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Title: A QUANTITATIVE INDEX FOR EVALUATION OF PLANT LAYOUT ALTERNATIVES

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The purpose of this study is to develop a workable plant layout evaluation technique incorporating adequate definitive measures of intangible plant layout considerations. A summary and critique is given of existing evaluation methods. A quantitative evaluation index (QEI) is proposed to remedy the described deficiencies.

The proposed index can be described by the following formula: Quantitative Evaluation Index (QEI) = $\alpha(D') + \beta(L') + \gamma(M') + \sigma(I') + \phi(P') + \theta(F')$, where D' = material handling distance factor, L' = location relationship factor, M' = related cost factor, I' = information flow factor, P' = performance factor, F' = flexibility factor, and α, β, γ, σ, ϕ, and θ are relative weighting factors. The factors D', L', M', I', P', and F' are ratios representing improvement realized over an existing or reference layout. Both present and probabalistic future conditions are included, and methods of quantification of intangibles are described.

In addition to the obvious industrial applications, the index is also useful for academic exercises. A sophisticated plant layout exercise was developed and tested in a classroom atmosphere. The complete exercise, its evaluation, and suggestions for further development are included in the thesis.

A Quantitative Index for Evaluation of Plant Layout Alternatives

by

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To my old man

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INTRODUCTION

The nature of plant layout problems necessitates the use of a multitude of evaluation techniques, each particular situation requiring its own appropriate solution procedures. Smaller layout problems can usually be evaluated by relatively simple means. The more complex problems demand the employment of more sophisticated, less qualitative procedures.

Although there are several quantitative tools available that might afford meaningful results, most of them are based on a rather narrow spectrum of criteria and cannot possibly give proper consideration to the many factors actually involved in determining the worth of a given layout design. This relative shortage of effective and usable quantitative evaluation techniques warrants a study of sufficient magnitude to demonstrate both the power and limitations of the several available methods and to establish some improvement suggestions. It is the purpose of this study to accomplish both of these objectives.

The scope of this study is limited to problems concerned with the improvement of an existing layout, although the basic principles involved are generally applicable to new-plant layout problems as well.

REVIEW OF ESTABLISHED LAYOUT TECHNIQUES

The plant layout problem has been approached from many different directions by many enlightened and knowledgeable individuals. Both qualitative and quantitative tools and techniques have been employed, their success depending to a great extent on the skill of the user. Activity relationship charts (Muther, 1961); cross charts (Hillier, 1963); operation process charts (Muther, 1961; Apple, 1963); optimal machine location techniques (Bindschedler and Moore, 1961); from-to charts (Apple, 1963); the relatively new computer techniques ((CRAFT (Armour, Vollman, and Buffa, 1964); CORELAP (Lee and Moore, 1967), ALDEP (Seehoff and Evans, 1967), and RMAComp I (Muther and Associates, 1970)); and the relatively simple "things-to-consider" checksheets (Apple, 1963; O'Hara, 1968) are among the most prominent.

Layout Evaluation Considerations

An inseparable input to plant layout considerations is the problem of layout evaluation. This problem, it seems, has been somewhat ignored, at least in print, by many of the layout authorities, although they must be aware that its solution is certainly an essential step in the layout process.

The evaluation of a layout may arise from either of two possibilities: (1) an evaluation of an existing layout for purposes of discovering improvements, or (2) an evaluation of alternative layouts under consideration for a single problem or project area. And the evaluation may be "either qualitative or quantitative." That is, it can consist of a relatively simple balancing of advantages versus disadvantages; or it can consist of some quantitative means of measuring the value of the layout or layouts (Apple, 1963).

There is, however, quite a bit of disagreement concerning qualitative versus quantitative evaluation techniques. Without question both qualitative and quantitative factors must be considered and evaluated. Seemingly unquantifiable factors such as safety, employee relations, and flexibility cannot be overlooked when developing a layout as they will certainly be affected.

Some approaches seem to leave evaluation of the intangibles up to the judgment and experience of the layout analyst, while others feel that unquantifiable criteria are invalid and should be discarded. In many real situations it may be impossible, impractical, or uneconomical to establish real values for mathematical or "full" quantitative evaluation; under these conditions reliance must be placed on the judgment and experience of available personnel (Reed, 1961). The criteria must be composed of the objectives of plant layout, and those objectives selected must be quantifiable in some manner; "if a layout objective is not quantifiable, that objective is not truly a criterion."

(Harris and Smith, 1968)

Determination of the relative importance of each criterion, both qualitative and quantitative, is a major problem encountered in layout evaluation. The solution to this problem is no doubt different for each layout to be evaluated. Varied conditions (material handling costs, labor rates, utility rates, and other similar factors) contribute to the relative worth of each criterion in a given layout situation. Harris and Smith (1968) state that the "absolute" worth of each criterion is usually not known and that some type of "measurement device" is needed that will allow evaluation of the relative importance of each criterion. Still, the most reliable measurement device available appears to be the judgment and experience of the analyst.

Apple (1968) divides the criteria for evaluation into four categories: (1) direct cost factors, (2) indirect cost factors, (3) indeterminate cost factors, and (4) intangible factors.[1] He admits that the indeterminate cost factors are vague and do not lend themselves to determination of a definite cost figure. He also admits that the intangible factors usually defy quantification and cannot be included in a cost comparison. But, he also says that in order to reach a final decision, all factors (direct, indirect, indeterminate, and intangible) have to be evaluated. His solution to the problem of quantification of the seemingly unquantifiable factors is to "weight" the cost factors by

[1]Definitions of these terms can be found in the appendix.

the value of the intangible factors:

$$\frac{\text{Total of Cost Factors}}{\text{Weighted Evaluation of Intangible Factors}} = \text{Weighted Evaluation of Cost Factors}$$

Apple states that the analyst must exercise his judgment in deciding whether or not the intangibles outweigh the quantifiable factors and to what extent. Hence, the problem of "weighting" the intangible factors is left up to the layout designer using judgment and experience as his basic tools.

A contradiction is apparent in Apple's handling of intangible considerations. Apple (1963) says that an evaluation may be qualitative "or" quantitative, while he also insists that a total evaluation must consider both the intangible (or qualitative) factors that "defy quantification" <u>and</u> the quantitative factors (1968). The author tends to agree that both qualitative <u>and</u> quantitative factors deserve consideration. The balancing of qualitative and quantitative factors is by no means an easily solved problem, but it is one that obviously must be solved with some degree of success if meaningful layout evaluations are to be made.

Several attempts have been made to quantify these indeterminate and intangible factors in order to permit a total quantitative layout evaluation. Muther (1961), in his "Factor Analysis" evaluation of layout alternatives, assigns quantitative values to factors such as convenience of service, flexibility, and ease of supervision. Harris and Smith (1968) quantify safety and flexibility as follows:

Safety:	X major injuries per man hours worked, Y minor injuries per man hours worked.
Flexibility:	X $ per production model changeover, Y $ per product changeover, Z $ per process investment.

The weakness in this type of quantification is, of course, that an evaluation using these factors can take place only on an existing layout; evaluation of proposed layouts would be possible only through some sort of simulation procedure and the validity of the results of such a procedure would certainly be questionable.

Apple (1963) suggests several quantitative evaluation techniques and also states that in using any such technique it is necessary to quantify the factors that are usually considered qualitative. He further suggests that such a technique will force better thinking from those involved in the evaluation process than could be obtained through purely qualitative means. This statement is reasonable in that better results are sure to be obtained when the layout analyst is forced to think about the relative worth of the qualitative factors involved. The mere fact that the analyst considers the relative worth of such factors brings him one step closer to a total quantitative evaluation.

It can be summarized, then, that in order to establish a method of total quantitative layout evaluation, the significant qualitative factors or criteria must be made quantitative. Anything short of a total quantitative evaluation involves vague, confusing parallelisms, and the validity of any such evaluation, especially in the comparison of several layout alternatives, would probably seem much more open to criticism and question than would a total quantitative approach.

Quantitative Techniques

One of the simplest forms of quantification involves the balancing or rating of advantages versus disadvantages (Muther, 1961; Apple, 1963). Using this method, numerical values are placed in the appropriate columns on a form similar to the one shown below.

Layout Evaluation Sheet

Alternative No.______ Date__________________

Advantages	Weight or value	Disadvantages	Weight or value
Total		Total	

Figure 1. Layout Evaluation Sheet

"Each advantage should be assigned a value relative to the importance of the item to the overall results of the proposed solution." (Apple,

1963) This method, of course, involves a great deal of judgment on the part of the layout evaluator and would certainly not be a practical solution to the evaluation problem given a layout of any significant size; however, small layout problems may be well suited for this type of subjective evaluation.

Muther's more objective "Factor Analysis" evaluation technique (1961) attacks the evaluation problem by analyzing one factor at a time. The procedure is basically as follows:

(1) List all significant factors involved in selecting between layout alternatives.

(2) Weigh the relative importance of the factors to each other.

(3) Rate the layout alternatives against each other, one factor at a time.

(4) Extend the rated values and compare the total value of the various alternatives.

The individual factors, criteria and objectives[2] are identified. Muther holds that the factors to be evaluated should be established by <u>one</u> person after discussions with those who will evaluate the layout. He maintains that clear concise definitions of the factors involved are imperative for good results and warns that "overlapping or duplication" can be as serious as omissions.

Apple (1963) suggests a similar method which entails essentially the following steps:

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[2]Factors, criteria, and objectives--the goals a layout must achieve.

(1) Identify the project.

(2) Establish the relative weight of each major criterion, based on company policies and objectives. This should be done by appropriate management personnel.

(3) Evaluate each factor on the basis of 1 - 10. Rate all layouts one item at a time to aid in comparison.

(4) Multiply each factor "weight" (step 2) by each factor "rating" (step 3) and record results.

(5) Sum the individual "weighted-ratings" for each alternative to determine its score.

The above "Evaluation of Layout Criteria" method and Muther's Factor Analysis are almost identical. These approaches to the evaluation problem more closely resemble a total quantitative technique than do any of the others thus far appearing in print. The main weakness of these techniques is their failure to offer any new suggestions as to establishment of the relative weights of the major criteria. Again, judgment and experience are offered as the best available tools.

A technique presented by Reed (1961) differs only slightly from those of Muther and Apple. This method, called Evaluation by Elemental Points Assignment,[3] consists primarily of the following two operations: (1) Reduce the overall problem to a series of smaller problems by dividing it into its "elemental parts" or factors, and

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[3]A more detailed explanation of this procedure is given in the appendix.

(2) evaluate these factors against a series of defined limited ranges or degrees. An "average relative evaluation" representing a fractional part of a maximum element value is assigned to each of these degrees. The maximum element value is in turn a fractional part of the maximum points assigned for layout evaluation.

Another noteworthy technique is the "Cost-Effectiveness" approach of Harris and Smith (1968). Its methodology, based on systems concepts, assumes that plant layout must be treated as a sub-system of production design in order to achieve valid results. Production scheduling, process design, and job design represent additional subsystems, and "each subsystem must be bounded by laws unique to it and particular to its function." Bounding the subsystem is imperative to maintain consistency with systems concepts.

Harris and Smith maintain that optimal solutions are not achieved through the sub-optimization of objectives. The optimal solution to a layout problem will be the alternative that maximizes the "relative good" of each component of that alternative. The cost effectiveness technique evaluates layout alternatives on the basis of satisfaction of specified criteria. Hence, validity of results depends on validity of criteria; this, of course, is true for any type of evaluation, qualitative or quantitative.

The worth of a layout, according to cost-effectiveness methodology, is a function of the "benefits"[4] it affords and the costs it requires for implementation. Hence, cost-effectiveness equals benefits minus costs or,

$$CE = B - C,$$

where the cost figure represents total cost of the layout for its entire life cycle.

The cost-effectiveness approach can be summarized as follows:

(1) Determine criteria to be evaluated.

(2) Set minimum performance levels for each criterion. Any alternative failing to meet minimum requirements is immediately eliminated.

(3) Determine "benefits."[5]

(4) Determine costs for each alternative.

(5) Calculate cost-effectiveness for each alternative and compare.

Cost-effectiveness is based on the assumptions that (1) layout design is a subproblem of the design of the total production system, (2) the layout objectives are quantifiable into a criteria set, and (3) after these objectives are quantified, the methods of cost effectiveness may be used to choose the best alternative over the life of the system. The first assumption is probably true in every case. The

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[4] A "benefit" is some measure of how well the layout measures up to criteria.

[5] Determination of "benefits" involves a matrix algebra procedure.

second assumption the author can accept as being true as long as it is understood that the validity of such quantification hinges entirely upon the "judgment and experience" of available personnel. Once again, no suggestions are given as to any quantitative methods for determining relative worth of the individual criteria. The validity of the third assumption is dependent upon the validity of the second and upon the validity of cost-effectiveness methodology itself.

Hillier's (1963) solution to the evaluation problem utilizes material handling distance as its sole criterion. The basic assumption here is that minimum material handling cost is achieved when material handling distance is minimized. This may be a valid assumption in the majority of cases, however, the author contends that material handling cost is but one of the several costs to be considered in planning a layout, and that the optimization of one criterion at the expense of others is probably a serious mistake. Such a procedure in all likelihood will not yield an optimal solution.

Hillier's method involves the minimization of a complex objective function, representing total material handling distance. Hillier admits this is a very complex problem, even admitting that it has not yet been solved. The objective function can be sub-optimized, however, by means of another procedure indicating improvements possible through the exchanges of locations of pairs of work centers. This procedure cannot guarantee an optimal solution because it is unable to identify all possible improvements.

Regardless of the validity of Hillier's procedure for minimization of material handling costs, the underlying assumption that material handling cost is the only factor worth consideration is highly questionable.

Computer techniques comprise a relatively new collection of layout evaluation tools. The techniques described here basically begin with some form of existing layout and improve it according to the criteria setforth. The evaluation of the individual layout is repeated over and over again as the layout is being designed. Evaluation of layout alternatives can be made after several layouts have been produced.

CRAFT, or Computerized Relative Allocation of Facilities Technique (Buffa, Armour, and Vollman, 1964), employs materials flow as the lone criteria for development of closeness relationships, these relationships being the sole basis for evaluation of the layout. Relationships are developed for each pair of activities forming the matrix to the program.

The CRAFT program is based on ideas resembling the concept underlying the linear programming algorithm which converges on an optimal solution. Unfortunately the solutions obtained through CRAFT are not necessarily optimal, as in Hillier's procedure, because the program cannot identify all possible solutions, but claims have been made by its originators that it does offer solutions that cannot easily be improved upon. CRAFT requires three sets of input data including material flow data (interdepartmental flow per unit time), moving cost data (cost per unit per distance moved), and space requirements in the form of an initial layout. The number of activities involved is limited to 40.

The basic procedure is best illustrated using a flow diagram as shown on the following page. It must be emphasized that the results are a product only of material flow and material handling cost data. Again, the author argues that a solution based on only one of the several factors actually involved will generally tend to be sub-optimal.

CORELAP, or Computerized Relationship Layout Planning (Lee and Moore, 1967), uses as input data the familiar vowel-letter closeness relationships[6] based on flow, material handling, and other significant factors. It is a "path-oriented logical analysis . . . which builds systematically by adding one department upon another until a final layout is achieved." Input includes relationship data, space requirements, and maximum acceptable building length-to-width ratio. The program consists of over 400 FORTRAN statements and

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[6]The vowel letter relationships (Apple, 1963) represent extremely vague, qualitative measures of closeness desirability of one department for another. They are as follows: A - closeness absolutely necessary; E - closeness especially important; I - closeness important; 0 - ordinary closeness OK; U - closeness unimportant; X - closeness undesirable.

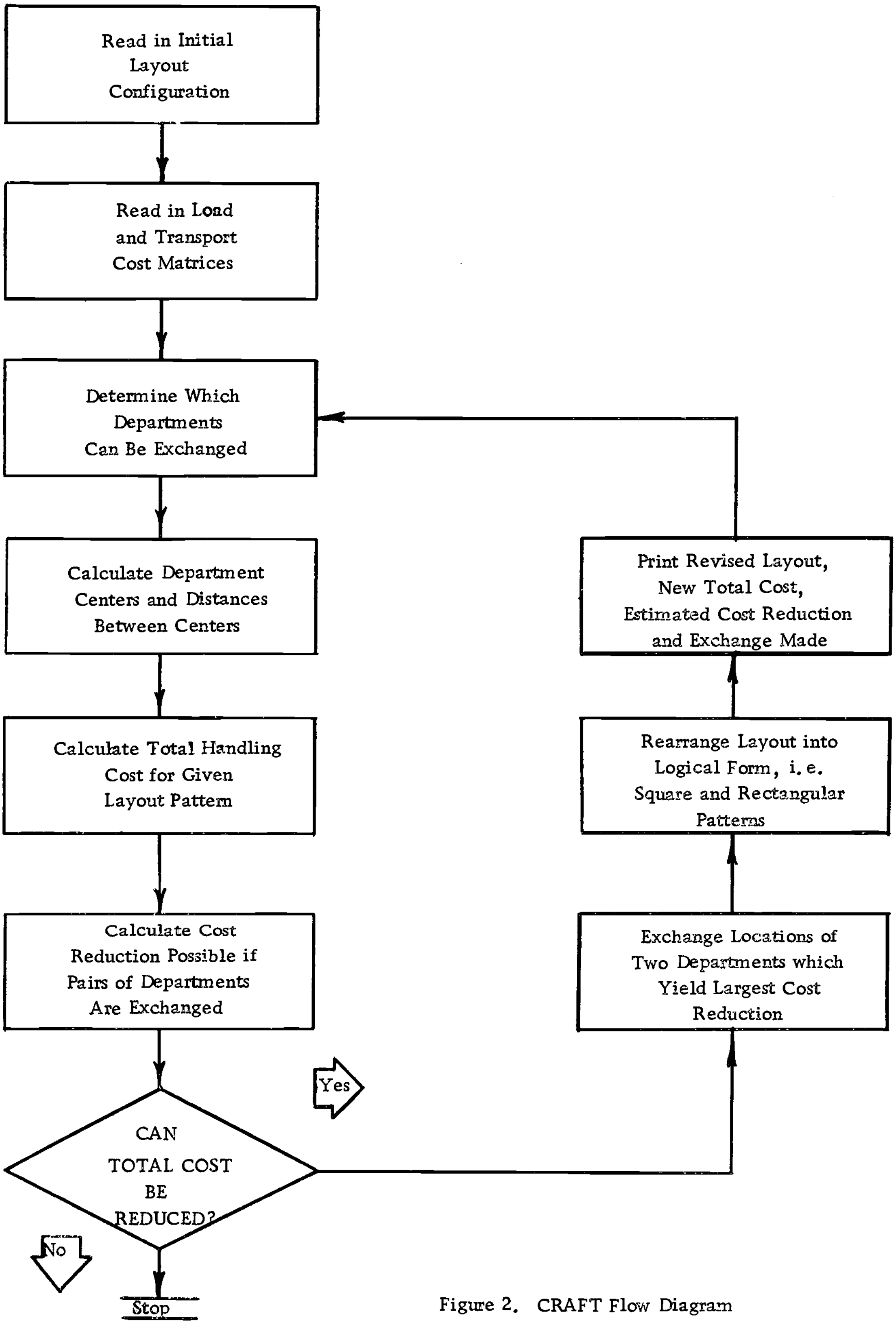

Figure 2. CRAFT Flow Diagram

10,000 more executable statements. The program essentially asks two questions: "Which department has the privilege of being placed next into the layout?" and "How is this department entered into the layout?" The flow diagram on the following page better illustrates the steps involved.

Basically the program inserts the "most related" department into the layout and places around it those departments with which it has an "A" rating. After all "A" relationships have been satisfied, the program searches for "E," "I," "O," and "U" relationships and places the departments into the layout in an effort to satisfy relationship requirements in an optimal manner.

CORELAP makes no attempt at numerical evaluation. Since CORELAP can come up with only one layout for a given set of input data, there is no evaluation of alternatives. The resulting layout can by no means be considered optimal in the true mathematical sense, and since it is usually printed out in an irregular shape, further manual adjustment is always necessary to obtain a workable layout. Given reliable and accurate input data, CORELAP will probably yield better results than CRAFT since it is based on more than one of the factors involved. The resulting layout can be only as good as the criteria set chosen and the relationship values applied. Hence, judgment and experience again are key factors in the employment of a layout technique.

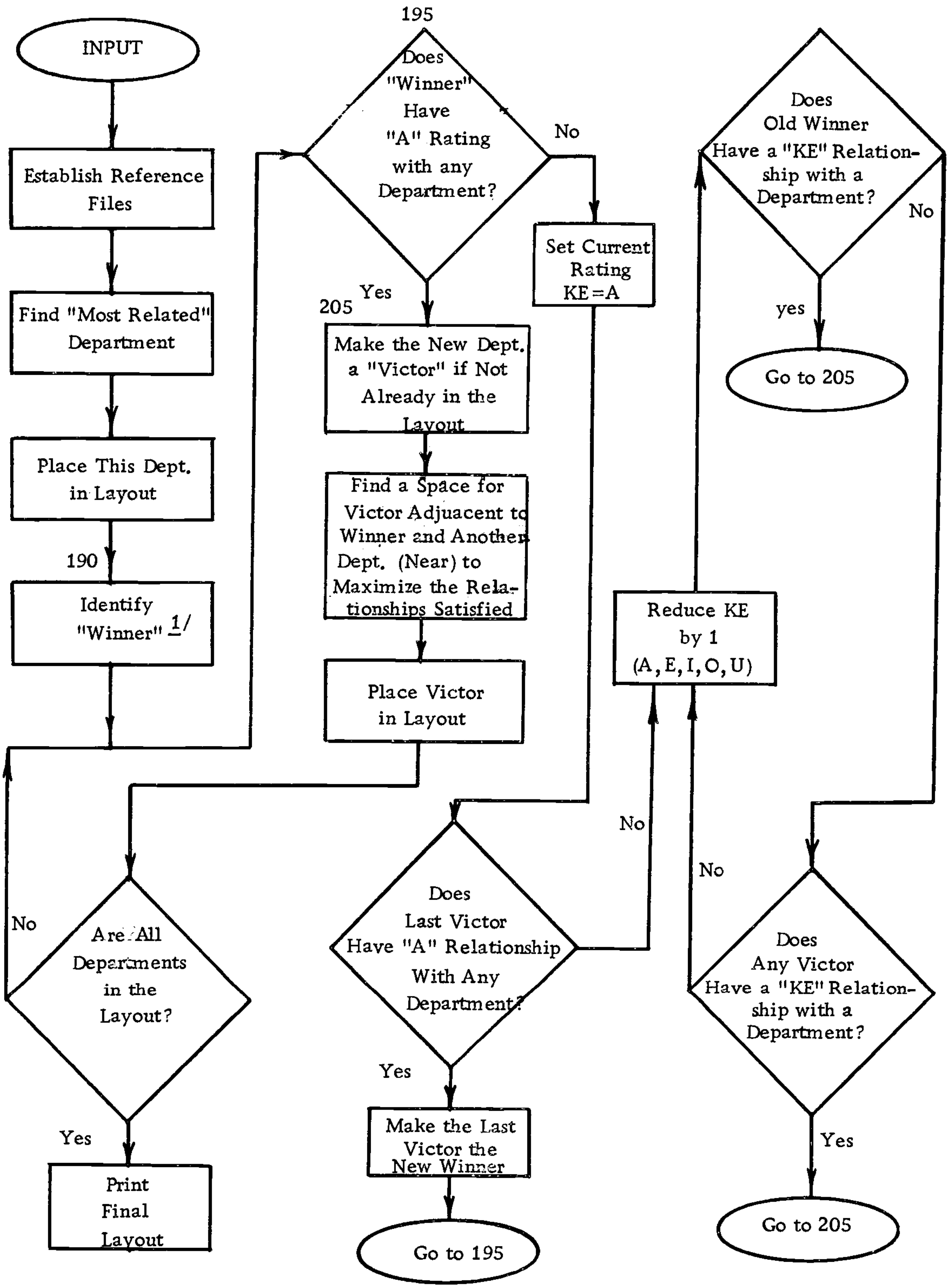

Figure 3. CORELAP General Flow Diagram

1/ Definitions of CORELAP terms can be found in the Appendix.

ALDEP or Automated Layout Design Program (Seehoff and Evans, 1967) requires as input data building specifications, departmental pre-assignments, and departmental location preferences. The program produces a predetermined number of layouts, scoring each one, and those meeting a predetermined minimum score are transfered to magnetic tape for input into another program which prints the layouts utilizing a digital plotter.

The ALDEP program has the added capability of multistory layouts of up to three floors, performing the following two-step process for each floor: (1) an available department is assigned to a specific floor, and (2) the department is then given a specific location on the floor. A somewhat modified random selection technique is used to process departments. After the initial department is inserted into the layout, a departmental preference search is made to find the "most related" departments, and those departments are inserted into the layout. When no more location preferences can be found, another department is randomly selected and the procedure is repeated until all departments are processed.

The layout score is the summation of the "preference values" for adjacent departments. Adjacent scoring, according to ALDEP originators, is not a severe limitation since functionally dependent departments will tend to group together due to their combined interrelational preference values.

ALDEP, like CRAFT and CORELAP, requires additional manual adjustment after the final printouts. The best layout must be selected from those receiving the highest scores. If the assumption is made that the best layout is the layout with the highest score, then selection is no problem. The validity of this assumption, however, is dependent on the validity of the relationship preference values selected and on the validity of the ALDEP evaluation procedure itself. If the evaluation procedure is indeed valid, then the success of its application is a function of the judgment and experience of the layout analyst.

RMA Comp I (Muther, 1970), like CORELAP and ALDEP, uses vowel letter relationships as its main input data. Additional input data includes activity area requirements and information concerning activity types. Using a procedure similar to CORELAP's, RMA Comp I selects the activity with the largest "total closeness rating" and places it in the center of the layout matrix. Other activities are placed in the layout according to their relationships with activities already in the layout as well as with those not yet placed in the layout. When the relationship diagram is complete, it is exploded into a space relationship diagram using the area requirement input data. Further manual adjustment is always necessary to produce a workable layout design.

RMA Comp I appears to be a slightly advanced version of

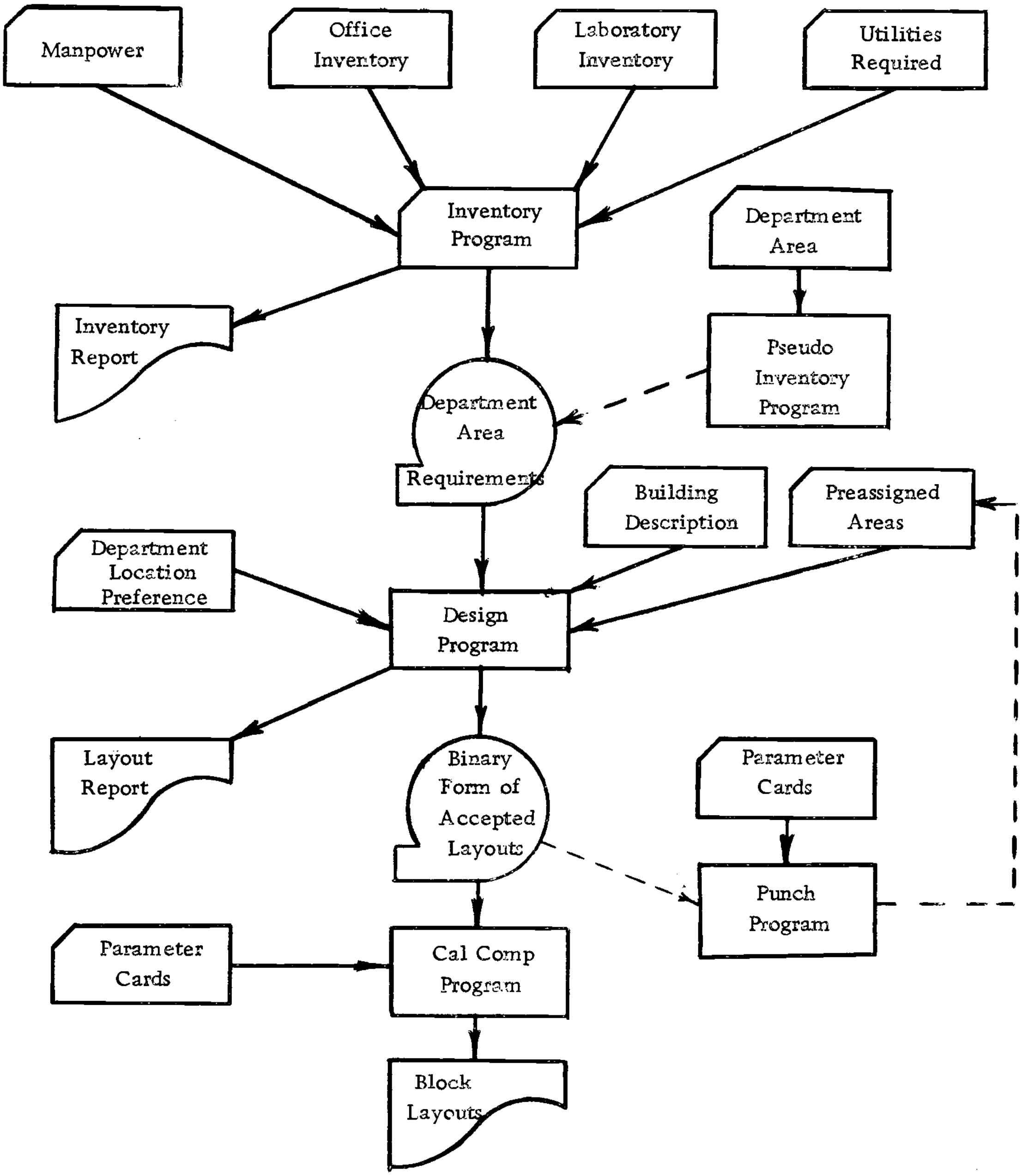

Figure 4. ALDEP General System Flow Chart

CORELAP, and like CORELAP, makes no attempt to present a numerical score. The success of this layout technique is also a function of judgment and experience in that valid results cannot be obtained without valid relationship inputs.

All four computerized layout techniques discussed in this paper must be classified as experimental. Thus far they can be considered only as layout aids in that further adjustments are always necessary to construct practical layouts.

Muther (1970) presents the following set of criteria for a "good" layout program:

(1) The program must be reliable. Layouts generated must honor desired closeness relationships as well or better than they can be honored manually.

(2) The required input data must be realistic. It must be meaningful data that can be practically measured.

(3) The program must honor negative relationships (closeness-not-desired).

(4) The program must be able to fix the location of certain activities and building features.

(5) The program must honor shape or configuration requirements of those activities that require it.

(6) The program must be able to handle multi-story problems realistically.

(7) The program must provide readily usable output. Shapes of activity areas and total layouts must be realistically practical. Some sort of graphic output is highly desirable.

(8) The program should generate alternate layouts and some sort of practical evaluation of tangible and intangible factors should be made.

(9) Finally, the program must be flexible enough to accommodate rapidly any changes in input data and design criteria, especially in the transition from developing block area layouts to developing detail layouts of machinery and equipment.

The computer programs available today, to say the very least, do not meet the above requirements, and it appears that a "good" program according to Muther's standards will not be available for quite some time.

THE MODEL

A formal mathematical model will now be presented. It has already been established that in order to provide a meaningful basis for evaluation of layout alternatives we must evaluate quantitatively both the obviously numerical and the qualitative, seemingly unquantifiable factors.

Consider the prospect of single numerical scores as the final measures of effectiveness of layout alternatives. Comparing such scores, the layout analyst's decision would be greatly simplified since the best layout would, of course, be the one with the best score. This score will be called the Quantitative Evaluation Index, or QEI, and will be composed of material handling, relationship, information flow, performance, flexibility, and related cost factors. These factors must be assigned relative weights in order to achieve proper balance. The QEI, then, is presented in the following equation:

$$QEI = \alpha(D') + \beta(L') + \gamma(M') + \sigma(I') + \phi(P') + \theta(F'),$$

where D' = material handling distance factor,

L' = location relationship factor,

M' = related cost factor,

I' = information flow factor,

P' = performance factor,

F' = flexibility factor,

and α, β, γ, σ, ϕ, and θ are weighting factors and are constant for a given layout evaluation problem. Since each of the factors (D', L', M', I', P', and F') represents a fraction of the QEI,

$$\alpha + \beta + \gamma + \sigma + \phi + \theta = 1$$

The specific values of α, β, γ, σ, ϕ, and θ will undoubtedly be different for each individual evaluation problem. It is very important that these values be extremely accurate, otherwise the results obtained may cause false conclusions to be drawn. This problem will be discussed later.

Material Handling Distance Factor (D')

Material handling distance is certainly one of the more important factors to be considered in the evaluation of most layouts. A production system requiring the movement of heavy or otherwise hard-to-handle materials might warrant a heavy weighting of the material handling distance factor. A highly automated system might also demand a heavy weighting. Smaller, easier-to-handle materials might justify a lower weighting factor.

Weighting problems are also likely to be encountered when dealing with a system involved in the movement of several types of materials. A considerable degree of difficulty and confusion may result when some materials requiring little effort to move and others requiring extensive man and machine power are part of the same system. Frequency of moves, manpower requirements per move, lot sizes, and material handling machine costs are a few considerations that must be included in establishing the relative weight of the material handling distance factor.

Suppose there are three different categories of material handling in one system, each requiring a different degree of man and machine power. The material handling distance factor, then, is a composite of the three different levels of material handling requirements, or

$$D' = \omega_i(D_i) + \omega_j(D_j) + \omega_k(D_k),$$

where D_i, D_j, and D_k are some measures of material handling effectiveness,

and ω_i, ω_j, and ω_k are weighting subfactors representing fractions of the total value of D', or

$$\omega_i + \omega_j + \omega_k = 1.$$

As a general measure of material handling effectiveness, the material handling distance factors can be determined as follows:

$$D_i = \frac{\sum^{i} \text{material handling distances for new layout}}{\sum^{i} \text{material handling distances for old layout}},$$

$$D_j = \frac{\sum^{j} \text{material handling distances for new layout}}{\sum^{j} \text{material handling distances for old layout}},$$

$$\text{and} \quad D_k = \frac{\sum^{k} \text{material handling distances for new layout}}{\sum^{k} \text{material handling distances for old layout}} \quad .$$

Assuming that improvement has been made over the old layout, these factors will all be less than one and greater than zero, or

$$0 < D_i \leq 1, \; 0 < D_j \leq 1, \; 0 < D_k \leq 1,$$

If material handling distances have not been changed, the values of these factors will be equal to one. Hence, when these factors are combined to form the composite material handling distance factor, we have the following:

$$D' = \omega_i(D_i) + \omega_j(D_j) + \omega_k(D_k), \text{ and}$$

$$D' \leq 1$$

It should be pointed out that it is entirely possible that a new layout design will include an increase in material handling distance for some of the material handling classifications. In this case an overall improvement in material handling is still possible. Consider the following: suppose

$$D_i < 1, \text{ and } D_j, \; D_k > 1.$$

An improvement in material handling ($D' < 1$) will result if

$$1 - \omega_i(D_i) > \omega_j(D_j) + \omega_k(D_k).$$

To determine the material handling distances for the new and old layouts, simply calculate the distances traveled in feet for each unit, part, or sub-assembly involved in the total production process. If a large number of parts renders this process impractical, a smaller number of representative distances might be sufficient to afford good results. A random selection process might be used in this case.

The material handling distance factor is purely quantitative and involves no quantification of qualitative factors.

Location Relationship Factor (L')

Procedure for determination of the location relationship factor is somewhat more complicated and involves the quantification of several qualitative factors. The first step in this procedure is to construct an activity relationship chart[7] employing techniques described by Muther (1961) and Apple (1963). Quantitative values must be assigned to the vowel-letter relationships as in the following table:

Closeness	Explanation	Quantitive Rating
A - absolutely necessary	Must be adjacent	100
E - especially important	Adjacency desired but not absolutely necessary	75
I - important	Adjacency not required but closeness necessary	60
O - ordinary closeness OK	Some degree of closeness desirable	40

[7] See appendix for illustration.

Closeness	Explanation	Quantitive Rating
U - unimportant	Closeness has no effect on operation of either area or on operation of total system	1
X - undesirable	Any degree of closeness harmful	0

Also, quantitative values must be assigned to the reasons for desired closeness. This might be done as in the following example:

Typical Reasons	Ratings
(1) Sequence of work flow	1.00
(2) Minimize materials handling	.95
(3) Ease of communication; information flow	.80
(4) Safety	.80
(5) Employee convenience	.50
(6) Unsafe, unsanitary, or unpleasant conditions	.00

Entering the qualitative parameters into the activity relationship chart we have something that looks like the following:

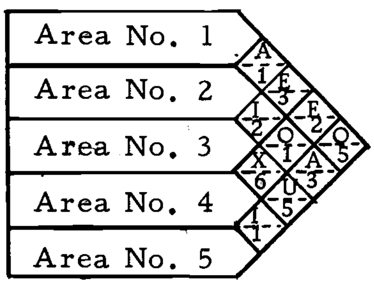

Figure 5. Activity Relationship Chart

Substituting the quantitative values we have:

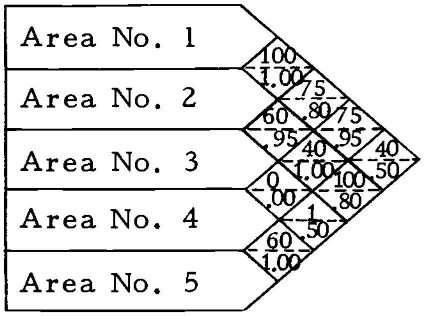

Figure 6. Modified Activity Relationship Chart

and finally, multiplying the closeness values by the reason ratings, we have the final activity relationship chart:

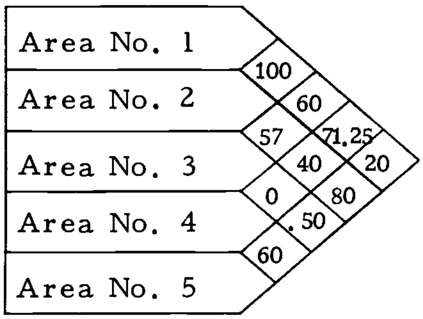

Figure 7. Final Activity Relationship Chart

The values in this chart represent the closeness desirabilities of each area for every other area in the layout. This final chart was constructed with assistance from a device similar to the following activity relationship rating table, illustrating all possible closeness-reason combination values.

Closeness	Reasons 1	2	3	4	5	6
A	100	95	80	80	50	0
E	75	71.25	60	60	37.5	0
I	60	57	48	48	30	0
O	40	38	32	32	20	0
U	1.00	.95	.80	.80	.50	0
X	0	0	0	0	0	0

Figure 8. Closeness-Reason Combination Values

Now it is necessary to compare the desired closeness ratings in the final activity relationship chart with the closeness actually attained in both the new and the old layouts. Scoring is done using a penalty table which assigns penalty scores on the basis of desired versus actual closeness. Such a table is illustrated below.

Closeness-Reason Scores	Adjacent	$\leq x_1$ ft.	$> x_1$ ft., $\leq x_2$ ft.	$> x_2$ ft., $\leq x_3$ ft.	$> x_3$ ft., $\leq x_4$ ft.	$> x_4$ ft.
$y_4 - y_5$	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}
$y_3 - y_4$	P_{21}	P_{22}	P_{23}	P_{24}	P_{25}	P_{26}
$y_2 - y_3$	P_{31}	P_{32}	P_{33}	P_{34}	P_{35}	P_{36}
$y_1 - y_2$	P_{41}	P_{42}	P_{43}	P_{44}	P_{45}	P_{46}
$0^+ - y_1$	P_{51}	P_{52}	P_{53}	P_{54}	P_{55}	P_{56}
0	P_{61}	P_{62}	P_{63}	P_{64}	P_{65}	P_{66}

Figure 9. Relationship Penalty Table

where $x_1 < x_2 < x_3 < x_4$

and $0^+ < y_1 < y_2 < y_3 < y_4 < y_5$;

y_5 is the maximum possible closeness-reason score. The penalty scores, all non-negative, range from 0 to p_{16}, or 0 to p_{61}, depending on whether $p_{16} > p_{61}$ or $p_{61} > p_{16}$, where p_{11}, p_{21}, p_{31}, p_{41}, p_{51}, are each equal to zero.

Also

$$p_{12} < p_{13} < p_{14} < p_{15} < p_{16},$$
$$p_{22} < p_{23} < p_{24} < p_{25} < p_{26},$$
$$p_{32} < p_{33} < p_{34} < p_{35} < p_{36},$$
$$p_{42} < p_{43} < p_{44} < p_{45} < p_{46},$$
$$p_{52} < p_{53} < p_{54} < p_{55} < p_{56},$$
$$p_{61} > p_{62} > p_{63} > p_{64} > p_{65} > p_{66},$$
$$p_{12} > p_{22} > p_{32} > p_{42} > p_{52},$$
$$p_{13} > p_{23} > p_{33} > p_{43} > p_{53},$$
$$p_{14} > p_{24} > p_{34} > p_{44} > p_{54},$$
$$p_{15} > p_{25} > p_{35} > p_{45} > p_{55}, \text{ and}$$
$$p_{16} > p_{26} > p_{36} > p_{46} > p_{56}.$$

It is noticed that only "X" relationships involve closeness-reason scores equal to zero. These zero values are not meant to indicate unimportant relationships; instead, they serve to identify "X" relationships. It is also noticed in the penalty table that any degree of closeness involving a zero closeness-reason score results in a high penalty score.

After penalty scores are summed for the new layout and the old layout, the location relationship factor, L', may be calculated as follows:

$$L' = \frac{\Sigma \text{ relationship penalty scores for new layout}}{\Sigma \text{ relationship penalty scores for old layout}}$$

Assuming that the new layout is an improvement over the old one, the location relationship factor will always be greater than zero and less than one, or $0 < L' \leq 1$. Obviously a lower score indicates a greater degree of improvement.

The calculations involved are relatively simple when the layout consists of only a few departments. However, layouts containing more than a few departments or sub-systems require a much greater number of calculations. The time and manpower involved may even tend to be prohibitive. Through employment of a computer program, these calculations could be made rather simple. Such a program is beyond the scope of this paper, but it is a possibility easily realizable.

Related Cost Factor (M')

Every plant layout design problem is accompanied by pecuniary restrictions, and naturally management will look more favorably upon a smaller financial investment in any situation, provided all other system requirements are met adequately.

Assume that management has set a maximum allowable expenditure for transition to the new layout design. The new layout, then, will not be acceptable if it requires a greater financial outlay; hence, the layout planner must design accordingly. A measure is needed, then, of how well the designer limits his proposed expenditure. The following measure is suggested:

$$\text{Related Cost Factor} = M' = \Sigma \frac{(\text{present worth}^{8} \text{ of comprehensive layout costs})}{Z},$$

where Z is the established maximum allowable expenditure. A score of greater than 1 indicates excess expenditure, and a lower score indicates smaller financial investment.

It should be pointed out that the objective here is not to minimize related costs at the expense of the system. Excess minimization of costs will inevitably show up in the other factors and result in a poorer overall Quantitative Evaluation Index (QEI). The mere fact that the layout planner is aware that the evaluation of his layout design will be significantly affected by costs incurred, he will certainly be a little more cost-conscious, and a more economical layout will be the probable result.

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[8]All cash flow discounted to a common point in time according to a rate of return considered adequate by the organization conducting the study.

"Comprehensive costs" is a rather general term, and careful consideration must go into its composition. Certainly the initial costs incurred should be included as well as other identifiable interest charges or additional labor costs. There are certainly additional costs that might warrant inclusion.

Information Flow Factor (I')

It is often the case that the efficiency of a production system is greatly reduced by an inadequate production information-communication network. In smaller plants this problem may be insignificant, but in the larger, more complex manufacturing organizations a poor information-communication network may cause costly production delays resulting in late shipments and lost profits. Although this particular problem seemingly has little to do with the design of a plant layout, the success of any layout design is tied directly to the efficiency of its associated information system.

It may be wasteful to redesign a reliable, efficient information system, but a careful analysis may turn up some yet uncovered improvement possibilities that could enhance the efficiency of the production system as a whole. What is desired is accurate, timely, useful information. Too little or too much information tends to cause confusion, and out-of-date information is useless. Correct information at the appropriate time is the only acceptable criterion.

To measure the improvement of a new information-communication system the following evaluation factor is suggested:

$$\text{Information flow factor} = I' = \frac{\Sigma\,(\text{total information flow time for new system})}{\Sigma\,(\text{total information flow time for old system})},$$

where flow time equals the total time involved in all information-communication exchanges during the manufacturing cycle of one production unit. This should include only paperwork exchanges from the initial entry of the work order through production planning, purchasing, receiving, fabrication, assembly, inspection, shipping, as well as any other related processes.

Information flow time might be measured as follows:

Information flow time = (number of necessary paperwork exchanges per unit of production) x (average time required to make the exchange).

Assuming that the new system constitutes an improvement, I' will always be greater than zero and less than one, or

$$0 < I \leq 1$$

Performance Factor (P')

Unfortunately, the actual performance of any proposed layout design cannot be measured until the system is tested under normal operating conditions. Given enough reliable information, however, it may be possible to make a meaningful performance evaluation using a simulation procedure. The following information may be helpful:

(1) Sales forecast information
    (a) predicted output requirements
    (b) probability distributions for predicted output levels

(2) Machine requirements per unit of output

(3) Process outlines, routing sheets

(4) Subcontract costs for various components

(5) Overtime costs

(6) Maintenance, depreciation, and interest charges

(7) Machine breakdown frequency distributions

The suggested simulation procedure involves the construction of a "decision tree" (Riggs, 1968) as shown on the following page. Branches extend from an initial decision point showing primary alternatives. These main branches then separate into several smaller branches indicating foreseeable outcomes associated with possible future events. The various events are then rated according to the probabilities of their respective occurrences. A second decision point is established when gains can be maximized by the introduction of new alternatives at a future date. Successive decision points can extend to the limit of forecasting ability.

Establishing the condition that sales requirements, and hence production schedules, <u>will</u> be met, the performance of the system can be measured with the following formula:

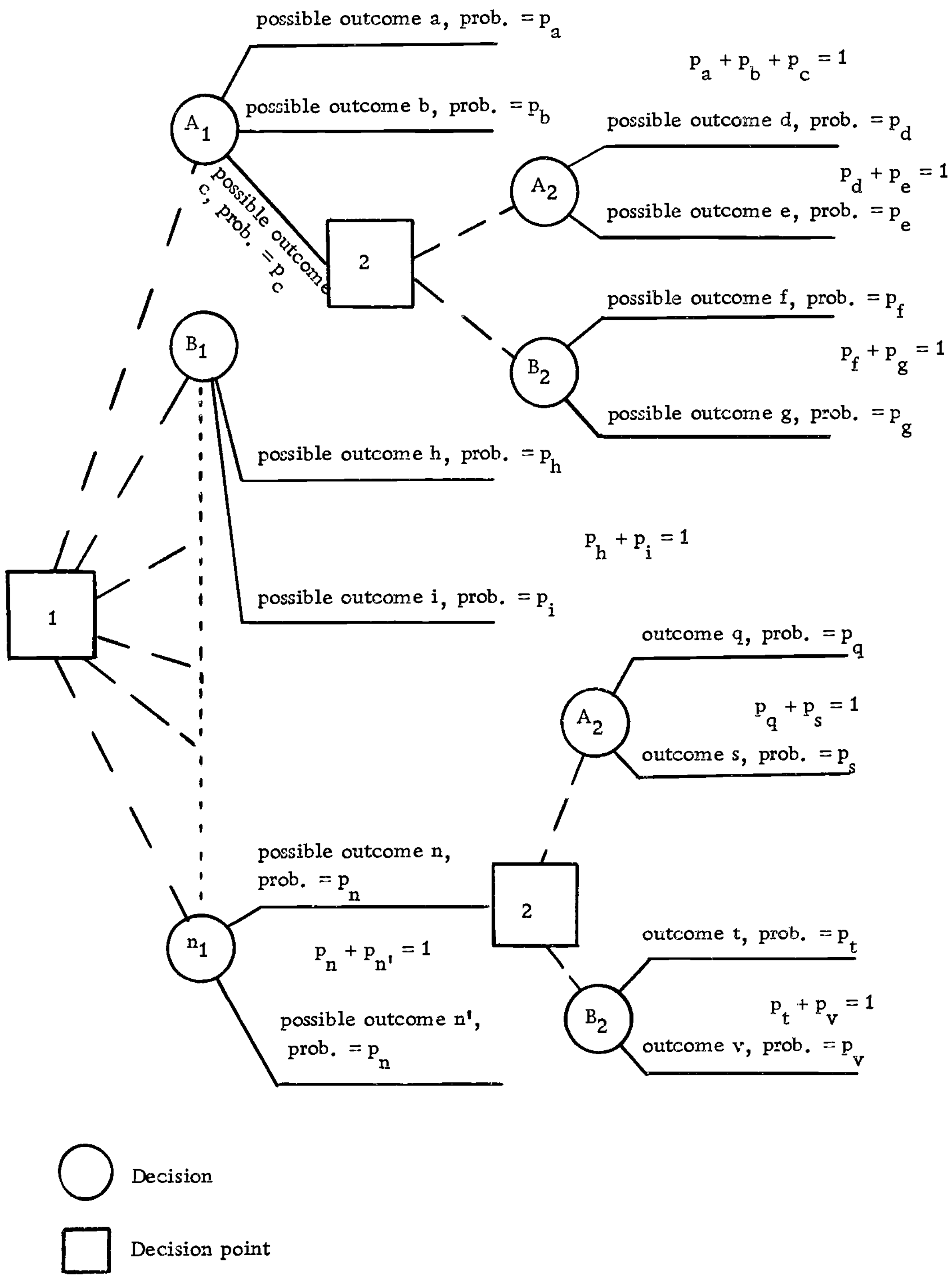

Figure 10. Decision Tree Format

$$\text{Performance factor} = P' = \frac{\sum \text{(present worth of all costs attributed to future occurrences for new system)}}{\sum \text{(present worth of all costs attributed to future occurrences for old system)}}$$

These costs should include machine repair costs, overtime costs, subcontract costs, idle machine interest charges, as well as any other costs incurred in meeting the required level of output under simulated conditions.

The validity of this procedure depends on the accuracy of the sales forecasts and related probability distributions involved in construction of the decision tree. Judgment and experience must be diligently quantified in order to attain a meaningful evaluation here.

Flexibility Factor (F')

A layout evaluation technique cannot be complete without some method of measuring system flexibility. The ability or inability of a production system to adjust to unforeseen requirements might be the difference between success or failure of an entire organization.

To measure flexibility, another simulation procedure is suggested: (1) simulate several major production design and process changes, (2) sum the costs related to meeting production requirements for both new and old systems, and (3) calculate the flexibility factor as follows:

$$\text{Flexibility Factor} = F' = \frac{\Sigma \text{ (present worth of costs attributed to simulated changes - new system)}}{\Sigma \text{ (present worth of costs attributed to simulated changes - old system)}} .$$

Assuming improvements have been made, F' will always be less than 1 and greater than zero. If simulated design and process changes are realistic, the above ratio will probably constitute a good measure of the improvement afforded by a new system. Perhaps historical data will provide a good basis for simulation of such changes.

To provide a realistic simulation of sales, production and design changes, machine breakdowns, and other related events, a Monte Carlo[9] simulation technique should be employed. This will introduce the full range of values that quantitatively describe a factor, while simple probability point estimates can not usually simulate realistic conditions.

Quantitative Evaluation Index (QEI)

The six factors having been calculated, the layout analyst is faced with the problem of weighting them in a manner that will result in the calculation of a meaningful quantitative evaluation index. There are several ways to do this, the least complex being a simple

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[9] The name Monte Carlo comes from the technique's similarity to gambling devices used to generate probabalistic data through unrestricted random sampling.

assignment of estimated relative values. The success of such a method, however, depends entirely upon available judgment and experience. Reliable inputs, even in such a seemingly unquantitative application, may produce valid results.

Since judgment and experience are often inadequate, a more quantitative approach is definitely needed. The factors may be divided into major and minor categories. For example, suppose it is decided that for a given system material handling distances and location relationships are of greater importance than the other four factors combined. Then the analyst would know that

(a) $\alpha + \beta > .50$, and

(b) $\gamma + \sigma + \phi + \theta < .50$

Although this simplifies the problem somewhat, the analyst must still determine the relative worths of all factors. A procedure similar to the following might be used:

(1) Calculate all direct material handling costs incurred for one unit of production. Call this value A.

(2) Calculate all manpower and machine direct costs incurred for one unit of production excluding material handling costs. Call this value B.

(3) Sum the values obtained in (1) and (2).

(4) Calculate relative worths using the following formulae:

Relative worth of material handling factor $= \frac{A}{A + B}$

and relative worth of location relationship factor $= \frac{B}{A + B}$.

This determines the relative worths of factors in category (a). Similar ratios might be used in calculation of relative worths in category (b). To find the absolute relative values of α and β the relative worth of category (a) must be determined. Assuming that judgment and experience are adequate to determine the relative worths of the major and minor categories, the values of α, β, γ, σ, ϕ, and θ can be established as follows:

category (a): $$\alpha = \frac{A_a}{A_a + B_a} (\alpha + \beta) \text{ and}$$

$$\beta = \frac{B_a}{A_a + B_a} (\alpha + \beta)$$

category (b): $$\gamma = \frac{A_b}{A_b + B_b + C_b + D_b} (\gamma + \sigma + \phi + \theta),$$

$$\sigma = \frac{B_b}{A_b + B_b + C_b + D_b} (\gamma + \sigma + \phi + \theta),$$

$$\phi = \frac{C_b}{A_b + B_b + C_b + D_b} (\gamma + \sigma + \phi + \theta),$$

and $$\theta = \frac{D_b}{A_b + B_b + C_b + D_b} (\gamma + \sigma + \phi + \theta),$$

where $(\alpha + \beta) + (\gamma + \sigma + \phi + \theta) = 1$.

The relative weighting factors being determined, the analyst is able to calculate the quantitative evaluation index:

$$QEI = \alpha(D') + \beta(L') + \gamma(M') + \sigma(I') + \phi(P') + \theta(F')$$

Since
$$0 < D' \leq 1,$$
$$0 < L' \leq 1,$$
$$0 < M' \leq 1,$$
$$0 < I' \leq 1,$$
$$0 < P' \leq 1,$$
$$0 < F' \leq 1, \text{ and}$$

$\alpha + \beta + \gamma + \sigma + \phi + \theta \equiv 1$, it is noticed that

$$0 < QEI \leq 1.$$

A QEI equal to one indicates that the new layout represents no improvement whatsoever over the old layout, while a low QEI indicates that significant improvements have been made.

It should be mentioned here that the numerical values of any of the six factors, D', L', M', I', P', or F', may exceed the value one (1). Although this indicates that the new layout is inferior to the old layout in one or several respects, it does not necessarily mean that the new layout is wholly inferior (QEI > 1). The new layout represents an overall improvement over the old layout as long as the quantitative evaluation index is less than one, or

$$1 - \Sigma \begin{matrix}\text{(weighting factors x factors}\\ \text{that are less than 1)}\end{matrix} \geq \Sigma \begin{matrix}\text{(weighting factors x fac-}\\ \text{tors that are greater than 1)}\end{matrix}$$

Another method that might be used is as follows: Suppose it is decided that the material handling and location relationship factors are of equal importance. It is also felt that (1) the related cost factor is worth about one half of the material handling factor, (2) the performance factor is one third as important as the related cost factor, (3) the information flow factor is twice as important as the flexibility factor and (4) the flexibility factor is only one fourth as important as the related cost factor. Having established these relationships, the relative weighting factors can now be determined. Assign an arbitrary weight of 100 to both the material handling distance factor and the location relationship factor, or

$$\alpha_a = 100$$

$$\beta_a = 100$$

The related cost factor is half as important, or

$$\gamma_a = 1/2\alpha_a = 50$$

The performance factor is worth one third the value of the related cost factor, or

$$\phi_a = 1/3\gamma_a = 16.67$$

The information flow factor is twice as important as the flexibility factor, or

$$\sigma_a = 2\theta_a$$

and the flexibility factor is only one-fourth as important as the related cost factor, or

$$\theta_a = 1/4 \quad \gamma_a = 12.5,$$

and since

$$\sigma_a = 2\theta_a,$$

$$\sigma_a = 25.$$

So the six arbitrary weighting factors are

$$\alpha_a = 100,$$

$$\beta_a = 100,$$

$$\gamma_a = 50,$$

$$\sigma_a = 25,$$

$$\phi_a = 16.67, \text{ and}$$

$$\theta_a = 12.5.$$

Summing these we have

$$\alpha_a + \beta_a + \gamma_a + \sigma_a + \phi_a + \theta_a = 303.92.$$

Calculation of the absolute relative weights can now proceed as follows:

$$\alpha = \frac{\alpha_a}{303.92}$$

$$\beta = \frac{\beta_a}{303.92}$$

$$\gamma = \frac{\gamma_a}{303.92}$$

$$\sigma = \frac{\sigma_a}{303.92}$$

$$\phi = \frac{\phi_a}{303.92}$$

$$\theta = \frac{\theta_a}{303.92}$$

The above method is certainly not wholly quantitative, and its results are open to criticism and question, but the fact that the layout analyst is forced to look more closely at these relationships will probably lead to a more thorough analysis, and consequently, a more effective layout.

A far superior procedure has been presented by Inoue and Ghaffari (1970). It involves a linear programming model consisting of an objective function and a series of constraints representing the estimated relative values of each of the factors to be weighted. Utilizing a time-sharing computer an accurate solution to the weighting problem can be obtained with relatively little effort.

The scope of application of the QEI can be extended to the new-plant problem with one slight modification. Since, in this case, there is no existing layout to serve as a basis for measurement of improvement, some sort of initial reference layout must ge generated. The layout alternatives, then, can be evaluated on the basis of improvement over this generated initial design.

A CLASSROOM APPLICATION

In May, 1969, the preceding quantitative evaluation procedure was put to a limited test in a plant layout course in the Department of Industrial Engineering at Oregon State University. A layout problem was given to six groups of three students involving the improvement of an already existing manufacturing facility. The problem was based on a real manufacturing organization and a real product, although much simplified due to the limited class time available.

The six groups were given identical existing layouts, a set of instructions and procedures, and additional necessary information.[10] Approximately seven class hours and an additional eight man-hours of evaluation time were required. Evaluation was limited to consideration of only three of the six factors since limited class time was available. These three factors were the material handling distance factor (D'), the location relationship factor (L'), and the related cost factor (M').

Each group completed an activity relationship chart, constructed a new layout, and determined material handling distances for a representative selection of manufactured parts. The project was completed using only in-class time; no related out-of-class assignments were given. Evaluation was completed by the author

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[10] The complete exercise is provided in the appendix.

and the following results were returned to the students:

Group 1		Group 2	
D'	= .586	D'	= .473
L'	= .877	L'	= .920
M'	= .201	M'	= .376
QEI	= .624	QEI	= .632

(α = .4, β = .4, γ = .2)[11]

Group 3		Group 4	
D'	= .430	D'	= .434
L'	= .792	L'	= .815
M'	= .263	M'	= .846
QEI	= .541	QEI	= .668

Group 5		Group 6	
D'	= .760	D'	= .689
L'	= .869	L'	= .910
M'	= .470	M'	= .292
QEI	= .746	QEI	= .708

At the conclusion of the exercise each student was asked to complete a critique-questionnaire form requesting comments and suggestions and asking the following questions:

(1) Were instructions, objectives, etc., adequate and easy to

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[11] These values were chosen using purely qualitative techniques and were used in evaluation of all layouts.

understand? What improvements would you suggest in this area?

(2) Do you feel that a layout exercise of this type has any value in a senior or graduate level plant layout or facilities planning course? Which parts were most valuable?

(3) Was time allotted adequate to permit satisfactory performance on your part? If not, how much time should have been allotted?

(4) Do you prefer working individually or in a group?

(5) Was the problem too complex? too simple?

(6) Was given information adequate? If not, what additional information should have been provided?

(7) Under what conditions could you have done a better job on this exercise?

(8) Did you benefit from participating in this exercise?

(9) Comments and suggestions.

The student response to these questions was very favorable. They seemed to agree that the exercise had been a beneficial part of their course and that the exercise could be expanded into a valuable college or graduate level course. A detailed summary of student response to the questionnaire can be found in the appendix.

The results seem to be encouraging and point to the employment of this technique as a teaching aid. Using the decision tree format, the exercise could be expanded into a non-competitive management game[12], assigning scores as measures of effectiveness of successive decisions. Not only would this provide the student with some decision making experience but would also provide the plant layout instructor with a purely quantitative basis for calculating grades. The grading system could be based on a profit figure calculated after each designated decision point. Three or four decision points and, hence, grading points, would afford the student the opportunity to keep up with his own performance and provide the pressures that accompany real world decisions.

Certainly a great deal of testing and refinement of techniques is in order, but this one somewhat successful classroom application indicates good student reception and leads the author to believe that the evaluation technique presented in this paper has significant academic value.

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[12] A non-competitive game is defined as one in which the decisions of one group are not affected by the decisions of other groups.

CONCLUSIONS AND RECOMMENDATIONS

The quantitative layout evaluation technique presented in this paper is an extension of existing plant layout tools. Unlike previously offered techniques, it is based on a broad selection of necessary criteria which cannot be neglected if thorough evaluations are to be made. It affords the analyst a relatively easy decision between alternatives. Possibly more important, through the required quantification of qualitative factors, it forces individuals to channel their judgment and experience into understandable and useful forms. It is through this forced analysis of factors that the greatest improvements in layouts and layout evaluation techniques are likely to result.

The primary contribution of this paper is the introduction of techniques for quantification of both tangible and intangible layout considerations. It has been shown that these ideas are workable at present. With additional refinement and development these techniques can certainly be expanded to encompass a broader scope of application.

In that this procedure was designed especially for evaluations concerning an already existing facility, it provides a somewhat unique academic approach to the plant layout problem. Most plant layout courses offered in colleges and universities today are geared to "new" layout problems and do not afford the student enough realistic problem-solving experiences. The re-layout problem developed in this thesis is designed to force students to consider the many factors that would not otherwise be taken into consideration.

Using the decision tree format, the potential of the technique as a learning device can be greatly enhanced. The introduction of probabalistic events and decision points not only adds color to a layout exercise, but also provides students with valuable decision making experiences that are usually left out of college level courses.

Additional development might result in a very interesting and beneficial university or management level course. The procedure can be expanded into a competitive type game situation in which the decisions of one group affect the decisions of other groups.

This thesis provides an excellent starting point for further research. Hopefully, it will inspire some ambitious person to look more deeply into the individual quantification and weighting problems involved in the derivation of sound, practical layout evaluation tools.

APPENDIX

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DEFINITIONS

1. Direct cost factors - those factors commonly associated with the operation of a piece of equipment.

2. Indeterminate cost factors - although related, these factors cannot be precisely determined, are vague, frequently not known in advance, or do not lend themselves to the determination of a definite cost figure.

3. Indirect cost factors - associated with investment or operation, but not directly.

4. Intangible factors - these usually defy quantification or calculation of a dollar value and therefore cannot be included as items in a cost comparison.

5. Total closeness rating - the summation for each department of its closeness relationships with all other departments. (CORELAP)

6. Victor - the department having the highest relationship with the winner. (CORELAP)

7. Winner - the department or subsystem with the highest "total closeness rating," giving it the privilege of being inserted into the layout. (CORELAP)

EVALUATION BY ELEMENTAL POINTS ASSIGNMENT

(Reed 1961): Step-by-step Procedure

Steps:

(1) Select and list those factors or elements which by judgment or concensus affect the decision.

(2) Assign relative weights to the factors or elements.

(3) Rank the various alternatives for each factor assigning the best alternative to position n, where n is the total number of alternatives.

(4) Assign points to each alternative for each factor by multiplying the relative value of the factor by the rank of the alternative.

(5) Sum the points for each alternative by adding the points assigned that alternative under each factor.

(6) The "best" alternative is the one with the maximum number of points.

PLANT LAYOUT EXERCISE

Top management has given us, a new corporate IE group, the exciting and challenging assignment of creating and implementing a new and more efficient machine shop layout. The present layout, management has decided, is highly inefficient and is the major reason why corporate profits are down 99%. The originator of the existing layout, N. E. Fishently, has been relieved of his duties as chief industrial engineer and transferred to Mule Shoe, Texas, a place where it is felt he can do the company, Inadvertent Electronics, Inc., the most good. We, the promising young industrial engineers, have been brought in to get things rolling on schedule again, realizing fully that the future of our jobs, as well as the reputation of Oregon State I. E. graduates everywhere, depends on our success or failure.

Our objective is to come up with the best possible layout according to management standards. Management will score our layout quantitatively using the following formula:

$$\text{Quantitative Evaluation Index} = \alpha(D') + \beta(L') + \gamma(M')$$

where D' = material handling distance factor
L' = location relationship factor
M' = departmental moving cost factor

and α, β, γ are constants.

(This is explained in greater detail in the following pages.)

We are to present management with a machine-shop layout consisting only of sub-systems (or departments) -- a "module" type layout. We are not responsible for the layouts of the individual departments at this time.

Management reminds us that there are also several other I. E. groups working on this project, and only the group submitting the best layout will remain here at plush corporate headquarters. Other groups will be transferred to the Mule Shoe, Texas, operation under Mr. N. E. Fishently.

To help us make the necessary decisions, management has provided us with the information on the following pages.

PROCEDURE

1. Complete Activity Relationship Chart

   Use the following helpful information:

   a. Activity relationship information sheet
   b. Activity relationship rating table
   c. Blank activity relationship chart
   d. From-to chart
   e. Operation-process outline

2. Make decisions as to number of each type machine needed in each department and determine space requirements.

   Use the following helpful information:

   a. Machine requirements per receiver
   b. Space requirements per machine
   c. Sales forecast information
   d. Idle machine penalty costs
   e. Overtime costs
   f. Subcontract costs

3. Construct "Module" type layout; include aisles

   Use the following helpful information:

   a. Activity relationship chart (completed)
   b. From-to chart
   c. Process outline/routings

4. Calculate material handling distances and sum (Calculate distances for required parts only)

TOTAL QUANTITATIVE EVALUATION

I. Material Handling Distance Factors

a. Raw Materials

$$D_r = \frac{\text{Distance for new layout}}{\text{Distance for old layout}}$$

b. In-Process Materials

$$D_i = \frac{\text{Distance for new layout}}{\text{Distance for old layout}}$$

c. Combined factor

$$D' = T(D_r) + R(D_i)$$

where T and R are constants

and $T < R$

II. Location Relationship Factor

$$L' = \frac{\Sigma\,(\text{relationship penalty scores for new layout})}{\Sigma\,(\text{relationship penalty scores for old layout})}$$

III. Moving Cost Factor

$$M' = \frac{\Sigma\,(\text{Departmental moving and related costs})}{Z}$$

where Z is a predetermined maximum \$ that can be spent on moving

(Departmental moving and related costs) = Sum of all moving costs plus costs of moving walls, reconditioning equipment, new construction, etc.

IV. Quantitative Evaluation Index

$$QEF = \alpha(D') + \beta(L') + \gamma(M')$$

where α, β, and γ, are constants.

RESTRICTIONS, REQUIREMENTS, AND NOTES

1. The High Bay Area must be left open (Bays AB_1 through 12).
2. The Publications office area cannot be touched.
3. The Assembly area must remain within the same boundaries (we will not worry about the assembly area layout-Bays FG-2 through FG-10).
4. The Model Shop is used for prototype production only (except for insertion of press nuts) and can be moved but with no more than a 10% reduction in total area.
5. A process type layout is mandatory, i.e. production groups may not be separated by product type.
6. A Nurse's/First Aid office must be located in the shop area. (Allow 200 ft^2 minimum)
7. An I. E. office must also be located somewhere in the shop area (provide space for 3 I.E.'s).
8. All shop departments must not lose any area if moved--any area not presently needed should be left open for expansion.
9. Main aisles must connect all departments and should be wide enough for a 4,000 lb. fork truck (10'-12').
10. Miscellaneous storage areas marked on original layout may be moved to outside storage area but must be covered (cost for covering outside storage area is $1,000).
11. Rest rooms may not be moved and no additional rest rooms may be built.
12. The shipping area must remain in its present location.
13. The building supports are permanent; Bay are 24'x 40'.
14. The silk screen area must be maintained with no reduction in area and must be adjacent to the paint shop.
15. The sandblast area is not presently in use and will not be in use anytime in the forseeable future.
16. The stock room ceiling is 20'. Material on the shelves is presently stacked only 8' high.
17. Cost for removing a concrete block wall is $50 per linear foot.
18. Requirements for the Plate shop are:
    a. ventilation
    b. protection against acid and fumes
    c. electrical insulation

    These facilities are already taken care of in the existing layout but must be replaced if moved at a cost of $2500 (in addition to the cost of moving).
19. . Requirements for the Paint shop are:
    a. ventilation
    b. fire protection
    c. heating

These facilities are also taken care of in the present layout but must be re-conditioned if moved at a cost of $1700 (in addition to the cost of moving).

20. The IBM 357 shop floor data collection system will remain in operation since we are bound by a long term contract with IBM--this is a top management directive. (The rumor is that the company president owns 7,000 shares of IBM stock and does not care to have his best interests overlooked, but this is only a rumor, of course.)
21. Quality control stations may be set up anywhere in the shop area, but the quality control inspection office must also be located in the shop area with no reduction in floor space.
22. The Test area and the Drawing Files must be left alone.
23. Power connections are readily available throughout the entire shop area.
24. Press nut insertion will continue to be done by the model shop.
25. Engineering offices cannot be moved.
26. Miscellaneous Storage Areas are presently used to 25% capacity.
27. The pattern shop may be eliminated if 200 ft^2 are added to the model shop.

SALES FORECAST INFORMATION

Inadvertent Electronics has been awarded a government contract for 5,000 model 4100 Telemetry Receivers over a two-year period (this is equivalent to 10 receivers per day). Our marketing group also tells us that there is a .35 probability that our sales will jump to 7,500 receivers over the next two years (15 per day) and a .25 probability that sales will reach 8,000 (18 per day). We are faced with the problem, then, of whether to purchase enough machines to build parts for 10, 15, or 18 receivers per day. If we should design for 10 receivers and the sales jump to 15 or 18, then we must subcontract, pay overtime premiums, or expand our operation to meet requirements; any of these alternatives would be extremely costly. On the other hand, if we design for more output than required, we are stuck with idle machines and an unproductive investment. However, these idle machines could help us meet schedules in case of machine breakdowns.

Given the above and the following information we must decide how many of each type machine we will provide for each department.

ACTIVITY RELATIONSHIP INSTRUCTIONS

1-Complete Activity Relationship chart using both "reason" and "closeness" values:

2-Refer to Rating table and insert quantitative values in place of closeness and reasons.

ACTIVITY RELATIONSHIP INFORMATION

Reasons	Ratings
1-Sequence of work flow	1.00
2-Minimize materials handling	0.95
3-Ease of communication information flow	0.80
4-Safety	0.80
5-Employee convenience	0.50
6-Unpleasant, unsanitary or unsafe conditions	0.00

Closeness	Explanation	Quantitative Rating
A	absolutely necessary--must be adjacent	100
E	especially important--adjacency desired; should be within easy talking and quick walking distance	75
I	important--adjacency not required but should be within shouting distance and easy walking distance	60
O	ordinary closeness ok--within short walking distance if possible	40
U	unimportant--no important interfaces. Closeness has no effect on operation of either area nor on operation of total system	1
X	undesirable--any degree of closeness harmful	0

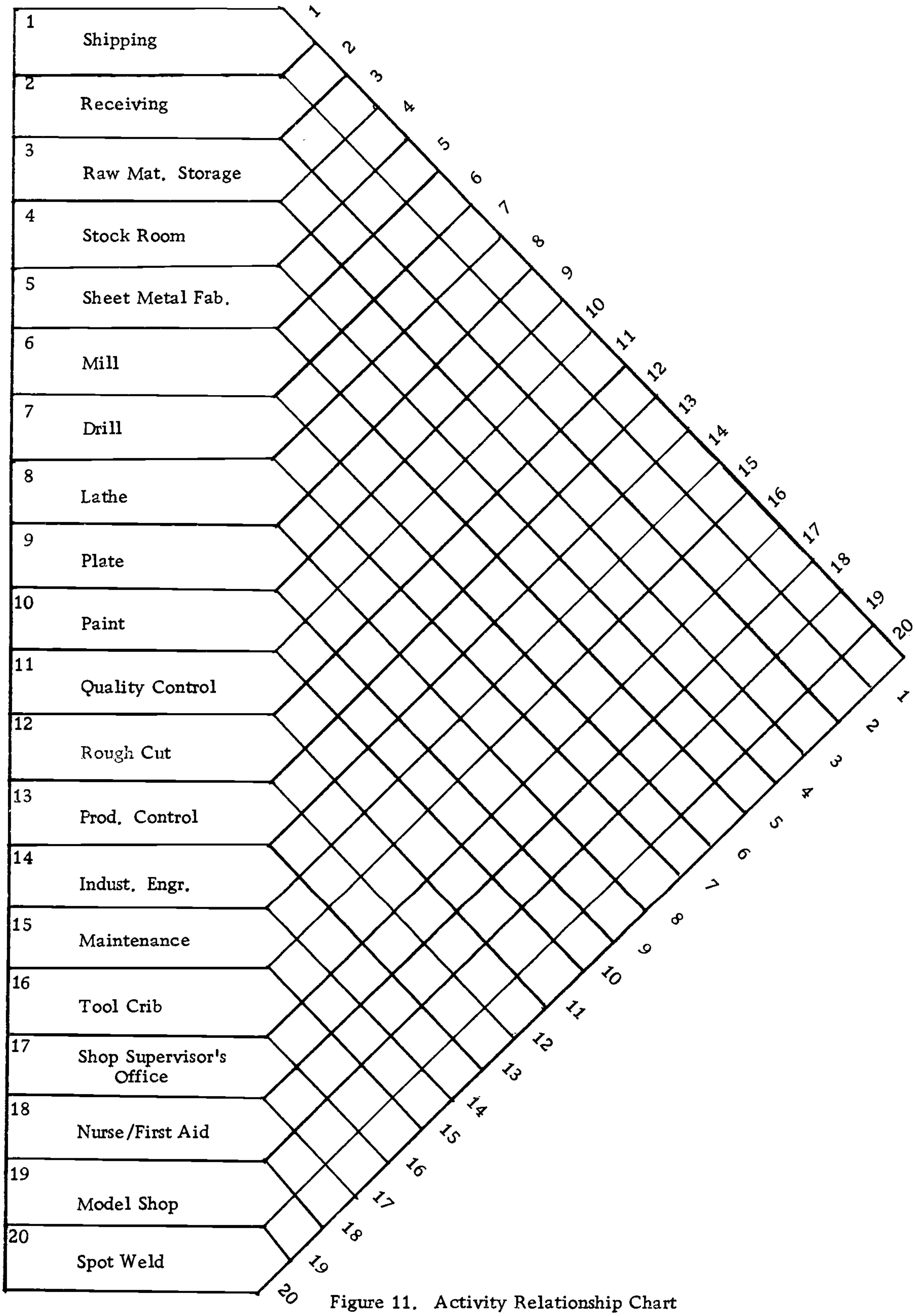

Figure 11. Activity Relationship Chart

ACTIVITY RELATIONSHIP RATING TABLE

	1	2	3	4	5	6
A	100	95	80	80	50	0
E	75	71.25	60	60	37.5	0
I	60	57	48	48	30	0
O	40	38	32	32	20	0
U	1.00	.95	.80	.80	.50	.00
X	0	0	0	0	0	0

MACHINE REQUIREMENTS

Machine Dept.	Man-machine hours/ receiver	Machine/operator requirements for predicted levels of output		
		10/day	15/day	18/day
Shear	1.48	2.11	3.17	3.90
Punch Press	2.60	3.71	5.57	6.68
Press Break	2.60	3.71	5.57	6.68
Spot Weld	1.88	2.69	4.04	4.84
Drill	4.44	6.34	9.51	11.41
Deburr	2.14	3.06	4.59	5.51
Mill	3.62	5.17	7.76	9.31
Lathe	4.80	6.86	10.29	12.35
Rough Cut	2.12	3.03	4.55	5.45
QC	4.95	7.07	10.61	12.73
Press Nut Press	3.38	4.83	7.25	8.69

MATERIAL HANDLING DISTANCE FACTOR INSTRUCTIONS

In-Process Materials

Upon completion of the layout, calculate the sum of the material handling distances for each of the 23 shop-made parts. Distances should be calculated along the main aisles and to the approximate center of each work group--from Raw Materials, through all scheduled departments, to the stock room.

Raw Materials

Measure the distance from the center of the Receiving dock, through receiving and receiving inspection, to the Raw Materials area along the main aisles.

MATERIAL HANDLING DISTANCES (IN PROCESS)

	Old	New
1-Main Chassis	1517'	
2-Dial Ass'y Chassis	1517'	
3-Separator Panel	1272'	
4-Chassis top	1176'	
5-Module Block	1517'	
6-Rear Panel	1517'	
7-Rear Panel	1517'	
8-Tuner Chassis	1517'	
9-Chassis Cover	1176'	
10-Tuner Block	1355'	
11-Tuner Block Rod	1225'	
12-Tuner Discs	1340'	
13-Side Panels	1665'	
14-Chassis	1270'	
15-Cover	1270'	
16-Chassis	1945'	
17-Cover	1035'	
18-Dial	775'	
19-Connector Rod	1075'	
20-Pulley	775'	
21-Dial Cover	775'	
22-PC Board	1655'	
23-Tuning Rod	1075'	
	Σ = 29,951'	

PROCESS OUTLINE/ROUTINGS

Part	Operations	
1-Main Chassis	1. Shear to size	7. Insert press nuts
	2. Punch holes	8. Plate
	3. Break to required shape	9. Paint
	4. Spot Weld	10. Quality Control--Inspect
	5. Drill holes	11. Stockroom
	6. Deburr	
2-Dial Assembly Chassis	1. Shear to size	7. Insert press nuts
	2. Punch holes	8. Plate
	3. Break to required shape	9. Paint
	4. Spot weld	10. QC
	5. Drill	11. Stockroom
	6. Deburr	
3-Separator Panel	1. Shear to size	6. Insert press nuts
	2. Punch holes	7. Plate
	3. Break	8. Paint
	4. Drill holes	9. QC
	5. Deburr	10. Stockroom
4-Chassis top	1. Shear to size	5. Plate
	2. Punch holes	6. Paint
	3. Drill	7. QC
	4. Deburr	8. Stockroom
5-Module Block	1. Shear to size	7. Insert press nuts
	2. Punch press	8. Plate
	3. Break	9. Paint
	4. Spot weld	10. QC
	5. Drill	11. Stockroom
	6. Deburr	
6-Rear Panel (plug-in)	1. Shear	7. Insert press nuts
	2. Punch press	8. Plate
	3. Break	9. Paint
	4. Spot weld	10. QC
	5. Drill	11. Stockroom
	6. Deburr	

Process Outline/Routings (continued)

Part	Operations	
7-Rear Panel (chassis)	1. Shear 2. Punch press 3. Break 4. Spot weld 5. Drill 6. Deburr	7. Insert press nuts 8. Plate 9. Paint 10. QC 11. Stockroom
8-Tuner Chassis	1. Shear 2. Punch holes 3. Break 4. Spot weld 5. Drill holes 6. Deburr	7. Insert press nuts 8. Plate 9. Paint 10. QC 11. Stockroom
9-Tuner Chassis DCover	1. Shear 2. Punch holes 3. Drill holes 4. Deburr	5. Plate 6. Paint 7. QC 8. Stockroom
10-Tuner Block	1. Rough Cut 2. Mill 3. Drill, tap 4. Deburr	5. Plate 6. Paint 7. QC 8. Stockroom
11-Tuner Block Rod	1. Rough Cut 2. Deburr 3. Lathe	4. Plate 5. QC 6. Stockroom
12-Tuner Discs	1. Rough Cut 2. Punch press 3. Lathe 4. Mill	5. Plate 6. QC 7. Stockroom
13-Side Panels	1. Rough Cut 2. Mill 3. Drill 4. Weld 5. Deburr	6. Plate 7. Paint 8. QC 9. Stockroom
14-Chassis (slide-in module)	1. Rough Cut 2. Mill 3. Drill 4. Deburr	5. Insert press nuts 6. Plate 7. QC 8. Stockroom

Process Outline/Routings (continued)

Part	Operations	
15-Cover (slide-in module)	1. Rough Cut 2. Mill 3. Drill 4. Deburr	5. Insert press nuts 6. Plate 7. QC 8. Stockroom
16-Chassis (internal modules)	1. Rough Cut 2. Break 3. Spot weld 4. Drill 5. Mill	6. Deburr 7. Insert press nuts 8. Plate 9. QC 10. Stockroom
17-Cover (internal module)	1. Shear 2. Punch holes 3. Break 4. Drill	5. Deburr 6. Plate 7. QC 8. Stockroom
18-Dial (tuner)	1. Rough Cut 2. Lathe 3. Drill	4. QC 5. Stockroom
19-Dial Connector Rod	1. Rough Cut 2. Lathe 3. Drill	4. Plate 5. QC 6. Stockroom
20-Tuner Disc Pulleys	1. Rough Cut 2. Drill 3. Lathe	4. QC 5. Stockroom
21-Tuner Dial Cover	1. Rough Cut 2. Precision Saw (Mill) 3. Drill	4. Deburr 5. QC 6. Stockroom
22-P.C. Boards	1. Saw (Sheet Metal) 2. Drill holes 3. QC	4. Subcontractor 5. QC 6. Stockroom
23-Tuning Rod	1. Rough Cut 2. Lathe 3. Drill	4. Plate 5. QC 6. Stockroom

MACHINE SPACE REQUIREMENTS
(machine, aux. equip., operator, material x 150% allowance)

Lathe	140 ft^2/machine
Milling Machine	125 ft^2/machine
Drill Press	50 ft^2/machine
Shear	250 ft^2/machine
Punch Press	150 ft^2/machine
Spot Weld Machine	150 ft^2/machine
Press Nut Press	50 ft^2/machine
Deburr Bench	50 ft^2/bench
Inspection Bench	50 ft^2/bench
Sheet Metal Saw	175 ft^2/machine
Precision Saw	120 ft^2/machine
Rough Cut Saw	200 ft^2/machine

SUBCONTRACT COSTS PER PART

	$ Per Part	Min Qty	Turn around time per lot	Notes
1-Main Chassis	$20.00	25	2 wks	No Plate or Paint
2-Dial Assy Chassis	16.00	25	2 wks	"
3-Separator Panel	6.00	25	2 wks	"
4-Chassis top	4.00	25	1 wk	"
5-Module block	12.00	25	2 wks	"
6-Rear Panel	7.00	25	2 wks	"
7-Rear Panel	7.00	25	2 wks	"
8-Tuner Chassis	25.00	25	3 wks	"
9-Tuner Chassis Cover	5.00	25	1 wk	"
10-Tuner Block	4.00	25	2 wks	"
11-Tuner Block Rod	2.00	50	1 wk	"
12-Tuner Discs	1.00	400	5 wks	"
13-Side Panels	4.00	50	3 wks	"
14-Chassis	4.00	50	3 wks	"
15-Cover	4.00	50	3 wks	"
16-Chassis	5.00	25	2 wks	"
17-Cover	2.00	50	1 wk	"
18-Dial	2.00	50	3 wks	"
19-Rod	1.00	100	8 wks	"
20-Pulley	.50	1000	9 wks	"
21-Cover	.50	100	3 wks	"
22-PC Bds	4.00 (Add't'l)	25	2 wks	"
23-Rod	.50	100	3 wks	"

OVERTIME COSTS
(differential costs over regular time)

Shear	$4.00/hour
Mill	4.50
Drill	3.75
Lathe	4.00
Rough Cut	3.00
Deburr	3.00
Press Nut	3.50
Precision Saw	4.50
Spot Weld	4.50
Press Break	4.00
Punch Press	4.50
QC	4.00

IDLE MACHINE PENALTY COSTS

Shear	$2,500/machine
Press Break	2,750/machine
Mill	3,300/machine
Lathe	3,000/machine
Drill	1,500/machine
Rough Cut Saw	950/machine
Precision Saw	1,150/machine
Spot Weld Machine	2,300/machine
Press Nut Press	150/machine
Punch Press	4,000/machine

Costs are for complete idleness; partial idleness will be charged proportionally.

List below the number of each type of the above machines that you will provide for the various shop departments.

DEPARTMENTAL MOVING COSTS

Department	0-20'	20-40'	40'-100'	100'-200'	>200'
Shipping	$ 325	350	375	400	475
Receiving	250	275	300	325	350
Raw Materials Storage	850	950	1,000	1,050	1,100
Stock Room	1,250	1,350	1,450	1,500	1,600
Sheet Metal Fabrication	600	750	900	1,000	1,100
Mill	950	1,000	1,050	1,100	1,150
Drill	750	800	850	900	950
Lathe	1,200	1,350	1,425	1,500	1,550
Plate	11,250	11,500	12,000	12,500	13,000
Paint	9,800	10,200	10,650	11,000	11,400
Quality Control	400	425	450	475	500
Rough Cut	875	1,000	1,125	1,200	1,250
Production Control	2,100	2,150	2,200	2,250	2,300
Industrial Engineering	Not Yet Existing (Design for 3 I. E.'s)				
Maintenance	725	750	775	800	825
Rest Rooms	F	I	X	E	D
Cafeteria	F	I	X	E	D
Tool Crib	800	825	850	875	900
Shop Supervisor's Office	100	110	120	130	140
Nurse/First Aid	100	110	120	130	140
Receiving Dock	F	I	X	E	D

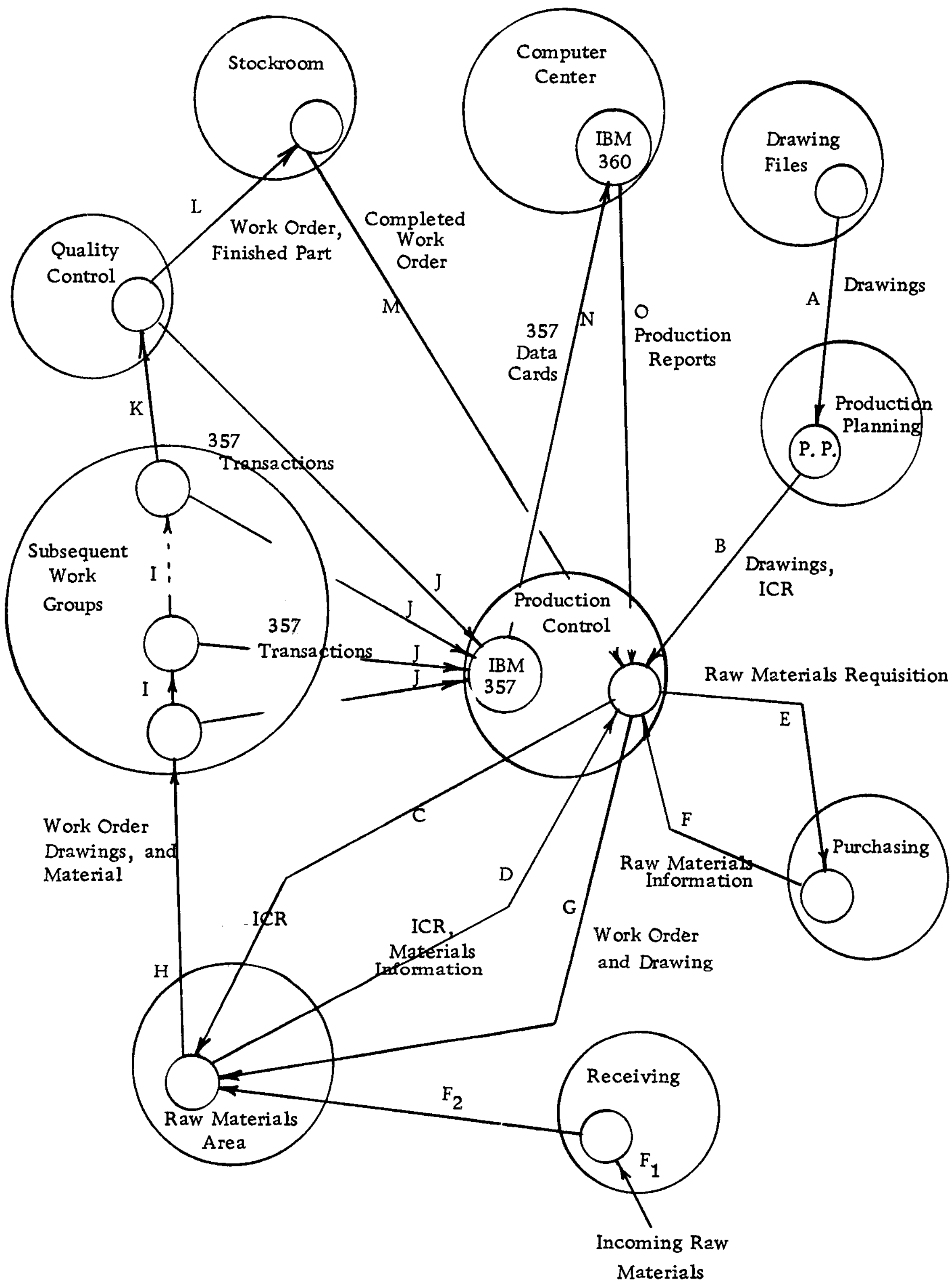

Figure 12. Information Network

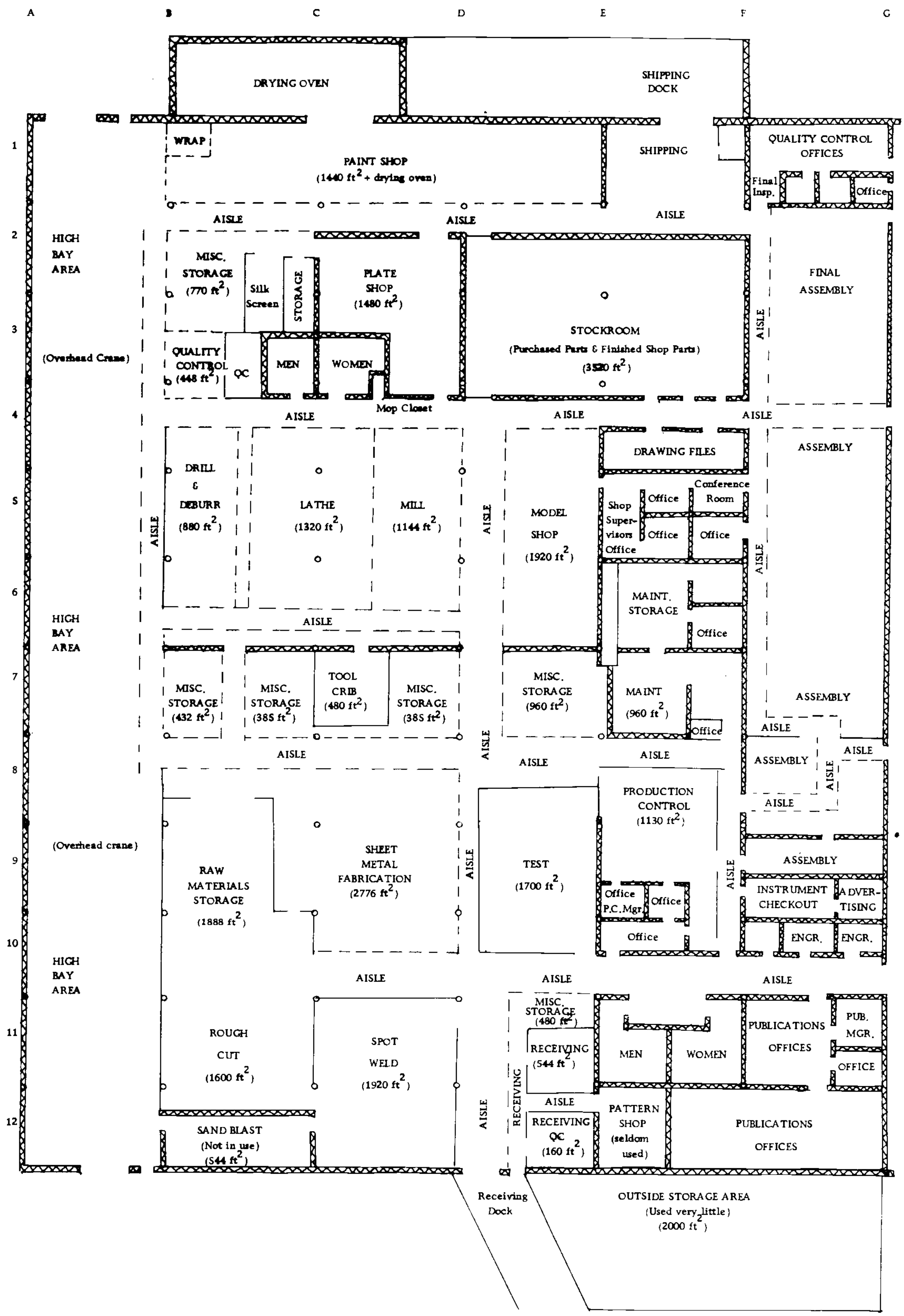

Figure 13. Existing Machine Shop Layout

PLANT LAYOUT EVALUATION WORK SHEET

I. Material Handling Distance Factor

a. Total Distance for New Layout = ____________________

b. Total Distance for Old Layout = ____________________

c. Material Handling Distance Factor $(a \div b)$ = ______________

II. Location Relationship Factor

a. Σ (Relationship Penalty Scores-New Layout) = ____________

b. Σ (Relationship Penalty Scores-Old Layout) = ____________

c. Location Relationship Factor $(a \div b)$ = _________________

III. Moving Cost Factor

a. Σ (Departmental Moving Costs) = __________________

b. Σ (Other Costs Related to New Layout) = _______________

c. Moving Cost Factor $((a \div b)/Z)$ = _________________

SUMMARY OF STUDENT RESPONSES TO CRITIQUE-QUESTIONNAIRE

(1) Were instructions, objectives, etc., adequate and easy to understand? What improvements would you suggest in this area?

Responses:

"Everything but knowledge of process was adequate." "Instruction was very adequate," "I think they were adequate," "Yes, I think they were adequate. No suggestions for improvement," "Adequate," "Could have been more clearly defined at the beginning," "Good under circumstances," "Could have used a little better overall look at the objective," "Yes," "Some pertinent data had to be given verbally, but then it is hard to set this up and remember every detail," "Yes," "Adequate," "Yes," "Yes," "Easy to understand," "Well explained."

(2) Do you feel that a layout exercise of this type has any value in a senior or graduate level plant layout or facilities planning course? Which parts were most valuable?

Responses:

"Yes, because it was quick and dirty," "This exercise has some value, but needs to be made a larger part of the course," "Yes, real life situation," "Yes, the non-theory parts," "Yes," "Actually laying out of the new plant on the existing drawing," "Yes, the cost calculations were particularly enlightening," "Yes. Area allocation and activity relationship exercises were the most valuable," "Some - it makes you think about things you might not consider otherwise," "Could be used as a final exam, putting various departments in the best possible location," "Not really," "Yes, if more time could have been spent on it with more attention to details," "No, it is too shotgun-like. It might work in a test situation but is frustrating while in process of learning," "Personally I feel that the project was much more important than the book," "Yes. This is better and more realistic than what we have been doing," "Of course. It allows us to apply the overall knowledge we have learned on a short project."

(3) Was time allotted adequate to permit satisfactory performance on your part? If not, how much time should have been allotted?

Responses:

"Yes," "No. Two to three weeks should be allotted to allow adequate consideration," "One week and outside-class project," "Adequate but somewhat hurried," "One extra period was needed," "This problem compared almost to the term project and was a little rushed," "Yes," "Not enough time to do a thorough job. Another two hours were needed," 'No, several weeks could have been allotted--or else homework," "Yes," "I had plenty of time," "For what we did, time was adequate," "No--about double time was needed for a complete job," "Yes," "Yes," "Yes."

(4) Do you prefer working individually or in a group?

Responses:

Group	14
Individual	4

(5) Was the problem too complex? to simple?

Responses:

"Just right," "Too confusing for such a short time," "little tough but good - real life," "A good problem but somewhat confusing," "OK," "Very good. Dealt with all factors yet not in a comfusing manner," "Adequate--I was confused in what we could do with the original factory and what we had to keep," "Neither, however it tended to be somewhat mechanical after the basic information was gathered," "too much for so late in the term!", "Adequate for the time we had," "I thought it was good as is; a lot of work at times," "Simple, once we got started," "Too complex for the time allowed," "The problem was simple at first, but as we became more involved in the plant layout it proved to be a good problem," "About right," "No, it was about right."

(6) Was given information adequate? If not, what additional information should have been provided?

Responses:

"Yes," "should have explained required results at beginning," "more than adequate," "More than enough information was given," "Yes," "Yes," "Yes," "Adequate," "Adequate," "Information was well organized," "Information was adequate," "Information was adequate," "Adequate," "Yes," "It was adequate," "Given information was adequate."

(7) Under what conditions could you have done a better job on this exercise?

Responses:

"More time, better understanding," "more familiarity with production processes," "A background in the manufacturing processes would have helped," "More time," "More time," "More time," "More time was needed to calculate the benefits and disadvantages of various moves," "More time," "More time and pressure for a grade," "None," "None," "More time and knowledge of the operation," "Improve the from-to chart with a volume density chart," "The conditions were as good as possible."

(8) Did you benefit from participating in this exercise? How?

Responses:

"Was more realistic than exercise we have been working on all term," "Not very much, too hurried," "Learned how to work under the gun - real life," "This exercise brought out some of the non-theoretical problems involved in a layout," "Yes, it helped consolidate different plant layout methods," "Yes, term problem was a new plant; this gave experience in existing plant," "Brought home some of the concepts we have learned," "Yes, good way to bring together all the material that was learned throughout the term," "Stayed out of the sun and probably avoided being burned," "Learning how to work and organize the work among the team members," "Yes, it has been of some help in other classes," "Yes, by dealing with changes in an existing layout. Up to now we have been concerned merely with a new layout," "Test of what was learned in this course. Challenging," "Yes, the assumptions were more realistic than Apple's exercise," "yes, application of what we had learned."

(9) Comments and suggestions.

Responses:

"Very interesting!," "Could use this type of thing as detailed, complex, case-study approach for upper division classes. Vary the problems to be solved. Would result in very interesting and beneficial class for I. E.'s," "Do an extension for a product flow as well as a process type of layout."

AUTHOR'S COMMENTS AND SUGGESTIONS CONCERNING THE EXERCISE

Basically the exercise ran very smoothly, but a few weaknesses and shortcomings became apparent during the course of its presentation and testing. These are listed below along with recommendations for improvement.

Because of their unfamiliarity with the product and processes, a few students became somewhat confused and misoriented as to their basic objectives. This was partly due to a rather incomplete set of instructions as it was difficult to anticipate every question that would arise concerning all aspects of the exercise. It is most important that all instructions, requirements, and procedures be written. Although some verbal communication will certainly be necessary, the author feels that a more complete set of written instructions would have eliminated much of the confusion that accompanied the original exercise.

The question arose as to the actual fairness of the grading system due to the fact that all groups were working from entirely different activity relationship charts. To remedy any inequality here it is suggested that one activity relationship chart be drawn up by the entire class for use by each of the individual groups.

Considerable time was required for the author to evaluate the data received from the respective groups, especially in determining the location relationship factor. Although the time and effort involved was not completely prohibitive, it must be remembered that only twenty departments were involved and that only six layouts had to be evaluated. The addition of only a few more departments would greatly increase the number of relationships. Needless to say, the addition of more groups would likewise add to the burden. There are several possible solutions to this problem. A rather simple computer program could digest this data and print results in a matter of a few seconds. An alternate solution would be to allow the students to participate in the evaluation procedure. This procedure, although somewhat more time-consuming than the computer solution, would afford students greater insight into the layout problem and enable them to see their errors more readily.

The author feels that a better overall exercise would result if some of the information provided for the students such as from-to charts, machine requirements, and labor overtime costs could instead be generated by the students themselves.

The experience of presenting an exercise of this type was extremely enlightening. The excellent student reception leads the author to believe that it has definite potential as an academic tool.