AN INTEGRATED OPTIMAL DESIGN PROCESS FOR A MANUFACTURING PLANT

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Alfred Tit Yu Chan

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AN INTEGRATED OPTIMAL DESIGN PROCESS

FOR A MANUFACTURING PLANT

Approved:

Paul S. Jones, Chairman

Donovan Young

James M. Apple

Date approved by Chairman: 5/26/75

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SUMMARY

The objective of this study was to develop a design process integrating the decisions that establish the major characteristics of a manufacturing plant. The problem of initiating a new branch plant was attacked. It was assumed that only one plant was built. Decisions on the following factors were studied:

1. Plant location.
2. Capacity.
3. Distribution pattern.
4. Number of manufacturing equipment.
5. Number and type of materials handling equipment.
6. Floor area.
7. Plant layout.

This study was intended to provide the user of the process with a set of optimal design parameters that include the above factors, rather than sub-optimal solutions for individual factors which often results if the factors are analyzed separately.

An operations research model including all interrelationships and individual constraints among the aforesaid factors was developed. The method of solution was based on the decomposition principle. The model was decomposed into a master program and three subprograms. The subprograms consisted of a plant location selection program, an equipment selection program, and a plant layout program. The master program integrated the subprograms recognizing cost interrelationships.

Specific factors observed in the data collection process were organized into a step-by-step application procedure. A computer program was developed to solve the model and tested on sample problems.

It was concluded that if the capacity of the branch plant to be established is predetermined, the process will guarantee near-optimal solution. If the capacity of the branch plant is not predetermined, the process can serve as a tool to investigate the influence of capacity on the cost structure. Once the capacity is determined, a final run with the specified capacity will then give the set of near-optimal solutions.

CHAPTER I

INTRODUCTION

Background

Many important decisions establish the structure of a manufacturing plant. A few of these are plant location, capacity, size, type and number of manufacturing machines and material handling equipment, and facility layout.

A vast number of quantitative methods have been derived to help the user to obtain an optimal or near optimal decision under a set of specific assumptions. However, each of the above mentioned decisions has been studied mostly on an individual basis. The decisions are generally highly dependent on each other. A decision is often made on the basis of other decisions while the resulting decisions also serve as an information input for the other decisions. Under these circumstances, a set of optimal decisions obtained from individual optimization methods does not necessarily represent an optimal solution to the system. (The system is defined as the set of plants, markets, manufacturing equipment, handling equipment, the layout and interrelationships among them.)

The purpose of this study is to build a quantitative model integrating the decisions on plant location, capacity, size, type and number of manufacturing equipment and materials handling equipment, and layout. The model should include all cost functions as well as interrelational and individual constraints among the factors affecting the aforesaid decisions. It should allow the user to obtain a set of optimal solutions referring to the entire system rather than sub-optimal solutions for individual components of the system.

The Problem

Assume a firm has several plants operating in different locations. For simplicity, assume it to be a single-product manufacturing firm with markets distributed over a large area and a total demand exceeding the total output of existing plants. A forecast of the demand over a long-term planning period, e.g., 10 years, is obtained. A new plant is to be built in order to have the supply meet the forecast demand. Decisions to be made include the following:

1. Plant location.
2. Capacity.
3. Distribution pattern.
4. Number of manufacturing equipment.
5. Number and type of materials handling equipment.
6. Floor area.
7. Plant layout.

The traditional way of solving the above problem is to isolate each sub-problem and try to get an optimal solution for each using mathematical equations or operations research models together with available data. A typical approach would be solve problems 1, 2, and 3 with a mixed integer programming model, 4 and 5 with mathematical functions depending on the capacity of the new plant, 6 with an equipment selection model, and 7 with a computerized plant layout program. Unfortunately, optimizing items separately does not necessarily give an optimal solution to the system problem. To illustrate this, consider this simplified example. Suppose the operating costs per month of three types of equipment at three different locations are represented by the matrix below:

		location 1	2	3
	A	70	80	90
equipment	B	88	78	98
	C	94	84	74

When the location with the minimum operating cost is to be selected, the type of equipment used has to be predetermined. However, different predetermined equipment yields different results. Locations 1, 2, 3 will be selected if equipments A, B, C are used respectively. A similar situation occurs when equipment selection is performed with predetermined locations. The ideal method is to compare the costs under every combination of equipment and location. This is possible for very small-scale simple problems. As the number of locations and equipment types to be considered becomes larger, this becomes impractical. Furthermore, in obtaining a solution for the entire system, the process of comparing results under combinations of all the factors is highly impractical even for small-scale problems.

The above mentioned problem suggests the need for a model from which an optimal set of solutions to the system can be obtained with minimal effort. The model developed for this purpose in this study will be referred to as Integrated Optimal Design Process (IODP).

Approach to the Problem

The seven factors, which establish the structure of a manufacturing plant, are the basic subjects of this study. When the factors are considered individually, the solution procedures include solving a location selection problem, an equipment selection problem, and a layout problem. Table 1 shows how the factors are classified.

Table 1. Classification of the Factors

Name of Problem	Factors Considered Directly	Factors Considered Indirectly
Location Selection	(1) Plant Location (3) Distribution Pattern	(2) Capacity (4) Number of Manufacturing Equipment (6) Floor Area
Equipment Selection	(5) Number and Types of Materials Handling Equipment	
Plant Layout	(7) Plant Layout	

Consideration of the factors indirectly means that the factors are obtained from mathematical equations associated with the direct solution of the problem.

Since there have been so many powerful methods developed for solving these problems, constructing a completely new model without using the available solution methods would be far from practical. With this in mind, the procedure followed in this study has been:

1. To select the appropriate location selection, equipment selection and plant layout methods.
2. To identify all the interrelationships among the factors considered.
3. To put all the above together into a single model and to develop the solution procedure.

Step 1 was accomplished as a result of a literature survey. Available models, with the greatest compatibility with other models in the system, were selected. Step 2 was accomplished through an analysis of the input and output structure of the selected models. The interrelationships identified are basically transfer functions, by which output from one model is transferred to input to the other models.

The decomposition principle developed by Dantzig and Wolfe (8)* provided the insight to develop the solution procedure for Step 3. The decomposition principle solves the problem by iterating through an alternate sequence of master program and subprograms. By solving a master program, a set of prices are generated which are fed into the subprograms. The subprograms which optimize their relative objective functions over specific sets of constraints are solved, generating new points. These points are fed into the master program to update the price vectors, which are in turn fed into the subprograms.

Utilizing the decomposition principle, the location selection model, the equipment selection model, and the layout model were treated

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* All literature references are listed in the bibliography.

as subprograms while the interrelationships among them made up the master program. Figure 1 illustrates the general structure of the IODP.

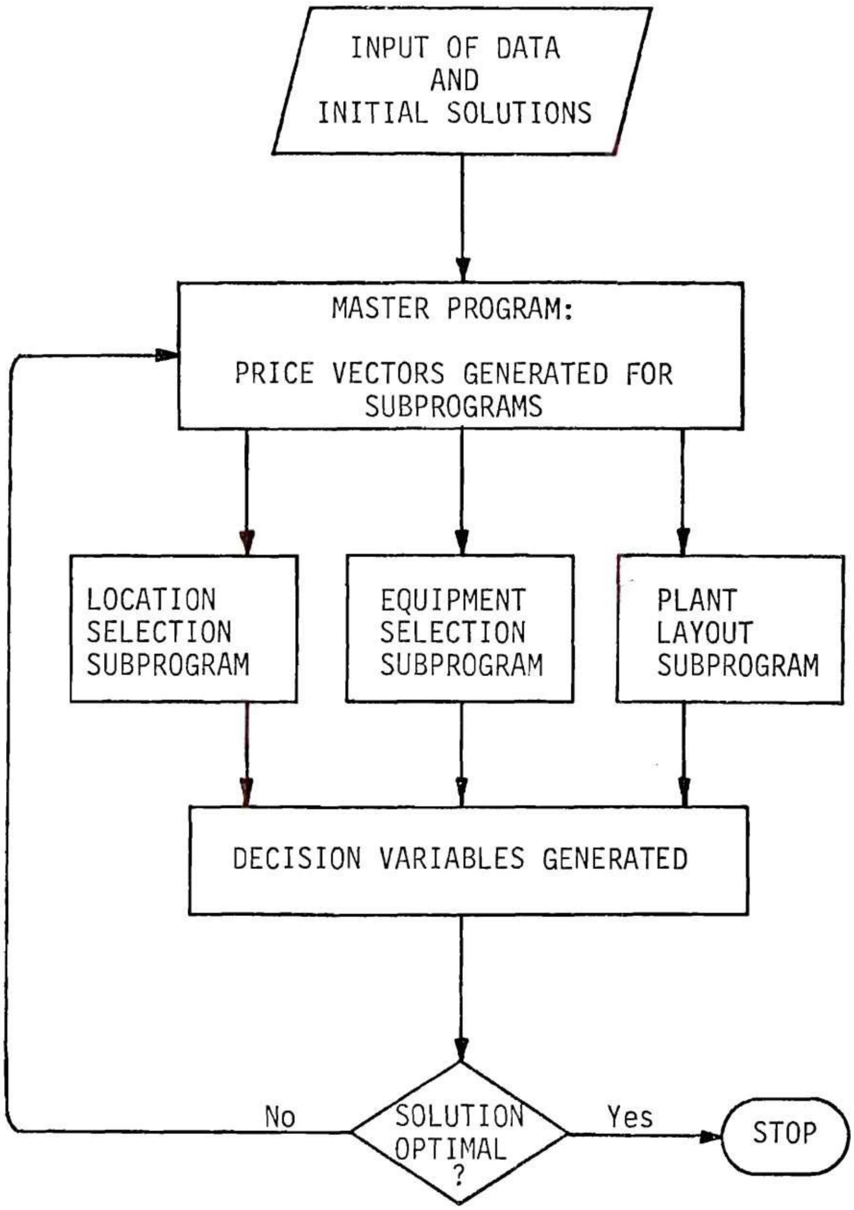


Figure 1. General Structure of the IODP

CHAPTER II

LITERATURE SURVEY

Location Selection Model

Problems in location analysis can be categorized into (1) location on a plane, and (2) location on a network. Location on a plane is characterized by an infinite solution space while location on a network has a solution space consisting of points on the network.

Revelle, Marks and Liebman (27) further classified location models into private sector models and public sector models. Private sector models are those in which the total cost of transportation and operating facilities is isolated as the objective to be minimized. Public sector models are problems with the dilimma that goals, objectives and constraints are no longer easily quantifiable, nor are they even necessarily commensurate nor easily defined.

The location model in this study selects a plant site from among a finite number of feasible locations based on obtainable cost data on transportation and operating the facilities, and is thus a private sector model on a network. A survey was made of research devoted to solve problems in this specific category.

Revelle, Marks and Liebman (27) defined the general mathematical formulation of the plant location problem as follows:

$$\text{minimize } Z = \sum_{j=1}^{n} \sum_{i=1}^{m} c_{ij}(x_{ij}) + \sum_{i=1}^{m} F_i(y_i)$$

subject to: $\sum_{j=1}^{n} x_{ij} = y_i \qquad i = 1,2,\ldots,m$

$$\sum_{i=1}^{m} x_{ij} = D_j \qquad j = 1,2,\ldots,n$$

$$x_{ij} \geq 0 \qquad i = 1,2,\ldots,m; \quad j = 1,2,\ldots,n$$

$$y_i \geq 0 \qquad i = 1,2,\ldots,m$$

where

x_{ij} = amount shipped from location i to market j ,

y_i = total amount shipped from location i ,

$C_{ij}(x_{ij})$ = cost of shipping the quantity x_{ij} from i to j ,

D_j = the demand at market j ,

n = the number of markets,

m = the number of proposed locations.

Except for the objective function, this formulation is identified as that of the classical Hitchcock transportation problem. However, since the facility function $F_i(y_i)$ is frequently nonlinear, the problem cannot be solved by linear programming. Generally, $F_i(y_i)$ includes a large fixed investment for land, equipment, utilities, etc.

A sizeable amount of research has been done to develop either an exact solution procedure or a heuristic solution procedure for the above problem. Two of the best known heuristic procedures are that of Kuehn and Hamburger (21), and Feldman, Lehrer, and Ray (14).

The Kuehn-Hamburger heuristic procedure assumes that the transportation costs are linear and that the facility cost function is in the form:

$$F_i(y_i) = a_i + b_i y_i \quad \text{, if facility exists}$$
$$= 0 \quad \text{, if it does not}$$

The procedure locates facilities one at a time until no additional facilities can be added without increasing total cost. Then the solutions are modified by evaluating the profit implications of dropping facilities or of shifting them from one location to another.

Feldman, Lehrer, and Ray (14) assume transport costs are linear and the facility cost function is a continuous concave function. The solution procedure starts by assuming all plants are assigned. Plants are then dropped one at a time until no plant can be dropped with saving achieved.

Efroymson and Ray (11) formulate the plant location problem as a mixed integer programming problem. The formulation is:

$$\text{minimize} \quad Z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} + \sum_{i=1}^{m} f_i y_i$$

$$\text{subject to:} \quad \sum_{i \in N_j} x_{ij} = 1 \, , \qquad j=1,2,\ldots,n$$

$$0 \leq \sum_{j \in P_i} x_{ij} \leq n_i y_i \, , \qquad i=1,2,\ldots,m \quad j=1,2,\ldots,n$$

$$y_i = (0,1) \quad \text{for all} \quad i$$

where

$c_{ij} = t_{ij} D_j$,

t_{ij} = the unit transportation cost from location i to market j ,

D_j = the demand at market j ,

x_{ij} = the fraction of D_j supplied from location i ,

$f_i \geq 0$ = the fixed cost associated with location i ,

y_i = 1 if the plant at location i is used, 0 if not,

m = number of possible plant locations,

n = total number of markets,

P_i = the set of markets that can be supplied by the plant at location i ,

n_i = the number of markets in P_i ,

N_j = the set of plants that can supply market j .

The solution method employed is an implicit enumeration known as branch and bound; and an exact solution is obtained.

A plant location problem frequently includes constraints on the configuration of plants. It may require that only a certain number of plants out of a given set be allowed open or closed, or that the opening or closing of one plant imply a similar or opposite action for a different plant. These side constraints are included in the Spielberg (31) formulation of the plant location problem. The algorithm employed by Spielberg is also branch and bound.

Another type of constraint that requires attention is capacity constraints. Sa´ (28) included capacity constraint but not the configuration constraint in his formulation of the problem. An exact solution method using the branch and bound treatment and an approximate routine borrowing the 'add' approach of Kuehn and Hamburger (21) and the 'drop' approach of Feldman, Lehrer and Ray (14) were developed by Sa'.

Capacity constraints were also studied by Marks (24). Marks' model allows warehouses to be considered as intermediate points between source and demand. The facility cost function is assumed to involve a fixed charge plus a linear expansion cost. The main characteristic of Marks' solution procedure is the use of Ford and Fulkerson's out-of-kilter network algorithm (15).

Ellwein and Gray (12) developed a formulation of the plant location problem including both the configuration and capacity constraints. The formulation is:

$$\text{minimize} \quad Z = \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij}x_{ij} + \sum_{i=1}^{m} g_i\Big(\sum_{j=1}^{n} x_{ij}\Big) + \sum_{i=1}^{m} f_i y_i$$

$$\text{subject to:} \quad \sum_{i=1}^{m} x_{ij} \geq b_j \qquad j=1,2,\ldots,n$$

$$\sum_{j=1}^{n} x_{ij} \leq a_i y_i \qquad i=1,2,\ldots,m$$

$$\sum_{i \in S_t} y_i \leq r_t \qquad t=1,2,\ldots,p$$

$$x_{ij} \geq 0$$

$$y_i = (0,1)$$

where

x_{ij} = amount that location i supplies to market j ,

d_{ij} = transportation cost per unit of product shipped from location i to market j ,

$g_i\left(\sum_{j=1}^{n} x_{ij}\right)$ = source variable costs,

f_i = fixed cost at location i ,

y_i = 1 if plant at location i is used, 0 if not,

b_j = demand at market j ,

a_i = capacity of plant at location i ,

S_t = a subset of the m source locations,

r_t < m , the configuration constraint.

When simplified, the objective function becomes:

$$\text{minimize} \quad \sum_{i=1}^{m} \sum_{j=1}^{n} v_{ij} x_{ij} + \sum_{i=1}^{m} f_i y_i$$

where v_{ij} = per unit variable cost.

The solution procedure utilizes an enumerative search scheme in conjunction with feasibility-optimality tests to reduce the size of the feasible set. Then for each of the small number of enumerated source configurations passed through the tests, a transportation problem is optimized to determine the minimum cost allocation.

The characteristics of the models included in this survey are summarized in Table 2.

Table 2. Characteristics of the Plant Location Models

Author	Exact Solution Procedure	Configuration Constraints	Capacity Constraints
Kuehn and Hamburger (21)	no	no	no
Feldman, Lehrer and Ray (14)	no	no	no
Efroymson and Ray (11)	yes	no	no
Spielberg (31)	yes	yes	no
Sa´ (28)	yes	no	yes
Marks (24)	yes	no	yes
Ellwein and Gray (12)	yes	yes	yes

Layout Models

Plant Layout, as defined by Apple (1), is planning and integrating the paths of the component parts of a product to obtain the most effective and economical interrelationship between men; equipment; and the movement of materials from receiving, through fabrication, to the shipment of the finished product.

This definition of plant layout clearly indicates that plant layout is directly associated with the flow of materials. Consequently, quantitative layout methods developed mostly have the objective of minimizing the material flow cost.

Early research on quantitative layout methods mainly devoted to the development of the Travel Chart. Cameron (7) used the name of From-

To Chart to replace the Travel Chart. The From-To Chart is basically a matrix summarizing numerical measure of the materials flow from one department to another.

A procedure utilizing the From-To Chart to solve process type layout problems was developed by Smith (30). Other charts similar to the From-To Chart are the Cross Chart of Farr (13) and Relationship Chart of Muther (25).

A complete procedure to utilize the From-To Chart was developed by Buffa (5). Buffa used a method called 'Sequence Analysis.' The sequence of operations is analysed from route sheets or operation sheets together with forecast data on the production of parts and data on the unit handling loads for parts. The results of the analysis are represented by (1) a 'Sequence Summary' which includes the move sequence of every part and the departmental space requirements, and (2) a summary of production and handling data including data on pieces per month, pieces per load and loads per month. Based on the above data, a load summary, which is equivalent to a From-To Chart, is constructed. This chart shows the frequency of material handling among all combinations of departments. A network diagram is then constructed with nodes representing departments and arcs representing the relative value obtained from the chart. A trial and error procedure is then carried out to rearrange the departments such that departments having material handling relationships are arranged adjacent to each other. The major disadvantage of using the above procedure is that in obtaining an ideal schematic diagram, the differences in departmental area requirements are disregarded.

As the layout problem becomes large in scale, computerized layout programs are often considered to be more efficient than traditional methods. The Computerized Relative Allocation of Facilities Technique developed by Buffa and Armour and Vollman (3,6) is the first computer model widely accepted. The program requires input of the following data:

1. Interdepartmental flow per time unit.
2. Unit load material handling cost per unit distance.
3. An initial layout.

The objective is to minimize the total material handling cost calculated from the distances, the volume flow, and the handling cost between each pair of the departments. The algorithm tests possible exchanges of departments and makes the exchange.

Seehof, Evans, Fredricks and Quigley (29) developed the Automated Layout DEsign Program (ALDEP) which can generate initial layouts of up to three floors. It requires the following input data:

1. Building description.
2. Departmental area requirements.
3. Departmental preference matrix.
4. Preassignment list of the departments to specific floors or locations.

The program generates layouts independently for each floor by a random selection technique. The objective is to generate layouts allowing the departments with the highest priority relationships to be placed adjacent to each other.

COmputerized RElationship LAyout Planning (CORELAP) developed by Lee and Moore (23) generates an initial layout based on the following input data:

1. A Relationship Chart of the Muther type (25).
2. Departmental area requirements.
3. Size of a unit block.
4. The maximal ratio of building length to width.

CORELAP uses a heuristic approach which maximizes the Total Closeness Rating (TCR) for each department. The first department placed in the layout is the one with the maximal TCR; then the rest of the departments are placed one at a time such that the department with maximum closeness rating with the previous department is selected. The placement procedure utilizes a 'sweep' routine which places the selected department closest to the previous department.

A series of studies by Gani (16), Devis (10), Klein (20), Deisenroth (9), and Apple at Georgia Institute of Technology resulted in the development of the Plant Layout Analysis aNd Evaluation Technique (PLANET). The major contribution of PLANET is the introduction of actual handling cost into the From-To Chart, which allows the generation of an initial layout that minimizes the total handling cost for the layout arrangement. The program requires the following input data:

1. Departmental area requirements.
2. Size of a unit block.
3. Priority of placement (optional).
4. Flow specification in three possible formats:
   (a) A part list including the frequency of movements, cost

per move and move sequence for every part making up a unit of product;

(b) A From-To Chart representing the cost of flow between the departments. Stating mathematically:

$$C_{ij} = \sum_{\text{all } k} c_{ijk} \quad \text{for all } i \text{ and } j$$

$$\text{and } c_{ijk} = f_k u_k d_{ij} \quad \text{for all } i, j \text{ and } k$$

where C_{ij} = total flow cost from department i to department j per time unit,

c_{ijk} = flow cost from department i to department j for part k per time unit,

f_k = frequency of movement for part k per time unit,

u_k = cost per move per 100 ft for part k,

d_{ij} = distance in 100 ft between department i and department j.

(c) A penalty matrix which causes the program to locate the departments with large penalty value close together.

The program utilizes two procedures: (1) the selection procedure, and (2) the placement procedure. Before the selection procedure starts, a Flow-Between Chart is constructed by adding the flow cost in one direction to that in the reverse direction. The program allows the user to compare results obtained from three selection methods of different approaches:

1. Selection method A -- First the pair of departments having the

highest flow-between cost is selected for placement. Then the rest of the departments are selected by taking the pair with the highest flow-between cost, where pairs are formed by combining departments in the available list with those in the placed list. Thus the size of the placement list increases while the available list reduces to zero when the layout is accomplished.

2. Selection method B -- This is similar to method A; but the department on the available list that has the highest total relationship to those departments in the layout is selected.
3. Selection method C -- By adding elements across each row of the Flow-Between Cost Chart, the 'Total Departmental Flow Between Cost' is obtained. The departments are then ranked in descending order based on these values. The order of placement then follows the ranking order.

The placement procedure utilized by the program first approximates the location of the center of the selected department along the perimeter of the existing layout. When the center is fixed, the blocks are added to the layout by a spiral or looping process in order to insure a relatively square shape.

Besides the heuristic models discussed above, mathematical programming approaches to the problem also exist in the works of Gilmore (16), and Lawler (21). However, their models are not practical owing to computational time requirements.

Equipment Selection Models

A list of items to be used in studies for machinery selection in manufacturing enterprises is suggested by Grant and Ireson (18) as follows:

- Investment
- Expected economic life in years
- Estimated salvage value at end of life
- Annual cost of taxes
- Annual cost of insurance
- Annual cost of materials
- Annual cost of direct labor
- Annual cost of indirect labor
- Annual cost of maintenance and repairs
- Annual cost of power
- Annual cost of supplies and lubricants
- Annual cost associated with space occupied

Reed (26) developed a step-by-step procedure to obtain estimates of labor costs, investment costs, and operating costs for movement, loading and unloading activities of a piece of materials handling equipment. In arriving at the costs, the following factors must be considered:

(a) Labor cost rate in dollars per man-hour.

(b) Operating cost rate in dollars per equipment-hour.

(c) Annual investment cost of the equipment, which is taken as a percentage of the initial cost.

(d) Actual working hours per year.

(e) Investment rate in dollars per equipment-hour; which is obtained by dividing item (c) by item (d).

(f) Utilization factor applied to correct for downtime of manpower and equipment.

(g) Loads per year derived from the quantity per year and the quantity per load.

(h) Hours per load, which is the sum of hours for the loaded trip, the unloaded return trip, and deadhead trips required to bring back empty containers.

(i) Annual cost of the containers used by the equipment.

Based on items (f), (g) and (h) stated above, the actual man-hours per year and equipment-hours per year are calculated. Multiplying these values by their relative cost rates represented by items (a), (b) and (e) gives annual labor costs, annual investment costs of equipment, and annual operating costs. The above mentioned observations and calculations are performed for each of the activities of movement, loading and unloading. The total of the annual costs obtained together with the annual investment costs on the containers used in the activities represents the annual equivalent cost of utilizing the piece of equipment. The equipment with the lowest annual equivalent cost is selected.

Most other work on equipment selection utilized standard discounted cash-flow procedures. The methods of transferring the cash flows of the alternatives to values on a comparable basis as summarized by Bazaraa (4), are:

1. Present worth method.

2. Final worth method.

3. Equivalent annual cost method.

4. Rate of return method.

5. Rate of return on additional investment method.

6. Adjusted rate of return on additional investment method.

Methods 1, 2, 3 and 4 are mostly used to compare mutually exclusive alternatives while method 5 and 6 can handle mixed type alternatives more effectively. Definition of the above methods can be found in most standard texts on engineering economics.

Criteria on comparison of alternatives developed generally use one of the above listed methods as the means of making final comparison. (In the case of equipment alternatives, the rate of return method cannot be applied because there is no direct return.) The main difference between criteria developed is the manner of treating the nonmonetary factors. Apple (2) developed a criterion by which a piece of equipment is selected on the basis of the value obtained from multiplying the total of direct costs, indirect costs and indeterminate costs by a weighted evaluation of intangible factors such as quality, availability, complexity, flexibility, etc.

A nine-step procedure developed by Bazaraa (4) takes the levels of mechanization into account. The levels of mechanization which best fit the given case are determined before the economic analysis is made. The pieces of equipment which do not fit into the situation are then eliminated. An economic analysis is made on the remaining pieces of equipment. The adjusted rate of return on additional investment method and/or the equivalent annual cost method is used for this purpose. The final step is to make the choice by one of the two procedures:

1. Consideration of the trade-off between economic and intangible factors, subjectively, by the materials handling engineer.
2. Construction of an indifference curve based on many other people's experience.

Since the latter method is expensive and time consuming, it is not recommended unless the equipment is very expensive.

Jones (19) has emphasized equipment compatibility in his work. Ten warehouse functions were identified. Numerical expressions for the interactions among equipment alternatives filling the different warehouse functions were developed in the framework of a queuing network analysis. These interactions allowed the construction of sets of alternatives which can satisfy all the warehouse activities. Equivalent daily costs (similar to equivalent annual cost in nature) were calculated for each set, and the least-cost set was identified.

CHAPTER III

THE INTEGRATED OPTIMAL DESIGN PROCESS

Formulation of Subprograms

Three subprograms were formulated to be utilized by the IODP. They are:

1. Location Subprogram
2. Layout Subprogram
3. Equipment Subprogram

These subprograms utilize models reviewed in the literature survey, which are able to give satisfactory solutions to the problem as stated in Chapter I, and also are able to facilitate the formulation of the master program. The formulation of the subprograms will be discussed below.

1. Location Subprogram

The location subprogram utilized in the IODP is designed to generate a distribution pattern while selecting the best location for the branch plant from a number of proposed locations. It is also assumed that there are one or more plants already existing in the system.

The structure of the problem implies that a model which includes configuration constraints on the number of plants used should be selected. Furthermore, a location model without the capacity constraints may generate a distribution pattern having the total supply from existing plants exceed their maximum capacities; thus the location model should also include the capacity constraints as well as configuration constraints.

Needless to say, as observed from Table 2, the Ellwein and Gray model is the only model that can handle both configuration and capacity constraints; and it is selected as the basis of the location subprogram in the IODP.

The objective function of the Ellwein and Gray model in its simplified form is:

$$\text{minimize} \qquad \sum_{i=1}^{m} \sum_{j=1}^{n} v_{ij} x_{ij} + \sum_{i=1}^{m} f_i y_i$$

Since the IODP has to include decisions on the utilization of manufacturing machines and materials handling equipment, cost variables relating to such activities should be introduced into the location model to insure integrity of the system. For this purpose, the per unit variable cost v_{ij} and the facility fixed cost f_i have been broken down to allow a clearer presentation of the costs involved. The formulation of the location subprogram then appears as follows:

$$\text{minimize} \quad Z_L = \sum_{i=1}^{E} \sum_{j=1}^{J} (C_{ij}+r_i)x_{ij} + \sum_{i=E+1}^{I} \sum_{j=1}^{J} (C_{ij}+p_i+h)x_{ij} \qquad \text{(L0)}$$

$$+ \sum_{i=E+1}^{I} (F_i+P_i+H_i)y_i$$

$$\text{subject to:} \quad \sum_{i=1}^{I} x_{ij} \geq D_j \qquad \text{for all } j \qquad \text{(L1)}$$

$$\sum_{j=1}^{J} x_{ij} \leq g_i y_i \qquad \text{for all } i \tag{L2}$$

$$\sum_{i=1}^{I} y_i \leq E + 1 \tag{L3}$$

$$\sum_{i=E+1}^{I} y_i \leq 1 \tag{L4}$$

$$y_i = (0,1) \qquad \text{for all } i \tag{L5}$$

$$x_{ij} \geq 0 \qquad \text{for all } i \text{ and } j \tag{L6}$$

where

E = Number of existing plants,

I = Number of plant locations including existing plants,

J = Number of markets,

C_{ij} = Cost of shipping one unit from location i to market j,

r_i = Cost of producing one unit in existing plant i,

F_i = Fixed cost per unit time of operating a plant at location i,

p_i = Cost of machining one unit at location i,

P_i = Fixed cost per unit time of machinery at location i,

h = Cost per unit time of handling one unit,

H_i = Fixed cost per unit time of materials handling at location i,

D_j = Demand at market j per unit time,

g_i = Maximum capacity allowed at location i,

x_{ij} = Amount shipped from location i to market j,

$$y_i = \begin{cases} 1 & \text{if plant is used at location } i\text{ ,} \\ 0 & \text{if not.} \end{cases}$$

Location 1 to E are assumed to be the locations of existing plants. Equations (L1) and (L2) are the demand and supply (capacity) constraints respectively. The configuration constraints are represented by equations (L3) and (L4). These two equations insure that the existing plants are included in the solution and only one location is selected from the proposed locations for the branch plant.

2. Layout Subprogram

As the IODP is complex in structure, a computerized layout program is preferred to traditional layout methods.

Since the IODP is a quantitative model, a layout program utilizing quantitative input is desirable. CRAFT program requires an initial layout as input. Preparation of this layout is too troublesome for a complex process. ALDEP program requires a preference matrix as input and uses a random selection technique. Since the construction of a preference matrix is often based on qualitative information rather than quantitative data, ALDEP program does not appear to be compatible with other subprograms in the system, and is therefore rejected. CORELAP is also rejected because the relationship chart which is used as input to the program represents qualitative ratings.

PLANET program was developed especially for the purpose of generating an initial layout for production facilities. It utilizes quantitative input data and uses actual materials handling cost between the departments as the scoring technique for the program. In every sense, it appears to be more compatible with the IODP than any other computerized layout models; and thus it is selected as the layout subprogram of the IODP.

The model can be represented mathematically as:

minimize $$Z_y = \sum_{e=1}^{k-1} \sum_{\ell \neq e}^{k} (\Delta_{e\ell} \gamma_{e\ell}) \qquad \text{(Y0)}$$

subject to $$\gamma_{e\ell} = \text{Function } (s_k, \Delta_{e\ell}) \qquad \text{(Y1)}$$

where

$\Delta_{e\ell}$ = Materials handling cost in dollars per ft. per unit time from department e to department ℓ ,

$\gamma_{e\ell}$ = Distance in ft. between department e and department ℓ ,

s_k = Area requirement in sq. ft. of department k ,

k = Number of departments.

PLANET program allows the user to compare results obtained from three alternative selection methods. However, only method C is used here in order to reduce the burden of decision making by the users of IODP. Since all of the selection methods use heuristic approaches, there is no guarantee that any of them is the best; method C is only selected at random.

3. Equipment Subprogram

As already pointed out in the literature survey, the criteria developed differ mostly only in their methods of utilizing the intangible factors to modify the cost factors. An economic analysis is included in any of the criteria developed. The equivalent annual cost method has been observed to be the most widely accepted method in equipment selection models. This method has also appeared to be the most appropriate method to be used in the IODP. Actually, the equivalent annual cost has already been applied in the development of the location subprogram when the cost factors F_i , P_i , and H_i are expressed in dollars per unit time.

Since only quantitative factors are considered in this study, the equipment subprogram will only utilize the costs associated with the equipment. Generally speaking, there are only two types of costs associated with a piece of equipment. They are the fixed cost expressed in dollars per unit time, and the operating cost expressed in dollars per equipment-hour or in dollars per distance unit travelled by the equipment. The cost factors suggested by Grant and Ireson (18) as listed in the literature survey are derived by breaking down these two types of costs. However, if the total equipment-hours or total distance traveled by a piece of equipment per unit time is known, the operating cost per unit time can be calculated. Adding the operating cost per unit time to the equivalent fixed cost per unit time gives the total equivalent cost per unit time. (If the unit of time is one year, then the value obtained is the equivalent annual cost.)

The equipment subprogram will use the equivalent cost per unit time for selecting the appropriate equipment. All costs involved are expected to be modified by intangible factors before they are input into the subprogram.

The equipment selection procedure presumes that the same piece of materials handling equipment can move parts between several pairs of manufacturing operations. Therefore, it is necessary to assure that only a single type of materials handling equipment is used to move a part. Relaxation of this requirement may create many complicating conditions which could make the IODP unmanageable. Based on this assumption, one type of equipment will be selected to move each part of a product throughout the process. Furthermore, the number of pieces of equipment required to move each part have also to be decided.

The above discussion has led to the formulation of the equipment subprogram. Equipment alternatives are set up for each part of a product; and the type with the least cost per unit time will be selected. The integer programming formulation is the best way to present the criteria. However, since only one alternative is chosen for each part, and the decision made for each part is assumed to be independent, the actual solution technique need not necessarily use integer programming solution techniques. The computer program developed for this purpose (see Appendix B) only uses a simple search technique to obtain the least-cost equipment. Expressing the equipment subprogram in an integer programming formulation is important only because it can generate a decision variable which can be useful in the formulation of the master program. The equipment subprogram is formulated as follows:

$$\text{minimize} \quad Z_E = \sum_{t=1}^{T} \sum_{n=1}^{N} (Q_n \tau_n + \pi_{tn}) z_{tn} \qquad \text{(E0)}$$

subject to: $$\sum_{n=1}^{N} z_{tn} = 1 \qquad \text{for all } t \qquad \text{(E1)}$$

$$z_{tn} = (0,1) \qquad \text{for all } t \text{ and } n \qquad \text{(E2)}$$

where

T = Number of parts per unit of product,

N = Number of materials handling equipment,

Q_n = Fixed cost of using one piece of discrete type handling equipment or one foot of continuous type handling equipment n per unit time,

τ_{tn} = Number of discrete type handling equipment or length in ft. of continuous type handling equipment n required for part t,

π_{tn} = Operating cost per unit time of using handling equipment n to move part t,

z_{tn} = 1 if part t is moved by handling equipment n, 0 if not.

Equation (E1) is the constraint to insure that only one type of equipment is chosen for each part. Detailed expressions to derive the parameters used in this subprogram will be developed in the formulation of the master program.

The parameters defined above possess different units of measurement for different classes of materials handling equipment. Generally, materials handling equipment can be classified into discrete and continuous types. Each type performs the handling activities in a distinct fashion and carries a different cost structure. A brief description of both types is presented:

(a) Discrete type -- Typical examples are fork truck, walkie pallet lift, and hand truck. This type of equipment moves items in discrete movements. A move is completed whenever the piece of equipment has transported a batch of items from a loading point to a discharge point. The capacity of every move depends on the equipment, and purchase price is fixed for a single piece of equipment.

(b) Continuous type -- Typical examples include various types of conveyors. This type of equipment transports items in a path predetermined by the design of the device and having fixed points of loading and discharge. The movement is continuous since items can be loaded onto or discharged from the device at any time or place. The purchase prices generally depend on the capacity (often expressed in weight units) that can be transported per unit time, and the length of the devices to be installed. In other words, the purchase price of a piece (or system) of equipment depends on its capability as well as the distance to be covered by the device.

The above definitions will be applied to materials handling equipment named as discrete type or continuous type hereafter.

Formulation of the Master Program

In this section, the interrelationships between all the factors considered by the IODP will be identified. Mathematical expressions of all the interrelationships will be the basic elements of the master program. The function of the master program thus developed is to generate a set of updated prices which are then fed into the subprograms developed in the last section.

The input to the master program includes (1) fixed parameters, and (2) decision variables output from the subprograms. The master program includes sixteen mathematical expressions and generates a set of nine price factors. The expressions are arranged in such an order that all variables included in an expression have been derived from previous ones. A block diagram summarizing all the input and output of the expressions is presented in Figure 2.

The formulation of the expressions will be discussed separately as follows:

1. Capacity

$$G = \sum_{i=E+1}^{I} \sum_{j=1}^{J} x_{ij} \tag{M1}$$

where

G = Capacity of the branch plan: in units per unit time,

x_{ij} = Amount shipped from location i to market j per unit time,

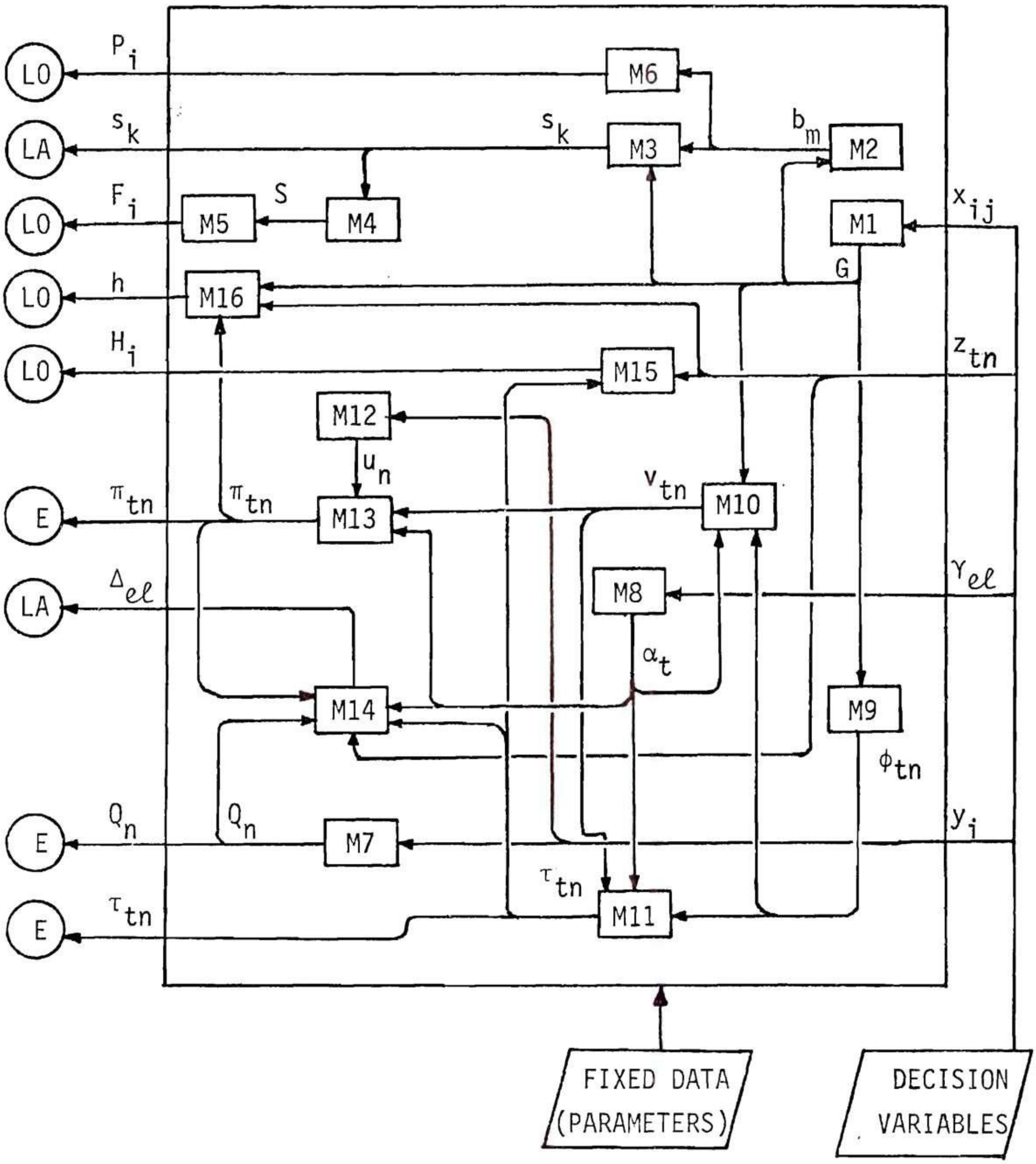
I = Number of locations (including existing plants),

J = Number of markets.

x_{ij} is decided by the location subprogram. Since the location subprogram will choose only one location, $\sum_{j}^{J} x_{ij}$ will equal to zero if i is not chosen, for i=E+1,...,M . 'G' will then represent the total amount shipped from the selected location, and is thus the capacity of the branch plant.

2. Number of Manufacturing Equipment

$$b_m = \binom{\text{largest}}{\text{integer}} \leq (G/\sigma_m) + \eta_1 \quad \text{for all } m , \tag{M2}$$



LO = LOCATION SUBPROGRAM

LA = LAYOUT SUBPROGRAM

E = EQUIPMENT SUBPROGRAM

Figure 2. Input/Output of the Master Program

where

b_m = Number of manufacturing equipment m required,

σ_m = Average number of units of product that can be produced by equipment m per unit time,

η_1 = Allowance factor for the manufacturing equipment.

G/σ_m gives the number of machine m required. However, the number thus obtained is often non-integer. For example, it may come up in the solution that 2.4 machines are required. Management has to make the decision whether two or three machines should be purchased. Such a decision largely depends on past experience or knowledge of the characteristics of the equipment such as the maximum capacity and probability of breakdown. In order to introduce this decision into the mathematical expression, an allowance factor η_1 is utilized. The value b_m then becomes the largest integer smaller than or equal to $\left[(G/\sigma_m)+\eta_1 \right]$, where $0 \leq \eta_1 < 1$.

If a relative rather than absolute allowance is desired, η_1 may be replaced by $\mu_1(G/\sigma_m)$, so that the expression in the brackets becomes $\left[(G/\sigma_m)(1+\mu_1) \right]$. For example, if $\mu_1=0.06$, then any roundoff will result in not more than a 6 percent undercapacity.

3. Departmental Area Requirement

$$s_k = \begin{cases} \beta_k + \delta_k b_m & \text{, if dept. } k \text{ uses manufacturing equipment } m\text{,} \\ \beta_k + \delta_k G & \text{, otherwise} \end{cases} \qquad \text{(M3)}$$

where

s_k = Departmental area requirement in sq. ft.

β_k = Fixed area in sq. ft. required by department k ,

δ_k = Area in sq. ft. required by a unit of manufacturing equipment m if department k uses machine m , or area in sq. ft. required by a unit of product if otherwise.

An assumption has to be made at this point that every department includes only one type of manufacturing machines such as in a job shop. Floor space requirement for a department will either depend on the number of manufacturing equipment it includes, or on the capacity of the plant if the department is not involved in direct manufacturing process, such as the raw materials storage.

Also, there may be a fixed space requirement for auxilary equipment in every department.

4. Building Floor Area

$$S = \sum_{k=1}^{K} s_k \qquad \text{(M4)}$$

where

S = Total floor space of building in sq. ft.

The summation of all departmental area requirements gives the physical size of the building. In order to be accurate, s_k should include space requirements for all kinds of activities including the administrative offices, cafeteria, etc.

5. Total Building Cost

$$F_i = \Phi_i + \Psi_i S \qquad i=E+1,\ldots,I \qquad \text{(M5)}$$

where

F_i = Total cost per unit time of owning the branch plant at location i ,

Φ_i = Fixed cost per unit time of owning the branch plant at location i ,

Ψ_i = Cost per sq. ft. per unit time of owning the plant at location i .

As already mentioned, the expression of F_i in cost per unit time has implied the application of the equivalent cost method used in economic analysis. Φ_i represents all the costs required to initiate the plant, which do not depend on the size of the plant. These costs will be converted to cost per unit time through the appropriate interest rate. Ψ_i is a more complicated cost factor. It may include the cost of land, cost of building, and all other costs which depend on the size of the plant. Needless to say, these costs will also be converted to dollars per unit time.

6. Fixed Machinery Cost

$$P_i = \sum_{m=1}^{M} P_{im} b_m \qquad i=E+1,\ldots,I \qquad \text{(M6)}$$

where

P_i = Fixed cost per unit time of machinery at location i ,

P_{im} = Fixed cost per unit time of a unit of manufacturing equipment m used at location i ,

M = Number of manufacturing equipment.

Expression (M6) is self explanatory. P_i is just the total fixed machinery cost at location i . Though the same machinery will be used wherever the plant is located, the purchase prices or maintenance costs of the machines may be influenced by the location of the plant. The purchase prices of some equipment may include a transportation cost; and the maintenance costs for specific equipment may also depend on where the plant is located. The parameter P_{im} is therefore set up for such conditions.

7. Fixed Cost of One Piece of Materials Handling Equipment

$$Q_n = \sum_{i=E+1}^{I} Q_{in} y_i \qquad \text{for all } n \tag{M7}$$

where

Q_n = Fixed cost per unit time of using one piece of discrete type materials handling equipment or one foot of continuous type materials handling equipment n ,

Q_{in} = Q_n at location i ,

y_i = 1 if plant at location i is used, 0 if not.

Q_{in} included in expression (M7) is expressed in units appropriate to both type of materials handling equipment mentioned.

Similar to the parameter P_{im} of expression (M6), fixed cost of a piece of equipment may also depend on where the plant is located. However, by utilizing the decision variable y_i generated from the location subprogram, only the cost vector at the selected location, which is now represented by Q_n , will be fed into the equipment subprogram.

8. Distance Traveled

$$\alpha_t = \sum_{e=1}^{K} \sum_{\ell=1}^{K} \gamma_{e\ell} \xi_{te\ell} \qquad \text{for all } t \tag{M8}$$

where

α_t = Total distance in units of 100 ft. traveled by part t in the manufacturing process,

$\gamma_{e\ell}$ = Distance in ft. between department e and department ℓ ,

$\xi_{te\ell}$ = 1 if part t is moved from department e to department ℓ ,
0 if not.

In order to represent the move sequence mathematically, the three dimensional vector space $\{\ \xi\ \}$ is set up. Each element in the vector space has a value of either 1 or 0 , where 1 implies a move has occurred. The introduction of $\xi_{te\ell}$ into expression (M8) has allowed all distances covered by part t in the manufacturing process to be summed up, giving α_t .

9. Number of Continuous Handling Devices

$$\phi_{tn} = \begin{pmatrix}\text{largest}\\ \text{integer}\end{pmatrix} \leq (G/\theta\lambda_n\rho_{tn})+\eta_2 \qquad \text{for all } t \text{ and continuous type equipment } n \qquad \text{(M9)}$$

where

ϕ_{tn} = Number of continuous type materials handling equipment n required to move part t ,

θ = Number of working hours available per unit time,

λ_n = Average moving speed in ft/hour of materials handling equipment n ,

ρ_{tn} = Maximum number of part t that can be carried by one foot of the continuous type materials handling equipment n ,

η_2 = Allowance factor for the materials handling equipment.

When the equipment to be considered is of continuous type, ρ_{tn}

is expressed in units per ft. Consequently, $(\theta\lambda_n\rho_{tn})$ gives the number of part t that can be transported by equipment n per unit time. This unit of measurement is derived from multiplying the units of the three parameters together: (hour/unit time)(ft/hour)(number/ft) = number/unit time. Since 'G' units of product are produced per unit time, there would also be 'G' number of part t to be moved through the process per unit time. Dividing 'G' by $(\theta\lambda_n\rho_{tn})$ would therefore give the exact number of pieces of equipment to be used. As this exact number will seldom be an integer, the allowance factor η_2 is introduced, where $\eta_2 \geq 0$, and < 1. The function of η_2 is similar to η_1 which has been discussed in detail when expression (M2) was developed.

It should be pointed out that θ need not necessarily correspond to the actual working hours. Allowance for recess and accidental delays may be subtracted from θ before it goes into the IODP. The expression of λ_n in average speed rather than maximum speed has also increased the flexibility in decision making.

10. Frequency of Move

$$v_{tn} = \begin{cases} G/\rho_{tn} & \text{, for } n \text{ is discrete type,} \\ (\phi_{tn}\theta)/(\alpha_t/\lambda_m) & \text{, for } n \text{ is continuous type.} \end{cases} \qquad \text{(M10)}$$

where

v_{tn} = Number of unit loads moved by discrete type materials handling equipment n or number of runs performed by the continuous type materials handling equipment n for part t per unit time,

ρ_{tn} = Maximum number of part t that can be combined to form a unit load for discrete type materials handling equipment n .

In order to develop materials handling costs, the frequency of moves should be determined. If a discrete type equipment is used, the frequency of moves can be represented implicitly by the number of unit loads formed. However, if continuous type equipment is used, it would be rather difficult to define a unit load since the device is transporting items continuously. Furthermore, under normal manufacturing conditions, the continuous type devices are usually kept running all the time. Because of these special characteristics, it would be better to develop a value based on the movement of the device itself rather than on the movements of the loads. v_{tn} is therefore expressed in 'runs' per unit time for continuous type equipment. A 'run' is defined as the movement from the starting point to the ending point of the device.

When the equipment n used is of the discrete type, the unit of ρ_{tn} is number of parts per unit load. Dividing G by ρ_{tn} thus gives the number of unit loads moved through the manufacturing process per unit time.

In order to obtain the number of runs per unit time for continuous type equipment, a series of calculations is required. (α_t/λ_n) represents the time required to complete a run. $(\phi_{tn}\theta)$ represents the total equipment-hours performed per unit time. Thus $(\phi_{tn}\theta)/(\alpha_t/\lambda_n)$ gives the number of runs performed per unit time.

11. Number of Discrete Handling Equipment or Length of Continuous Device

$$\tau_{tn} = \begin{cases} \binom{\text{largest}}{\text{integer}} \leq (v_{tn}\alpha_t/\theta\lambda_n)+\eta_2 & \text{, for discrete type equipment } n \\ \phi_{tn}\alpha_t & \text{, for continuous type equipment } n \end{cases} \quad \text{(M11)}$$

where

τ_{tn} = Number of discrete type or length of continuous type materials handling equipment n required for part t

The number of continuous type handling equipment to be used has been derived from expression (M9); but the information for purchase to be made is incomplete as the lengths of the devices are not specified. τ_{tn} represents the total length of the continuous type device n to be installed for part t . It is obtained by multiplying the total distance covered by part t through the process by the number of devices used.

In case discrete type equipment is used, τ_{tn} represents the number of pieces of equipment to be used and is obtained by a series of calculations. (α_t/λ_n) gives the total time that part t spends in movement through the manufacturing process. Assuming that time delays occurred in the manufacturing process, loading and unloading time, and time for return trips have been included in the determination of the moving speed, $\theta/(\alpha_t/\lambda_n) = (\theta\lambda_n/\alpha_t)$ would represent the number of moves that a piece of discrete type equipment n can perform per unit time. Since the number of moves required should be v_{tn} , dividing v_{tn}

by $(\theta\lambda_n/\alpha_t)$, which becomes $(v_{tn}\alpha_t/\theta\lambda_n)$, gives the exact number of discrete type equipment n required. The allowance factor η_2 is then introduced into the expression to allow τ_{tn} to be an integer.

τ_{tn} thus derived from expression (M11) will be fed into the equipment subprogram. The total overhead costs referring to every combination of part t and equipment n would then be obtained by multiplying π_{tn} by the relative Q_n derived from expression (M7).

12. Operating Cost of Materials Handling Equipment ($/100 ft)

$$u_n = \sum_{i=E+1}^{I} u_{in} y_i \qquad \text{for all } n \qquad \text{(M12)}$$

where

u_n = Operating cost of materials handling equipment n ($/100 ft)

u_{in} = Operating cost per 100 ft. of materials handling equipment n at location i .

Utilizing the decision variable y_i from the location subprogram, the cost vector u_n which corresponds to the selected location is extracted.

13. Total Operating Cost of Materials Handling Equipment ($/unit time)

$$\pi_{tn} = u_n v_{tn} \alpha_t \qquad \text{for all } t \text{ and } n \qquad \text{(M13)}$$

where

π_{tn} = Operating cost per unit time of using materials handling equipment n to move part t .

$(v_{tn}\alpha_t)$ gives the total distance covered by part t per unit time if discrete type equipment is used. If continuous type equipment is used instead, the result will be the total distance covered by the 'runs'. Since in both cases, the unit of measurement is unchanged, $(v_{tn}\alpha_t)$ can be multiplied by u_n directly. As u_n is expressed in dollars per 100 ft., the output from the expression π_{tn} is expressed in dollars per unit time and will be fed into the equipment subprogram.

14. Distance Between Departments

$$\Delta_{e\ell} = \sum_{t=1}^{T} \sum_{n=1}^{N} \left((Q_n \tau_{tn} + \pi_{tn})/\alpha_t\right) z_{tn} \xi_{te\ell} \qquad \text{(M14)}$$

for all e and ℓ

where

$\Delta_{e\ell}$ = Materials handling cost per ft. per unit time from department e to department ℓ ,

z_{tn} = 1 if part t is moved by equipment n ,
0 if not.

$\Delta_{e\ell}$ actually represents elements of the From-To Chart which serves as input data to the layout subprogram.

The function of z_{tn} in the expression is to assign the handling equipment to every part t , where z_{tn} is the decision output from the equipment subprogram.

Introduction of $\xi_{te\ell}$ into the expression informs the expression which parts are moving between the departments and in what direction. Handling costs of all the parts moved from one department to the other are summed up to give $\Delta_{e\ell}$.

$(Q_n \tau_n + \pi_{tn})$ is the total handling cost per unit time for the relative part t and equipment n . Since the elements of the From-To Chart are required to be expressed in dollars per unit time per ft., the total handling costs are divided by the relative total distance covered in the manufacturing process.

It should be pointed out here that the handling costs used here are somewhat different from that used in the original PLANET. PLANET considers only variable costs as the handling cost; but here in expression (M14), the fixed cost per unit time is also included. This difference is due to the basic assumptions of the two models. PLANET assumes that the type of handling equipment selected for each part remains the same. However, IODP assumes no predetermined assignment of handling equipment. Though the introduction of z_{tn} assigns the handling equipment to move the parts, this assignment is subject to change in the next iteration. Since the fixed costs also depend heavily on the distances the parts are moved, it would be reasonable to minimize the distance between departments.

15. Total Fixed Materials Handling Costs

$$H_i = \sum_{n=1}^{N} \left(Q_{in} \sum_{t=1}^{T} (\tau_{tn} z_{tn}) \right) \qquad \text{for all } i \qquad \text{(M15)}$$

where

H_i = Fixed materials handling cost per unit time at location i,

Q_{in} = Fixed cost per unit time of using one piece of discrete type materials handling equipment or one foot of continuous type handling equipment n at location i,

The fixed cost of materials handling at each location is one of the elements making up the facility cost at that location. The function of expression (M15) is to update the price vector H_i corresponding to the decision output z_{tn} from the equipment subprogram. H_i is actually the total of all the fixed costs of the selected equipment.

16. Variable Handling Cost

$$h = \left(\sum_{t=1}^{T} \sum_{n=1}^{N} \pi_{tn} z_{tn}\right)/G \qquad \text{(M16)}$$

where

h = Cost of handling one unit of product.

The function of the expression (M16) is similar to that of expression (M15). The variable cost of the handling equipment per unit time is updated. However, since h is to be fed into the location subprogram as an element of variable cost, it should be expressed in dollars per unit. The cost is therefore divided by G, the capacity in units per unit time, to give h in terms of dollars per unit.

All the expressions in the master program have now been developed. Figure 2 is a block diagram summarizing all the input and output flows of the master program.

Summary and Limitations of the Model

The mathematical model of IODP is summarized as follows:

$$\text{minimize} \quad Z = \sum_{i=1}^{E} \sum_{j=1}^{J} (C_{ij}+r_i)x_{ij} + \sum_{i=E+1}^{I} \sum_{j=1}^{J} (C_{ij}+p_i+h)x_{ij}$$

$$+ \sum_{i=E+1}^{I} (F_i+P_i+H_i)y_i + \sum_{e=1}^{K-1} \sum_{\ell \neq e}^{K} (\Delta_{e\ell}\gamma_{e\ell})$$

$$+ \sum_{t=1}^{T} \sum_{n=1}^{N} (Q_n\tau_{tn}+\pi_{tn})z_{tn}$$

subject to:

$$\sum_{i=1}^{I} x_{ij} \geq D_j \qquad \text{for all } j \tag{L1}$$

$$\sum_{j=1}^{J} x_{ij} \leq g_i y_i \qquad \text{for all } i \tag{L2}$$

$$\sum_{i=1}^{I} y_i \leq E + 1 \tag{L3}$$

$$\sum_{i=E+1}^{I} y_i \leq 1 \tag{L4}$$

$$y_i = (0,1) \qquad \text{for all } i \tag{L5}$$

$$x_{ij} \geq 0 \qquad \text{for all } i \text{ and } j \tag{L6}$$

$$\gamma_{e\ell} = \text{Function } (s_k, \Delta_{e\ell}) \tag{Y1}$$

$$\sum_{n=1}^{N} z_{tn} = 1 \qquad \text{for all } t \tag{E1}$$

$$z_{tn} = (0,1) \qquad \text{for all } t \text{ and } n \tag{E2}$$

$$G = \sum_{i=E+1}^{I} \sum_{j=1}^{J} x_{ij} \tag{M1}$$

$$b_m = \begin{pmatrix}\text{largest}\\ \text{integer}\end{pmatrix} \leq (G/\sigma_m)+\eta_1 \qquad \text{for all } m \tag{M2}$$

$$s_k = \begin{cases} \beta_k + \delta_k b_m & \text{, if dept. } k \text{ uses manufacturing equipment } m \text{ ,} \\ \beta_k + \delta_k G & \text{, otherwise} \end{cases} \tag{M3}$$

$$S = \sum_{k=1}^{K} s_k \qquad (M4)$$

$$F_i = \Phi_i + \Psi_i S \qquad i=E+1,\ldots,I \qquad (M5)$$

$$P_i = \sum_{m=1}^{M} P_{im} b_m \qquad i=E+1,\ldots,I \qquad (M6)$$

$$Q_n = \sum_{i=E+1}^{I} Q_{in} y_i \qquad \text{for all } n \qquad (M7)$$

$$\alpha_t = \sum_{e=1}^{K} \sum_{\ell=1}^{K} \gamma_{e\ell} \xi_{te\ell} \qquad \text{for all } t \qquad (M8)$$

$$\phi_{tn} = \begin{pmatrix}\text{largest}\\ \text{integer}\end{pmatrix} \leq (G/\theta\lambda_n \rho_{tn}) + \eta_2 \qquad (M9)$$

for continuous type n

$$v_{tn} = \begin{cases} G/\rho_{tn} & \text{for discrete type } n \\ (\phi_{tn}\theta)/(\alpha_t/\lambda_n) & \text{for continuous type } n \end{cases} \qquad (M10)$$

$$\tau_{tn} = \begin{cases} \begin{pmatrix}\text{largest}\\ \text{integer}\end{pmatrix} \leq (v_{tn}\alpha_t/\theta\lambda_n) + \eta_2 & \text{for discrete type } n \\ \phi_{tn}\alpha_t & \text{for continuous type } n \end{cases} \qquad (M11)$$

$$u_n = \sum_{i=E+1}^{I} u_{in} y_i \qquad \text{for all } n \qquad (M12)$$

$$\pi_{tn} = u_n v_{tn} \alpha_t \qquad \text{for all } t \text{ and } n \qquad (M13)$$

$$\Delta_{e\ell} = \sum_{t=1}^{T} \sum_{n=1}^{N} \left[(Q_n \tau_{tn} + \pi_{tn}) / \alpha_t \right] z_{tn} \xi_{te\ell} \qquad \text{(M14)}$$

for all e and ℓ

$$H_i = \sum_{n=1}^{N} \left[Q_{in} \sum_{t=1}^{T} (\tau_{tn} z_{tn}) \right] \text{ for all } i \qquad \text{(M15)}$$

$$h = \left[\sum_{t=1}^{T} \sum_{n=1}^{N} \pi_{tn} z_{tn} \right] / G \qquad \text{(M16)}$$

All variables involved in the model can be classified into (1) parameters, (2) numerical variables, and (3) decision variables. Parameters refer to fixed input data to the IODP. Numerical variables are all numerical representations, either final or intermittent, of the factors processed by the IODP. These variables are actually the sixteen factors processed by the master program. Decision variables refer to the variables directly output from the subprograms, from which the solution set is derived.

Definitions of the symbols in the model are summarized by Tables 3, 4 and 5.

Table 3. Parameters of the IODP

Symbol	Definition
E	Number of existing plants
I	Number of locations including existing plants
J	Number of markets
M	Number of manufacturing equipment
N	Number of materials handling equipment
K	Number of departments
T	Number of parts per unit of product
θ	Number of working hours available per unit time
η_1	Allowance factor for the manufacturing equipment
η_2	Allowance factor for the materials handling equipment
C_{ij}	Cost of shipping a unit from location i to market j
D_j	Demand of market j per unit time
g_i	Units produced in location i per unit time
r_i	Cost of producing a unit in existing plant i
Φ_i	Fixed cost per unit time of owning a plant at location i
Ψ_i	Cost per sq. ft. per unit time of owning a plant at location i
P_{im}	Fixed cost per unit time of using a unit of manufacturing equipment m at location i
p_i	Cost of machinery of a unit of product at location i
σ_m	Average number of units of product produced by manufacturing equipment m per unit time
Q_{in}	Fixed cost per unit time of using a piece of discrete type materials handling equipment n or one foot of continuous type materials handling equipment n
ρ_{tn}	Maximum number of part t that can be combined to form a unit load for discrete equipment n or maximum number of part t that can be carried by one foot of continuous equipment n
λ_n	Average moving speed in ft/hr of materials handling equipment n

u_{in} Operating cost per 100 ft. of materials handling equipment n at location i

β_k Fixed area in sq. ft. required by department k

δ_k Area in sq. ft. required by a unit of machine m if dept. k uses machine m , or area in sq. ft. required by a unit of product otherwise

$\xi_{te\ell}$ =1 if part t is moved from department e to department ℓ, =0 if not

Table 4. Numerical Variables of the IODP

Symbol	Definition
G	Capacity of the branch plant in units per unit time
b_m	Number of manufacturing machines m required
s_k	Departmental area requirement
S	Building floor area
F_i	Total cost per unit time of operating the branch plant at location i
P_i	Fixed cost per unit time of machinery at location i
Q_n	Fixed cost per unit time of using one piece of discrete type handling equipment n or one foot of continuous type handling equipment n
α_t	Total distance in 100 ft. traveled by part t in the manufacturing process
ϕ_{tn}	Number of continuous type equipment n required to move part t
v_{tn}	Number of unit loads moved by discrete type equipment n or number of runs performed by the continuous type equipment n for part t per unit time
τ_{tn}	Number of discrete type or length of continuous type equipment n required for part t
u_n	Operating cost per 100 ft. of materials handling equipment n
π_{tn}	Operating cost per unit time of using materials handling equipment n to move part t
$\Delta_{e\ell}$	Materials handling cost per ft. per unit time from department e to department ℓ
H_i	Fixed cost per unit time of using one piece of discrete type handling equipment or one foot of continuous type handling equipment n at location i
h	Cost of handling one unit of product

Table 5. Decision Variables of the IODP

Symbol	Definition
x_{ij}	Amount shipped from location i to market j per unit time
y_i	=1 if plant at location i is used, =0 if not
$\gamma_{e\ell}$	Distance in ft. between department e and department ℓ
z_{tn}	=1 if materials handling equipment n is used to move part t , =0 if not

All the parameters listed in Table 3 are assumed to be known in order to carry out the IODP. In the collection of the data, the following conditions have to be observed:

1. The lives of the machines and handling equipment are estimated and the interest rate for transferring the investment costs to equivalent costs per unit time is decided.
2. The manufacturing process is assumed to be optimal. That is, any possibility of improving the manufacturing process should be investigated and adjustment made before the IODP is used.
3. The types of manufacturing equipment used are fixed. If several types of manufacturing equipment can be used for the same purpose, the right type should be decided first, because the IODP only gives the number of machines to be purchased; it does not make comparisons among alternative machines.

4. Every department contains only one type of manufacturing equipment.
5. No repetition of move sequence is allowed for any of the parts. For example, 1-2-4-6-2-4-5, where the numbers represent the names of departments, is not allowed since sequence 2-4 is repeated.
6. At a certain stage of the manufacturing process, if a few parts are combined to form a sub-unit, the sequences of the parts are terminated and the new sub-unit begins its sequence as a new part.
7. If more than one piece of a specific part is required to produce a unit of product and all of them follow the same sequence, these pieces can be combined as one part. The total weight and size is used accordingly in the calculation of maximum number making up a unit load.
8. Table 6 and 7 show the general cost items included as fixed and variable costs of the equipment and facilities.

Table 6. Fixed and Variable Costs of Equipment

Fixed Costs (\$/unit time) (P_i , H_i)	Variable Costs (\$/unit of product) (r_i , p_i , h)
Capital Recovery of Investment in Equipment and Installation	Utility Costs (including fuel, electricity, etc.)
Labor Cost*	Maintenance Cost**
Maintenance Cost**	
Insurance	
Taxes	

Table 7. Fixed and Variable Costs of Building

Fixed Costs (\$/unit time) Φ_i	Variable Costs (\$/sq ft) Ψ_i
Initiation Cost (including costs in making contracts, etc.)	Capital Recovery of Investment in Land, Building and Improvements
Indirect Labor†	Insurance
	Taxes
	Maintenance Cost
	Utility Cost
	Indirect Labor†

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* Labor cost is included in the fixed cost based on the assumption that the operator of a piece of equipment is employed full time even though the equipment is not under full work load.

** Maintenance cost is often semi-variable. It is a combination of a fixed cost and a variable cost depending on the work load of the equipment.

† Indirect labor is often semi-variable, e.g., high level staff is fixed and low level staff is always variable.

Figure 3 shows the operation of the IODP. In testing for the optimality of the solution set, the value of the objective function for the location subprogram, i.e., equation (LO) is used as the score. The other two objective functions relating to the layout and equipment subprograms are not included because the variables included in these two functions have already been represented either directly or indirectly by the variables included in equation (LO). The solution set is said to have arrived at optimal when the score comes to a constant value after certain number of iterations. However, this does not necessarily imply that the scores converge to the constant value. At times when the location subprogram generates the decision variables y_i and x_{ij} different from the existing ones, delay in the updating process of the system would occur and output from the following iteration would not be feasible.

To illustrate what 'delay' means, let us first make an observation on the mathematical relationship between the factors in the master program.

At the end of an iteration, a set of decision variables (y_i, x_{ij}, z_{tn}, $\gamma_{e\ell}$) is generated. This set then goes into the master program. The first factor derived from x_{ij} is the capacity G. This factor is found to have influence on every other factor except Q_n, α_t and u_n. The following factors will be increased in value as G increases: b_m, s_k, S, F_i, P_i, ϕ_{tn}, v_{tn}, τ_{tn}, π_{tn}, $\Delta_{e\ell}$, and H_i. Also, α_t is derived from $\gamma_{e\ell}$, and if $\sum\alpha_t$ is increased, $\sum\tau_{tn}$, $\sum\pi_{tn}$, H_i and h will be increased. The factor H_i is found

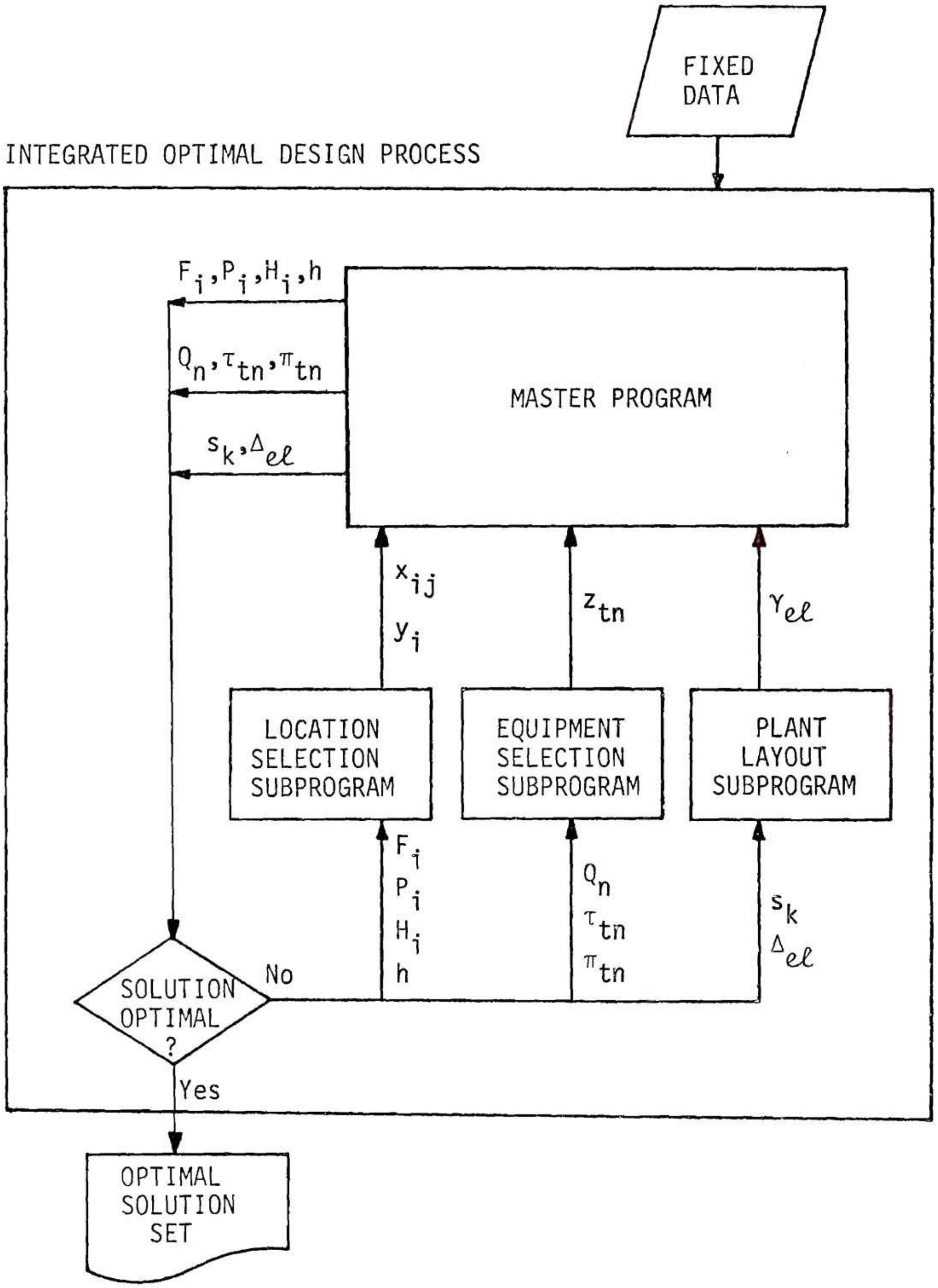

Figure 3. Input/Output of the IODP

to be used in the computation of the score of the IODP and is subject to increase if either G or α_t increases.

Now, consider at the end of an iteration, the decision set is $(y_i^{1}, x_{ij}^{1}, z_{tn}^{1}, \gamma_{e\ell}^{1})$, and G^1 and $\sum\alpha_t^{1}$ are derived from this set. The optimal solution has not been reached and the updated price vectors are then fed into the Location subprogram, Layout subprogram, and Equipment subprogram simultaneously. The Layout subprogram then generates $\gamma_{e\ell}^{2}$ based on s_k^{1} and $\Delta_{e\ell}^{1}$, where $\gamma_{e\ell}^{2} = \gamma_{e\ell}^{1}$ and thus $\sum\alpha_t^{2} = \sum\alpha_t^{1}$. The Equipment subprogram also gives $z_{tn}^{2} = z_{tn}^{1}$. However, the Location subprogram generates $y_i^{2} \neq y_i^{1}$ and thus $G^2 > G^1$, and also $s_k^{2} > s_k^{1}$. Though $h_i^{2} > H_i^{1}$, the score Z^2 would be smaller than Z^1 since y_i^{2} is obtained from a minimization program. However. Z^2 is noticed to be infeasible. The components making up the score Z^2 are based on a different capacity. F_i^{2} and P_i^{2} are based on G^2 while H_i and h are based on $\sum_t\alpha_t^{2}$ which is based on $\gamma_{e\ell}^{2}$ and in turn based on G^1. As $G^1 \neq G^2$, the updating of H_i and h is said to be 'delayed'. If y_i, x_{ij} and z_{tn} would not change in the next iteration, then $\gamma_{e\ell}^{3}$ generated will be based on G^2, but since $G^2 > G^1$ and thus $s_k^{2} > s_k^{1}$, $\sum_t\alpha_t^{3} > \sum_t\alpha_t^{2}$ as a result and $Z^3 > Z^2$, where Z^3 is feasible now as its components are based on G^3, where $G^3 = G^2$.

The above discussion illustrates how the variation of G during the process affects the score. The following discussion shows how the capacity will affect the decision set.

The original Ellwein-Gray location-allocation model assumes the facility costs are fixed, that is, they are independent of the supplies from the locations. Observing the input and output flows of the IODP, it can be noticed that the facility costs are not really 'fixed'. Their values would actually increase with the capacity of the branch plant, 'G' , determined by the Location subprogram itself.

Consider during an iteration, the price vectors F_i^1 , P_i^1 , and H_i^1 , which are updated according to G^1 , are fed into the Location subprogram, which then generates $y_i^2 \neq y_i^1$ and gives $G^2 > G^1$. Assume the Z^2 obtained will remain constant for further iterations and thus y_i^2 and the related solution set is said to be optimal. However, the above deduction would imply that y_i^2 is optimal only when the capacity is G^2 . In other words, G^2 does not necessarily become the optimal capacity. A location n , which implies $y_n \neq y_i^1$, and $\neq y_i^2$ may exist such that for facility costs of F_i^1 , P_i^1 and H_i^1 , if y_n is selected, then G_n , which is derived from the corresponding supply, will be smaller than G^2 ; but y_n is not selected since the objective function obtained if it is used will be greater than that obtained if y_i^1 is used. However, if F_i , P_i and H_i are based on G_n , then the total of F_n , P_n and H_n thus derived would be less than that derived from y_i^1 or y_i^2 , and the difference would be significant enough to have y_n chosen. Since G^1 is used at iteration 1 and G^2 for iteration 2 as the base for deriving the facility costs, there is no chance for G_n to be used. Therefore the final solution set does not necessarily become the exact optimal solution set.

The final output of the IODP consists of information required to make the decisions as specified, when the problem to be studied is defined as in Chapter I. Under some circumstances, the capacity of the branch plant may be predetermined because of various economical or political reasons outside the scope of this study. For such a case, the capacity G would not be changed during the process and the final solution set will guarantee a near-optimal solution.

As discussed previously, an optimal solution cannot be obtained because the facility costs F_i, P_i and H_i vary with the value of capacity G, and thus also $\sum x_{ij}$, which is determined by the Location subprogram itself. This condition actually invalidates the basic assumption of the Ellwein-Gray location model, which is that the facility costs are fixed. If the capacity is predetermined, the fixed facility cost assumption of Ellwein-Gray location model is then valid, since the capacity is not allowed to vary and the facility costs are thus independent of $\sum x_{ij}$, the distribution pattern.

When the capacity G is a fixed value, each of the three subprograms will tend to generate an optimal solution by a minimization process. The behavior of the solution procedure of the IODP is similar to the solution procedure of a large linear system by the decomposition principle; therefore it is reasonable to believe that if capacity G is fixed, the IODP will converge to an optimal solution after a certain number of iterations. Experience in using the IODP on sample problems has indicated this to be true.

On the other hand, even if the capacity is fixed, the solution obtained may not be the exact optimal solution. The Layout subprogram uses the PLANET layout program, which depends on a heuristic solution procedure, which can not guarantee an exact optimal solution. The

IODP is therefore believed to obtain at least a near-optimal solution.

An experimental computer program in FORTRAN IV has been developed for the IODP. The Location and Layout subprograms are modified versions of the programs for the original Ellwein-Gray model and PLANET.

Based on computation experience on some sample problems, cycling may occur at runs where G is allowed to vary. This will happen when y_m is selected if its corresponding price vectors depend on G_n ; but G_m is derived from y_m and the relative price vectors will cause y_n to be generated, from which G_n is derived. When cycling occurs, an optimal solution set would not be obtained from the first run and the user is advised to make runs based on fixed capacities and make the comparison.

Furthermore, the IODP is based on deterministic forecasts of market demands. Frequently, the forecasting of market demands is stochastic and therefore it would be necessary to perform a sensitivity analysis referring to the demand characteristics in order to get a satisfactory solution set. Recommendations on performing this sensitivity analysis will be included in the procedure of application developed in the next section.

Procedure of Application

The following step-by-step procedure is suggested for users of the IODP:

Step 1. Establish the set of locations to be considered. All intangible requirements such as climate, transportation facilities, availability of building, etc., are assumed to be satisfied by every location.

Step 2. Decide the unit time on which all of the costs can be based. Also establish a long term planning horizon and obtain the forecast of the market demands at the end of the planning period. Frequently, an upper limit and a lower limit of demand is estimated for every market. The user must then decide the value on which the set of market demands should be based, since either the upper limit, the lower limit, or the mean can be used. Such a decision must make use of past experience, technical knowledge and intuitive judgement. The user may also prefer to make runs on different frames of reference for the market demands; such as making three separate runs with each based on either the lower limits, the means or the upper limits of the market demands.

Step 3. Estimate the maximum capacity allowed at each location. This will consider the availability of labor, resources and facilities. If there is no limitation on the capacity for a location, the respective parameter g_i can be assigned a value larger than the total demand.

Step 4. Establish the materials handling equipment set to be considered. All intangible factors should be considered in establishing this set. If such methods as multiplying the actual costs by indexes derived from intangible factors are used, the relative costs are adjusted before they are used for the IODP. If some types of equipment cannot be used on some parts of the product because of technical difficulties, the respective parameter ρ_{tn} , the number of parts making up a unit load or carried by a foot of conveyor, can be assigned a zero value, the program will automatically reject the equipment n for the part t if ρ_{tn} is zero.

Step 5. Determine all parameters referring to the building, machines and equipment characteristics based on past experience and information from vendors and operating manuals. Such parameters include σ_m, ρ_{tn}, λ_n, β_k, and δ_k.

Step 6. Making use of the assembly charts, operation process charts, etc., determine the move sequence of every part.

Step 7. Estimate the number of hours available per unit time. Allowances on down time and other delays are included.

Step 8. Decide the allowance factors η_1 and η_2. Characteristics of these two factors have been discussed in Chapter III.

Step 9. Estimate all data required to develop the cost parameters included in Table 3: C_{ij}, r_i, Φ_i, Ψ_i, P_{im}, p_i, Q_{in}, u_{in}. This step involves a vast data collection effort. Detail labor and power costs for all activities of purchase, operation and maintenance have to be obtained for every proposed location and the existing plants.

Step 10. Transfer all the costs obtained in Step 8 to equivalent costs per unit time by a specific interest rate decided by the financial policy of the firm. In general, if unit time is taken as 1 year, then equivalent annual cost is:*

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* This formula is discussed in detail in Thuesen, Fabrycky and Thuesen (31).

$$C = (P - F)\left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) + Fi + M$$

$$= (P - F)(A/P, i, n) + Fi + M$$

where

P = Initial cost of asset,

F = Salvage value at the end of life,

n = Life in years,

M = Constant yearly cost.

Step 11. Decide other parameters which are required for the operation of the IODP computer program. These are shown in Table 8.

Table 8. Special Parameters for the Computer Program

Code	Definition
BSIZE	Size of a unit block in sq. ft. for layout
DISINT	The initial distance assigned to every $Y_{e\ell}$
IDEQ(N)	= 1 if n is discrete type equipment, = 2 if n is continuous type equipment.
INDEX(K)	= m if area of department k depends on machine m , = 0 if area of department k depends on capacity.
NSQ(T)	Number of departments included in the path of part t
MVSQ(T,L)	Move sequence of part t expressed in $(L_1, L_2, \ldots, L_{NSQ})$
KPRIOR(K)	Priority of department k in the layout process

Step 12. Calculate the lower limit of capacity of the branch

plant. This is done by subtracting the total supply of the existing plants from the total demand. There may be a few values of lower limit, referring to the lower limits, the means and the upper limits of the market demands.

Step 13. Provide an initial decision variables set to start the program.

Step 14. Prepare the input.

Step 15. Run the program.

Step 16. At least four runs are suggested. These four runs have the following input structure:

Run 1. Market demands at their mean values. Capacity free to vary.

Run 2. Market demands at their upper limits. Capacity free to vary.

Run 3. Market demands at their mean values. Capacity fixed at respective lower limit.

Run 4. Market demands at their upper limits. Capacity fixed at respective lower limit.

The market demands at their lower limits may be neglected since it will give a tight plan, not allowing much room for expansion. Other runs with combinations of means and upper limits of the market demands may also be made if the user feels it necessary to get more information on some particular markets.

It should be pointed out that if cycling occurs in either Run 1 or Run 2 where the capacity is free to vary, a sequence of runs with the capacity fixed at different values can be carried out for both cases of using means or upper limits of market demands.

Step 17. Collect all results from Step 15 and make the analysis based on such indications as the change of solution set, the total variable cost, and the facility cost. Here no specific rules are set up in making the final decision. The final decision will depend on the experience and intuitive judgement of the analyst, and other economical and political factors not considered in this study. For example, at the selected location, there may be some large scale transportation projects being carried out, which when completed will provide suitable transportation facilities to evoke a much lower cost for products shipped from that location. Therefore it may be better to build a plant with very large capacity even if it means closing one of the existing plants in the future.

On the other hand, since the facility costs of existing plants are assumed to be zero, and the facility cost of the branch plant actually depends on its capacity, the value of the objective function tends to be lowest when the capacity of the branch plant is allowed at the lower limit; but it does not necessarily mean that the capacity is best to be set at its lower limit.

CHAPTER IV

A SAMPLE PROBLEM

Data Setup

Step 1 through Step 11 of the procedure for application are actually devoted to the data collection process. Since the IODP attacks the problem of initiating a new branch, it is difficult to have real world data at hand. The sample problem presented here has been set up on an imaginary basis; but an effort has been made to make it look reasonable.

The IODP is applied to the determination of the decision set for a branch plant producing air compressors (Apple, 33). The data setup presented below will follow the procedure of application developed in the last chapter. However, only the final data collected in every step are shown; the treatment with intangible factors are not presented.

Step 1. The firm is assumed to have two existing plants. They are located at:

1. Atlanta
2. Los Angeles

The set of proposed locations for the branch plant includes five locations which are numbered from 3 to 7 as follows:

3. Boston
4. Cleveland
5. Denver
6. Minneapolis

7. New York

Step 2. The unit time is one month and planning horizon is ten years.

A forecast of demand from 12 markets after 10 years is assumed, expressed in units per month and shown in Table 9. It can be seen that the locations of existing plants are markets themselves.

Table 9. Forecast of Market Demand

Market No.	Market Location	Lower Limit	Mean	Upper Limit
1	Atlanta	6400	7000	7600
2	Los Angeles	5600	5900	6200
3	Boston	6300	7050	7800
4	Cleveland	2800	3000	3200
5	Denver	6000	6250	6500
6	Minneapolis	5900	6300	6700
7	New York	5400	6000	6600
8	San Francisco	5500	6000	6500
9	Dallas	5200	5500	5800
10	Chicago	4800	5500	6200
11	Buffalo	5700	6000	6300
12	Miami	5250	5500	5750

Step 3. The maximum capacity is shown in Table 10.

Table 10. Maximum Capacities of Plant Locations

Location No.	Location	Max. Capacity
1	Atlanta	30000
2	Los Angeles	30000
3	Boston	40000
4	Cleveland	35000
5	Denver	35000
6	Minneapolis	35000
7	New York	50000

Step 4, 5 and 6. Data collected in Step 4 and 5 are shown in Table 11, 12, 13 and 14.

Table 11. Characteristics of Materials Handling Equipment

Equipment No.	Materials Handling Equipment	Type	Average Moving Speed in ft/hr
1	Man with hand truck	Discrete	800
2	Walkie Pallet Lift	Discrete	1400
3	Fork Lift Truck	Discrete	12000
4	Belt Conveyor	Continuous	3600
5	Trolley Conveyor	Continuous	1800
6	Overhead Towline Cart	Continuous	1600
7	Underfloor Towline Cart	Continuous	2400

Table 12. Characteristics of Parts

Part No.	Part	Units making up a load or carried by 1 ft of equipment 1	2	3	4	5	6	7	Move Sequence
1	Crankcase	9	27	227	0	3	4	5	1-2-3-6-4-10-11
2	Cylinder	20	60	500	1	6	7	8	1-3-4-7-10-11
3	Cylinder Head	33	100	833	0	6	7	8	1-3-4-10-11
4	Crankshaft	67	200	1667	1	6	7	8	1-8-3-2-4-10-11
5	Connecting Rod	133	400	3333	1	7	8	9	1-5-4-9-4-2-6-4-6-10-11
6	Piston	200	600	5000	0	8	10	10	1-3-4-10-11
7	Piston Pin	800	2400	20000	1	8	10	10	1-8-3-5-10-11
8	Outside Bearing	400	1200	10000	1	8	10	10	1-3-10-11
9	Inside Bearing	667	2000	16667	1	8	10	10	1-3-10-11
10	Breather	200	600	5000	1	8	10	10	1-2-4-10-11
11	Flywheel	6	17	139	0	0	3	4	1-3-6-10-11
12	Cover Plate	0	0	0	1	8	10	10	1-6-10-11
13	Suction Fitting	400	1200	10000	1	8	10	10	1-3-10-11
14	Discharge Fitting	800	2400	20000	1	8	10	10	1-3-2-10-11
15	Valve	0	0	0	1	8	10	10	1-6-10-11
16	Cover Gasket	0	0	0	1	8	10	10	1-6-10-11
17	Breather Plate	0	0	0	1	[illegible]	10	10	1-6-10-11

Table 13. Characteristics of Manufacturing Machines

Machine No.	Machine	Machinery Time per unit (hr)	Avg. Production Rate (u/mo)	Floor Space (ft^2)
1	Mill	0.168	750	80
2	Lathe	0.677	188	100
3	Drill	0.205	614	40
4	Grinder	0.016	7875	30
5	Press	0.068	1853	40
6	Hone	0.009	14000	40
7	Saw	0.018	7000	60
8	Bore	0.072	1750	40

Table 14. Characteristics of Departments

Dept. No.	Department	Fixed Area (ft^2)	Variable Area (ft^2/machine)	Variable Area (ft^2/unit)
1	Receiving and Rough Stores	2500		0.10
2	Mill	50	80	
3	Lathe	50	100	
4	Drill	50	40	
5	Grinder	50	30	
6	Press	50	40	
7	Hone	50	40	
8	Saw	50	60	
9	Bore	50	40	
10	Final Inspection	500		0.05
11	Assembly, Packing, Shipping	2000		0.20
12	Administration	5000		0.01

Step 7. Number of working hours available per month: 126 hr, assuming 252 working days per year, 21 days per month, 8 hours per day, and an allowance factor of 0.75.

Step 8. Allowance factor for manufacturing equipment: 0.75; allowance factor for materials handling equipment: 0.75.

Step 9 and 10. Transportation costs are assumed proportional to the distance between the plant locations and the markets. The figures shown in Table 15 are derived from the actual distances between the locations and markets.

Table 15. Transportation Costs

	Plant Location						
Market	1	2	3	4	5	6	7
1	0	1.60	0.77	0.50	1.01	0.77	0.62
2	1.60	0	2.17	1.72	0.84	1.41	2.01
3	0.77	2.17	0	0.45	1.42	0.99	0.15
4	0.50	1.72	0.45	0	0.96	0.53	0.35
5	1.01	0.84	1.42	0.96	0	0.60	1.25
6	0.77	1.41	0.99	0.53	0.60	0	0.88
7	0.62	2.01	0.15	0.35	1.25	0.88	0
8	1.82	0.28	2.25	1.79	0.89	1.43	2.12
9	0.59	1.02	1.29	0.85	0.56	0.68	1.14
10	0.50	1.49	0.70	0.24	0.72	0.29	0.58
11	0.63	1.85	0.32	0.13	1.10	0.67	0.26
12	0.47	1.30	1.10	0.96	1.51	1.24	0.94

The production cost per unit (including handling and machinery cost) at the existing plants are:

Existing plant at location 1: 0.380

Existing plant at location 2: 0.360

The machinery cost per unit of product at the proposed locations are:

Location No.:	3	4	5	6	7
Product unit Machinery Cost:	$0.368	0.346	0.352	0.360	0.368

In real practice, the above production and machinery costs have to be based on time-study results for the manufacturing machines and handling equipment.

Table 16 shows the cost of building at each proposed location. The annual interest rate i is assumed to be 15 per cent. Since the life n of a building is very long, the factor for converting capital to equivalent cost per unit time, $i(i+1)^n/\{(1+i)^n-1\}$, approaches i as n approaches infinity. Therefore if a piece of land costs \$10 per square foot, its cost will be equivalent to an annual cost of about \$1.50 per square foot, or about \$0.125 per square foot per month. The overhead cost per month and the variable cost per square foot per month shown in Table 16 are set up in such a way as to have the figures look close to real costs derived from the calculation mentioned above.

Table 16. Costs of Building

Location Number	3	4	5	6	7
Fixed Cost/mo	\$2000	1800	1900	1800	2200
Cost/ft^2/mo	\$0.15	0.12	0.12	0.10	0.15

For obtaining the costs associated with the manufacturing machines and materials handling equipment, the annual cost formula presented in Step 10 of the procedure for application is applied. The costs per month are obtained by dividing the annual costs by 12. Table 17 and 18 show the raw data assumed, and the calculation.

Table 17. Fixed Costs of Manufacturing Equipment

Location No.	Machine No.	Life n	Purchase Price P	Salvage Value F	Annual Labor, Maintenance, tax, etc. M	Equivalent Cost per month at 10 per cent interest (incl. F, M)
3	1	8	900	100	8100	688.3
	2	8	1000	110	8100	689.8
	3	8	800	90	8100	688.1
	4	8	500	55	8100	682.4
	5	8	900	100	8100	688.3
	6	8	700	80	8100	685.3
	7	8	800	90	8100	686.8
	8	8	800	90	8100	686.8

4	1	8	950	100	7300	622.4
	2	8	1000	110	7300	623.2
	3	8	850	90	7300	621.0
	4	8	550	55	7300	616.5
	5	8	900	100	7300	621.7
	6	8	650	80	7300	617.9
	7	8	750	90	7300	619.4
	8	8	800	90	7300	620.2
5	1	8	920	100	7600	647.0
	2	8	1000	110	7600	648.2
	3	8	800	90	7600	645.2
	4	8	650	55	7600	641.5
	5	8	900	100	7600	646.7
	6	8	720	80	7600	644.0
	7	8	780	90	7600	644.8
	8	8	800	90	7600	645.2
6	1	8	900	100	7100	605.0
	2	8	1000	110	7100	606.5
	3	8	820	90	7100	603.8
	4	8	520	55	7100	599.4
	5	8	900	100	7100	605.0
	6	8	700	80	7100	602.0
	7	8	800	90	7100	603.5
	8	8	780	90	7100	603.2
7	1	8	950	100	8100	689.1
	2	8	1000	110	8100	689.8
	3	8	850	90	8100	687.7
	4	8	550	55	8100	683.2
	5	8	900	100	8100	688.3
	6	8	720	80	8100	685.7
	7	8	780	90	8100	686.5
	8	8	800	90	8100	686.8

Table 18. Fixed Costs of Materials Handling Equipment

Location No.	Equipment No.	Life n	Purchase Price P	Salvage Value F	Annual Labor, Maintenance, tax, etc. M	Equivalent Cost per month at 10% interest (incl. F, M)
3	1	15	55	5	5555	463.5
	2	8	2000	200	5595	499.2
	3	8	2500	250	5600	503.9
	4	8	200	15	40	6.3
	5	8	250	25	42	7.7
	6	8	275	25	45	7.9
	7	8	300	30	45	8.3
4	1	15	55	5	4545	379.3
	2	8	2080	200	4585	413.2
	3	8	2500	250	4590	419.8
	4	8	200	15	40	6.3
	5	8	210	25	42	6.6
	6	8	250	25	45	7.5
	7	8	250	30	45	7.5
5	1	15	50	5	5050	421.4
	2	8	2100	200	5090	455.5
	3	8	2450	250	5095	461.1
	4	8	180	15	40	6.0
	5	8	200	25	40	6.3
	6	8	225	25	43	6.9
	7	8	250	30	43	7.3
6	1	15	50	5	4545	379.3
	2	8	2050	200	4585	412.7
	3	8	2450	250	4590	419.0
	4	8	180	15	40	6.0
	5	8	200	25	40	6.3
	6	8	250	25	43	7.3
	7	8	250	30	43	7.3
7	1	15	50	5	5555	463.5
	2	8	2050	200	5595	496.8
	3	8	2500	250	5600	503.9
	4	8	180	15	42	6.2
	5	8	200	25	42	6.5
	6	8	250	25	45	7.5
	7	8	250	30	45	7.5

Table 19 shows the operating cost per 100 ft. of the materials handling equipment. These figures may be very unreal since in order to make them look close to real data, a number of operating characteristics, including horsepower and efficiency, have not been considered.

Table 19. Operating Costs of Materials Handling Equipment

Location	Equipment Number						
No.	1	2	3	4	5	6	7
3	0	0.0015	0.0025	0.0009	0.0060	0.0080	0.0080
4	0	0.0015	0.0025	0.0009	0.0058	0.0088	0.0080
5	0	0.0014	0.0024	0.0008	0.0050	0.0080	0.0080
6	0	0.0015	0.0025	0.0009	0.0055	0.0085	0.0085
7	0	0.0015	0.0025	0.0009	0.0060	0.0080	0.0080

Step 11. BSIZE = 25 sq. ft.

DISINT = 100 ft.

IDEQ(N) = (1,1.1,2.2,2.2)

INDEX(K) = (0,1,2,3,4,5,6,7,8,0,0,0)

NSQ(T) = (7,6,5,7,11,5,6,4,4,5,5,4,4,5,4,4,4)

MVSQ(T,L) : Already defined in Table 9

KPRIOR(K) = (2,1,1,1.1,1.1,1,1,2,2,3)

Results and Analysis

The rest of the steps in the procedure of application are carried out as follows:

Step 12. Lower limit of the branch plant is: 10,000 units/month if means of market demands are used.

Step 13. The initial set assumes location 5 is selected and a distribution of x_{ij} is input to make the capacity = 15,000 units/ month. Also equipment no. 1 is assumed to be used by all parts. DISINT = 100 ft. as defined in Step 11 has assumed an initial value for $Y_{e\ell}$.

Step 14. Figure 4 shows the printout of information from the data cards prepared for Run 1. Other runs have the same figures, except for card number 16 and 17, which represent the market demands and maximum capacities for the locations respectively.

Step 15 and 16. Table 20 is a summary of the results of the runs carried out. Location 6 is observed to be selected in every run. As expected, the value of the objective function is lowest when the capacity of the branch plant is set at its lowest limit. However, a further look at the cost structure indicates that the variable cost per unit under such a capacity is very high. What has made the value of the objective function increase when the capacity of the branch plant is enlarged, is the facility cost.

Furthermore, if the capacity of the branch is set at its lower limit, all three plants in the system have to be operated at full capacity in order to meet the demand.

The above two facts, together with other factors outside this study, may give the user reason to initiate a branch plant with a capacity much larger than the lower limit. One such factor may be the trend of the demand forecast. If the market demand is observed to increase at a rapid rate, it is highly likely that the user will prefer

Card No.

```
 1     2  7 12   8  7 12 17  126.750.75 49.0  100
 2         0     1.60     .77     .50    1.01     .77     .62    1.82     .59     .50
 3       .63      .47
 4      1.60        0    2.17    1.72     .84    1.41    2.01     .28    1.02    1.49
 5      1.85     1.30
 6       .77     2.17       0     .45    1.42     .99     .15    2.25    1.29     .70
 7       .32     1.10
 8       .50     1.72     .45       0     .96     .53     .35    1.79     .85     .24
 9       .13      .96
10      1.01      .84    1.42     .96       0     .60    1.25     .89     .56     .72
11      1.10     1.51
12       .77     1.41     .99     .53     .60       0     .88    1.43     .68     .29
13       .67     1.24
14       .62     2.01     .15     .35    1.25     .88       0    2.12    1.14     .58
15       .26      .94
16    7000  5900  7050  3000  6250  6300  6000  6000  5500  5500  6000  5500
17     30000   30000   40000   35000   35000   35000   50000
18       0.30       0.36
19          0           0        2000       1800       1900       1600       2200
20          0           0        0.15       0.10       0.12       0.10       0.15
21     688.3   689.8   688.1   682.4   688.3   685.3   686.8   686.8
22     622.4   623.2   621.0   616.5   621.7   617.9   619.4   620.2
23     647.0   648.2   645.2   641.5   646.7   644.0   644.8   645.2
24     605.0   606.5   603.8   599.4   605.0   602.0   603.5   603.2
25     689.1   689.8   687.7   683.2   688.3   685.7   686.5   686.8
26         0       0    .368    .346    .352    .360    .368
27       750     188     614    7875    1850    1400    7000    1750
28         1       1       1       2       2       2       2
29     463.5   499.2   503.9     6.3     7.7     7.9     8.3
30     379.3   413.2   419.8     6.3     6.6     7.5     7.5
31     421.4   455.5   461.1     6.0     6.3     6.9     7.3
32     379.3   412.7   419.0     6.0     6.3     7.3     7.3
33     463.5   496.8   503.9     6.2     6.5     7.5     7.5
34       0   27  227   0    3    4    5
35      20   60  500   1    6    7    8
36      33  100  833   0    6    7    8
37      67  200 1667   1    6    7    8
38     133  400 3333   1    7    8    9
39     200  600 5000   0    8   10   10
40     800 240020000   1    8   10   10
41     400 120010000   1    8   10   10
42     667 200016667   1    8   10   10
43     200  600 5000   1    8   10   10
44       6   17  139   0    0    3    4
45       0    0    0   1    8   10   10
46     400 120010000   1    8   10   10
47     800 240020000   1    8   10   10
48       0    0    0   1    8   10   10
49       0    0    0   1    8   10   10
50       0    0    0   1    8   10   10
51     800  1400 12000  3600  1800  1600  2400
52       0.0015.0025.0009.0060.0080.0080
53       0.0015.0025.0009.0058.0086.0088
54       0.0014.0024.0008.0050.0080.0080
55       0.0015.0025.0009.0055.0085.0085
56       0.0015.0025.0009.0060.0080.0080
```

Figure 4a. Printout of Information from Data Cards

Card No.

```
 57          0     1     2     3     4     5     6     7     8     0     0     0
 58       2500    50    50    50    50    50    50    50    50   500  2000  5000
 59        .10    80   100    40    30    40    40    60    40   .05    .2   .01
 60       7 1 2 3 6 41011
 61       6 1 3 4 71011
 62       5 1 3 41011
 63       7 1 8 3 2 41011
 64      11 1 5 4 9 4 2 6 4 61011
 65       5 1 3 41011
 66       6 1 8 3 51011
 67       4 1 31011
 68       4 1 31011
 69       5 1 2 41011
 70       5 1 3 61011
 71       4 1 61011
 72       4 1 31011
 73       5 1 3 21011
 74       4 1 61011
 75       4 1 61011
 76       4 1 61011
 77       2 1 1 1 1 1 1 1 1 2 2 3
 78        6000       0       0  3000  2800  2600  2600  2600  2600  2600  2600  2600
 79           0    6000       0  2500  2500  2000  2000  2000  2000  2000  2000  2000
 80           0
 81           0       0       0
 82           0       0       0
 83           0       0       0
 84           0       0    6000       0   500  1200  1800  1400   900   900  1400   900
 85       1 1 0 0 1 0 0
 86       1
 87       1
 88       1
 89       1
 90       1
 91       1
 92       1
 93       1
 94       1
 95       1
 96       1
 97       1
 98       1
 99       1
100       1
101       1
102       1
@PRT FACILITY,MAIN
```

Figure 4b. Printout of Information from Data Cards

Table 20. Summary of the Computer Runs

Run No.	Input Characteristics: Demand Pattern	Total Demand	Capacity Constraint	Output: Location Selected	Total Variable Cost V	Facility Cost of Branch Plant A	Objective Function Value Z	Capacity of Existing Plants 1	Capacity of Existing Plants 2	Capacity of Branch Plant G
1	All at Means	70,000	Free to Vary	6	53,515.37	221,898.50	275,413.87	30,000	11,900	28,100
2	All at Upper Limits	75,150	Free to Vary	6	57,639.62	250,243.29	307,882.91	30,000	12,700	32,450
3	All at Means	70,000	Fixed at 10,000	6	62,736.26	105,474.10	168,210.36	30,000	30,000	10,000
4	All at Upper Limits	75,150	Fixed at 15,150	6	65,239.37	137,968.00	203,207.36	30,000	30,000	15,150
5	D1 Upper Limit All Others at Means	70,600	Free to Vary	6	53,785.47	226,932.60	280,718.07	30,000	11,900	28,700
6	D3 Upper Limit All Others at Means	70,750	Free to Vary	6	54,430.52	227,530.50	281,961.02	30,000	11,900	28,850
7	D6 Upper Limit All Others at Means	70,400	Free to Vary	6	53,659.57	225,503.90	279,163.47	30,000	11,900	28,500

8	D7 Upper Limit All Others at Means	70,600	Free to Vary	6	54,157.47	226,932.60	281,090.07	30,000	11,900	28,700
9	D8 Upper Limit All Others at Means	70,500	Free to Vary	6	53,835.37	221,898.50	275,733.87	30,000	12,400	28,100
10	D10 Upper Limit All Others at Means	70,700	Free to Vary	6	53,970.50	226,912.20	280,882.70	30,000	11,900	28,800

a branch plant with higher capacity. Since having the branch plant with a low capacity would imply that all three plants operated at almost full capacity; this would not allow much room for further expansion beyond the planning horizon. If the market demand grows slowly, large scale expansion is not likely to occur and a smaller capacity may be enough.

One other advantage of setting a high capacity for the branch plant is that in case the market demand declines in the future, one of the presently existing plants which has the highest production cost may be closed down and a huge overhead cost can be saved. Of course, this is based on the assumption that the branch plant initiated under the IODP will have a production cost lower than that of the existing plants.

As mentioned previously, the results shown in Table 20 serve only as a means at helping the user. The capacity is left to the decision of the user; and a final run may be required if the capacity determined is different from that shown in Table 20.

Figures 5 and 6 show the results obtained from Run 1. The user must adjust the layout shown in Figure 22 into the building configuration desired.

**** ITERATION NO. 4 ****

BRANCH PLANT IS BUILT AT LOCATION: 6

CAPACITY OF BRANCH PLANT IS 28100

SIZE OF BRANCH PLANT IS 45373 SQ.FT.

DISTRIBUTION MATRIX:COL-SOURCE

MARKET: 1	7000	0	0	0	0	0	0
MARKET: 2	0	5900	0	0	0	0	0
MARKET: 3	7050	0	0	0	0	0	0
MARKET: 4	0	0	0	0	0	3000	0
MARKET: 5	0	0	0	0	0	6250	0
MARKET: 6	0	0	0	0	0	6300	0
MARKET: 7	6000	0	0	0	0	0	0
MARKET: 8	0	6000	0	0	0	0	0
MARKET: 9	4450	0	0	0	0	1050	0
MARKET:10	0	0	0	0	0	5500	0
MARKET:11	0	0	0	0	0	6000	0
MARKET:12	5500	0	0	0	0	0	0

NO. OF MACHINE 1 USED IS 44

NO. OF MACHINE 2 USED IS 156

NO. OF MACHINE 3 USED IS 52

NO. OF MACHINE 4 USED IS 10

NO. OF MACHINE 5 USED IS 21

NO. OF MACHINE 6 USED IS 26

NO. OF MACHINE 7 USED IS 10

NO. OF MACHINE 8 USED IS 22

Figure 5a. Printout of the Final Iteration of Run 1

```
PART  1 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  3
PART  2 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  3
PART  3 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  3
PART  4 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  3
PART  5 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  3
PART  6 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  3
PART  7 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  2
PART  8 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  2
PART  9 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  2
PART 10 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  2
PART 11 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  3
PART 12 IS HANDLED BY  1 SYSTEMS OF CONTINUOUS TYPE EQUIPMENT NO.  4 TOTAL OF      236 FEET
PART 13 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  2
PART 14 IS HANDLED BY      1  UNITS OF DISCRETE TYPE EQUIPMENT NO.  2
PART 15 IS HANDLED BY  1 SYSTEMS OF CONTINUOUS TYPE EQUIPMENT NO.  4 TOTAL OF      236 FEET
PART 16 IS HANDLED BY  1 SYSTEMS OF CONTINUOUS TYPE EQUIPMENT NO.  4 TOTAL OF      236 FEET
PART 17 IS HANDLED BY  1 SYSTEMS OF CONTINUOUS TYPE EQUIPMENT NO.  4 TOTAL OF      236 FEET
```

VARIABLE COST MATRIX:COL-SOURCE,ROW-MARKET

MARKET: 1	.38	1.96	1.14	.85	1.36	1.13	.99
MARKET: 2	1.98	.36	2.54	2.07	1.19	1.77	2.38
MARKET: 3	1.15	2.53	.37	.60	1.77	1.35	.52
MARKET: 4	.88	2.09	.82	.35	1.31	.69	.72
MARKET: 5	1.39	1.20	1.79	1.31	.35	.96	1.62
MARKET: 6	1.15	1.77	1.36	.88	.95	.36	1.25
MARKET: 7	1.00	2.37	.52	.70	1.60	1.24	.37
MARKET: 8	2.20	.64	2.62	2.14	1.24	1.79	2.49

Figure 5b. Printout of the Final Iteration of Run 1

MARKET: 9	.97	1.38	1.66	1.20	.91	1.04	1.51
MARKET:10	.83	1.65	1.07	.59	1.07	.65	.95
MARKET:11	1.01	2.21	.69	.48	1.45	1.03	.63
MARKET:12	.85	1.66	1.47	1.31	1.86	1.60	1.31

FIXED COST AT EACH LOCATION

.00	.00	254024.54	227923.59	237589.15	221898.50	253945.54

DISTANCE IN FEET BETWEEN DEPARTMENTS

DEPT: 1	.0	76.9	102.2	145.1	140.1	106.8	182.2	118.2	188.8	176.3	230.0	259.8
DEPT: 2	76.9	.0	136.8	83.6	63.2	51.5	105.3	119.6	119.4	99.4	153.6	182.8
DEPT: 3	102.2	136.8	.0	120.7	115.8	85.4	157.9	74.0	164.5	152.0	206.3	235.4
DEPT: 4	145.1	83.6	120.7	.0	53.5	42.8	37.2	187.7	43.7	96.6	151.9	114.7
DEPT: 5	140.1	63.2	115.8	53.5	.0	37.8	42.1	182.8	89.2	43.1	98.5	110.7
DEPT: 6	106.8	51.5	85.4	42.8	37.8	.0	80.0	144.9	86.5	74.0	128.3	157.5
DEPT: 7	182.2	105.3	157.9	37.2	42.1	80.0	.0	224.9	65.5	66.8	122.2	77.5
DEPT: 8	118.2	119.6	74.0	187.7	182.8	144.9	224.9	.0	231.5	219.0	273.2	302.4
DEPT: 9	188.8	119.4	164.5	43.7	89.2	86.5	65.5	231.5	.0	132.3	187.7	71.0
DEPT:10	176.3	99.4	152.0	96.6	43.1	74.0	66.8	219.0	132.3	.0	55.3	98.8
DEPT:11	230.0	153.6	206.3	151.9	98.5	128.3	122.2	273.2	187.7	55.3	.0	154.1
DEPT:12	259.8	182.8	235.4	114.7	110.7	157.5	77.5	302.4	71.0	98.8	154.1	.0

Figure 5c. Printout of the Final Iteration of Run 1

AREA REQUIREMENTS FOR EACH DEPARTMENT

5309 3570 15650 2130 350 890 1090 650 930 1904 7619 5281

FROM-TO-CHART OF TOTAL COST FLOW IN DOLLARS PER FOOT

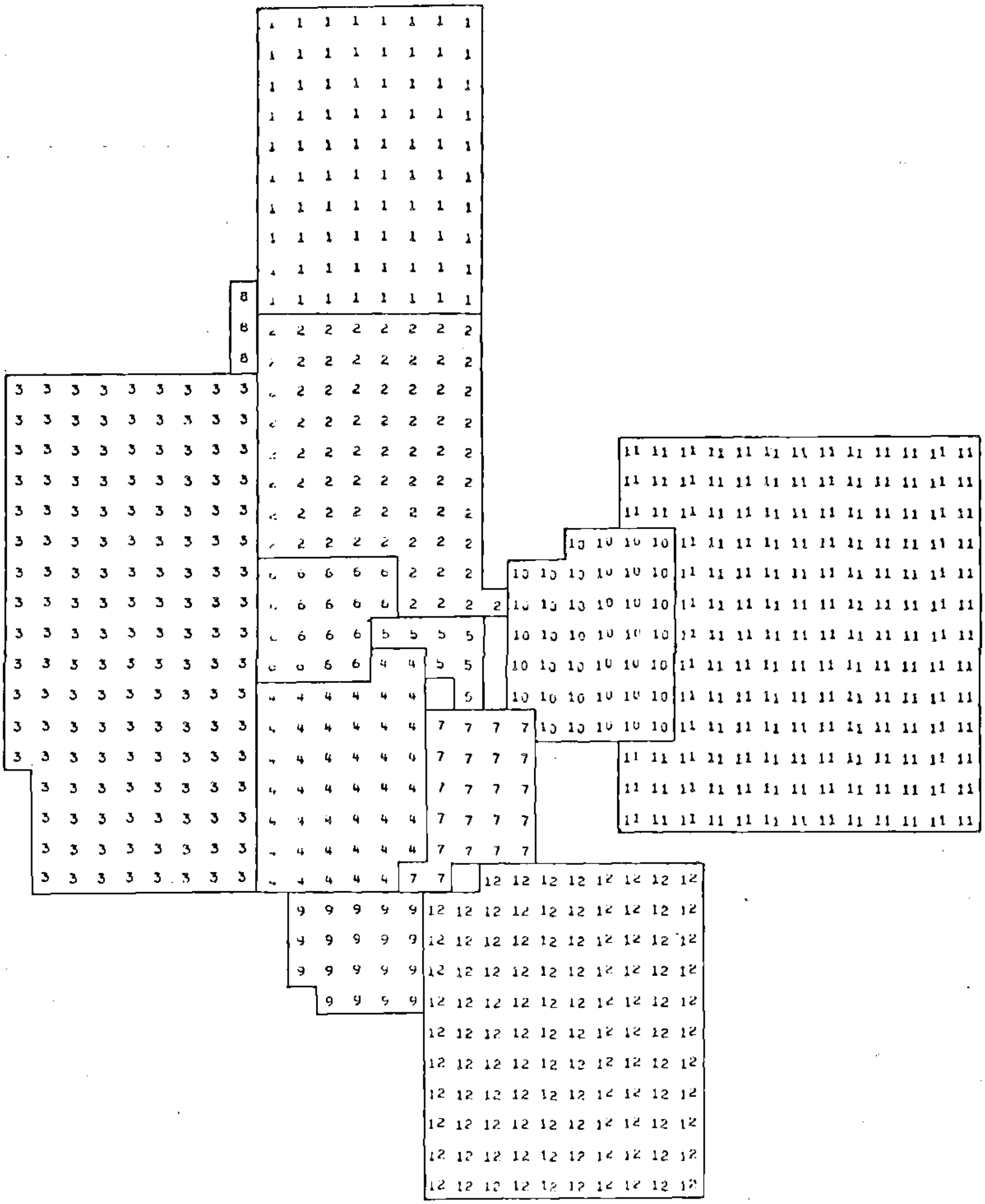
DEPT: 1	.0000	2.1727	7.6804	.0000	.6641	23.9860	.0000	1.7582	.0000	.0000	.0000	.0000
DEPT: 2	.0000	.0000	.8515	2.0638	.0000	.6641	.0000	.0000	.0000	.8534	.0000	.0000
DEPT: 3	.0000	1.5959	.0000	2.6924	1.0156	1.8862	.0000	.0000	.0000	3.0999	.0000	.0000
DEPT: 4	.0000	.6641	.0000	.0000	.0000	.6641	.8886	.0000	.6641	4.7190	.0000	.0000
DEPT: 5	.0000	.0000	.0000	.6641	.0000	.0000	.0000	.0000	.0000	1.0156	.0000	.0000
DEPT: 6	.0000	.0000	.0000	1.5156	.0000	.0000	.0000	.0000	.0000	25.6849	.0000	.0000
DEPT: 7	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.8886	.0000	.0000
DEPT: 8	.0000	.0000	1.7582	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
DEPT: 9	.0000	.0000	.0000	.6641	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
DEPT:10	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	36.2614	.0000
DEPT:11	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
DEPT:12	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000

TOTAL VARIABLE COST: 53515.37

FACILITY COST 221898.50

$$$$$$$ OBJECTIVE FUNCTION VALUE = 275413.87

Figure 5d. Printout of the Final Iteration of Run 1



THE ORDER OF PLACEMENT WAS 3 6 4 2 7 8 5 9 10 11 1 12

Figure 6. Layout Resulted from Run 1

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The contribution of this study is the integration of the major activities in facilities planning into a unique system. However, the process does not pretend to provide a solution set with exact numerical figures. Flexibility in decision making has been emphasized in the form of applying various allowance factors throughout the process. Accuracy of such factors will depend on the users experience and technical knowledge.

Seven factors have been included in the solution set defined for the problem studied. The major shortcoming of the IODP falls on the capacity factor. It has been found that if the capacity of the branch plant is predetermined, a near-optimal solution can be guaranteed; but if the capacity is allowed to vary, there is no guarantee of an optimal solution and it is possible for cycling to occur. Based on the above observation, the following conclusions are reached from this study:

1. Given the capacity of the branch plant to be established, the IODP can be used to obtain a near-optimal solution set including (a) plant site, (b) distribution pattern, (c) floor area, (d) number of manufacturing equipment, (e) number and type of materials handling equipment and (f) plant layout.
2. If the capacity of the branch plant is not predetermined,

the IODP can help the user to make a decision on the capacity by providing useful information on the optimal plant site and costs under specific capacities. After the capacity has been fixed, the final run using the determined capacity would then give the near-optimal solution.

Recommendations for Further Study

The following suggestions are outlined for extension of this work:

1. The IODP assumes that every part is moved by one type of equipment throughout the manufacturing process. Enforcing such a condition may not always be economical or even possible. It may be also reasonable to consider movements between two departments done by a single type or combination of materials handling equipment.
2. Treat the allowance factors more precisely such as assigning a different allowance factor for every machine or piece of equipment. Also when the exact number of a piece of materials handling equipment used is less than 0.5, the equipment may be used to handle other parts in order not to permit the equipment to be idle too much.
3. Develop an efficient search procedure, which allows the user to make use of the IODP to get an optimal capacity; or develop a model which will guarantee optimal capacity.
4. Include the stochastic behavior of the market demands implicitly in the model.
5. Modify the model to fit a multi-product plant.

6. Consider the problem of initiating more than one branch plant at the same time.
7. Consider a plant with a multi-storied building.
8. Application of the model to environments other than production, such as in hospitals or urban planning.

APPENDICES

APPENDIX A

PREPARATION OF INPUT

The input data consist of twelve single variables and twenty-three dimensional variables. Table 21 shows the format for the first card which includes all the twelve single variables. Table 22 shows the format for the dimensional variables. The user is expected to have a basic knowledge of the format statements of FORTRAN programming. Definitions of the symbols have been shown in Table 2, 4 and 5.

Table 21. Format of the First Card

Column	Symbol	Computer Code	Format
1-3	E	EXIS	I3
4-6	I	INO	I3
7-9	J	JNO	I3
10-12	M	MNO	I3
13-15	N	NNO	I3
16-18	K	KNO	I3
19-21	T	TNO	I3
22-25	θ	HOUR	I4
26-29	η_1	F1	F4.0
30-33	η_2	F2	F4.0
34-38	-	BSIZE	F5.0
39-43	-	DISINT	F5.0

Table 22. Format of the Data Cards

Symbol	Computer Code	Format on Each Card	Arrangement on the Cards
C_{ij}	CTRAN(I,J)	10F8.0	$C_{1,1};C_{1,2};\ldots;C_{1,10}$
			$C_{1,11};\ldots;C_{1,J}$
			$C_{2,1};C_{2,2};\ldots;C_{2,10}$
			$C_{2,11};\ldots;C_{2,J}$
			$\vdots$
			$C_{I,1};C_{I,2};\ldots;C_{I,10}$
			$C_{I,11};\ldots;C_{I,J}$
D_j	DEM(J)	13I6	$D_1,D_2,\ldots,D_{13}$
			$D_{14},D_{15},\ldots,D_J$
g_i	CAP(I)	10I8	$g_1,g_2,\ldots,g_{10}$
			$g_{11},g_{12},\ldots,g_I$
r_i	OPINIT(I)	8F10.0	$r_1,r_2,\ldots,r_E$
Φ_i	PLB(I)	8F10.0	$\Phi_1,\Phi_2,\ldots,\Phi_8$
			$\Phi_9,\Phi_{10},\ldots,\Phi_I$
Ψ_i	PLV(I)	8F10.0	$\Psi_1,\Psi_2,\ldots,\Psi_8$
			$\Psi_9,\Psi_{10},\ldots,\Psi_I$

P_{im}	FMACH(I,M)	10F8.0	$P_{E+1,1};P_{E+1,2};\ldots;P_{E+1,10}$ $P_{E+1,11};\ldots;P_{E+1,M}$ $P_{E+2,1};P_{E+2,2};\ldots;P_{E+2,10}$ $P_{E+2,11};\ldots;P_{E+2,M}$ $\vdots$ $P_{I,1};P_{I,2};\ldots;P_{I,10}$ $P_{I,11};\ldots;P_{I,M}$
p_i	CPRO(I)	10F8.0	$p_1,p_2,\ldots,p_{10}$ $p_{11},\ldots,p_I$
σ_m	MNUM(M)	10I8	$\sigma_1,\sigma_2,\ldots,\sigma_{10}$ $\sigma_{11},\ldots,\sigma_M$
-	IDEQ(N)	10I8	$IDEQ_1,IDEQ_2,\ldots,IDEQ_{10}$ $IDEQ_{11},\ldots,IDEQ_N$
Q_{in}	FEQP(I,N)	10F8.0	$Q_{E+1,1};Q_{E+1,2};\ldots;Q_{E+1,10}$ $Q_{E+1,11};\ldots;Q_{E+1,N}$ $Q_{E+2,1};Q_{E+2,2};\ldots;Q_{E+2,10}$ $Q_{E+2,11};\ldots;Q_{E+2,N}$ $\vdots$ $Q_{I,1};Q_{I,2};\ldots;Q_{J,10}$ $Q_{I,11};\ldots;Q_{I,N}$

ρ_{tn}	UNIT(T,N)	16I5	$\rho_{1,1};\rho_{1,2};\ldots;\rho_{1,16}$
			$\rho_{1,17};\ldots;\rho_{1,N}$
			$\rho_{2,1};\rho_{2,2};\ldots;\rho_{2,16}$
			$\rho_{2,17};\ldots;\rho_{2,N}$
			$\vdots$
			$\rho_{T,1};\rho_{T,2};\ldots;\rho_{T,16}$
			$\rho_{T,17};\ldots;\rho_{T,N}$
λ_n	RATE(N)	13I6	$\lambda_1,\lambda_2,\ldots,\lambda_{13}$
			$\lambda_{14},\ldots,\lambda_N$
u_{im}	CMV(I,N)	16F5.0	$u_{E+1,1};u_{E+1,2};\ldots;u_{E+1,16}$
			$u_{E+1,17};\ldots;u_{E+1,N}$
			$u_{E+2,1};u_{E+2,2};\ldots;u_{E+2,16}$
			$u_{E+2,17};\ldots;u_{E+2,N}$
			$\vdots$
			$u_{I,1};u_{I,2};\ldots;u_{I,16}$
			$u_{I,17};\ldots;u_{I,N}$
-	INDEX(K)	16I5	$INDEX_1,INDEX_2,\ldots,INDEX_{16}$
			$INDEX_{17},\ldots,INDEX_K$
β_k	SPA(K)	16I5	$\beta_1,\beta_2,\ldots,\beta_{16}$
			$\beta_{17},\ldots,\beta_K$

δ_k	SPB(K)	16F5.0	$\delta_1, \delta_2, \ldots, \delta_{16}$ $\delta_{17}, \ldots, \delta_K$
-	NSQ(T), MVSQ(T,L)	40I2	$NSQ_1, MVSQ_{1,1}; MVSQ_{1,2}; \ldots; MVSQ_{1,NSQ_1}$ $NSQ_q, MVSQ_{2,1}; MVSQ_{2,2}; \ldots; MVSQ_{2,NSQ_2}$ ⋮ $NSQ_T, MVSQ_{T,1}; MVSQ_{T,2}; \ldots; MVSQ_{T,NSQ_T}$
-	KPRIOR(K)	40I2	$KPRIOR_1, KPRIOR_2, \ldots, KPRIOR_K$
x_{ij}	XDIS(I,J)	13I6	$x_{1,1}; x_{1,2}; \ldots; x_{1,13}$ $x_{1,14}; \ldots; x_{1,J}$ $x_{2,1}; x_{2,2}; \ldots; x_{2,13}$ $x_{2,14}; \ldots; x_{2,J}$ ⋮ $x_{I,1}; x_{I,2}; \ldots; x_{I,13}$ $x_{I,14}; \ldots; x_{I,J}$
y_i	Y(I)	40I2	$y_1, y_2, \ldots, y_I$
z_{tn}	Z(T,N)	40I2	$z_{1,1}; z_{1,2}; \ldots; z_{1,N}$ $z_{2,1}; z_{2,2}; \ldots; z_{2,N}$ ⋮ $z_{T,1}; z_{T,2}; \ldots; z_{T,N}$

APPENDIX B

LISTING OF FORTRAN PROGRAM

```
C*******************************
C                             *
C      THE MASTER PROGRAM     *
C                             *
C*******************************
      COMMON/LOC1/EXIS,VAR,INF
      COMMON/LOC2/CAP,DEM,INO,JNO
      COMMON/LOC3/XDIS
      COMMON/LOC4/Y
      COMMON/LAY/DIST(20,20)
     *       /LAY1/KNO,BSIZE,AREA
     *       /LAY2/TLYST,NDILAY,NDPAVL,LISTOR(99)
      COMMON/BLKA/CLAY(20,20)
     *       /BLKE/KPRIOR(20)
     *       /BLKC/ LAYOUT(100,100),MAXI,MAXJ,MINI,MINJ
     *       /BLKG/ KSYM(99),BLANK
      COMMON/EQ/EQUIP(20,20),Z,INO,NNO
      INTEGER UNIT(20,20),RATE(20),SPA(20),MNUM(20),
     *        MZ(20),NSQ(20),M VSQ(20,39),X(25),
     *        W(20,20,20),NMACH(20),VT(20,20),
     *        AREA(20),E,I,J,M,N,K,T,HOUR,CAPAC,SIZE,NEQ(20,20) ,
     *        Z(20,20),KEQ(20,20),INO
      INTEGER*4 EXIS,INF(25),CAP(25),DEM(50),INO,JNO,XDIS(25,50)
     *,Y*2(25)
      DIMENSION CTRAN(25,50),PLB(25),PLV(25),FMACH(25,20),
     *          FEQP(25,20),CMV(25,20),SPB(20),CPRO(25),FPRO(25),
     *          TD(20),FBLD(25),FQ(20),CMOV(20),CHD(20,20),
     *          CFLOW(20,20),FNN(20),INDEX(20),IDEQ(20)
     *          ,FFF(25),FHDL(25),OPINIT(25)
      REAL*4 VAR(25,50)
 1000 FORMAT (7I3,I4,2F4.0,F5.0,F5.0)
 1001 FORMAT (10F8.0)
 1002 FORMAT (13I6)
 1003 FORMAT (10I8)
 1004 FORMAT (6F10.0)
 1005 FORMAT (26I3)
 1006 FORMAT (16I5)
 1007 FORMAT (16F5.0)
 1008 FORMAT (20I4)
 1009 FORMAT (40I2)
 1010 FORMAT (1H1,////10X,'**** ITERATION NO.',I2,' ****'//)
 1011 FORMAT (////10X,'****** PROGRAM TERMINATED ******'/10X,'PROBLEM CO
     *NVERGES TOO SLOW,MAXIMUN NO. OF ITERATIONS REACHED')
 1500 FORMAT (1H0,'BRANCH PLANT IS BUILT AT LOCATION: ',I2)
 1501 FORMAT (1H0,'CAPACITY OF BRANCH PLANT IS ',I8)
 1502 FORMAT (1H0,'SIZE OF BRANCH PLANT IS ',I8,' SQ.FT.'/)
 1503 FORMAT (1H ,'NO. OF MACHINE ',I2,' USED IS ',I6/)
 1504 FORMAT (1H0,'PART ',I2,' IS HANDLED BY',I6,'  UNITS OF DISCRETE TY
     *PE EQUIPMENT NO. ',I2)
```

```
 1505 FORMAT (1H0,'PART ',I2,' IS HANDLED BY',I3,' SYSTEMS OF CONTINUOUS
     * TYPE EQUIPMENT NO. ',I2,' TOTAL OF ',I7,' FEET')
 2000 FORMAT (1H0,4X,'VARIABLE COST MATRIX:COL-SOURCE,ROW-MARKET')
 2001 FORMAT (1H0,1X,'MARKET:',I2,2X,11(F8.2,2X),4(/12X,11(F8.2,2X)))
 2003 FORMAT (///4X,'FIXED COST AT EACH LOCATION'/3(/5X,10(F10.2,2X)))
 2004 FORMAT (///4X,'EQUIPMENT COST MATRIX:COL-EQUIPMENT,ROW-PART')
 2006 FORMAT (1H0,1X,'DEPT:',I2,2X,10(F8.1,2X)/10X,10(F8.1,2X))
 2007 FORMAT (///4X,'AREA REQUIRMENTS FOR EACH DEPARTMENT'//2X,17
     *(I5,2X)/2X,17(I5,2X))
 2008 FORMAT (///4X,'FROM-TO-CHART OF TOTAL COST FLOW IN DOLLARS PER FOO
     *T')
 2009 FORMAT (1H0,1X,'DEPT:',I2,2X,11(F8.4,2X)/10X,11(F8.4,2X))
 2010 FORMAT (1H0,'$$$$$$$$    OBJECTIVE FUNCTION VALUE :',F14.2)
 2012 FORMAT (////10X,'*******************************'/10X,
     *'* OPTIMAL SOLUTION IS ARRIVED *'/10X,'**************************
     *****')
 2017 FORMAT (///4X,'DISTANCE IN FEET BETWEEN DEPARTMENTS')
 2025 FORMAT (1H0,'TOTAL VARIABLE COST:',F12.2//1X,'FACILITY COST',F12.2
     *)
 2026 FORMAT (1H0,1X,'MARKET:',I2,2X,11(I8,2X),4(/12X,11(I8,2X)))
 2027 FORMAT (1H0,4X,'DISTRIBUTION MATRIX:COL-SOURCE')
C
C---READ IN ALL FIXED VARIABLES FOR THE MODEL---
C
      OLDTAL=999999999.0
      ITER=0
    1 READ (5,1000) EXIS,INO,JNO,MNO,NNO,KNO,TNO,HOUR,F1,F2,BSIZE
     *,DISINT
      LL=EXIS+1
      DO 3 I=1,INO
    3 READ (5,1001)(CTRAN(I,J),J=1,JNO)
      READ (5,1002) (DEM(J),J=1,JNO)
      READ (5,1003) (CAP(I),I=1,INO)
      READ (5,1004) (OPINIT(I),I=1,EXIS)
      READ (5,1004) (PLB(I),I=1,INO)
      READ (5,1004) (PLV(I),I=1,INO)
      DO 4 I=LL,INO
    4 READ (5,1001) (FMACH(I,M),M=1,MNO)
      READ (5,1001) (CPRO(I),I=1,INO)
      READ (5,1003) (MNUM(M),M=1,MNO)
      READ (5,1003) (IDEQ(N),N=1,NNO)
      DO 8 I=LL,INO
    8 READ (5,1001) (FEQP(I,N),N=1,NNO)
      DO 10 T=1,TNO
   10 READ (5,1006) (UNIT(T,N),N=1,NNO)
      READ(5,1002) (RATE(N),N=1,NNO)
      DO 12 I=LL,INO
   12 READ (5,1007) (CMV(I,N),N=1,NNO)
      READ (5,1006) (INDEX(K),K=1,KNO)
      READ (5,1006) (SPA(K),K=1,KNO)
      READ (5,1007) (SPB(K),K=1,KNO)
      DO 14 T=1,TNO
   14 READ (5,1009) NSQ(T),(MVSQ(T,L),L=1,39)
      READ (5,1009) (KPRIOR(K),K=1,KNO)
C
C---READ IN THE INITIAL SOLUTIONS---
C
```

```
      DO 21 I=1,INO
   21 READ (5,1002) (XDIS(I,J),J=1,JNO)
      READ (5,1009) (Y(I),I=1,INO)
      DO 23 T=1,TNO
   23 READ (5,1009) (Z(T,N),N=1,NNO)
      DO 27 E=1,KNO
      DO 26 L=1,KNO
      IF(E.NE.L) GO TO 24
      DIST(E,L)=0
      DIST(L,E)=0
      GO TO 26
   24 DIST(E,L)=DISINT
      DIST(L,E)=DISINT
   26 CONTINUE
   27 CONTINUE
   30 DO 29 I=1,EXIS
      DO 28 J=1,JNO
   28 VAR(I,J)=CTRAN(I,J)+OPINIT(I)
   29 CONTINUE
      ICN=0
C
C---THE MASTER PROGRAM BEGINS---
C
C---FIRST TRANSFER THE FLOW SEQUENCE INTO 0,1 VARIABLES---
C
      WRITE (6,1010)ITER
      DO 33 T=1,TNO
      DO 32 E=1,KNO
      DO 31 L=1,KNO
   31 W(T,E,L)=0
   32 CONTINUE
   33 CONTINUE
      DO 35 T=1,TNO
      NN=NSQ(T)-1
      DO 34 MM=1,NN
      E=MVSQ(T,MM)
      L=MVSQ(T,MM+1)
   34 W(T,E,L)=1
   35 CONTINUE
C
C---EQ.(M1)---
C
      DO 41 I=1,INO
      X(I)=0
      DO 40 J=1,JNO
   40 X(I)=X(I)+XDIS(I,J)
   41 CONTINUE
      CAPAC=0
      DO 42 I=LL,INO
   42 CAPAC=CAPAC+X(I)
C
C
C---EQ.(M2)---
C
      DO 44 M=1,MNO
   44 NMACH(M)=(FLOAT(CAPAC)/MNUM(M))+F1
C
```

```
C---EQ.(M12)---
C
      DO 47 N=1,NNO
      CMOV(N)=0
      DO 46 I=LL,INO
   46 CMOV(N)=CMOV(N)+CMV(I,N)*Y(I)
   47 CONTINUE
C
C---EQ.(M6)---
C
      DO 63 I=LL,INO
      FPRO(I)=0
      DO 62 M=1,MNO
   62 FPRO(I)=FPRO(I)+FMACH(I,M)*NMACH(M)
   63 CONTINUE
C
C---EQ.(M3)---
C
      DO 72 K=1,KNO
      IF (INDEX(K).EQ.0) GO TO 71
      MMU=INDEX(K)
      AREA(K)=SPA(K)+SPB(K)*NMACH(MMU)
      GO TO 72
   71 AREA(K)=SPA(K)+SPB(K)*CAPAC
   72 CONTINUE
C
C---EQ.(M4)---
C
      SIZE=0
      DO 74 K=1,KNO
   74 SIZE=SIZE+AREA(K)
C
C---EQ.(M5)---
C
      DO 76 I=LL,INO
   76 FBLD(I)=FLV(I)*SIZE
C
C---EQ.(M8)---
C
  400 DO 403 T=1,TNO
      TD(T)=0
      DO 402 E=1,KNO
      DO 401 L=1,KNO
  401 TD(T)=TD(T)+DIST(E,L)*W(T,E,L)
  402 CONTINUE
  403 CONTINUE
C
C---EQ.(M9,M10,M11)---
C
      DO 90 N=1,NNO
      IF(IDEQ(N).EQ.2) GO TO 83
C
C---FOR DISCRETE TYPE EQUIPMENT---
C
      DO 82 T=1,TNO
      NEQ(T,N)=0
      IF(UNIT(T,N).EQ.0) GO TO 82
```

```
      VT(T,N)=FLOAT(CAPAC)/UNIT(T,N)+0.5
      NEQ(T,N)=((FLOAT(VT(T,N))*TD(T))/(FLOAT(HOUR)*RATE(N)))+F2
      IF(NEQ(T,N).EQ.0)NEQ(T,N)=1
   82 CONTINUE
      GO TO 90
C
C---FOR CONTINUOUS TYPE EQUIPMENT---
C
   83 DO 86 T=1,TNO
      KEQ(T,N)=0
      NEQ(T,N)=0
      IF(UNIT(T,N).EQ.0) GO TO 86
      KEQ(T,N)=FLOAT(CAPAC)/(HOUR*(RATE(N)*UNIT(T,N)))+F2
      IF(KEQ(T,N).EQ.0)KEQ(T,N)=1
      VT(T,N)=KEQ(T,N)*FLOAT(HOUR)/(TD(T)/RATE(N))+0.5
      NEQ(T,N)=KEQ(T,N)*TD(T)+0.5
   86 CONTINUE
   90 CONTINUE
C
C---EQ.(M7)---
C
      DO 93 N=1,NNO
      FQ(N)=0
      DO 92 I=LL,INO
   92 FQ(N)=FQ(N)+FEQP(I,N)*Y(I)
   93 CONTINUE
C
C---EQ.(M13)---
C
      DO 109 T=1,TNO
      DO 108 N=1,NNO
      CHD(T,N)=CMOV(N)*VT(T,N)*(TD(T)/100)
  108 CONTINUE
  109 CONTINUE
C
C---EQ.(M14)---
C
      DO 123 T=1,TNO
      DO 122 N=1,NNO
      IF(Z(T,N).EQ.0) GO TO 122
      FNN(T)=(CMOV(N)/100)*VT(T,N)+FQ(N)*NEQ(T,N)/TD(T)
      GO TO 123
  122 CONTINUE
  123 CONTINUE
      DO 127 E=1,KNO
      DO 126 L=1,KNO
      CFLOW(E,L)=0
      CLAY(E,L)=0
      DO 125 T=1,TNO
      CFLOW(E,L)=CFLOW(E,L)+FNN(T)*W(T,E,L)
  125 CLAY(E,L)=CLAY(E,L)+FNN(T)*W(T,E,L)
  126 CONTINUE
  127 CONTINUE
C
C ---EQ (M15)---
C
  299 DO 114 I=LL,INO
```

```
      FHDL(I)=0
      DO 113 N=1,NNO
      NZ(N)=0
      DO 112 T=1,TNO
  112 NZ(N)=NZ(N)+(NEQ(T,N)*Z(T,N))
  113 FHDL(I)=FHDL(I)+FEQP(I,N)*NZ(N)
  114 CONTINUE
C
C--- EQ(M16) ---
C
      CHDL=0
      DO 1302 T=1,TNO
      DO 1301 N=1,NNO
      CHDL=CHDL+CHD(T,N)*Z(T,N)
 1301 CONTINUE
 1302 CONTINUE
      CHDL=CHDL/CAPAC
C
      DO 300 I=LL,INO
      IF (Y(I).EQ.1) KBRAN=I
  300 CONTINUE
      WRITE (6,1500) KBRAN
      WRITE (6,1501) CAPAC
      WRITE (6,1502) SIZE
      WRITE (6,2027)
      DO 303 J=1,JNO
  303 WRITE (6,2026) J,(XDIS(I,J),I=1,INO)
      DO 301 M=1,MNO
  301 WRITE (6,1503) M,NMACH(M)
      DO 309 T=1,TNO
      DO 308 N=1,NNO
      IF(Z(T,N).EQ.0) GO TO 308
      IF(IDEQ(N).EQ.1) GO TO 304
      WRITE (6,1505) T,KEQ(T,N),N,NEQ(T,N)
      GO TO 309
  304 WRITE (6,1504) T,NEQ(T,N),N
      GO TO 309
  308 CONTINUE
  309 CONTINUE
      WRITE (6,2000)
      DO 163 I=LL,INO
      DO 162 J=1,JNO
  162 VAR(I,J)=CTRAN(I,J)+CPRO(I)+CHDL
  163 CONTINUE
      DO 165 J=1,JNO
  165 WRITE (6,2001) J,(VAR(I,J),I=1,INO)
      DO 169 I=1,INO
      FFF(I)=(FBLD(I)+FPRO(I)+FHDL(I))
  169 INF(I)=FFF(I)*100+0.5
      WRITE (6,2003) (FFF(I),I=1,INO)
      DO 173 T=1,TNO
      DO 172 N=1,NNO
  172 EQUIP(T,N)=(FQ(N)*NEQ(T,N))+CHD(T,N)
  173 CONTINUE
      WRITE (6,2017)
      DO 174 E=1,KNO
  174 WRITE (6,2006) E, (DIST(E,L),L=1,KNO)
```

```
      WRITE (6,2007) (AREA(K),K=1,KNO)
      WRITE (6,2008)
      DO 176 E=1,KNO
  176 WRITE (6,2009) E,(CFLOW(E,L),L=1,KNO)
C
C---TEST FOR OPTIMALITY
C
      VC=0
      DO 204 I=1,INO
      DO 202 J=1,JNO
  202 VC=VC+VAR(I,J)*XDIS(I,J)
  204 CONTINUE
      FC=0
      DO 211 I=LL,INO
  211 FC=FC+FFF(I)*Y(I)
  224 CONTINUE
      TOTAL=VC+FC
      WRITE (6,2025) VC,FC
      WRITE (6,2010) TOTAL
      DIFF=TOTAL-OLDTAL
      IF(DIFF) 273,280,273
  273 ITER=ITER+1
      OLDTAL=TOTAL
      IF(ITER.GT.7) GO TO 290
      DO 276 I=1,INO
      DO 275 J=1,JNO
  275 VAR(I,J)=VAR(I,J)*100
  276 CONTINUE
      CALL LOCMIN
      CALL EQMIN
      CALL LAYMIN
      DO 411 E=1,KNO
      DO 410 L=1,KNO
  410 DIST(E,L)=DIST(E,L)*SQRT(BSIZE)
  411 CONTINUE
      GO TO 30
  280 CALL OUTPUT
      WRITE(6,2012)
      STOP
  290 WRITE (6,1011)
      STOP
      END
*
*
*
*
*
C*********************************
C                               *
C     EQUIPMENT SUBPROGRAM      *
C                               *
C*********************************
      SUBROUTINE EQMIN
      COMMON/EQ/EQUIP(20,20),Z,TNO,NNO
      INTEGER T,TNO,Z(20,20)
      WRITE(6,300)
  300 FORMAT(1X,'EQUIPMENT IS CALLED')
```

```
      DO 3 T=1,TNO
      DO 2 N=1,NNO
    2 Z(T,N)=0
    3 CONTINUE
      DO 50 T=1,TNO
      I=1
    4 J=1
    5 IF(I.GT.NNO.OR.(I+J).GT.NNO) GO TO 30
      IF(EQUIP(T,I).LE.0) GO TO 25
      IF (EQUIP(T,I+J)-EQUIP(T,I)) 20,20,15
   15 KS=I
   18 J=J+1
      GO TO 5
   20 IF(EQUIP(T,I+J).LE.0) GO TO 18
      KS=I+J
      I=I+J
      GO TO 4
   25 I=I+1
      GO TO 4
   30 Z(T,KS)=1
   50 CONTINUE
      RETURN
      END
*
*
*
*
*
C*****************************
C                           *
C     LAYOUT SUBPROGRAM     *
C                           *
C*****************************
      SUBROUTINE LAYMIN
      INTEGER BLANK,AREA(20)
      COMMON /BLKA/ CSTMAT(20,20)
     *       /BLKB/ NBLKS(99)
     *       /BLKE/ KPRIOR(20)
     *       /BLKF/ KLASS(9)
     *       /BLKG/ KSYM(99),BLANK
      COMMON /LAY/DIST(20,20)
     *       /LAY1/NDPTS,BSIZE,AREA
     *       /LAY2/TLYCST,NDILAY,NUPAVL,LISTOR(99)
      DATA BLANK/2H  /
      DATA (KSYM(I),I=1,20)/2H 1,2H 2,2H 3,2H 4,2H 5,2H 6,2H 7,2H 8,2H 9,
     *,2H10,2H11,2H12,2H13,2H14,2H15,2H16,2H17,2H18,2H19,2H20/
  521 FORMAT (30X,35H NORMALIZED FLOW-BETWEEN COST CHART,15X,E14.7,///,
     *5X,15(6X,A2),/)
  522 FORMAT (/,4X,A2,15F8.4)
  523 FORMAT (5X,10H THERE ARE,I3,39H DEPARTMENTS AVAILABLE FOR ARRANGEM
     *ENT,,)
  903 FORMAT (10(3H **),4X11HDEPARTMENT ,A2,36H WILL NOT APPEAR IN THE F
     *INAL LAYOUT,3X,10(3H **),/,10(3H **),4X,51HSINCE THE AREA REQUIRED
     * FOR IT IS LESS THAN A BLOCK ,1X,10(3H **),/)
  910 FORMAT (//,66(2H *),//,84H ERROR NUMBER 010 -- THE PROGRAM HAS FOU
     *ND THE MAXIMUM COST VALUE TO BE NONPOSITIVE. ,//,66(2H *))
      WRITE (6,999)
```

```
  999 FORMAT (//1X'LAYOUT IS CALLED'/)
      KLINES = 11
C     READ AREA REQUIREMENTS FOR EACH DEPARTMENT.
      NDPOMT=0
      DO 1010 I = 1,NDPTS
 1008 NBLKS(I) = FLOAT(AREA(I)) / BSIZE + 0.5
      IF (KPRIOR(I).EQ.0) KPRIOR(I) = 1
      KLINES = KLINES + 2
      IF (NBLKS(I).GT.0) GO TO 1009
      KPRIOR(I) = -1
      NDPOMT = NDPOMT + 1
      WRITE (6,903) KSYM(I)
      KLINES = KLINES + 2
 1009 IF (KLINES.LT.50) GO TO 1010
      KLINES = 5
 1010 CONTINUE
      NDPAVL = NDPTS - NDPOMT
      DO 1015 ITHD = 1,NDPTS
      IF (KPRIOR(ITHD).EQ.-1) GO TO 1015
      DO 1014 KTH = 1,9
      IF (KPRIOR(ITHD).GT.KTH) GO TO 1014
      KLASS(KTH) = KLASS(KTH) + 1
 1014 CONTINUE
 1015 CONTINUE
C     THIS SECTION WILL TAKE THE COST CHART FROM THE PARTS LIST
C     OR THE FROM-TO CHART DATA AND NORMALIZE IT AND THEN PRINT
C     A COPY.
 1065 CONTINUE
      DO 1070 ITHD = 1,NDPTS
      DO 1069 JTHD = 1,NDPTS
      IF (CSTMAT(ITHD,JTHD).LE.CSTMAX) GO TO 1069
      CSTMAX = CSTMAT(ITHD,JTHD)
 1069 CONTINUE
 1070 CONTINUE
      IF (CSTMAX) 1071,1071,1072
 1071 WRITE (6,910)
      STOP
 1072 CONTINUE
      DO 1075 ITHD = 1,NDPTS
      DO 1075 JTHD = 1,NDPTS
 1075 CSTMAT(ITHD,JTHD) = CSTMAT(ITHD,JTHD) / CSTMAX
 1140 CONTINUE
      NDPTM1 = NDPTS - 1
      DO 1150 ITHD = 1,NDPTM1
      DO 1150 JTHD = ITHD,NDPTS
      CSTMAT(ITHD,JTHD) = CSTMAT(ITHD,JTHD) + CSTMAT(JTHD,ITHD)
 1150 CSTMAT(JTHD,ITHD) = CSTMAT(ITHD,JTHD)
      DO 1160 J = 1,NDPTS,15
      JSTART = J
      JSTOP = J + 14
      IF (JSTOP.GT.NDPTS) JSTOP = NDPTS
      DO 1160 I = 1,NDPTS,25
      ISTART = I
      ISTOP = I + 24
      IF (ISTOP.GT.NDPTS) ISTOP = NDPTS
      DO 1160 II = ISTART,ISTOP
 1160 CONTINUE
```

```
      CALL SEL3 (NDPTS)
      RETURN
      END
*
*
*
      SUBROUTINE SEL3 (NDPTS)
C     THIS SUBROUTINE SELECTS THE ENTERING DEPARTMENTS BASED ON
C     AN ORDERED LIST OF THEIR RELATION TO THE OTHER DEPARTMENTS.
      DIMENSION LIST(99),TDPCST(99)
      COMMON /BLKA/CSTMAT(20,20)
     *       /BLKD/KSTATE(99)
     *       /BLKE/KPRIOR(20)
     *       /BLKF/KLASS(9)
     *       /LAY/DIST(20,20)
     *       /LAY2/TLYCST,NDILAY,NDPAVL,LISTOR(99)
      NDILAY = 0
      DO 902 KE=1,NDPTS
      DO 900 KL=1,NDPTS
  900 DIST(KE,KL)=0
  902 CONTINUE
 1010 CALL CLEAR
      DO 1020 ITHD=1,NDPTS
      DO 1015 JTHD=1,NDPTS
 1015 TDPCST(ITHD) = TDPCST(ITHD) + CSTMAT(ITHD,JTHD)
      LIST(ITHD) = ITHD
 1020 KSTATE(ITHD) = KPRIOR(ITHD)
      LASTK = NDPTS + 1
 1026 LASTK = LASTK - 1
      DO 1030 K=2,LASTK
      I = LIST(K-1)
      J = LIST(K)
      IF (TDPCST(J).LT.TDPCST(I)) GO TO 1030
      LIST(K) = I
      LIST(K-1) = J
 1030 CONTINUE
      IF (LASTK.NE.2) GO TO 1026
      LASTK = NDPTS + 1
 1031 LASTK = LASTK - 1
      DO 1035 K=2,LASTK
      I = LIST(K-1)
      J = LIST(K)
      IF (KSTATE(J).GE.KSTATE(I)) GO TO 1035
      LIST(K-1) = J
      LIST(K) = I
 1035 CONTINUE
      IF (LASTK.NE.2) GO TO 1031
      DO 1040 I=1,NDPTS
      K = LIST(I)
      IF (KSTATE(K).NE.-1) GO TO 1045
 1040 CONTINUE
 1045 KTHD = I-1
 1050 KTHD = KTHD + 1
      INDEPT = LIST(KTHD)
      CALL PLACE (NDILAY,INDEPT,NDPTS,TLYCST)
      LISTOR(NDILAY) = INDEPT
      IF (NDILAY.LT.NDPAVL) GO TO 1050
```

```
      RETURN
      END
*
*
*
      SUBROUTINE CLEAR
C     THIS SUBROUTINE CLEARS THE LAYOUT MATRIX
      COMMON /BLKC/ LAYOUT(100,100),MAXI,MAXJ,MINI,MINJ
      DO 1100 I=1,100
      DO 1100 J=1,100
 1100 LAYOUT(I,J) = 0
      RETURN
      END
*
*
*
      SUBROUTINE PLACE (NDILAY, INDEPT, NDPTS, TLYCST)
C     THIS SUBROUTINE PLACES THE DEPARTMENTS IN THE EXISTING
C     LAYOUT. INDEPT IS THE INCOMING DEPARTMENT.
      DIMENSION DEPTMD(99,2),IJPER(900,2)
      COMMON /BLKA/ CSTMAT(20,20)
     *       /BLKB/ NBLKS(99)
     *       /BLKC/ LAYOUT(100,100),MAXI,MAXJ,MINI,MINJ
     *       /BLKD/ KSTATE(99)
     *       /LAY/DIST(20,20)
      IF (NDILAY-1) 1010,1100,1200
 1010 KTHD = INDEPT
C     THIS SECTION PLACES THE FIRST DEPARTMENT IN THE MIDDLE OF A
C     BLANK LAYOUT.
      IMID = 50
      JMID = 50
      NBLK = NBLKS(INDEPT)
      NBSD = SQRT(NBLK)
      NBRM = NBLK - NBSD ** 2
      IFST = IMID - NBSD / 2
      ILST = IFST + NBSD - 1
      JFST = JMID - NBSD + 1
      JLST = JFST + NBSD - 1
      KSUMI = 0
      KSUMJ = 0
      DO 1020 I = IFST,ILST
      DO 1020 J = JFST,JLST
      KSUMI = KSUMI + I
      KSUMJ = KSUMJ + J
 1020 LAYOUT(I,J) = INDEPT
      MINI = IFST
      MAXI = ILST
      MINJ = JFST
      MAXJ = JMID
      IF (NBRM.EQ.0) GO TO 1050
 1030 NJ = JFST - 1
 1031 CONTINUE
      MINJ = NJ
      DO 1040 I = IFST,ILST
      KSUMI = KSUMI + I
      KSUMJ = KSUMJ + NJ
      LAYOUT(I,NJ) = INDEPT
```

```
      NBRM = NBRM - 1
      IF (NBRM.EQ.0) GO TO 1050
 1040 CONTINUE
      NJ = NJ - 1
      GO TO 1031
 1050 CONTINUE
      KSTATE(INDEPT) = 0
      AUX1 = KSUMI
      AUX2 = KSUMJ
      AUX3 = NBLK
      DEPTMD(INDEPT,1) = AUX1 / AUX3
      DEPTMD(INDEPT,2) = AUX2 / AUX3
      NDILAY = NDILAY + 1
      RETURN
 1100 CONTINUE
C     THIS SECTION PLACES THE SECOND DEPARTMENT IN THE LAYOUT.
C     ADJACENT TO THE FIRST DEPARTMENT.
      NBLK = NBLKS(INDEPT)
      NBSD = SQRT(NBLK)
      NBRM = NBLK - NBSD ** 2
      IFST = IMID - NBSD / 2
      ILST = IFST + NBSD - 1
      JFST = JMID + 1
      JLST = JFST + NBSD - 1
      KSUMI = 0
      KSUMJ = 0
      DO 1110 I = IFST,ILST
      DO 1110 J = JFST,JLST
      KSUMI = KSUMI + I
      KSUMJ = KSUMJ + J
 1110 LAYOUT(I,J) = INDEPT
      IF (IFST.LT.MINI) MINI = IFST
      IF (ILST.GT.MAXI) MAXI = ILST
      MAXJ = JLST
      IF (NBRM.EQ.0) GO TO 1140
      NJ = JLST + 1
 1120 MAXJ = NJ
      DO 1130 I = IFST,ILST
      KSUMI = KSUMI + I
      KSUMJ = KSUMJ + NJ
      LAYOUT(I,NJ) = INDEPT
      NBRM = NBRM - 1
      IF (NBRM.EQ.0) GO TO 1140
 1130 CONTINUE
      NJ = NJ + 1
      GO TO 1120
 1140 CONTINUE
      KSTATE(INDEPT) = 0
      AUX1 = KSUMI
      AUX2 = KSUMJ
      AUX3 = NBLK
      DEPTMD(INDEPT,1) = AUX1 / AUX3
      DEPTMD(INDEPT,2) = AUX2 / AUX3
      XI = DEPTMD(KTHD,1)
      XJ = DEPTMD(KTHD,2)
      YI = DEPTMD(INDEPT,1)
      YJ = DEPTMD(INDEPT,2)
```

```
      DST = ABS(XI-YI) + ABS(XJ-YJ)
      TLYCST = CSTMAT(KTHD,INDEPT) * DST
C
      DIST(KTHD,INDEPT)=DST
      DIST(INDEPT,KTHD)=DST
C
      NDILAY = NDILAY + 1
      RETURN
 1200 COSMIN = 2 ** 27
      IFST = MINI - 6
      ILST = MAXI + 6
      JFST = MINJ - 6
      JLST = MAXJ + 6
      IF (IFST.LT.1) IFST = 1
      IF (JFST.LT.1) JFST = 1
      DO 1210 I = IFST,ILST
      DO 1210 J = JFST,JLST
      IF (LAYOUT(I,J).LT.0) LAYOUT(I,J)=0
 1210 CONTINUE
      NBRM = NBLKS(INDEPT)
      DO 1213 I=2,5
      INDEX = I - 1
      ITEST = (I * 2 - 1) ** 2
      IF (NBRM.LT.ITEST) GO TO 1214
 1213 CONTINUE
      INDEX = 5
 1214 INDXP = -1
 1215 NBLKIP = 0
      I = MINI + INDXP
      JFST = MINJ + INDXP
      DO 1220 J = JFST,80
      IF (LAYOUT(I+1,J+1).NE.0) GO TO 1225
 1220 CONTINUE
 1225 NBLKIP = NBLKIP + 1
      IJPER(NBLKIP,1) = I
      IJPER(NBLKIP,2) = J
      LAYOUT(I,J) = INDXP
      KPB = 1
 1230 I = IJPER(KPB,1)
      J = IJPER(KPB,2)
      IM1 = I - 1
      IP1 = I + 1
      JM1 = J - 1
      JP1 = J + 1
      IDUM1 = -1
      IDUM2 =  1
      DO 1260 II = IM1,IP1
      DO 1260 JJ = JM1,JP1
      IDUM2 = IDUM1 * IDUM2
      IF (IDUM2.EQ.-1) GO TO 1260
      IF (LAYOUT(II,JJ).NE.0) GO TO 1260
      IIM1 = II - 1
      IIP1 = II + 1
      JJM1 = JJ - 1
      JJP1 = JJ + 1
      DO 1240 III = IIM1,IIP1
      DO 1240 JJJ = JJM1,JJP1
```

```
      IF (LAYOUT(III,JJJ).EQ.0) GO TO 1240
      IF (LAYOUT(III,JJJ).GT.INDXP) GO TO 1250
 1240 CONTINUE
      GO TO 1260
 1250 NBLKIP = NBLKIP + 1
      IF (NBLKIP.GT.900) STOP
      IJPER(NBLKIP,1) = II
      IJPER(NBLKIP,2) = JJ
      LAYOUT(II,JJ) = INDXP
 1260 CONTINUE
      IF (KPB.EQ.NBLKIP) GO TO 1270
      KPB = KPB + 1
      GO TO 1230
 1270 IF (INDEX + INDXP) 1275,1280,1275
 1275 INDXP = INDXP - 1
      GO TO 1215
 1280 CONTINUE
      DO 1320 K = 1,NBLKIP
      CST = 0
      XI = IJPER(K,1)
      XJ = IJPER(K,2)
      DO 1310 KTHD =1,NDPTS
      IF (KSTATE(KTHD).NE.0) GO TO 1310
      YI = DEPTMD(KTHD,1)
      YJ = DEPTMD(KTHD,2)
      DST = ABS(XI-YI) + ABS(XJ-YJ)
 1300 CST = CSTMAT(KTHD,INDEPT) * DST + CST
 1310 CONTINUE
      IF (CST.GT.COSMIN) GO TO 1320
      COSMIN = CST
      KBEST = K
 1320 CONTINUE
      KFLAG = 0
      I = IJPER(KBEST,1)
      J = IJPER(KBEST,2) -1
      JDT = 1
      IDT = 0
      K1I = 0
      K1J = 0
      KONTI = 0
      KONTJ = 0
      KSUMI = 0
      KSUMJ = 0
C     GENERAL PLACEMENT PROCEDURE.
 1400 I = I + IDT
      J = J + JDT
      IF (I.LE.9.OR.I.GT.90) GO TO 1440
      IF (J.LT.9.OR.J.GT.90) GO TO 1440
      IF (LAYOUT(I,J).GT.0) GO TO 1440
      IF (KFLAG.EQ.0) GO TO 1420
C     THIS SECTION TESTS FOR CONTIGUITY
      IM1 = I - 1
      IP1 = I + 1
      JM1 = J - 1
      JP1 = J + 1
      DO 1410 II = IM1,IP1
      DO 1410 JJ = JM1,JP1
```

```
      IF (LAYOUT(II,JJ).EQ.INDEPT) GO TO 1420
 1410 CONTINUE
      GO TO 1440
 1420 LAYOUT(I,J) = INDEPT
      KFLAG = 0
 1430 CONTINUE
      KSUMI = KSUMI + I
      KSUMJ = KSUMJ + J
      NBRM = NBRM - 1
      IF (I.LT.MINI) MINI = I
      IF (I.GT.MAXI) MAXI = I
      IF (J.LT.MINJ) MINJ = J
      IF (J.GT.MAXJ) MAXJ = J
      IF (NBRM.EQ.0) GO TO 1490
      GO TO 1441
 1440 KFLAG = 1
 1441 CONTINUE
C     THIS SECTION SELECTS THE NEXT BLOCK TO BE TESTED.
      IF (KONTI.NE.K1I) GO TO 1460
      KONTI = 0
      IF (IDT.EQ.0) GO TO 1450
      IDT = 0
      GO TO 1460
 1450 IDT = (-1) ** (K1I + 2)
      K1I = K1I + 1
 1460 KONTI = KONTI + 1
      IF (KONTJ.NE.K1J) GO TO 1480
      KONTJ = 0
      IF (JDT.EQ.0) GO TO 1470
      K1J = K1J + 1
      JDT = 0
      GO TO 1460
 1470 JDT = (-1) ** (K1J + 1)
 1480 KONTJ = KONTJ + 1
      GO TO 1400
 1490 CONTINUE
      AUX1 = KSUMI
      AUX2 = KSUMJ
      AUX3 = NBLKS(INDEPT)
      DEPTMD(INDEPT,1) = AUX1 / AUX3
      DEPTMD(INDEPT,2) = AUX2 / AUX3
      XI = DEPTMD(INDEPT,1)
      XJ = DEPTMD(INDEPT,2)
      DO 1510 KTHD = 1,NDPTS
      IF (KSTATE(KTHD).NE.0) GO TO 1510
      YI = DEPTMD(KTHD,1)
      YJ = DEPTMD(KTHD,2)
      DST = ABS(XI-YI) + ABS(XJ-YJ)
C
      DIST(KTHD,INDEPT)=DST
      DIST(INDEPT,KTHD)=DST
C
      TLYCST = TLYCST - CSTMAT(KTHD,INDEPT) * DST
 1510 CONTINUE
      KSTATE(INDEPT) = 0
      NDILAY = NDILAY + 1
      RETURN
```

```
      END
*
*
*
      SUBROUTINE OUTPUT
C     THIS SUBROUTINE PRINTS THE LAYOUTS AS REQUESTED BY THE USER.
      INTEGER BLANK
      DIMENSION LINE(40)
      COMMON /BLKC/ LAYOUT(100,100),MAXI,MAXJ,MINI,MINJ
     *        / BLKG / KSYM(99),BLANK
     *        /LAY2/TLYCST,NDILAY,NDPAVL,LISTOR(99)
  100 FORMAT (1H1,55X,6HLAYOUT,10X,E14.7,//)
  101 FORMAT (5X,40(1X,A2),/)
  102 FORMAT (1H1,40X,20H LEFT HALF OF LAYOUT,//)
  103 FORMAT (1H1,40X,21H RIGHT HALF OF LAYOUT,10X,E14.7,//)
  104 FORMAT (28H THE ORDER OF PLACEMENT WAS ,30(A2,1X),/,13X,35(A2,1X)
     */,13X,35(A2,1X))
      DO 1010 L=1,40
 1010 LINE(L) = BLANK
      K = MAXJ - MINJ + 1
      IF (K.GT.40) GO TO 1050
      WRITE(6,100) TLYCST
      DO 1040 I = MINI,MAXI
      L = 20 - K/2
      DO 1030 J = MINJ,MAXJ
      L = L + 1
      NUM = LAYOUT(I,J)
      IF (NUM.LE.0) GO TO 1020
      LINE(L) = KSYM(NUM)
      GO TO 1030
 1020 LINE(L) = BLANK
 1030 CONTINUE
 1040 WRITE (6,101)(LINE(K),K=1,40)
      IF (NDILAY.EQ.NDPAVL) GO TO 2000
      RETURN
 1050 WRITE (6,102)
      DO 1080 I = MINI,MAXI
      DO 1070 J = MINJ,50
      NUM = LAYOUT(I,J)
      IF (NUM.LE.0) GO TO 1060
      LINE(J) = KSYM(NUM)
      GO TO 1070
 1060 LINE(J) = BLANK
 1070 CONTINUE
 1080 WRITE (6,101) (LINE(K),K=1,40)
      WRITE(6,103) TLYCST
      DO 1110 I = MINI,MAXI
      DO 1100 J = 51,MAXJ
      L = J - 50
      NUM = LAYOUT(I,J)
      IF (NUM.LE.0) GO TO 1090
      LINE(L) = KSYM(NUM)
      GO TO 1100
 1090 LINE(L) = BLANK
 1100 CONTINUE
 1110 WRITE (6,101) (LINE(K),K=1,40)
      IF (NDILAY.EQ.NDPAVL) GO TO 2000
```

```
      RETURN
 2000 DO 2010 I=1,NDILAY
      J = LISTOR(I)
 2010 LISTOR(I) = KSYM(J)
      NUM = NDILAY + 1
      DO 2020 I=NUM,99
 2020 LISTOR(I) = BLANK
      WRITE(6,104) LISTOR
      RETURN
      END
*
*
*
*
*
C*****************************
C                            *
C     LOCATION SUBPROGRAM    *
C                            *
C*****************************
      SUBROUTINE LOCMIN
      COMMON/LOC1/EXIS,VAR,F
      COMMON/LOC2/A,B,M,N
      COMMON/LOC3/XDIS
      COMMON/LOC4/YSTAR
      COMMON/BLK1/INSUFF,I1,FIXCST,IFS,FDIFF,ORDER,IH
      COMMON/BLK2/NETM,NETN,CMIN,IR,REFNOD,G,ISMJ,C,X,DUAL,NS,Y,
     1 NT
      DIMENSION  VAR(25,50)
      LOGICAL FIXED,CAPAC,CAPEQL,INITAL,ENUM
      INTEGER*4 M,N,SPRIME,S,F(25),A(25),B(50),C(1376 ),Y*2(25),FIXCST,
     1    EXIS,ORDER(25),CMIN,CAP,NFXENM/0/,AVLCAP/0/,T/0/,DELTAV(25),
     2          DUAL(77),P/0/, LC/0/,XSTAR(1376),G,SUM/0/,IH*2(25),FKO,
     3    NS*2(1376),NT*2(1376),SUMUBJ(90),DCOEFF(25,90),YSTAR*2(25),
     4          ISTAT*2(25),V(90)/90*0/,VMIN,VMINL,FMAXL/0/,SUMFKO,
     5          E*2(25,99),NFREE/0/,CKOI,CKOI1,GSTAP/999999999/,NDC/0/,
     6      INEQKO(25),IC*2(99),L*2(25)/25*9/,X(1376),REFNOD,FDIFF(25)
     *,XDIS(25,50)
C     READ IN NUMBER OF SOURCES AND DESTINATIONS, CAPACITIES, DEMANDS,
C     CONSTRAINTS, AND COSTS.
C
C
C   RESET VARIABLES  FOR NEW  PROBLEM
C
 4000 AVLCAP = 0
      T = 0
      NFXENM = 0
      P = 0
      LC = 0
      SUM = 0
      FMAXL = 0
      NFREE = 0
      NDC = 0
      GSTAR = 999999999
      DO 4001 I=1,90
 4001 V(I) = 0
      DO 4002 I=1,25
```

```
 4002 L(I) = 9
C
C   SPRIME = L.B. ON NO. OF SOURCES TO BE USED  AND S = U.B. ON NO. OF S.
C
      SPRIME=EXIS+1
C
      S=SPRIME
 1    FORMAT (16I5)
  2   FORMAT (10I8)
 3    FORMAT (10I5)
 4    FORMAT (15I5)
C
      NETM=M+N+2
      NETN=M*N+M+N+1
      DO 305 J=1,N
      C(J)=0
 305  CONTINUE
      NPM=N+1
      IZ=NETN-M-1
      WRITE (6,141)
  141 FORMAT (///1X,'LOCATION IS CALLED'/)
C
C---TRANFER VAR(I,J) INTO C(J)---
C
      IYY=1
      JWW=1
      DO 208 J=NPM,IZ
      C(J)=VAR(IYY,JWW)
      IYY=IYY+1
      IF(IYY.LE.M) GO TO 208
      IYY=1
      JWW=JWW+1
      IF (JWW.GT.N) GO TO 209
  208 CONTINUE
  209 NPM=IZ+1
C
      DO 306 J=NPM,NETN
      C(J)=0
 306  CONTINUE
C
C     INITIALIZE THE SOURCE AND SINK LISTS FOR NETWRK
      NPM=N+M
      DO 310 J=1,NPM
      NS(J)=J
 310  CONTINUE
      IZ=M*N-M
      NP1=N+1
      DO 330 J=M,IZ,M
      DO 320 I=NP1,NPM
      NS(I+J)=I
 320  CONTINUE
 330  CONTINUE
      IZ=M*N+N
      DO 340 I=1,M
      NS(IZ+I)=NPM+1
      NT(IZ+I)=N+I
 340  CONTINUE
```

```
      NS(IZ+M+1)=NPM+2
      NT(IZ+M+1)=NPM+1
      DO 350 J=1,N
      NT(J)=NPM+2
 350  CONTINUE
      DO 370 J=1,N
      IZ=N+J*M-M
      DO 360 I=1,M
      NT(IZ+I)=J
 360  CONTINUE
 370  CONTINUE
C     MAKING THIS ASSIGNMENT FOR REFNOD WE WILL HAVE ALL DUAL > 0
      REFNOD=M+N+1
      IR=0
C
      FIXED=.TRUE.
      CAPAC=.TRUE.
C  CAPEQL =.TRUE.  ONLY WHEN ALL CAPACITIES =.
      CAPEQL=.FALSE.
      INITAL=.FALSE.
      ENUM=.TRUE.
C
C
C     STEP 1& FEASIBILITY CHECK
      NSTEP=1
      FIXCST=0
      CMIN=0
      DO 5 J=1,N
      CMIN = CMIN + B(J)
    5 CONTINUE
      DO 6 I=1,M
      ORDER(I)=A(I)
      IH(I)=I
      Y(1)=1
    6 CONTINUE
      IF (.NOT.CAPAC) GO TO 10
      IF (S.EQ.M.OR.CAPEQL) GO TO 7
      CALL SORT (1,M)
   7  CAP = -CMIN
      MMS=M-S+1
      DO 8 I=MMS,M
      CAP=CAP+ORDER(I)
    8 CONTINUE
      IF (CAP.GE.0) GO TO 10
      WRITE (6,9)
   9  FORMAT (T40,'A FEASIBLE SOLUTION DOES NOT EXIST')
      STOP
C
C
C     STEP 2          INITIAL SOLUTION
   10 NSTEP=2
C     CALCULATE DELTAV(I)
      DO 11 I=1,M
      Y(1)=0
C
C     WE ASSUME PROBLEM IS FEASIBLE WITH ANY SINGBLE SOURCE NOT USED--CH
C
```

```
      CALL NETWRK
      DELTAV(I)=G
      Y(I)=1
   11 CONTINUE
C     CALCULATE VMIN
      CALL NETWRK
      VMIN=G
      DO 1111 I=1,M
      DELTAV(I)=DELTAV(I)-VMIN
      FDIFF(I)=F(I)-DELTAV(I)
      IF (F(I).LT.DELTAV(I)) FDIFF(I)=F(I)
 1111 CONTINUE
C
C     ATTEMPT TO FIX Y(I) TO ONE AT LEVEL ZERO
C
      IF (S.LT.M) GO TO 14
      DO 13 I=1,M
      MAXDV=DUAL(N+I)*A(I)
      IF (DELTAV(I).GE.MAXDV) MAXDV=DELTAV(I)
      IF (MAXDV.GT.F(I)) GO TO 12
      GO TO 13
 12   L(I)=0
      FIXCST=FIXCST+F(I)
      AVLCAP=AVLCAP + A(I)
      LC=LC+1
   13 CONTINUE
      IZ=N+M*N
 14   IF (INITAL) GO TO 241
      IF (.NOT.FIXED) GO TO 21
C
C     FIND SOLUTION WITH Y(I) FRACTIONAL
C
      DO 15 J=NP1,IZ
      XSTAR(J)=C(J)
      I=NS(J)-N
      IF (L(I).EQ.0) GO TO 15
      C(J)=C(J)+F(I)/A(I)
   15 CONTINUE
      CALL NETWRK
  152 MINOPT=G+FIXCST
C
C     NOW WE MUST RESTORE C(I,J) TO THE PROPER VALUES
C
      DO 16 J=NP1,IZ
      C(J)=XSTAR(J)
   16 CONTINUE
C
C     SECOND INITIAL SOLUTION PROCEDURE
C
      IZ=IZ+1
      IZZ=NETN-1
      DO 17 J=IZ,IZZ
      I=NT(J)-N
      RX=-X(J)
      RX=(1.0+RX/A(I))*F(I)+.5
      ORDER(I) =INT(RX)
      IH(I)=I
```

```
   17  CONTINUE
       CALL SORT (1,M)
       DO 18 I=1,M
       IF((AVLCAP .GE. CMIN ).AND.(LC .GE. SPRIME))GO TO 19
       IHH=IH(I)
       IF (L(IHH).EQ.0) GO TO 18
       L(IHH)=1
       AVLCAP=AVLCAP+A(IHH)
       LC=LC+1
       FIXCST=FIXCST+F(IHH)
   18  CONTINUE
       GO TO 25
   19  DO 20 K=I,M
       IHA=IH(K)
       IF (L(IHA).EQ. 0) GO TO 20
       Y(IHA)=0
   20  CONTINUE
       GO TO 25
C
C      FIRST INITIAL SOLUTION PROCEDURE OR PROCEDURE FOR READ IN SOLUTION
C
  241  READ (5,1) (XSTAR(I),I=1,M)
   21  MINOPT=G
       DO 24 I=1,M
       IF (L(I).EQ. 0) GO TO 24
       IF (INITAL.AND.XSTAR(I).EQ.1) GO TO 23
       IF (.NOT.INITAL.AND.X(IZ+I).GT.0) GO TO 23
       Y(I)=0
       GO TO 24
   23  LC=LC+1
       FIXCST=FIXCST+F(I)
       AVLCAP=AVLCAP+A(I)
   24  CONTINUE
C
C      CHANGING INITIAL SOLUTION IF IT DOES NOT SATISFY Y < S CONSTRAINT
C
   25  IF (LC .LE. S) GO TO  31
       IF (.NOT.CAPEQL) GO TO 258
       DO 255 I=1,M
       ORDER(I)=DELTAV(I)
       IH(I)=I
  255  CONTINUE
       GO TO 265
  258  DO 26 I=1,M
       ORDER(I)=A(I)
       IH(I)=I
   26  CONTINUE
  265  CALL SORT (1,M)
       ML=1
       MU=M
       I=1
   27  MU=MU-I+1
       DO 28 I=ML,M
       IHB=IH(I)
       IF (Y(IHB).EQ.0) GO TO 28
       IF ((AVLCAP-A(IHB)).LT.CMIN) GO TO 29
       LC=LC-1
```

```
      Y(IHB)=0
      FIXCST=FIXCST-F(IHB)
      AVLCAP=AVLCAP-A(IHB)
      IF (LC.LE.S) GO TO 31
   28 CONTINUE
   29  ML=I
      DO 295 I=1,MU
      MMS=MU-I+1
      IHC=IH(MMS)
      IF(Y(IHC).EQ.1) GO TO 295
      LC=LC+1
      IHD=IH(I)
      Y(IHD)=1
      FIXCST=FIXCST+F(IHC)
      AVLCAP=AVLCAP+A(IHC)
      GO TO 27
  295 CONTINUE
C
C     STEP 3& INITIALIZATION STEP
C     IF CAPAC AND S<M THEN WE WILL NEED THE SOURCES ORDERED ON CAPACITI
C     IN STEP 8 BUT WE SORT HERE SINCE STEP 8 IS AN ITERATIVE STEP.
C
   31 IF ((.NOT.CAPAC).OR.(S.EQ.M)) GO TO 34
      DO 33 I=1,M
      ORDER(I)=A(I)
      IH(I)=I
   33 CONTINUE
      CALL SORT (1,M)
   34 DO 36 I=1,M
      IF (Y(I) .EQ. 0) GO TO 32
      IF (L(I).GT. 0) L(I)=LC
      ISTAT(I)=1
      GO TO 36
   32 ISTAT(I)=-1
      NFREE=NFREE+1
      L(I)=LC
   36 CONTINUE
C
      IF (.NOT.ENUM) GO TO 39
C   NFXENM = MAX NO. OF ENUMERATION CONSTRAINTS
C
      NFXENM=50
      T=2
C
   37 FORMAT (40I2)
C
      DO 38 LL=1,M
   38 E(LL,1)=1
      IC(1)=EXIS+1
      KKK=EXIS+1
      DO 2200 LL=KKK,M
 2200 E(LL,2)=1
      IC(2)=1
C
   39 NSTEP=3
      VMINL=VMIN
      IF (S .LT. M) GO TO 52
```

```
      DO 51 I=1,M
      IF (Y(I).EQ.0) VMINL=VMINL+DELTAV(I)
   51 CONTINUE
      GO TO 54
   52 DO 53 I=1,M
      IF (Y(I).EQ.1) GO TO 53
      IF ((ISTAT(I).EQ.-1).AND.(F(I).LT.DELTAV(I))) GO TO 53
      VMINL=VMINL+DELTAV(I)
   53 CONTINUE
   54 FMAXL=GSTAR-VMINL
      KO=1
      GO TO 130
C
C     STEP 4& DUALITY CONSTRAINT CHECK
C     ALL DUALITY CONSTRAINTS ARE UPDATED IN STEPS 6,11, AND 13
C
   45 IF (V(KO).LT.0) GO TO 70
C
C     STEP 5& DESCENDANT FEASIBILITY CHECK FOR DUALITY CONSTRAINT
C
      IF (LC .EQ.S) GO TO 110
C     FMAXL IS UPDATED IN STEPS 6,11,AND 13
      DO 55 I=1,M
      INEQKO(I)=-DCOEFF(I,KO)
   55 CONTINUE
      NEGVKO=0
      ISTEP=5
C
C     THE DETERMINATION OF FKO WHICH FOLLOWS WILL ALSO UB USED AS A PART
C     OF THE STEPS 8 AND 10.
C
  510 FKO=0
      SUMFKO=0
      DO 59 I=1,M
      IF (ISTAT(I) .GE. 0) GO TO 59
  511 IF (DCOEFF(I,KO).GE.NEGVKO.AND.ISTEP.NE.8) GO TO 59
      IF (FIXCST+FDIFF(I).GT.FMAXL) GO TO 59
  531 IF (T .EQ. 0) GO TO 58
      DO 57 LL=1,T
      SUM=0
      DO 56 II=1,M
      IF (Y(II).EQ.1) SUM=SUM+E(II,LL)
   56 CONTINUE
      SUM=SUM+E(I,LL)
      IF (SUM .GT. IC(LL)) GO TO 59
   57 CONTINUE
   58 IF (FKO .EQ. 0) I1=I
      FKO=FKO+1
      IH(FKO)=I
      SUMFKO=SUMFKO-DCOEFF(I,KO)
      IF (INEQKO(I).GT.INEQKO(I1)) I1=I
   59 CONTINUE
      IF (FKO .EQ. 0) GO TO 110
      IF (ISTEP-8) 591,866,60
  591 IF (SUMFKO .LE. V(KO)) GO TO 110
      IF (FKO.EQ.1.OR.INEQKO(I1).GT.V(KO)) GO TO 60
      CALL PROBE(INEQKO,FKO,V(KO))
```

```
      IF (IFS.GT.FMAXL.OR.INSUFF.EQ.1) GO TO 110
C
C     NOTE THAT AT THIS POINT WE HAVE I1
C    STEP 6% FORWARD BRANCH
C
  60  LC =LC+1
      ISTAT(I1)=1
      Y(I1)=1
      NFREE=NFREE-1
      L(I1)=LC
      AVLCAP=AVLCAP+A(I1)
      FIXCST=FIXCST+F(I1)
      IF (F(I1).GE.DELTAV(I1)) FMAXL=FMAXL+DELTAV(I1)
      KO=1
      DO 63 K=1,NDC
      V(K)=V(K)+DCOEFF(I1,K)
      IF (V(K).GT.V(KO)) KO=K
  63  CONTINUE
      GO TO 45
C
C     STEP 7& CMIN AND Y>S' CONSTRAINT CHECK
C
  70  CAP=AVLCAP-CMIN
      IF (CAP.LT.0) GO TO 80
      IF (LC .LT. SPRIME) GO TO 87
      GO TO 90
C
C     STEP 8& DESCENDANT FEASIBILITY CHECK FOR COMIN AND Y>S' CONSTRAINT
C
  80  NSTEP=8
      IF ((S-LC).GE.NFREE) GO TO 83
C     RECALL THAT SOURCES ARE STILL ORDERED BY CAPACITY FROM STEP 3.
      SUM=0
      DO 82 I=1,M
      MMS=M-I+1
      IHE=IH(MMS)
      IF (ISTAT(IHE).GE.0) GO TO 82
      SUM=SUM+1
      IF (SUM.GT.(S-LC)) GO TO 85
      CAP = CAP + ORDER(MMS)
  82  CONTINUE
  83  DO 84 I=1,M
      IF (ISTAT(I) .EQ. -1) CAP=CAP+A(I)
  84  CONTINUE
  85  IF (CAP .LT. 0) GO TO 110
C     RECALL THAT WE HAVE ALL V(K) FOR THE CURRENT NODE FORM STEP 4.
      DO 86 I=1,M
      INEOKO(I)=(DELTAV(I)-F(I))/A(I)
  86  CONTINUE
  865  NEGVKO=-V(KO)
      ISTEP=8
      GO TO 510
 866  IF (DCOEFF(I1,KO).LT.NEGVKO.AND.A(I1)+AVLCAP.GE.CMIN) GO TO 60
      IF (FKO.EQ.1) GO TO 867
      CALL PROBE(A,FKO,CMIN-AVLCAP)
      IF (IFS.GT.FMAXL.OR.INSUFF.EQ.1) GO TO 110
 867  I1=IH(1)
```

```
      IJK=0
      DO 868 I=1,FKO
      IHF=IH(I)
      IF (DCOEFF(IHF,KO).GE.NEGVKO) GO TO 868
      IJK=1
      IF (INEQKO(IHF).GT.INEQKO(I1)) I1=IH(I)
  868 CONTINUE
      IF (IJK.EQ.0) GO TO 110
      GO TO 60
C     THE FOLLOWING PERTAINS WHEN CMIN CONSTRAINT IS NOT VIOLATED
   87 IF ((NFREE+LC).LT.SPRIME) GO TO 110
C     RECALL THAT WE HAVE ALL V(K) FOR THE CURRENT NODE FROM STEP 4.
      DO 88 I=1,M
      INEQKO(I)=DELTAV(I)-F(I)
   88 CONTINUE
      GO TO 865
C
C     STEP 9& CURRENT NODE FIXED COST TEST
C
   90 NSTEP=9
      IF (S .EQ. M) GO TO 130
      SUM=VMIN
      DO 91 I=1,M
      IF (Y(I) .EQ. 0) SUM=SUM+DELTAV(I)
   91 CONTINUE
      IF (FIXCST.LE.(GSTAR-SUM)) GO TO 130
C
C     STEP 10& DESCANDANT FEASIBILITY CHECK FOR FMAXL CONSTRAINT
C
      IF (LC .EQ. S) GO TO 110
C     NOTE THAT WE HAVE ALL V(K) FOR THE CURRENT NODE
      DO 101 I=1,M
      INEQKO(I)=DELTAV(I)-F(I)
  101 CONTINUE
      NEGVKO=-V(KO)
      ISTEP=10
      GO TO 510
C
C     STEP 11& BRANCH BACKWARD
C
  110 NSTEP=11
      IF (LC.EQ.0) GO TO 140
      I1P=0
      DO 113 I=1,M
      IF ((Y(I).LT. 1).OR.(L(I).EQ. 0)) GO TO 113
      CKOI=DCOEFF(I,KO)
      IF (FDIFF(I).LE.CKOI) CKOI=FDIFF(I)
      IF (I1P .EQ. 1) GO TO 112
      I1P=1
  111 I1=I
      CKOI1=CKOI
      GO TO 113
  112 IF (CKOI1 .GE. CKOI) GO TO 113
      GO TO 111
  113 CONTINUE
      IF (I1P .EQ. 0) GO TO 140
C
```

```
C     DETERMINE WHETHER AN ENUMERATION CONSTRAINT WILL BE NEEDED
C
      IF (L(I1).EQ. LC) GO TO 116
      DO 115 I=1,M
      IF (ISTAT(I).NE. 0) GO TO 115
      IF((L(I) .GE. LC).OR.(L(I).LT.L(I1))) GO TO 115
      T=T+1
      IF (T.GT.99) GO TO 1155
      IC(T)=-1
      DO 114 LL=1,M
      E(LL,T)=0
      IF ((LL.EQ.I).OR.((ISTAT(LL).EQ.1).AND.(L(LL).LE.L(I)))) E(LL,T)=1
      IC(T)=IC(T)+E(LL,T)
  114 CONTINUE
      IF (T.GT.P) P=T
  115 CONTINUE
      GO TO 116
 1155 WRITE (6,1156)
 1156 FORMAT ('  WE HAVE EXCEEDED LIMIT ON ENUM CONST')
      STOP
C
C     THE REASSIGNMENTS ARE NOW MADE IN WHAT FOLLOWS
C
  116 LC=LC-1
      DO 118 I=1,M
      IF (ISTAT(I).NE. 0) GO TO 117
      IF (L(I).LT.L(I1)) GO TO 118
      ISTAT(I)=-1
      IF(F(I).LT.DELTAV(I)) FMAXL=FMAXL+DELTAV(I)
      GO TO 118
  117 IF (ISTAT(I).NE. 1) GO TO 118
      IF (I .EQ. I1) GO TO 118
      IF (L(I).EQ.(LC+1)) L(I)=LC
  118 CONTINUE
      ISTAT(I1)=0
      Y(I1)=0
      L(I1)=LC
      FIXCST=FIXCST-F(I1)
      AVLCAP=AVLCAP-A(I1)
      FMAXL=FMAXL-DELTAV(I1)
      KO=1
      DO 1180 K=1,NDC
      V(K)=V(K)-DCOEFF(I1,K)
      IF (V(K).GT.V(KO)) KO=K
 1180 CONTINUE
C     DETERMINING WHETHER ANY ENUMERATION CONSTRAINT CAN BE DROPPED
      ITL=NFXENM+1
 1183 ITU=T
      IF(ITL.GT.ITU) GO TO 120
      DO 119 IT=ITL,ITU
      IF(IC(IT).LE.LC) GO TO 119
      IF (E(I1,IT).EQ. 0) GO TO 119
      DO 1185 I=1,M
      IF ((ISTAT(I).EQ.1).AND.(E(I,IT).NE.1)) GO TO 119
 1185 CONTINUE
      GO TO 1195
  119 CONTINUE
```

```
      IF (ITL.EQ.NFXENM+1) GO TO 120
      GO TO 120
 1195 T=T-1
      ITL=IT
      IF(IT.GT.T) GO TO 1183
      DO 1197 K=IT,T
      IC(K)=IC(K+1)
      DO 1196 I=1,M
      E(I,K)=E(I,K+1)
*
*
*
      SUBROUTINE SORT(II,JJ)
C     SORTS ARRAY A INTO INCREASING ORDER, FROM A(II) TO A(JJ)
C     ORDERING IS BY INTEGER SUBTRACTION
      COMMON/BLK1/INSUFF,I1,FIXCST,IFS,FDIFF,A,IH
      INTEGER*4 A(25),T,TT,IU(6),IL(6),IH*2(25),FDIFF(25),FIXCST
      M=1
      I=II
      J=JJ
    5 IF(I .GE. J) GO TO 70
   10 K=I
      IJ=(J+I)/2
      T=A(IJ)
      IT=IH(IJ)
      IF(A(I) .LE. T) GO TO 20
      A(IJ)=A(I)
      IH(IJ)=IH(I)
      A(I)=T
      IH(I)=IT
      T=A(IJ)
      IT=IH(IJ)
   20 L=J
      IF(A(J) .GE. T) GO TO 40
      A(IJ)=A(J)
      IH(IJ)=IH(J)
      A(J)=T
      IH(J)=IT
      T=A(IJ)
      IT=IH(IJ)
      IF(A(I) .LE. T) GO TO 40
      A(IJ)=A(I)
      IH(IJ)=IH(I)
      A(I)=T
      IH(I)=IT
      T=A(IJ)
      IT=IH(IJ)
      GO TO 40
   30 A(L)=A(K)
       IH(L)=IH(K)
      A(K)=TT
      IH(K)=ITT
   40 L=L-1
      IF(A(L) .GT. T) GO TO 40
      TT=A(L)
      ITT=IH(L)
   50 K=K+1
```

```
      IF(A(K) .LT. T) GO TO 50
      IF(K .LE.L) GO TO 30
      IF(L-I .LE.J-K) GO TO 60
      IL(M)=I
      IU(M)=L
      I=K
      M=M+1
      GO TO 80
   60 IL(M)=K
      IU(M)=J
      J=L
      M=M+1
      GO TO 80
   70 M=M-1
      IF(M .EQ. 0) RETURN
      I=IL(M)
      J=IU(M)
   80 IF(J-I .GE. II) GO TO 10
      IF(I .EQ. II) GO TO 5
      I=I-1
   90 I=I+1
      IF(I .EQ. J) GO TO 70
      T=A(I+1)
      IT=IH(I+1)
      IF(A(I) .LE. T) GO TO 90
      K=I
  100 A(K+1)=A(K)
      IH(K+1)=IH(K)
      K=K-1
      IF(T .LT. A(K)) GO TO 100
      A(K+1)=T
      IH(K+1)=IT
      GO TO 90
      END
*
*
*
      SUBROUTINE PROBE (AORF,NUM,VAL)
      COMMON/BLK1/INSUFF,I1,FIXCST,IFS,FDIFF,ORDER,IH
      REAL*4 RATIO(25)
      INTEGER*4 AORF(25),IH*2(25),LST(25),VAL,NUM,ORDER(25),FDIFF(25),
     1          FIXCST
C
      IRR=0
      ISUM=0
      IFS=FIXCST
      INSUFF=0
1     FORMAT (' NUM=',I8)
      WRITE (6,1) NUM
      DO 10 I=1,NUM
      LST(I)=I
      IHG=IH(I)
      RATIO(I)=FLOAT(AORF(IHG))/FDIFF(IHG)
10    CONTINUE
      DO 30 I=1,NUM
      DO 20 J=1,NUM
      LSTA=LST(J)
```

```
      LSTB=LST(I)
      IF (RATIO(LSTA).LE.RATIO(LSTB)) GO TO 20
      IT=LST(I)
      LST(I)=LST(J)
      LST(J)=IT
20    CONTINUE
      IRR=IRR+1
      IHHH=IH(LSTB)
      ISUM=ISUM+AORF(IHHH)
      IF (ISUM.GE.VAL) GO TO 40
30    CONTINUE
      INSUFF=1
      RETURN
40    IZ=IRR-1
      IF (IZ.GT.0) GO TO 50
      LSTC=LST(1)
      I1=IH(LSTC)
      RETURN
50    DO 52 I=1,IZ
      LSTF=LST(I)
      IHZ=IH(LSTF)
      IFS=IFS+FDIFF(IHZ)
52    CONTINUE
      LSTD=LST(IRR)
      IHY=IH(LSTD)
      IFS=IFS+FDIFF(IHY)*(VAL-(ISUM-AORF(IHY)))/
     1                                               AORF(IHY)
      RETURN
      END
*
*
*
      SUBROUTINE NETWRK
C
C     THIS IS THE OUT-OF-KILTER POUTINE BASED ON CLASEN'S ALGOL CODE
C     CHANGES WERE MADE TO MAKE IT ADAPT TO THE REQ'MNTS OF THE SEL-ALLO
C     CATION ALGORITHIM
C
      COMMON/LOC2/ALGA,ALGB,ALGM,ALGN
      COMMON/BLK2/M,N,CMIN,IR,REFNOD,ISUM,ISMJ,C,X ,
     1            PI,S,Y,T
      LOGICAL BRKTHR
      INTEGER*4 M,N,REFNOD,OUTKIL,S*2(1376),T*2(1376),C(1376),CMIN,BJJ,
     1          X(1376),PI(77),G*2(1376),H*2(1376),L(77),R(77),JJ,AA,
     2          TERM,LABORG,ORIGIN,P,SS,A,KP,KQ,EPS,EPSL,ALGM,ALGN,
     3          U*2(79),V*2(79),ALGA(25),ALGB(50),Y*2(25),BJ,BKP
C
      IR=IR+1
      JJ=N-ALGM
      OUTKIL=0
      IF (IR.GT.1) GO TO 81
C     COUNT ARCS BEGINNING AND ENDING AT NODES AND INITIALIZE X AND PI
      MM=M+2
      DO 3 I=3,MM
      U(I)=0
      V(I)=0
    3 CONTINUE
```

```
      DO 4 J=1,N
      KS=S(J)
      KSS=S(J)
      U(KS+2)=U(KSS+2) + 1
      KT=T(J)
      V(KT+2)=V(KT+2) + 1
      X(J)=0
    4 CONTINUE
      DO 5 I=1,M
      PI(I)=0
    5 CONTINUE
C     CUMMULATE COUNTS
      U(1)=1
      U(2)=1
      V(1)=1
      V(2)=1
      MM=M+1
      DO 6 I=3,MM
      U(I)=U(I)+U(I-1)
      V(I)=V(I)+V(I-1)
    6 CONTINUE
C     SET UP ARC LOCATOR LISTS
      DO 8 J=1,N
      KAS=S(J)
      MMUU=U(KAS+1)
      G(MMUU)=J
      KAT=T(J)
      LLV=V(KAT+1)
      H(LLV)=J
         U(KAS+1)=U(KAS+1) + 1
      V(KAT+1)=V(KAT+1) + 1
    8 CONTINUE
      NN=M+2
   81 DO 9  J=1,N
      KBS=S(J)
      KBT=T(J)
      C(J)=C(J)+PI(KBS)-PI(KBT)
    9 CONTINUE
C     LOOK FOR AN OUT-OF-KILTER ARC
   10 IF (IR.EQ.1.OR.IR.GT.ALGM.AND.IR.LE.ALGM+3) JJ=1
C     UNLESS THIS IS THE FIRST PROBLEM THE FIRST N-ALGM-1 ARCS ARE IN KI
      AA=0
      BRKTHR=.TRUE.
      EPS=99999999
   15 BJJ=CMIN
      LJJ=0
      IF (JJ.LE.ALGN) LJJ=ALGB(JJ)
      IF (JJ.GE.N-ALGM.AND.JJ.NE.N) BJJ=ALGA(JJ-N+ALGM+1)*Y(JJ-N+ALGM+1)
C
      IF (X(JJ).LT.LJJ.OR.C(JJ).LT.0.AND.X(JJ).LT. BJJ  ) GO TO 25
C
      IF (X(JJ).GT. BJJ  .OR.C(JJ).GT.0.AND.X(JJ).GT.LJJ) GO TO 30
C
      IF (LJJ.EQ.BJJ.AND.C(JJ).NE.0.AND.BRKTHR.AND.EPS.NE.0) GO  TO 25
   20 JJ=JJ+1
      EPS=99999999
      IF (JJ.LE.N) GO TO 15
```

```
      DO 22 J=1,N
      KCS=S(J)
      KCT=T(J)
      C(J)=C(J)-PI(KCS)+PI(KCT)
   22 CONTINUE
      GO TO 200
   25 TERM=S(JJ)
      ORIGIN=T(JJ)
      LABORG=JJ
      GO TO 35
   30 TERM=T(JJ)
      ORIGIN=S(JJ)
      LABORG=-JJ
   35 R(1)=ORIGIN
   40 IF (.NOT.BRKTHR.AND.JJ.EQ.AA)GO TO 45
C     ZERO OUT LABELS
      DO 42 I=1,M
      L(I)=0
   42 CONTINUE
      SS=1
   45 P=1
      AA=JJ
      BRKTHR=.FALSE.
      L(ORIGIN) = LABORG
C
C     TRY TO LABEL THE FORWARD ARCS
   50 I=R(P)
      I1=U(I)
      IN=U(I+1)-1
      DO 51 A=I1,IN
      J=G(A)
      K=T(J)
      IF (L(K).NE.0) GO TO 51
      BJ=CMIN
      LJ=0
      IF (J.LE.ALGN) LJ=ALGB(J)
C
      IF (J .GE.N-ALGM.AND.J .NE.N) BJ=ALGA(J -N+ALGM+1)*Y(J -N+ALGM+1)
C
      IF (L(K).EQ.0.AND.(X(J).LT.LJ.OR.C(J).LE.0.AND.X(J).LT.  BJ ))
     1                                                          GO TO 52
      GO TO 51
   52 L(K)=J
      SS=SS+1
      R(SS)=K
   51 CONTINUE
C
C     TRY TO LABEL THE BACKWARD ARCS
      I1=V(I)
      IN=V(I+1)-1
      DO 53 A=I1,IN
      J=H(A)
      K=S(J)
      IF (L(K).NE.0) GO TO 53
      BJ=CMIN
      LJ=0
```

```
      IF (J.LE.ALGN) LJ=ALGB(J)
      IF (J .GE.N-ALGM.AND.J .NE.N) BJ = ALGA(J -N+ALGM+1)*Y(J-N+ALGM+1)
C
      IF (L(K).EQ.0.AND.(X(J).GT. BJ .OR.C(J).GE.0.AND.X(J).GT.LJ))
     1                                                          GO TO 54
      GO TO 53
   54 L(K)=-J
      SS=SS+1
      R(SS)=K
   53 CONTINUE
C     TEST FOR TERMINAL LABELED
      IF (L(TERM).NE.0) GO TO 55
      P=P+1
C     IF SCAN LIST EXHAUSTED, NON-BREAKTHRU
      IF (P.GT.SS) GO TO 90
      GO TO 50
C     FIND FLOW INCREMENT IN CYCLE
   55 EPS=999999999
      BRKTHR=.TRUE.
      KT=TERM
      J=1
   60 KQ=L(KT)
      KP=IABS(KQ)
      IF (KQ.GT.0) GO TO 65
      KT=T(KP)
      IF (C(KP).GE.0)GO TO 75
      GO TO 70
   65 KT=S(KP)
      IF (C(KP).GT.0) GO TO 75
   70 BKP=CMIN
      IF (KP.GE.N-ALGM.AND.KP.NE.N) BKP=ALGA(KP-N+ALGM+1)*Y(KP-N+ALGM+1)
      IB=IABS( BKP  -X(KP))
      IF (EPS.GT.IB) EPS=IB
      GO TO 80
   75 LKP=0
      IF (KP.LE.ALGN) LKP=ALGB(KP)
      IB=IABS(LKP-X(KP))
      IF (EPS.GT.IB) EPS=IB
   80 R(J)=KQ
      IF (KT.EQ.TERM)GO TO 85
      J=J+1
      GO TO 60
C     INCREMENT FLOW
   85 DO 88 I=1,J
      IF (R(I).LE.0) GO TO 87
      NAR=R(I)
      X(NAR)=X(NAR)+EPS
      GO TO 88
   87 NBR=R(I)
      X(-NBR)=X(-NBR)-EPS
   88 CONTINUE
      GO TO 15
C     FIND DELTA FOR NON-BREAKTHRU
   90 EPSL=999999999
      DO 92 J=1,N
      BJ=CMIN
      LJ=0
```

```
      IF (J.LE.ALGN) LJ=ALGB(J)
      IF (J .GE.N-ALGM.AND.J .NE.N) BJ=ALGA(J -N+ALGM+1)*Y(J -N+ALGM+1)
C
      KDS=S(J)
      KDT=T(J)
      IF (L(KDS).NE.0.AND.L(KDT).EQ.0.AND.X(J).LT. BJ  .OR.L(KDS).EQ.00
     1   0.AND.L(KDT).NE.0.AND.X(J).GT.LJ) GO TO 91
      GO TO 92
   91 LAC=C(J)
      IB=IABS(LAC)
      IF (EPSL.GT.IB) EPSL=IB
   92 CONTINUE
C
C     TEST FOR CASE 2
      EPS=EPSL
      IF (EPS.NE.999999999) GO TO 95
      ILOR=L(ORIGIN)
      ICJJ=C(JJ)
      IF (C(JJ).EQ.0) GO TO 100
      IF (ILOR.GE.0.AND.ICJJ.GE.0) GO TO 100
      IF (ILOR.LT.0.AND.ICJJ.LT.0) GO TO 100
      EPS=IABS(C(JJ))
C     CHANGE REDUCED COSTS
   95 DO 955 J=1,N
      KES=S(J)
      KET=T(J)
      IF (L(KES).EQ.0.AND.L(KET).NE.0)  C(J)=C(J)+EPS
      IF (L(KES).NE.0.AND.L(KET).EQ.0) C(J)=C(J)-EPS
  955 CONTINUE
C     CHANGE NODE PRICES
      IF (L(REFNOD).EQ.0) GO TO 97
      DO 96 I=1,M
      IF (L(I).EQ.0) PI(I)=PI(I)+EPS
   96 CONTINUE
      GO TO 99
   97 DO 98 I=1,M
      IF (L(I).NE.0) PI(I)=PI(I)-EPS
   98 CONTINUE
   99 BJJ=CMIN
      LJJ=0
      IF (JJ.LE.ALGN)LJJ=ALGB(JJ)
      IF (JJ.GE.N-ALGM.AND.JJ.NE.N) BJJ=ALGA(JJ-N+ALGM+1)*Y(JJ-N+ALGM+1)
C
      IF (EPS.EQ.EPSL.OR.X(JJ).EQ.LJJ.OR.X(JJ).EQ. BJJ  ) GO TO 15
  100 OUTKIL=OUTKIL+1
      GO TO 20
  200 ISUM=0
      NN=N-ALGM-1
      DO 210 J=ALGN,NN
      ISUM=ISUM+C(J)*X(J)
  210 CONTINUE
      ISMI=0
  216 DO 214 I=1,ALGM
      IF (Y(I).EQ.1) ISMI=ISMI+PI(ALGN+I)*ALGA(I)
  214 CONTINUE
      ISMJ=0
      DO 219 J=1,ALGN
```

```
      ISMJ=ISMJ+PI(J)*ALGB(J)
219   CONTINUE
      IF (ISMJ-ISMI.NE.ISUM) GO TO 230
 220  RETURN
230   WRITE (6,231)
231   FORMAT ('  PROBLEM SOLUTION HAS INCORRECT DUALS')
      STOP
      END
```

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BIBLIOGRAPHY

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