projects. This provides not only greater continuity,

fewer "Charettes," and less job-hopping, but also allows the client to benefit from more economical operation of the project.

Technological Changes

Because processes are overlapped, design decisions can be made much closer to the time when they are needed in the field. This deferment until just before construction can provide a far more sensitive response to technological innovation.

V. CONCLUSION

The first motivation of this study was to analyze management tools which could be effective in smoothing complex passages from theory to practice. O.R. techniques were described for this purpose. Fully detailed, O.R. techniques were shown to be useful not only for solving management problems, but also for solving many problems arising at all the levels of the construction process. This statement was made considering O.R. capabability to solve specific problems; we conclude that the O.R. view point is applicable as well to the tasks and interrelationships of the participants in the construction process.

But these tasks are difficult to define because of the gap between professional title and function to be performed which seems to grow wider and wider:

- Law in code form imposes design and technology solutions.
- The Architect makes but a few of the design decisions.
- The Contractor is limited in the exercise of his task of deciding how to built a project.

The general term "decision maker" is perhaps more accurate than professional titles.

A decision is a resolution of alternative choices. Today, in the construction sector, the "dedision maker" has to provide formally, functionnaly, and economically optimal solutions. Since problems are growing in number, kind and complexity, since there are more constraints, and since resources are not unlimited, the decision maker must not

only find optimal solutions but must also provide services to reach these findings; he must be involved in the solving of the problem as well as the statement of the problem.

With an historical viewpoint, Stuart Chase[41] has described ways to approach problem solving:

1. Appeal to the supernatural.
2. Appeal to the wordly authority (The older the better).
3. Intuition.
4. Common sense.
5. Pure logic.
6. Scientific method.

It is interesting to project this classification into the history of construction:

1. The biggest builders in the antique civilizations were "Grands pretres" (Pyramides, temples, etc. . .)
2. Gothic cathedrals were built by "Compagnonnages". Among those workers the oldest was "le Chef" or master builder.
3. The "Beaux Arts" Architect's intuition has been preponderant for a long time.
4. Indian villages, Arabic Medina and Medieval towns, to day admired and sometimes copied, were built without central direction.
5. Nineteenth century workers or miner's villages composed of parallel and identical houses were designed with a dry logical mind.

6. Scientific method is the classification given by Chase beyond these five.

In the second chapter, the application of "Scientific method" was defined as process whereby it is necessary to identify the problem, to abstract its essence and to establish objectives to be fulfilled. When this is achieved, a model is derived with the assumption that such a model is an accurate representation of the real world. The model is then tested, verified, modified or rejeted within a feed-back process.

Unfortunately, in construction it seems impossible to develop a model that adequately reflects reality. The construction process is so complex that it does not permit mathematical representation in a feasible model. All that can be done now is to apply available techniques, as we have seen in this study, to a piece of the whole: to components or subsystems of the construction process. These techniques must not only use the already traditional methods but also apply other means which look feasible for research in optimality. O.R. techniques are in the mainstream of this new direction.

O.R. applied in the construction field implies a break with traditions in approaching problems: it encourages the development of interdisciplinary teams; it applies scientific methods; it forces a search for new means in the quest for the optimum in quality, cost and time.

This idea has already been proved in sectors other than construction; from these a great deal of experience can be gained by decision makers involved in construction. management is the process by which disorganized resources are organized into a total system for objectives accomplishment; we hope this study has confirmed the imperative that "The remedy for the inefficiency in most all of our daily acts lies in systematic management rather than in searching for some unusual or extraordinary man."[42]

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4. Ex: The TRW civil system program: an integrated application of the life and physical sciences.
"Architects are trained in creative problem solving; they should start applying this ability to things totally different from structures, to subsystems and networks."
5. Ibid: "A manager's guide to Operations Research," p. 35.
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9. There are two basic types of large scale system simulation:

   1 - The decision making process is programmed into the simulation in order that the entire system may be run automatically without involvement of human decision makers. (System simulation)

   2 - It requires recurrent decisions on the part of outside decision makers. (Gaming)

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