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A QUANTITATIVE METHOD FOR EVALUATING ALTERNATIVE PLANT LAYOUTS

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Gregory B. Brown

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ALTERNATIVE PLANT LAYOUTS

APPROVED:

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Chairman

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SUMMARY

The problem of selecting the "best" layout from a group of alternative layouts for the same manufacturing facility has, in the past, been a decision based almost entirely on engineering judgment with very little quantitative justification. The purpose of this thesis was to develop a general methodology, so that an engineer and a decision maker can quantitatively evaluate all the alternatives and select a layout for implementation. The purpose method contained certain diagnostic properties so that the engineer was afforded the opportunity to combine specific aspects of alternatives to improve the chosen layout.

The methodology developed consists of six steps: 1) select criteria, 2) determine measures of performance, 3) weigh criteria, 4) specify scoring functions, 5) construct an evaluation model and 6) verify the output. An example problem is worked to illustrate the concepts and the procedures developed for each step.

The research indicates that the proposed methodology can evaluate a set of alternatives and serve as a basis not only for selecting a layout, but in improving the chosen layout. The quantitative method was somewhat limited by the deficiency of quantitative techniques and evaluators for specific plant layout objectives other than Materials Handling and Flow of Materials. The application and the adaptation of decision theory scoring functions to the alternative plant layout selection problem was found to be practicable and expedient.

CHAPTER I

INTRODUCTION

The problem of selecting the "best" layout for implementation from a group of alternative layouts for the same manufacturing facility has, in the past, been a decision based almost entirely on engineering judgment with very little quantitative justification. Although judgment in the selection process will probably never be eliminated, there is a definite need for a more exact approach to this problem. Such a technique would be useful not only in the selection of a layout, but also in point out areas for possible improvement of the chosen layout, or possible combinations of alternative layouts to achieve an even better overall layout.

The purpose of this research is to develop a workable methodology, so that an engineer, faced with several alternative layouts, can quantitatively choose a layout. It will consist of a series of steps and related procedures for achieving this purpose, since the nature of the problem is such that four related subproblems must be solved before the technique can be accepted for use. A review of previous research efforts in this field, as presented in the literature, reveals that a combination of the best aspects of four previous approaches and a decision theory approach was indicated.

The Nature of the Problem

The development of such an evaluative technique has been hindered by four subproblems. These difficulties, which had prevented the wide acceptance of previously proposed quantitative procedures, were the problems of uniqueness, singularity, the proper place of judgment, and the possibility of unconsidered and unknown better layouts. The first three of these had to be solved by this research before it could be considered capable of achieving application.

The first of these, the uniqueness problem was due to the fact that no two plant layouts are ever really the same, or every plant layout is unique. Because what was present in one plant layout might be absent or even detrimental if present in another plant layout, no general mathematical relationships could be formulated or derived between variables. This meant that no method of quantitative evaluation was possible unless the method was itself general enough to be readily adaptable, or contained elements which could easily be tailored, added or deleted to meet the unique layout situation facing the evaluating engineer.

The second difficulty was that of singularity or the problem of selecting only one criterion as the significant factor in the evaluation and selection technique. Considering one factor alone could only give an indication of part of the usefulness of a given layout and subsequent efforts were required to give consideration to the very large number of other factors important in a good layout. It would have been possible, for example, to assign a small machine to a large area resulting in the inefficient use of floor space if the engineer used a wrong or incomplete single criterion as his measure of effectiveness. The difficulty of singularity could be overcome by developing a model that could consider several factors simultaneously.

The problem of determining the amount of engineering judgment or intuition to be used in the evaluation process was the third difficulty which a layout evaluation method must solve. Enough judgment must be included so that the engineer can readily adapt the process to his unique situation; for example, determining the relative importance and weighting of each criterion in a pertinent criteria set, or the merit or value to be associated with a calculated measure of criterion performance. However, not too much could be included or the evaluation would lose its quantifiable aspects, and become purely judgmental, imprecise, and too subject to human variances, as in the case of a qualitative evaluation of the effectiveness of a criterion in one of the alternative layouts. The problem is that of finding the balance between intuition on one hand and purely quantitative techniques on the other--a difficult situation at best.

Finally, the problem of unknown or unconsidered alternative layouts presented a theoretical difficulty to general methodologies. This problem was concerned with possible layouts which the engineer had not yet designed, but which might possibly exist, and might be better than the alternatives being considered. Because there is a large number of activities in a given plant area, there is practically an infinite number of layouts possible for any given layout project. Clearly, this is a problem for computer search routines.

Thus, the development of a quantitative methodology for the evaluation and selection of alternative layouts had to resolve the problems of uniqueness, singularity and the proper place of judgment in order to become a practical technique. The last of these difficulties, the possibility of unknown better layouts, is a problem which would not prevent the acceptance of a general methodology. The first three form the central focus for the methodology developed in this research. The CRAFT algorithm, and similar approaches might be used to generate "unknown" better layouts after the initial selection by the procedure developed here.

Survey of the Literature

The difficulties of uniqueness, singularity, judgment, and unknown alternatives have been dealt with in the literature over the past several years. However, with the possible exception of the system approach, each of the literature approaches concerned itself with only one of these problems at a time. The first such efforts were reported in the early 1950's, and subsequent literature has appeared sporadically since then, culminating with the most recent attempts to involve computers in the process. Perhaps the best way to summarize these research efforts is to classify the literature into four areas of approach to the problem: charting techniques, judgment techniques, computer programs, and systems approaches.

The first of these, charting techniques, appeared in the literature in the middle 1950's. Generally, these methods analyzed some single aspect of a layout design, for example, material handling distance, through the use of some type of form or chart in order to arrive at a numerical value for layout efficiency or cost. Alternative layouts could be evaluated by these techniques, and the one with the lowest cost or highest efficiency could be considered the best. However, the results of these techniques were necessarily limited to the specific aspect considered in the evaluation (an example of the problem of singularity), and could therefore only give a relative indication of the effectiveness of a layout involving many other critical factors besides the one being analyzed. The From-To Chart (20), Cross Chart (1), Link Analysis (28), and Operation Sequence Analysis (29) are examples of this method of approach.

Judgment techniques appeared in the literature mainly in the early 1960's. The primary contribution was the development of systematic procedures for determining, through sound engineering judgment, the critical factors in any layout design and their relative importance to that design. After a list of criteria and their respective relative weights were established, each of the alternative layouts was judged quantitatively on how well it fulfilled each criterion on the list. Then, the evaluations of the several criteria, multiplied by weighting factors, were added to give a layout score, and the layout with the highest score was chosen as best. Despite the fact that quantitative measures were applied to purely qualitative criteria, these methods did force more logical thinking on the part of those involved in the evaluation process. However, because such methods are based entirely on individual judgment, the results varied depending upon the judge. Factor Analysis (1), Value Rating (16), Ranking (29), and Audit Analysis (29) are examples of this approach.

The third approach, computer programs, has developed only recently with ALDEP (Automated Layout Design Program), CORELAP (Computerized Relative Allocation of Facilities Technique) being the most prominent. The CRAFT program (36) utilized an heuristic search for lower material handling costs to achieve an optimum layout by interchanging plant components or areas, resulting in an overall broad configuration. Similarly, ALDEP (35) interchanged plant components, but did it on the basis of available space and managerial preference in arriving at its best layout.

CORELAP (19), another heuristic program, generates a good layout by adding various departments in a logical fashion according to judgment values in a Relationship Chart. These programs extend by a large factor the actual number of layouts considered, attempting to cope with the problem of unknown better layouts, but suffer because of the presence of the singularity and judgment problems.

The final and most promising approach has been the systems (34) or cost-effectiveness approach. Advocating an outer-directed orientation in which the layout design is considered a subsystem of the overall manufacturing system, a cost-effectiveness approach (15) was used in the evaluation process. The boundaries of this system were then defined by a quantifiable criteria set relevant to the particular layout situation, and the costs and benefits of each criterion for each alternative were measured and used in a model to calculate the overall effectiveness of each layout. Seemingly, this approach might have overcome the difficulties of uniqueness, singularity, and too much reliance upon judgment; however, though methods of establishing the quantitative set and developing the benefits and costs associated with individual criteria were presented, further efforts are necessary before the approach can become practical.

In summary, the evaluation of alternative layouts in the literature has been approached in four ways: charting techniques, judgment techniques, computer programs and systems approaches. Each of these was able to overcome at least one of the difficulties facing the layout engineer. However, a combination of these four approaches, utilizing the best aspects of each, was indicated by the literature survey.

A Decision Theory Approach

In the selection of alternative research and development projects, a rational decision-making technique--the scoring model--to evaluate each proposal relative to a hierarchy of objectives has been applied. The plant layout proposal could be considered a research proposal in that it is a specific recommendation for an allocation of resources to achieve a specified goal. Though a plant layout is more likely to be concerned with more physical resources, such as machinery, to achieve a more physical output, a specific product, the findings and results of the decision theory research in the area of project evaluation and selection should be applicable and adaptable to the layout selection problem.

The first publications reporting on scoring models for evaluating Research and Development projects appeared prior to 1959 and have been presented in five different forms since then. Generally, these methods calculated an effectiveness value for each alternative based on ratings or utility scores for both subjective and objective criteria, and the plan selected would have the highest value. The power of this approach was the flexibility in its structure allowing for any number of criteria to be used in the evaluation of alternatives. Of the five forms researched, the Moore and Baker approach will be the one used in this research for it proved to be the one that was most adaptable to the alternative plant layout problem. For a more complete literature survey in this field it is recommended that the reader see (3) and (8).

In 1959, Mottley and Newton (28) presented a scoring model which well represents the early forms in the project evaluation and selection problem. In their approach each alternative project was subjectively rated on a three point scale of value for five selected criteria. A project score was computed by multiplying the five numerical ratings together, and the projects were then ranked in order of decreasing score. In another format, Gargiulo, and others (14), ranked, listed, and rated, according to three qualitative factors, eleven technical and economic elements of each research proposal relative to all projects under consideration. The ratings in each group were totaled and assigned numerical scores by a "Project Score Dictionary," and multiplied together to give the score used to determine the final ranking. However, neither method included a relative weighting as is required in solving the uniqueness problem of alternative layouts, and could not be applied in this research.

A somewhat more complex model was specified by Pound (31) in 1964. After relative weights and degrees of attainment from 0 to 10 were rated for each of four objectives, the expected value for a project for one of four decision makers was computed by multiplying the degree of attainment numbers by the appropriate objective weights, and summing the products. Projects were ranked by a combined score determined by normalizing the expected values for all projects for a decision maker, and calculating an average of the normalized expected values for a project from each decision maker. In the Dean and Nishry (9) method, a three phase approach was used in establishing total project scores. In the first phase a set of relevant factors--partitioned into two characteristic categories, an accompanying five statements representing scale values for each factor, and factor weights were derived. In the second phase, all projects were listed for preparation of data for each project. Finally, each project was evaluated for ecch factor by selecting the appropriate statement, multiplying by its corresponding weight, summing over all factors with in the two categories, and computing a weighted sum of the two category scores. Although relative weightings were included in both models, the use of judgment appeared to play too strong a role in estimating factor values. Secondly, the categorization used in the Dean model and the complexity of the Pound model appeared to limit their ease of applicability to layout evaluation.

In two related papers Moore and Baker (26), (27) solved the problems of applicability in the four previous models. The structure of this model was defined in terms of scores for criteria values associated with statistical probability distributions of that factor, instead of determining the value of a criterion by a direct subjective estimate as in the judgment techniques, thus reducing the amount of judgment to be used in the model. The results were multiplied by a relative weight for each criterion and summed, to rank the projects by their total score. Through simulation studies, a workable methodology to design and verify the scoring model for use in other fields was also established. The model solves the problems of uniqueness and singularity by consideration of several factors chosen by the decision maker for the problem before him. The proper amount of judgment is included so that the results are determined by a balance of purely qualitative and purely quantitative methods. Because of its simplicity, the use of tangible and intangible criteria, and its adaptability to the plant layout problem the scoring model and its related methodology as presented by Moore and Baker will form the basis for the layout evaluation of this research.

Purpose and Scope

As evidenced in the plant layout literature survey, there is an obvious need for a different approach to the problem of quantitatively evaluating alternative plant layouts. The characteristics of this approach should be threefold. It should be capable of integrating several factors into a mathematical model to overcome the problem of singularity. It must contain flexibility features so that, with insight, the model can be adapted to the unique layout problem. Finally, it should incorporate a proper amount of judgment, and yet not lose its quantifiable aspects, by using the engineer's judgment in selecting criteria, weighting them and selecting good measures of performance for each.

All three of these characteristics are present in the scoring model and its related methodology in decision theory, and will be the basis for ranking alternative layouts. From previous layout evaluation approaches, certain techniques were found useful in quantifying individual criteria within the final criteria set, in the multifactor orientation required and in the tailoring of this set to the individual layout problem. Computer programming for unknown alternatives was considered beyond the scope of this research, and a problem for future effort in this field.

In satisfying the above conditions, the scope of this research is to establish a methodology for:

1) Determining a list of criteria the layout should accomplish.

2) Establishing a measure of performance for each objective as a criterion for evaluation.

3) Setting up criteria weights to reflect the varying degrees of importance of each criterion.

4) Finding performance score assignment distributions and scoring performance measures for each criterion.

5) Setting up a scoring model for use in the final calculations.

6) Selecting the best alternative layout and verifying the results.

The above will constitute the general procedure readily conformable to many different kinds of plant layout. At each step in the presentation of this research, an example layout problem, the "Toy Train Factory" problem (of I. E. 447) will be presented to demonstrate the application of the concepts described and the workability of the proposed methodology.

Such a tool or technique will prove valuable to the layout engineer not only in the selection, but also in the discovery of weaknesses in the best layout as indicated by its "low" scores relative to a criterion or criteria, and opportunities for evolving better layouts by combining the best aspects of layouts that finished high in overall score or in a particular criterion. The model could also serve as a screening device to reduce the actual number of layouts presented to the decision maker, but its true value will be found in the wide range of information it can generate for use by the layout engineer.

CHAPTER II

DETERMINE CRITERIA SET

The first step in the evaluation process is to select from five to ten criteria from a list of objectives to be accomplished by the final plant layout. Before presenting the criteria set for the Toy Train problem a general comment is made to distinguish an objective from a criterion, and three possible sources of objectives are discussed. In Chapter III quantitative measures of performance will be established for each criterion determined in this chapter.

General Comment

In plant layout problems, an objective is a desirable characteristic that should be incorporated into the final design. Any specification that the decision maker feels would affect the acceptability of the best layout is an objective. Both quantitative goals, such as a production quota, or intangibles, such as worker morale, are admissible as long as they are determinants of the best alternative.

In comparison to an objective, a criterion is defined as an objective which is accomplished in varying degrees by all alternatives and upon which an evaluation and selection of alternative plant layouts decision may be based. The difference is that some requirements will be explicitly satisfied by all proposals, and not all objectives will be significant in affecting the final selection. For example, all layouts in the Toy Train Factory problem are capable of achieving the production goal of 100,000 trains per year, and that objective and others like it would not help delineate between good and bad alternatives. A criteria set is formed by eliminating all satisfied and insignificant objectives from a preliminary comprehensive series of requirements.

In specifying this set, it should be made certain that each chosen objective or criterion is relevant, measurable, doesn't overlap with others, and is concisely stated. Each criterion must be concisely stated so that quantitative schemes and measures can be derived in the next step in the selection procedure. Since data collection for these schemes increases as the number of criteria increases, the true relevance of each member of the set should be questioned before the set is accepted as complete. The list should be also checked to eliminate duplication and overlap between criteria. Although there is not a correct number of objectives to be included in this set, a number between five and ten should be sufficient to give an accurate selection.

Sources of Objectives

Because every layout problem is essentially unique, there will never be a "true" list of objectives applicable for every plant layout, and the evaluating engineer must develop his own list. To aid in the establishment of this set, if it is not readily available, three possible sources for such information are managerial desires, engineering checklists, and lists found in the literature of the field. The final set might well be a composite of the objectives selected from each of these sources.

The first source of objectives should be management desires. The final decision maker will have some definite ideas about what the final layout should accomplish and the levels of performance that would be acceptable. Usually this entails several special objectives, for example, a specific quality of output level, which will be peculiar to this layout problem.

A second source of objectives are engineering checklists found in professional journals. A thoroughly detailed checklist will serve to stimulate ideas on what the plant should ideally contain and as a "safety" device for requirements that even an experienced plant layout engineer might easily have overlooked. For one of the more detailed of such lists found in the literature see the checklist compiled by Hanson (13).

Despite the uniqueness of a layout problem several elements are common in most layouts; for example, a materials handling activity of some form exists in most every plant layout. Although these objectives are very general in nature, they wtill are helpful in the establishment of relevant objectives. The best source for this type of objectives is from the composite literature of the plant layout field. The sets described by Apple (1), Buffa (15), Reed (32), Muther (29), and Harris (15) were combined to form a composite list of plant layout objectives:

1) Reduce risk to health and safety of employees
2) Minimize materials handling
3) Maintain flexibility of arrangement and of operation
4) Increase output
5) Reduce manufacturing time
6) Reduce hazard to material or its quality
7) Make economical use of floor area
8) Obtain greater utilization of machinery and manpower
9) Minimize equipment investment

10) Maintain high turnover of work-in-process

11) Improve morale and worker satisfaction

12) Reduce clerical work and indirect labor

13) Achieve easier and better supervision

14) Reduce congestion and confusion

15) Obtain smoother flow of materials

16) Improve production methods

17) Allow for building expandability

18) Minimize and improve the efficiency of storage, shipping, and receiving facilities

19) Improve the efficiency of plant services

After compiling a master list of pertinent objectives from the above three sources, the engineer and the decision maker should select the most significant objectives from the list to serve as the criteria set for the problem under consideration. From five to ten objectives should prove sufficient for evaluating the layouts with a minimum of data collection on the part of the analyst. Since it is important to have the most critical objectives included in this set, it is recommended that the engineer first form a long list of goals, and then select the more significant ones to be a part of his criteria set. As a definitive illustration of this process and its output, a set of objectives for the Toy Train problem, described in Appendix I, has been derived below.

The Criteria Set for the Toy Train Problem

The criteria set for the Toy Train problem was determined from goal statements derived from the original problem statement, from the composite list of plant layout objectives, and from decision maker directives. Engineering checklists were not found to be useful in determining this set. A list of nineteen objectives resulted, and seven of these became the criteria set for evaluation.

From the original problem statement, five directives were discussed as prerequisites for an acceptable layout. After studying all the alternative layouts, it was discovered that all met these requirements, and therefore, these five objectives could not serve as criteria:

1) Produce Toy Trains at the rate of 100,000 per year

2) All operations on lumber done in plant, including painting and packaging

3) Include approximately 1000 square feet of office space

4) Provide a tool room and a tool crib.

5) Include first aid station(s), toilet facilities and food services in some form

In the assignment of grades for student layout projects, an evaluation sheet, consisting of eleven achievement categories and their relative weights was used by Professor Apple. The eleven objectives from the composite list related to these areas were used as a basis for the set of objectives:

6) Obtain a smooth flow of materials

7) Minimize materials handling

8) Improve production methods

9) Make economical use of floor area

10) Improve the efficiency of shipping and receiving facilities

11) Reduce clerical work and indirect labor, and achieve easier and better supervision

12) Improve efficiency in plant services

13) Provide adequate storage facilities

14) Maintain flexibility of arrangement and of operation

15) Allow for building expandability

16) Building and utility aspects properly considered in the layout

The decision maker designated three more objectives that should be added to this list:

17) The layout should have a good overall appearance.

18) Traffic should be able to move through good and efficient aisles.

19) Good office appearance and efficiency should be a part of the layout.

From this list of nineteen objectives, the decision maker and the analyst identified the most important objectives. Seven were selected as the criteria set for this evaluation. After minor changes in the wording, the criteria set for the Toy Train example problem became:

1) Provide a smooth and efficient flow of materials

2) Use good production methods to achieve the required output of finished goods.

3) Allow for building expandability

4) Maintain flexibility of arrangement and operation

5) The layout should have a good overall appearance

6) Adequate-sized and located aisles should be used to allow easy traffic flow

7) Plant services should be efficient and office should be of good overall appearance

The adequacy of this set could be tested by presenting the above list for the decision maker's approval. However, a better method was to have the decision maker select the best layout from a sample of the alternative layouts available, and, while doing so, have him explain to the analyst why and how he made his selection. In addition to comparing the list mentioned by the decision maker in this simple exercise with the above list, the analyst made notes on characteristics that the decision maker expressed during this process for each criterion. These later proved useful in determining measures of performance in Chapter III for the approved criteria set above.

CHAPTER III

DETERMINE MEASURES OF PERFORMANCE

After a set of criteria has been established, a measure of performance to indicate the degree of goal accomplishment for each criterion must be determined by the engineer and the decision maker. In an effort to simplify this task, a master list of possible factors which might serve as measures for the composite objective list of Chapter II was developed and a related analysis technique for those objectives in the criteria set obtained from the other two sources, as well as three methods for determining a measure from this list are included. However, a definition and the characteristics of a performance measure must first be considered.

A Measure of Performance

A measure of performance is a quantitative scheme or expression which indicates the effectiveness of an alternative layout with respect to a particular criterion. For example, the number of handling moves could be a performance measure of the criterion "minimize materials handling." In order to be useful in the plant layout selection process, a good indicator must be 1) representative, 2) reliable with a minimum of variability, 3) efficient, 4) sensitive to change, and 5) understandable. A measure which possesses all of these traits is obviously ideal, and the engineer must usually be content with a measure that satisfies a compromise of the five characteristics:

1) Representative. The measure of performance should be representa-

tive of the criterion it is supposed to measure. It must be capable of serving as a yardstick that will fairly depict the criterion and indicate, simultaneously, levels of performance relative to that criterion.

2) Reliable. It must be reliable in the sense that it will give consistent results with the same data, or changes with a change in the data. If the individual effectiveness measures are not reliable, the scoring model can not be considered reliable and will become valueless in the selection process.

3) Efficient. The indicator should be efficient in that extraordinary efforts will not be involved in the data collection and calculation of the results.

4) Sensitive. The measure must be capable of responding quickly and accurately to changes in the data, as well as picking out performance effectiveness with respect to the criterion.

5) Understandable. The best measure is of little value in the selection if it is incorrectly or incompletely used. The engineer must understand and have confidence in each indicator he selects for the scoring model to be effective in determining the best layout.

A Master List of Plant Layout Factors

Since a large percentage of layout criteria will be drawn in some form from the composite list of objectives in Chapter II, a master list of plant layout factors related to these objectives was developed by this research. The first part of the list consisted of a number of factors which could serve as measures of performance for each objective. They were then re-analyzed and classified into two major orders, as to where the engineer could find the data necessary to calculate the measure of performance. For objectives of the final criteria set that did not originate from the composite list, an analysis by classification similar to the one used below should be undertaken to help determine good measures of performance.

As a first step in developing the master listing, a list of factors derived from several sources (1) (29) (32) was drawn up. A factor is defined as a pertinent observable characteristic of an objective which easily describes it and could serve as a measure representing it. A large number of such factors were found to exist for most of the objectives, and although the list included in this research must be considered incomplete, it should prove to be representative and should stimulate further efforts to develop a more exhaustive listing.

Certainly, the analyst could establish part of his criteria set measures from the "raw" listing, however, it was decided to classify the factors according to their case of measurability to help insure that good quantifiable indicators are chosen to serve as measures of performance. Four degrees of measurability were ascertained for this delineation: 1) direct (D), 2) indirect (I), 3) indeterminate (ID) and 4) intangible (IT). A criterion which could easily be measured and was associated with the operation of a plant was classified as direct. An indirect connotation implied that the factor was associated with plant operation, but not directly. Any factor that could be measured, but only with some difficulty; that is, it did not easily lend itself to quantification, was classified as indeterminate. Intangible factors could not be measured, in the strict sense of the word, and required judgment for their evaluation.

From the resulting list, the elements were then re-analyzed to establish whether the factors could be measured on the layout blueprint itself, or--if the factor is unmeasurable until after the plant is actually in operation. If an operating plant from which measurements must be taken does not exist, then such factors cannot be measured, and must be evaluated by other means. It should be pointed out that the categories selected for each factor on the listed presented at the end of this section are not necessarily "fixed," but are somewhat subject to interpretation and reassignment by the analyst.

The rationality behind such a master listing is that the engineer would select factors f om each set, and simultaneously have some basic information about where and how to start the search for quantitative measures of performance for each criterion in the set. The same analysis would be performed on the objectives derived from management directives and goals, and engineering checklists. With this knowledge the analyst would then go through the somewhat difficult task of determining the best measure of performance from this set of factors, or combinations and ratios of them, for each criterion, through one of the three methods suggested in the section following the master list.

Determining Measures of Performance

The determination of measures of performance to fit the five characteristics is not an easy or well-defined task. In searching the above master list of factors, three situations usually develop: 1) a known technique for evaluating the criterion will yield results related to one of the factors; 2) a technique does not exist, but a good measure can be created through a combination or ratio of factors; or 3) the criterion is unique with many factors requiring evaluation by judgment. Although a

MASTER LIST OF CRITERIA AND FACTORS FOR EVALUATION

Factors	where: Layout				Operation			
how:	D	I	ID	IT	D	I	ID	IT
1. REDUCE RISK TO HEALTH AND SAFETY OF EMPLOYEES								
a. Minor injuries			x		x			
b. Major injuries			x		x			
c. Safety codes satisfied	x				x			
d. First aid facilities	x				x			
e. Light and ventilation				x		x		
f. Type of flooring	x				x			
g. Floor load limits	x				x			
h. Noise, vibration, heat, light			x			x		
i. Hazards								
j. Fatigue				x			x	
2. MINIMIZE MATERIALS HANDLING								
a. Frequency of moves	x				x			
b. Distances moved	x				x			
c. Short hauls	x				x			
d. Size of loads	x				x			
e. Straight hauls	x				x			
f. Capacity		x			x			
g. Flexibility			x		x			
h. Handling time	x				x			
i. Delays, unnecessary handling		x	x			x		
j. Materials handling planned for				x			x	
3. MAINTAIN FLEXIBILITY OF OPERATION AND ARRANGEMENT								
a. Material changes		x			x			
b. Machine changes		x			x			
c. Man changes		x			x			
d. Supporting activity changes		x			x			
e. Versatility				x				x
f. Mobile equipment	x				x			
g. Self-contained machines	x				x			
h. Readily accessible service lines	x				x			
i. Standardized equipment	x				x			
j. Fixed, permanent, or special features		x			x			
4. INCREASE THROUGHPUT								
a. Units produced			x		x			
b. Operation time			x		x			
c. Output--volume		x			x			
d. Man hours worked		x			x			
e. Materials required	x				x			
f. Number of operations	x				x			
g. Equipment required	x				x			
h. Production efficiency			x			x		
i. Routing	x				x			
j. Tooling required		x				x		

	Layout				Operation			
	D	I	ID	IT	D	I	ID	IT
5. REDUCE MANUFACTURING TIME								
a. Units produced		x			x			
b. Production rate		x			x			
c. Schedule			x			x		
d. Delays			x			x		
e. Start-up			x		x			
f. Jobs lost				x	x			
g. Contracts lost				x	x			
h. Demurrage				x	x			
i. Breakdowns			x			x		
j. Improper standards				x			x	
6. REDUCE HAZARD TO MATERIAL OR ITS QUALITY								
a. Rejects			x		x			
b. Returns			x		x			
c. Reworks			x		x			
d. Units produced		x			x			
e. Inspection operations	x				x			
f. Amount of precision and accuracy		x			x			
g. Cost of getting given degree of quality				x		x		
h. Accuracy and speed of inspection			x		x			
i. Measuring instruments required	x				x			
7. MAKE ECONOMICAL USE OF FLOOR AREA								
a. Space	x				x			
b. Cube--warehouse		x			x			
c. Machine dimensions	x				x			
d. Total floor area	x				x			
e. Total production cube		x			x			
f. Total aisle area	x				x			
g. Total storage area	x				x			
h. Work area required by operators	x				x			
i. Office space	x				x			
j. Between equipment space	x				x			
8. OBTAIN GREATER UTILIZATION OF MACHINES AND MEN								
a. Paid wages	x				x			
b. Production time			x		x			
c. Absenteeism			x		x			
d. Downtime			x			x		
e. Operator performance				x			x	
f. Idle machinery				x			x	
g. Turnover			x			x		
h. Capacity				x	x			
i. Type of workers required	x				x			
j. Number of workers required	x				x			
9. MINIMIZE EQUIPMENT INVESTMENT								
a. Cost		x			x			
b. Excessive maintenance cost		x			x			
c. Taxes and interest		x			x			
d. Mechanization	x				x			

	Layout				Operation			
	D	I	ID	IT	D	I	ID	IT
e. Depreciation	x				x			
f. Repair		x			x			
g. Labor cost for operators	x				x			
h. Power costs		x			x			
i. Amortization	x				x			
j. Operating cost per unit handled				x	x			
10. MAINTAIN HIGH TURNOVER OF WORK-IN-PROGRESS								
a. Production costs			x		x			
b. Tied up assets cost				x		x		
c. In-process storage area	x				x			
d. Pieces idle between operations				x	x			
e. Minimum of goods in process				x			x	
f. Excessive temporary storage				x		x		
11. IMPROVE MORALE AND WORKER SATISFACTION								
a. Payment of wages	x				x			
b. Attitude toward management				x				x
c. Bad working conditions				x				x
d. Washrooms, lockers, drinking fountains, etc.	x				x			
e. Recreational facilities	x				x			
f. Parking facilities	x				x			
12. REDUCE CLERICAL WORK AND INDIRECT LABOR								
a. High indirect payroll	x				x			
b. Materials waiting for papers		x			x			
13. ACHIEVE EASIER CONTROL AND BETTER SUPERVISION								
a. Manager-employee contact				x			x	
b. Better control				x			x	
c. Improved job knowledge				x				x
d. Thoroughness of employee evaluation				x				x
e. Direction of group performance				x				x
f. Motivation				x				x
g. Easier communication			x				x	
h. Direct accessibility to production line	x				x			
14. LESS CONGESTION AND CONFUSION								
a. Cluttered aisles			x		x			
b. Cluttered work space			x		x			
c. Crowded space	x				x			
d. Excessive aisles	x				x			
e. Good housekeeping				x	x			
15. SMOOTHER FLOW OF MATERIALS								
a. Obstacles to materials flow	x				x			
b. Delays in materials moving				x	x			
c. Misdirected materials	x				x			
d. Direct path as possible	x				x			
e. Rehandling		x			x			
f. Backtracking and cross traffic	x				x			
g. Bottlenecks	x				x			

	Layout				Operation			
	D	I	ID	IT	D	I	ID	IT
h. Related	x				x			
i. Supplies moved by poor techniques	x				x			
16. IMPROVE PRODUCTION METHODS								
a. Unbalanced sequence of operations			x		x			
b. Operators walking for materials				x	x			
c. Adequate operator space	x				x			
d. Individual work areas coordinated	x				x			
e. Work place layout				x				x
f. Uniform rate of flow			x		x			
g. Production time predictable				x		x		
h. Minimum of scheduling difficulties			x			x		
i. Easier adjustment to changing conditions				x	x			
j. Marginal ratio of processing to production time				x	x			
17. BUILDING EXPANSION								
a. Walls	x				x			
b. Roof	x				x			
c. Basement	x				x			
d. Other locations	x				x			
e. Provision for expansion	x				x			
f. Utilities location	x				x			
g. Bay size	x				x			
18. ADEQUATE STORAGE,SHIPPING,AND RECEIVING FACILITIES								
a. Disorderly storage			x		x			
b. Excessive wasted cube in storage			x		x			
c. Material flow		x			x			
d. Relative location to external transportation	x				x			
e. Relative location to first operation	x				x			
f. Size	x				x			
g. Stock control difficulties			x		x			
h. Identifying and sorting materials		x			x			
i. Ready accessibility of all items		x			x			
j. Packing of items for shipment		x			x			
19. EFFICIENCY OF PLANT SERVICES								
a. Poor locations of service areas	x				x			
b. First aid location	x				x			
c. Utilities	x				x			
d. Tool crib location	x				x			
e. Fire equipment	x				x			
f. Food services	x				x			
g. Heating, lighting, and air conditioning				x				x

general method for handling each of these cases does not exist, three methods will be proposed for determining a suitable measure for each situation.

1. Known Techniques

In the first case a well-known technique exists for evaluating a given criterion in terms of one of its factors. Through a previous research, the author surveyed the literature of the plant layout and some related fields for recorded, well-known or obvious techniques for evaluating performances relative to some of the objectives found in the previous master list. Many measures were discovered, but only a few were applicable to a situation in which the only input information could come from a blueprint and an accompanying engineering report. In summarizing this effort for possible use in the evaluation model, eight of the nineteen objectives of Chapter II and their methods of evaluation will be presented, first, by giving a brief definition of the objective, then introducing several methods of evaluation derived from the literature, referenced for the interested reader to pursue in finding out more about the measure. A summary chart is included for ease of reference in Figure 3-1.

In using the chart, the engineer should first check this listing of recommended measures to find those relevant to his problem. If the measure suggested is not pertinent, the related information material presented below, from which the chart was derived, should be checked for other possible measures and reference material. For example, although several good measures exist for the criterion Flow of Materials, the Travel Chart Technique is specified. However, if this is not applicable, several ratios and indices shown in the "Flow of Materials" section below might also be useful.

Materials Handling. Materials Handling has been defined as the art and science involving the movement and storage of materials at the lowest possible cost through proper methods, equipment and manpower. Two methods were found that were applicable to the quantitative evaluation of Materials Handling: the Gantz and Pettit Index of Materials Handling (12) and the Bright Movement/Operation ratio (5).

1) The Index of Materials Handling: a/b.

   Where a is the sum of the distances that a part moves automatically from machine to machine without external materials handling.

   b is the total distance that the part travels on the production route from raw stores to finished stores.

2) The Movement/Operation ratio: M/O.

   Where M is the actual number of times that a part moves, and

   O is the number of operations performed on the part.

Flexibility. Flexibility is the capability built into a plant that will allow it to adjust to future changes quickly, economically and with a minimum of cost and inconvenience. The Index of Production Line Flexibility and the Index of Work Station Flexibility, both Gantz and Pettit ratios (12), are suggested for evaluating characteristics of this objective:

1) The Index of Production Line Flexibility: J_1/K_1

   Where J_1 is the number of machines or work stations so designed that can be moved to a new location, and

   K_1 is the total number machines performing the operation

2) The Index of Work Station Flexibility: J_2/K_2

   Where J_2 is the number of machines or work stations within an area 6 so designed that they can be moved to any other location in one shift

K_2 is the total number of machines or work stations within the area

Throughput. Throughput is the amount of raw material that flows through the processing or finishing operations in a specific time. Four measures of evaluating throughput were:

1) The Manhours Index (15): $\dfrac{\text{the number of manhours worked}}{\text{unit of product manufactured}}$

2) The Productivity Index (10): $\dfrac{\text{the output of completed products}}{\text{raw material input}}$

3) The Production Index (23): $\dfrac{\text{the number of units produced}}{\text{plant operation hour}}$

4) Pans/year for a given part. The use of "pans" is explained by Noy, to serve as a common denominator for a number of dissimilar operations which use pans for a materials handling devide throughout the production process. The value and the number of pieces used to put in the pans were different, but all operations used them, hence they became a basis for his method of evaluation (30).

Manufacturing Cycle Time. Manufacturing cycle time is the period of time for a sequence or pattern of machines and/or operators to perform operations on a unit quantity of material. The Time Analysis Sheet (29) and the Line Time ratio (7) were found to be adequate indicators of this objective:

1) The Time Analysis Sheet is a listing of all operation elements and their corresponding times of performance through the use of predetermined motion times.

2) The Line Time ratio is evolved from the sum of all operating times for the stations on a production line from the following formulas:

a) $\text{Cycle time} = \dfrac{60}{\text{hourly rate of production}}$

b) $\text{Speed of the line} = \dfrac{\text{Space per station}}{\text{cycle time}}$

c) $\text{Line Time ratio} = \dfrac{\text{length of the line}}{\text{speed of the line}}$

Floor Space Utilization. This objective is defined as the square footage actually used in relation to the available, required, or to be allocated for each activity, area or function. Five good measures for evaluation were:

1) The Space Index (15): $\dfrac{\text{the percent available space utilized}}{\text{plant dollar spent}}$

2) The Index of Plant Floor Space Utilization (12): $\dfrac{(m + 2)(n + 2) + p}{q - (r + u)}$

Where m is the extreme machine length

n is the extreme machine width

p is the total work area normally required by operator

q is the total layout floor area

r is the total aisle area

u is the total floor area occupied by temporary or controlled storage of materials

3) The Index of Aisle Space (12): r/q

4) The Index of Storage Space (12: $(q - u)/q$

5) Cost of floor area on a dollar per square foot basis (1).

Manpower-machine Utilization. This has been defined as the design of individual operations, the process, flow and materials handling in such a manner that each worker is effectively applying his activities to the best overall plant effort. Three measures of evaluation were the utilization index (15), the average machine utilization ratio (23), and the machine use index (37):

1) The Utilization Index: $\frac{\text{percent utilized available time}}{\text{dollar wages paid}}$

2) Average Machine Utilization ratio: $\frac{\text{Production rate}}{\text{Capacity}}$

3) The Machine Use Index: C_v/C

Where C_v is the total time the facility is in use

C is the total clock time

Materials-in-Process Inventory. All product materials on which the company has performed some manufacturing, processing, or converting operations, but which are not yet finished in form ready for sale or for storage as component parts is considered materials-in-process. The Turnover ratio for Work-in-Process (6), the Inventory Bank summation (18) and the In-Process Cycle time (21) are three methods of evaluating this objective:

1) The Turnover ratio for Work-in-Process:

$$\frac{\text{Cost of Finished Goods}}{\text{Average Work-in-Process Inventory}}$$

2) The summation of the quantities of changes in banks of inventory in the production process, or $B_{12} = (C_1 - C_2)\ T$

Where B_{12} is the change in inventory over time T

C_1 and C_2 are output capacities of operations 1 and 2, respectively

Then all the B's are added to give the total amount of in-process inventory.

3) The In-Process Cycle Time is defined as the amount of in-process inventory, or the product of the rate of input per working day and the number of working days as item is in process:

$$C_t = \left[\frac{Sm + Ept \times Np + T_1(O - Os - D) + T_2\ (D + 1)}{Ns} \right]$$

Where C_t -- the in process cycle time

Sm -- the sum of the make ready and set up times plus the average delay in making set ups (the times that machines are inoperative because of changing jobs).

Ept -- the sum of each-piece times for all operations except those run simultaneously with other operations

Np -- the number of pieces on order

T_1 -- time allowed to make moves between operations

O -- number of operations

Os -- number of operations that can be run simultaneously with preceding operation

D -- number of departments in which operations are performed

T_2 -- time for moves between departments (if applicable)

Ns -- number of shifts (if applicable)

Flow of Materials. Flow of Materials is the path or paths by which items move or progress from the point at which they enter the operation, through the necessary operations, to the point at which they leave, or are delivered, stored or shipped. Two well-known measures for evaluating the flow of materials in a layout are the Travel Chart and the Activity Relationship Chart.

1) The Travel Chart (20) is a matrix of distances traveled between points in a facility. When the number of moves required to move the part through the facility is superimposed on this matrix, the engineer will have an effective evaluator of the total distance that a part travels from raw material to finished product.

2) The Activity Relationship Chart (1) (22) can be constructed in the form of an array of values which quantitatively indicates which plant activities are related to each other and how important each closeness relationship is.

Although only eight of the nineteen objectives in the master list were found to have adequate, known measures of performance, others might be discovered by a more extensive research. If the analyst selects one of the measures included in the Summary Chart, the reference for that measure should be checked to insure that the technique is properly applied. If a well-known technique does not yield an applicable measure, then the engineer should try the second approach determining a measure by definition.

2. Determining a Measure by Definition

Frequently, an extensive definition of a criterion will lead to an appropriate measure in the form of some ratio or combination of the quantifiable factors. In this case a good measure might be created by the following method. First, a complete definition of the criterion is made. Next, units of measure, such as feet or hours or some other factor, that would normally accompany such a definition are taken from the dual list. Third, functions or techniques related to the criterion which would yield results

Summary Chart

Objective	Quantifiable Factor	Units	Evaluator
Materials Handling	Distances moved	feet	Index of Materials Handling
	M. H. plan	----	Move/Operation ratio
Flexibility	Machine changes	#	Index of Production Line Flexibility
	Self-contained machines	#	Index of Work Station Flexibility
Throughput	Manhours worked	hrs	Manhours Index
	Materials	items	Productivity Index
	Units produced	items	Production Index
Manufacturing Cycle Time	Production rate	units/hours	Time Analysis Sheet
			Line Time Ratio
Floor Space Utilization	Space	ft^2	Space Index
	Tot. Floor Area	ft^2	Index of Floor Space Utilization
	Tot. Aisle Area	ft^2	Index of Aisle Space
Manpower-Machine Utilization	Paid Wages	$	Utilization Index
	Capacity	units	Average Machine Utilization ratio
	Production time	hr	Machine Use Index
Material-in-Process	Production costs	$	Turnover ratio
	Minimum of goods in Process	items	Summation of Inventory Banks
		items	In-Process Cycle Time
Flow of Materials	Moves	#	Travel Chart
	Distance	Ft	Activity Relationship Chart

Figure 3 - 1. Summary Chart

in these units are researched or created. Finally, one of these techniques is selected which best satisfies the five characteristics. For example, consider the criterion Safety:

1. Definition: Safety is the use of techniques and designs to reduce, control, or eliminate accidents.[1]
2. Factors: From the dual list come such factors as injuries, severity of injuries, or the number of hazardous jobs.
3. Functions: Several useful ratios of injuries to hours worked are found in the literature, or may be created.
4. Selection: The best measure found was the injury frequency rate:

$$\text{I.F.R.} = \frac{\text{the number of disabling injuries} \times 10^6}{\text{the total number of man hours worked}}$$

If the definition approach fails to yield a good measure of performance for a criterion, then the analyst should investigate the third approach - determining a measure by a survey of pertinent criterion characteristics.

3. Determining a Measure by Survey

In the case where neither of the above methods will succeed, as might be true with a unique criterion with many factors that can only be evaluated by judgment, an artificial measure must be created. The approach in this case is to create a scheme or survey which will encompass management opinion or expert knowledge as to the appropriate levels of performance for each alternative. An easy method of doing this is to list from four to six relevant factors of the criterion, and then estimate the percentage that each alternative layout accomplishes relative to the "ideal" performance with respect to that criterion. For example, the critee criterion "general appearance" might have the factors of neatness, crowded-

[1]Blake (4)

ness and excess space. Relative to the ideal, one alternative might have ratings of 70,30, and 60 for these respective characteristics (see Figure 3-2). These results may be averaged, or weighted and averaged, to give the final level of effectiveness for that layout. Since the decision maker determines the results, the levels should be reliable and sensitive to changes in his opinion.

The task of defining acceptable measures is a difficult task, since there is a deficiency of quantitative techniques or functions for measuring criteria, in the plant layout field other than for Materials Handling or Flow Materials, and most often the analyst will have to create his own measure.

Measures of Performance for the Example Problem

For each of the seven criteria listed at the end of Chapter II, (p. 17) measures were selected by the procedures developed in this Chapter. First, measures of performance described in the summary chart (Figure 3-1) were checked. If the measures described there or in the related material proved to be inadequate, the second approach of defining the criterion and investigating combinations of factors from the dual list was taken. If this also failed to yield an acceptable measure, then third a survey was created utilizing pertinent factors from the master list, or additional factors as specified by the decision maker. By following this procedure, a combination of one well-known technique, three definitions, and three surveys were used as measures of performance for the Toy Train Criteria Set. The measures were:

1) Provide a smooth and efficient flow of materials. The Travel Chart Technique described in the summary chart for this criterion was

Criterion: General Appearance

CHARACTERISTICS percent:	0	10	20	30	40	50	60	70	80	90	100
1. Neatness								✓			
2. Crowdedness				✓							
3. Excess Space							✓				

EVALUATION

Item	% Performance	% Weight	Product
1. Neatness	70	30	.21
2. Crowdedness	30	50	.15
3. Excess Space	60	20	.12
		100%	.48

Measure of performance: .48

Figure 3-2. A Weighted Survey Scheme as a Measure of Performance adopted as its measure of performance. Further study revealed that factors 15 a, d, f, and h, from the master list were represented in various forms in the Travel Chart, suggesting that it should be a good measure of performance for this criterion. The Travel Chart provides a matrix summarizing material travel between related activities, yielding data results in terms of the total distance that the components of a product must move through the plant to yield a finished product.

2) Use good production methods. Since a method of manufacture was highly individualized among all the alternatives, quantitative comparisons were almost impossible, and no evaluation technique or definition led to an acceptable measure. Therefore, a synthetic measure involving a decision-maker survey was created by pulling factors 16 c, d, and e, from the master list, and <u>adding</u> two factors relating to production methods within the Toy Train factory to form the following evaluation categories and their corresponding relative weights:

1. General Work Place Layout:
   - a. Adequate operator space (15%)
   - b. Adequate material space (10%)
   - c. Individual work areas coordinated (30%)
   - d. Material handling indicated, compatible (20%)
   - e. Access for repair and maintenance, adjustment (5%)
2. Specific
   - a. Finishing operations layout (10%)
   - b. Packing operations arrangement (10%)

The two categories, "General" and "Specific," were used to aid the decision maker in arriving at his estimation of the procedure.

3) Allow for building expandability. Since this criterion was not included in the summary chart, the analyst explored the definition approach.

This led to the selection of factor 17a, the number of external directions in which plant operation could be extended. When the measure was applied to the Toy Train layouts, the levels of performance described by the decision maker were: 2, $2\frac{1}{2}$ and 3 directions. Internal measures of expandability were considered, but were included in two other criterion measures, production methods and flexibility.

4) The layout should have a good overall appearance. This criterion was quite unique and very hard to define. Since the criterion was not found in the summary list, a definition approach was tried and yielded only a good set of characteristics, but no real measure of performance. Consequently, a survey was set up employing three of these characteristics and evaluation categories:

1. Neatness (30%)
2. Crowdedness (50%)
3. Minimum excess space (20%)

Some conflict arose as to how a layout could be crowded yet have excess space, but was resolved by the argument that an alternative could have its machines placed tightly together and yet waste space between departments or production centers.

5) Adequate aisles used to allow easy traffic flow. This was the second criterion added by the decision maker. However, the analyst discovered that some aspects of this criterion as defined by the decision maker were listed under the composite criterion, "Make Economical Use of Floor Area," and that the Gantz and Pettit Aisle Space Index, described in the summary chart, was an adequate measure of performance for this criterion. The ratio is defined as the total asile area divided by the total layout floor area, which were factors 7d and f from the master list.

6) Efficient services and office with a good general appearance. This was the third criterion added by the decision maker. A measure of performance for it was defined by a survey, for little aid was given by the Summary Chart or the definition approach. The categories of the survey and their relative weights in the decision maker's opinion were:

1. Service areas close to areas served
   a. Maintenance and tool room (7.5%)
   b. Locker (7.5%)
   c. Food (7.5%)
   d. First aid (7.5%)
2. Utilities--panel outside, permanent wall (10%)
3. Adequate fire equipment, sprinkler outside (10%)
4. General Office Appearance
   a. Crowded (5%)
   b. Traffic (5%)
   c. Aisles (5%)
   d. Interrelationship (5%)
   e. Cluttered (5%)
5. Entries--front, plant, office to plant (10%)
6. Toilets, locker room (15%)

Sub-factors were included to better describe some of the main characteristics in which case the weight for the main category was divided evenly among the sub-factors if weights for them were not specified by the decision maker.

7) Maintain flexibility of arrangement and operation. Flexibility was a difficult criterion to define or to find a measure of performance. It was found that the Gantz and Pettit Index of Production Line Flexibility recommended in the Summary Chart was applicable, and further proved to be the ratio of two factors from the master list (3b and 4g) and represented factors 3f, g, h, i and j. The index is calculated as the number

of machines or work stations performing operations on the product, so designed that they can be moved to a new location in one working shift, divided by the total number of machines or work stations performing operations on the product, in the production line.

CHAPTER IV

WEIGHT CRITERIA

After a set of evaluative criteria has been selected and a corresponding set of quantitative measures determined, the relative importance or weight of each criterion must be considered. In this chapter, a general comment is made on the significance of a criteria weight; four methods are offered for establishing these weights when there are several decision makers evaluating the alternative layout plans; and the criteria weights for the example problem are presented. In Chapter V these weights will play a major role in defining the scoring model used for the selection of the best alternative.

Criteria Weight

In any set of objectives for evaluation there are always some that have a greater bearing on the final results than others. It is not enough to establish a list of criteria; additional factors must be included to indictte the criterion's relationship to the system as a whole. For example, the criterion "materials handling" might be more important than "flexibility" in the Toy Train Layout problem. Similar orderings could be made for all of the objectives in the criteria set; e.g., materials handling is more important than flexibility, but less important than flow of materials; so that a definite hierarchy of objectives would be developed. Such a system of priorities must be reflected in the final scoring model if it is to be a valid representation of the layout environment, and is accomplished through criteria weighting.

A criteria weight is a numerical quantity signifying the degree of importance of a factor, according to the decision maker's personal usefulness for each criterion, relative to all other factors in the system. In a somewhat secondary role, the criteria weight functions as a coefficient in a complex sooring function to denote the performance level trade offs between individual criteria within the set.

Methods of Determining Relative Importance

Determination of how much adjustment is necessary for the various criteria must be made through the judgment of persons doing the evaluation based on experience, consultation with plant personnel, and data peculiar to the layout problem itself. Four of the more prominent methods of computing this adjustment factor are the ranking, rating, paired comparison, and the successive comparison methods. All four are presented below so that the engineer may choose the one that best suits him and has the highest confidence of the ultimate decision maker. For a single judge, the ranking method is probably the best.

The ranking technique is essentially a method of classifying objectives into quantitative categories, and is the easiest to use of the four methods. Each judge places a numerical rank next to each criterion, indicating by "one", the most valuable in the set, by "two", the next most valuable, etc. The ranks are then reconverted so that a rank of one will be given a value of "m", and a rank of two given an M - 1, etc., down to one for the lowest. Since each judge produces only a set of integers, it is not possible to develop a set of weights for each judge for diagnostic purposes. The weight is determined as follows:

$$R_c = \sum_{j=1}^{n} R_{cj}$$

$$w_c = \frac{R_c}{\sum_{c=1}^{m} R_c}$$

Where m is the number of criteria,

n is the number of judges,

R_c is the sum of the converted ranks across judges for each criterion

R_{cj} is the converted rank assigned by judge "j" to Criterion "c,"

w_c is the relative weighting.

The rating technique allows more freedom on the part of the judge and in its sclae than the ranking method in an effort to yield a more accurate relative weighting. In this method the criteria set is presented next to a continuous scale marked off in units from zero to ten, lowest to highest importance. The judge is asked to draw a line from each criterion to any appropriate point on the value scale, and he is permitted to select points between numbers or to assign more than one criterion to a single position on the scale. The weighting is computed by:

$$w_{cj} = \frac{p_{cj}}{\sum_{c=1}^{m} p_{cj}}$$

$$w_c = \frac{\sum_{j=1}^{n} w_{cj}}{\sum_{j-1}^{n} \sum_{c=1}^{m} w_{cj}}$$

Where w_{cj} is the weight computed for criterion "c" from the rating given by judge "j."

p_{cj} is the rating given by judge "j" to criterion "c."

The method or paired comparisons consists of a list of pairs of criteria, and the judge is asked to choose the member of each pair that is more valuable to the layout. Each criterion is paired once with every other criterion. The number of times each criterion is chosen over each other criterion is tabulated for each judge, and the number of times each criterion is chosen over all other criteria is determined by addition, and w_c is calculated as follows:

$$f_{cj} = \sum_{c=1}^{m-1} f_{(c/c')j}$$

$$w_{cj} = \frac{f_{cj}}{J}$$

Where f_{cj} -- is the frequency of choice by judge j of criterion c over all other criteria

$f_{(c/c')j}$ -- the frequency of choice of criterion c over criterion c'.

J -- the total number of judgments made: $\frac{(m - 1)\, m}{2}$

The method of successive comparisons is a ranking and comparison scheme somewhat different from the previous three methods. Its sequence of steps is as follows:

1. Rank criteria in order of importance as in the ranking method.

2. Tentatively assign the value (V_1) of 1.0 to the most important criterion, and other values (V_i), between 0 and 1, to other criteria in order of importance.

3. Decide whether the criterion with 1.0 is more important than all other criteria combined:

a. If so, increase V_1 so that V_1 was greater than the sum of subsequent V's, i.e. $V_1 > \sum_{i=2}^{n} V_i$.

b. If not, adjust V_1 so that V_1 was less than the sum of all subsequent V's, i.e. $V_1 < \sum_{i=2}^{n} V_1$.

4. Decide whether the second most important value, V_2, was more important than all lower-valued criteria; and proceed as in step 3.

5. Continue until n - 1 criteria have been so evaluated, and calculate the relative weighting by:

$$w_{cj} = \frac{p_{cj}}{\sum_{c=1}^{n} p_{cj}}$$

$$w_c = \frac{\sum_{j=1}^{n} w_{cj}}{\sum_{j=1}^{n} \sum_{c=1}^{m} w_{cj}}$$

In two independent research situations each of the above four produced similar weightings (11) (34). The ranking technique was shown to be by far the simplest to use, and was the method chosen for the example problem. However, this does not preclude the use of the other three in different situations, for the analyst should utilize whichever method elicits ease of use and the greatest confidence from the decision maker. Also, it should be noted that once the criteria weight values have been calculated they should be submitted to the decision maker to insure that they accurately reflect his opinions as to actual significance of each criterion on the final selection. Minor adjustments of these values should be made until the decision maker is satisfied that the weights realistically reflect his opinions.

Relative Importance Values for the Example Problem

The criteria weights for the Toy Train Factory problem were calculated by the ranking method. The seven objectives were ordered according to their significance to the final selection decision. Since only one judge was used in determining these values, the w_c could be calculated as follows:

$$w_c = \frac{R_c}{\sum_{c=1}^{m} R_c}, \text{ where } m = 7.$$

The results are presented in Table 4 - 1.

Table 4 - 1

Criterion	Rank	Converted Rank	$\frac{Rc}{\sum Rc}$	w_c
General Appearance	4	4	4/28	.143
Traffic	3	5	5/28	.179
Flow of Materials	1	7	7/28	.250
Production Methods	2	6	6/28	.214
Expandability	6	2	2/28	.071
Flexibility	5	3	3/28	.107
Offices and Services	7	1	1/28	.036
		28	1.00	1.000

These values were then presented to the decision maker for his approval and necessary adjustments. The weights were accepted as they are in the above table, implying that the values fairly accurately agreed with the decision maker's estimation of the significance of each of the criteria to the final selection decision.

CHAPTER V

THE EVALUATION MODEL

The next step in developing the evaluation methodology is the definition of scoring functions for measures of performance determined in Chapter III, and then, as step 5, interrelate them with the relative weights of Chapter IV in an evaluation model. However, before the topic of scoring functions can be introduced, a possible structure of the evaluation model must be evolved. The resulting form presented two inherent problems but scoring functions were used to solve them. A procedure for constructing a scoring function is included before the final model form is presented and applied to the example problem. Normally, the specification of the scoring functions would come first in the actual application of the methodology, but due to the originality of this research, the presentation of the model structure must precede the scoring function development to make the final model form more understandable and the use of scoring functions in that model more obvious. Verification of the model and analysis of its results are presented in Chapter VI.

Combining Multiple Factors

Once the weights and the measures of performance for each criterion have been defined, a model must be found that systematically integrates these heterogeneous factors into a coherent numerical output on which the selection of the best layout may be based. This model must have four intrinsic characteristics to be applicable to the plant layout problem:

1) it must be flexible in structure in order to incorporate an unspecified number of criteria, 2) it must consider all criteria values simultaneously in its formulation, 3) it must logically combine the criteria weights and performance results, and 4) its output should be of such a nature that the better layouts will receive significantly higher scores.

As the first of these requirements, the model structure itself must be flexible in that it will be able to incorporate an unspecified number of criteria as dictated by the unique layout problem before it. It must be capable of handling three criteria as well as ten--depending upon the problem.

Secondly, the model should consider all criteria simultaneously. Optimization with respect to one criterion while using the other criteria in the set as constraints on the solution will lead to the optimum layout with respect only to that criterion, but may not lead to the best overall layout. Also, there is some doubt as to whether certain criteria can be expressed as constraints, for the designer may not know what the upper or lower bounds on a constraint variable--say the maximum acceptable materials flow travel distance--may be, consistent with all other criteria. By considering all criteria at the same time in one objective function, the evaluation model will not fall into this trap of singularity. This means that instead of choosing a layout which places a small machine in a large space to optimize materials handling, but at the same time wasting floor space, the model should select the layout with the best compromise between the two criteria. This requirement, in conjunction with the previous one, suggests a model involving a summation of values where a variable number may be included, or

$$C = \sum_{j=1}^{n} V_j$$

Where C is the total layout score

V_j is the value for criterion j

n is the number of criteria in the set.

Although it is recognized that other forms such as multiplication may also be suggested, this research will use the summation.

Since not all criterion values will have equal importance in determining the best layout, the model must be able to combine a relative weight value with the criteria effectiveness value to indicate the relationship of that criterion to the criteria set as a whole. The dilemma of uniqueness in the plant layout problem is solved by the fusion of these two factors. A product of the type, $w_j\ c_j$, where w_j if the relative weight, is suggested by this consideration. Depending upon the size of w_j the relative weight would adjust a criterion value to reflect its degree of importance to the set as a whole.

Finally, the model must produce an output that will effectively result in the best layout receiving the highest score and the remaining layouts with lower scores. This indicates that the model should be a maximization problem, so the analyst will be able to identify the best layouts, analyze the more important aspects of each, and then combine selected aspects into an even better layout. A summation of values is suggested by this constraint, so that only positive contributions to the overall score should be allowed, and the best layout will be that with the highest total.

Summarizing these four requirements of the evaluation model, it should have the following form in order to efficiently evaluate a given layout;

$$C = \sum_{j=1}^{n} w_j \, c_j$$

Where w_j is the relative weight of criterion j

c_j is the value for criterion j

n is the number of criteria.

However, two major problems immediately arise from these requirements. If the performance results for some criteria within the set are predominantly large, they will subordinate the performance results of other and possibly more important criteria, and will bias the output. For example, if "Flow of Materials" had a performance value of 1000 and a relative weight of .4, and "Materials Handling" had values of .9 and .6, respectively, the model's output would be: (1000)(.4) + (.9)(.6) = 4000 + .54 = 400.54. The first criterion's large performance value dominates the results, overriding the more important (.6 to .4 relative weights) second criterion. Also, the problem of combining criteria whose most desirable performances are a minimum value with those whose best is a maximum value in a maximization model is present, for instance, combining the criterion "minimize the number of serious injuries' with the criterion "maximize manufacturing output." The model must be able to include both of these types of criteria if it is to be of any value whatsoever in its application to real situations.

Scoring Functions

One of the most interesting aspects of the decision theory research in its application to the plant layout problem is its use of scoring functions. In addition to solving the above two problems this approach reduces the amount of judgment used in the evaluation by deriving criteria values not from an engineering estimate, but based on actual levels of performance and in terms of statistics of a criterion's measurement space. In other words, judgment is used to assign an integer value to a performance result, like an aisle space index of .107 for an alternative, rather than subjectively rate how well this particular layout did with respect to the criterion, "Adequate and Well Located Aisles," without knowledge of this data, as is often done in the judgment techniques. Rating still plays a role in this process, but it is used in a relatively small capacity rather than in the actual placement of values on performance results, as previous models had done. Judgment has been limited to a level that is more effective, sensitive to the criterion's performance, and hopefully, more accurate in that it will not suffer greatly from human variances. Therefore, before a general procedure for constructing a scoring function can be presented, it must be precisely defined and the elemental and assumed characteristics of the function must be considered.

A scoring function is defined by attaching an integer-valued score to specified intervals of a statistical distribution of performance results for a criterion, indicating how well a particular alternative compares with others within the competing set of layouts with respect to that criterion (see Figure 5-1). Since the same number of intervals are used for all criteria scoring functions, it becomes a mechanism for mapping performances in the criterion's measurement space onto a common base, CRITERION: Materials Handling Index

Layout Performance	Score
Over m + 1.755	9
m + 1.75 s to m + 1.25 s	8
m + 1.25 s to m + .75 s	7
m + .75 s to m + .35 s	6
m + .25 s to m - .25 s	5
m - .25 s to m - .75 s	4
m - .75 s to m - 1.25 s	3
m - 1.25 s to m - 1.75 s	2
Under m - 1.75 s	1

Where m is the mean of the data values
s is the standard deviation

Figure 5-1. A Scoring Function for Materials Handling

CRITERION: Flow of Materials Distance Traveled

Layout Performance	Score
Over m + 1.75 s	1
m + 1.75 s to m + 1.25 s	2
m + 1.25 s to m + .75 s	3
m + .75 s to m + .25 s	4
m + .25 s to m - .25 s	5
m - .25 s to m - .75 s	6
m - .75 s to m - 1.25 s	7
m - 1.25 s to m - 1.75 s	8
Under m - 1.75 s	9

Where m is the mean of distribution of value
s is the standard deviation

Figure 5-2. A Scoring Function for Flow of Materials to be Minimized preventing a bias by criteria with large results over those with small ones. Reconsidering the previous example, the scoring function for "flow of Materials" might assign to a performance of 1000 the "score" of 5, while the Material Handling function would give a "score" of 8 to .9 resulting in the model's output now to be: 5(.4) + 8(.6) = .68, which is less sensitive and more realistic.

Another adherent characteristic of these functions is their ability to handle different types of criteria. Often, a given criteria set will contain some whose optimum performance is a minimum value and others where the best is represented by a maximum value. The combination of the two such criteria into one objective function is a problem that is solved by reversing the scale for the criteria to be minimized so that the highest "scores" will be given to the lowest performance results (Figure 5-2). This means that both types of criteria may be included in the model, so that it will become a more relevant and effective tool.

The scoring function itself consists of three basic components: a mean, a standard deviation and several scoring intervals. The number of intervals will be initially set from the closed interval (1,9), and the interval widths are originally defined in terms of the mean and some multiple of the standard deviation of the distribution of performance results. By means of the guide to be proposed, these intervals are adjusted by the decision maker and the analyst so that the function finally specified will discriminate between good and average or poor alternatives over the entire distribution of data points.

In establishing such a function for each criterion, it must be assumed that the layout performance relative to that criterion is distributed according to a specific probability distribution function. In actuality this means that the engineer is extracting data from the alternatives, and then fitting the results to some statistical function. Ideally, enough points or alternatives will exist so that a function may be derived by statistical analysis. However, this occurance is rare since it is common to have generated a large enough number of alternatives to have several that are partially repetitions. Therefore, one must be satisfied with the approximation of the function provided by the scoring intervals.

Construction of a Scoring Function

Although a scoring function was defined and some characteristic elements were presented in the literature, a general method for constructing a scoring function from a set of data was not obvious. To overcome this, the present study will propose a five step guide with a brief explanation of each step. Briefly, the steps are: 1) gather data, 2) determine parameters, 3) specify scoring intervals, 4) score, and 5) review. An example is selected from the Toy Train criteria set to illustrate the application of this procedure. The ultimate goal of this guide is for the analyst to derive a scoring function with a satisfactory set of partitions and related integer scores that is sufficiently attuned to the decision maker's conception of an effective discrimination between good, average and poor layouts relative to one criterion; and then repeat the process for every other criterion with the set.

1) Gather data. After the data from the measures of effectiveness have been collected, each result is located on a continuous scale which covers the entire range of data points to help visualize the distribution.

Clusters of points are indications of various "levels" of achievement and become "natural" partitions which might prove useful in a later step where adjustment of the intervals is necessary. Although it might be possible to merely "attach" scores to these clusters at this point, the process of working with the mean and standard deviation parameters should prove to be a better first approximation from which adjustments can easily be made. As an illustration consider the criterion, "make economical use of floor space" and its related measure of performance, the aisle space index, in Figure 5-3a.

2) Determine parameters. Next, the distribution parameters are calculated to form a more concrete basis for specifying the scoring intervals. The formulae to be used in finding these parameters from the sample or in this case, the number of competing layouts, are calculated as follows:

$$\text{the Distribution Mean: } \frac{\sum x}{n}\text{, and}$$

$$\text{the Standard Deviation: } \left[\frac{\sum x^2 - (\sum x)^2/n}{n-1}\right]^{\frac{1}{2}} .$$

Where x is a data value, and n is the total number of points. Figure 5-3b shows this for the example.

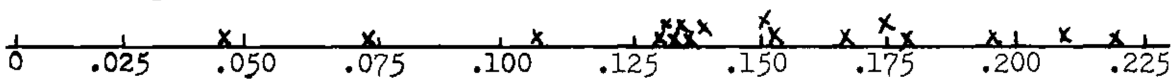
3) Specify scoring intervals. The third step is to specify the scoring intervals. However, first the number of intervals to use must be resolved. Moore and Baker recommended that a maximum of nine intervals be used, at least at the outset, for this showed the highest consistency between their model and an economic test model. The analyst and the

Criterion No. 2: Adequate Aisles

Measure of Performance: Aisle Space Index

(a) Gather data:

Layout	r	q	r/q
Bertz	1220	7956	.153
Brown	350	8080	.043
Dean	1075	8400	.128
Dornbos	888	8160	.109
Elliot	1104	8285	.133
Green	1674	7515	.223
Kent	1052	8192	.128
Moore	1103	8400	.131
Ottati	1290	8500	.152
Payne	1532	8514	.180
Pitman	1603	8200	.195
Smith	1123	8100	.139
Spence	1460	8640	.169
Sturdivant	1504	8585	.175
Sweet	618	8340	.074
Williams	1628	11200	.145
Young	1992	9052	.220



(b) Determine parameters:

Mean = .147; Standard Deviation = .047

(c) Set up initial intervals

Performance	Value	Score
under m - 1.75 s	under .065	1
m - 1.75 s to m - 1.25 s	.065 to .088	2
m - 1.25 s to m - .75 s	.089 to .112	3
m - .75 s to m - .25 s	.113 to .135	4
m - .25 s to m + .25 s	.136 to .158	5
m + .25 s to m + .75 s	.159 to .181	6
m + .75 s to m + 1.25 s	.182 to .207	7
m + 1.25 s to m + 1.75 s	.208 to .229	8
over m + 1.75 s	over .229	9

(d) Assign scores

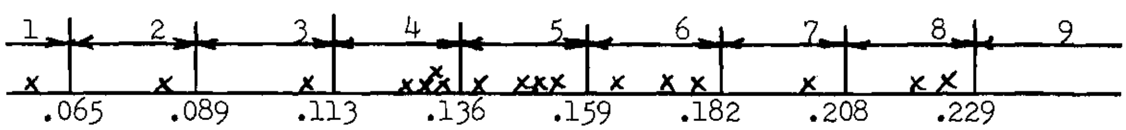


Figure 5-3. Specification of a Scoring Function

decision maker should start with nine, but may have to reduce it to seven or five or three in order to improve the consistency of results between the evaluation model and the base used to test it, or make it conform more closely with the decision maker's ability to discriminate. Once the number of classes has been chosen, they are used for all performance data to prevent biasing of criteria with larger intervals and higher possible scores over those with a smaller number of classes. The initial set of intervals is arbitrarily defined to set the partitions every half a standard deviation centered on the mean of the distribution as in Figure 5-1. By observing how the clusters fall within these intervals the analyst will have some idea of how to adjust the widths to improve the discriminatory power of the function. This step is illustrated in Figure 5-3c.

4) Assign Scores. An integer score from one to the number of intervals used is assigned to each class with the highest integer given to the performance interval, the next highest to the next best, and so on down to one for the worst level (Figure 5-3d). It must be remembered that the best performance might occur in the lowest class as in the Flow of Materials example, or the highest as in the Materials Handling measure, Figure 5-1, depending upon the criterion. The intrinsic flexibility of the model is revealed by the fact that good performances relative to both criteria will be equally treated by the scoring model, despite their opposite orientations.

5) Review. At this point the decision maker and the engineer should review the scores achieved by each alternative, and check to see that all levels of performance are properly distinguished in their opinion. If not, the engineer must return to Step 3 and adjust the class intervals

to improve the results. In the example, two such attempts were required before a satisfactory set of intervals was found (Figures 5-3e and f). Figures 5-3d and 5-3e were unacceptable because the high frequency of points in some classes did not yield an adequate discrimination between the alternatives.

The Special Discrete Case

Occasionally, a criterion will not be susceptible to the above synthesis as in the case of a discrete criterion where only a finite number of results are possible. If the number of possible points is less than the number of scoring intervals used, a certain amount of unintentional weighting will occur. For example, the criterion "Building Expandability" and its measure of performance, the number of directions in which operations could be expanded, might have data points of 1, 2, or 3 directions in a criteria set consistently using nine scoring intervals. Since a relative weight is already included in the model, special care must be taken not to bias it by giving additional emphasis to a criterion. This study will first "equi-space" the data points on the scoring function, Figure 5-4, and then look at these type of criteria first if problems arise in the verification procedure used in Chapter IV.

The Evaluation Model

The evaluation model is a quantitative relationship which computes a dimensionless number or utility value to indicate the overall effectiveness of a layout relative to a pertinent set of criteria. The model proposed in the first section of this chapter will be developed in more precise mathematical terms and matrix notation will be introduced as a vehicle for data presentation, now that the two problems have been solved.

Layout Performance	Score
over .185	9
.175 to .185	8
.164 to .174	7
.153 to .163	6
.142 to .152	5
.131 to .141	4
.120 to .130	3
.108 to .119	2
under .108	1

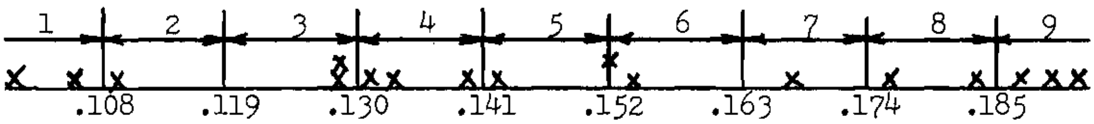


Figure 5-3 (e) Contract Intervals to Improve Discrimination

Layout Performance	Score
over .195	9
.180 to .195	8
.164 to .179	7
.153 to .163	6
.142 to .152	5
.131 to .141	4
.120 to .130	3
.108 to .119	2
under .108	1

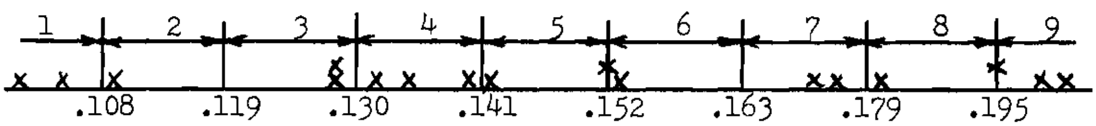


Figure 5-3 (f) Final Specification

CRITERION: Building Expandability Directions

Layout Performance	Score
Three Directions	9
	8
	7
Two Directions	6
	5
	4
One Direction	3
	2
	1

Figure 5-4. A Discrete Criterion with More Scoring Intervals than Performance Results

Stated in more exact terms, the total utility or score of a layout, L_i, $(i = 1,m)$, is determined by the summation of the products of the individual criteria performance scores, c_{ij}, and its corresponding relative weight, w_j, for each member of the criteria set, C_j, $(j = 1,n)$. The relative weights for the model were determined in Chapter IV and the effectiveness scores were extracted from the scoring function. Formally, the evaluation model is:

$$U_i = \sum_{j=1}^{n} c_{ij}w_j \text{ , } i = 1, 2, 3, \ldots m.$$

Where U_i is the total score for alternative layout i

w_j is the relative weight of criterion j

c_{ij} is the criteria value of alternative i with respect to criterion j.

For ease of presentation, a matrix notation was introduced and the model was represented as the product of a relative weight and a criteria value matrix. The former is a lxm column vector made up of the various numerical weights of the m members of the criteria set:

The Relative Weight Matrix

Criterion	Relative Weight
1	w_1
2	w_2
3	w_3
⋮	⋮
j	w_j
⋮	⋮
n	w_n

The criteria value matrix consists of performance score results for each alternative relative to each criterion, or would be formulated as the following m x n matrix:

The Criteria Value Matrix

Alternative Plan	C_1	C_2	C_3	C_4	C_n
L_1	C_{11}	C_{12}	$C_{13} \cdots$	$C_{1j} \cdots$	C_{1n}
L_2	C_{21}	C_{22}	$C_{23} \cdots$	$C_{2j} \cdots$	C_{2n}
L_3	C_{31}	C_{32}	$C_{33} \cdots$	$C_{3j} \cdots$	C_{3n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
L_i	C_{i1}	C_{i2}	$C_{i3} \cdots$	$C_{ij} \cdots$	C_{in}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
L_m	C_{m1}	C_{m2}	$C_{m3} \cdots$	$C_{mj} \cdots$	C_{mn}

Summarized, in matrix notation the decision model may be stated as:

$$
\begin{matrix} U_1 \\ U_2 \\ U_3 \\ \vdots \\ U_i \\ \vdots \\ U_m \end{matrix}
=
\begin{matrix}
C_{11} & C_{12} & C_{13} \cdots & C_{1j} \cdots & C_{1n} \\
C_{21} & C_{22} & C_{23} \cdots & C_{2j} \cdots & C_{2n} \\
C_{31} & C_{32} & C_{33} \cdots & C_{3j} \cdots & C_{3n} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
C_{i1} & C_{i2} & C_{i3} \cdots & C_{ij} \cdots & C_{in} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
C_{m1} & C_{m2} & C_{m3} \cdots & C_{mj} \cdots & C_{mn}
\end{matrix}
\quad
\begin{matrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_j \\ \vdots \\ w_m \end{matrix}
$$

Or, this can be restated as $U = C\,w$

Where U is the total utility matrix

C is the criteria value matrix

w is the relative weight matrix.

The layout possessing the highest total utility should be the alternative recommended to management.

The Inclusion of Constraints in the Evaluation Model

Before the evaluation model can be considered as complete the possibility of adding constraints on criteria value scores in the form of upper or lower bounds on these scores must be examined. A constraint should be included in the model if the performance relative to a particular criterion is so bad that it will make implementation of that layout difficult or impossible. Obviously, if a layout proposal can not be made operational, it should not be considered as an alternative in a set of layouts from which the best will be chosen. For example, an alternative may score impressively on all but one criterion, "General Appearance," and have a high overall score. However, if its general appearance is such that the crowded conditions of the plant will prohibit or inhibit production, then that layout must be eliminated as an alternative.

It should be emphasized that the use of such constraints is optional, in the sense that only through interaction between the decision maker and the analyst, and the observation of the alternatives, can it be determined, first, if constraints are needed for a criterion, and second, what level of performance they should be. After these decisions have been made, the score from the scoring function to be attached to the selection level of performance becomes the bound on the constraint equation. Some adjustments may have to be made within that scoring function for performances better than the limit, but within in the same scoring interval. Thus, if a crowdedness of .45 is unacceptable, but .50 is acceptable, and both fall with in the scoring interval 3, then the scoring function should be adjusted to give a score of 4 to performances about .45.

More formally, the above situation is represented in the model by the inclusion of as many equations as is necessary involving a criterion value score variable and an integer in the form:

$$C_{ij} \geq K_j \quad \forall\ i = 1, 2, \ldots m \text{ and}$$
$$\text{any } j = 1, 2, \ldots n$$
$$k_j = \text{integer } (1,9)$$

Where j is the j^{th} criterion in the criteria set to which the constraint applies, and k is the integer score established by the decision maker and the analyst which will make an alternative unacceptable. For the example cited above, it might take the form $C_{i6} \geq 3$, where "General Appearance" is the sixth criterion, and any score below three means that conditions in the layout's general appearance would prohibit its implementation if selected. Also, the layouts which fail to satisfy one or more constraints should not be totally discarded, but should be temporarily set aside; they may contain valuable information that will be useful to the engineer in the verification and analysis step presented in Chapter VI.

Application to the Toy Train Example

Steps 4 and 5 of the proposed method have been presented in this chapter and will be illustrated by their application to the Toy Train layouts. Step 4 is to specify scoring functions for the distributions of performance results of the measures selected in Chapter III. The general procedure for deriving each scoring function was exemplified by the aisle space index scoring function derived in an earlier section. For brevity, only the first and last steps in specifying this function for each criterion will be included here, and the intervening steps will be described in Appendix II for the interested reader. Pertinent raw data or performance results for four of the criteria will be included in Appendix III. The specified scoring functions for the Toy Train criteria set are presented in Figures 5-5 through 5-11. The criteria value matrix (Table 5-1)

TABLE 5 - 1

Criteria Value Matrix

Criterion Layout	(1) General Appearance	(2) Adequate Aisles	(3) Flow of Materials	(4) Production Methods	(5) Expand- ability	(6) Flexi- bility	(7) Offices & Services
Bertz	4	6	9	4	3	6	7
Brown	1	1	4	6	3	2	3
Dean	6	3	3	8	9	6	2
Dornbos	4	2	1	7	9	3	6
Elliot	8	4	8	5	6	6	9
Green	4	9	1	1	3	2	6
Kent	3	3	3	4	9	1	7
Moore	3	4	8	3	9	5	7
Ottati	6	5	8	5	9	9	1
Payne	5	8	9	2	3	5	7
Pitman	5	8	6	3	6	3	7
Smith	8	4	3	8	9	7	6
Spence	8	7	8	2	9	5	1
Sturdivant	8	7	4	7	9	9	4
Sweet	2	1	7	3	3	4	6
Williams	8	5	4	5	9	7	4
Young	4	9	1	8	9	7	4

summarizing the scores for the performance of each layout relative to each criterion is shown above. Thus, if the Bertz layout had a Travel Chart flow distance of 2451 feet (Appendix III), it was given a score of 9 for the Flow of Materials scoring function. This value was then placed in column three, "Flow of materials," as the criteria value for flow of materials for the Bertz layout. The other values were derived similarly.

Criterion No. 1: General Appearance

Measure of Performance: Survey of Characteristics

Data

Name	Performance	Score
Bertz	.83	4
Brown	.72	1
Dean	.88	6
Dornbos	.83	4
Elliot	.90	8
Green	.83	4
Kent	.80	3
Moore	.80	3
Ottati	.88	6
Payne	.85	5
Pitman	.85	5
Smith	.90	8
Spence	.90	8
Sturdivant	.90	8
Sweet	.77	2
Williams	.90	8
Young	.83	4

Final Specification

Layout Performance	Score
over .905	9
.895 to .905	8
.884 to .894	7
.863 to .883	6
.842 to .862	5
.821 to .841	4
.800 to .820	3
.769 to .799	2
under .769	1

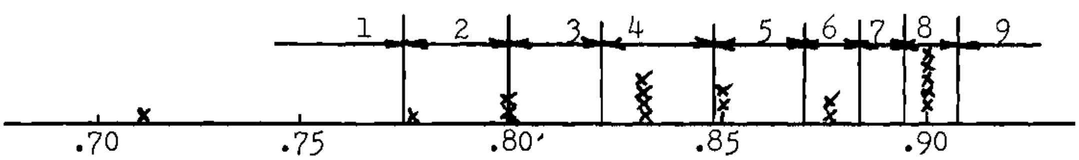


Figure 5-5. The Scoring Function for General Appearance

Criterion No. 2: Adequate Aisles

Measure of Performance: Aisle Space Index

Data

Name	Performance	Score
Bertz	.153	6
Brown	.043	1
Dean	.128	3
Dornbos	.109	2
Elliot	.133	4
Green	.223	9
Kent	.128	3
Moore	.131	4
Ottati	.152	5
Payne	.180	8
Pitman	.195	8
Smith	.139	4
Spence	.169	7
Sturdivant	.175	7
Sweet	.074	1
Williams	.145	5
Young	.220	9

Final Specification

Layout Performance	Score
over .196	9
.180 to .196	8
.164 to .179	7
.153 to .163	6
.142 to .152	5
.131 to .141	4
.120 to .130	3
.109 to .119	2
under .109	1

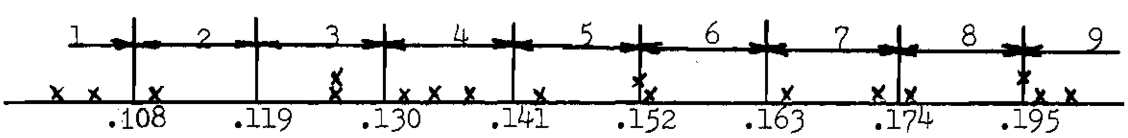


Figure 5-6. The Scoring Function for Adequate Aisles

Criterion No. 3: Flow of Materials

Measure of Performance: Travel Chart

Data

Name	Distance	Score
Bertz	2451	9
Brown	3116	4
Dean	3225	3
Dornbos	3629	1
Elliot	2635	8
Green	3677	1
Kent	3234	3
Moore	2525	8
Ottati	2523	8
Payne	2366	9
Pitman	2874	6
Smith	3168	3
Spence	2510	8
Sturdivant	3097	4
Sweet	2709	7
Williams	3054	4
Young	3836	1

Final Specification

Layout Performance	Score
Under 2500	9
2501 to 2653	8
2654 to 2779	7
2780 to 2905	6
2906 to 3031	5
3032 to 3157	4
3158 to 3283	3
3284 to 3409	2
over 3410	1

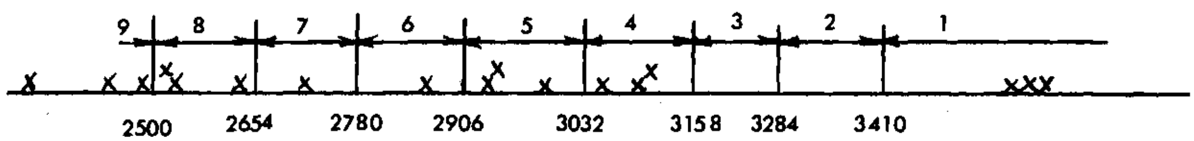


Figure 5-7. The Scoring Function for Flow of Materials

Criterion No. 4: Production Methods

Measure of Performance: Survey of Characteristics

Data

Name	Performance	Score
Bertz	.86	4
Brown	.88	6
Dean	.90	8
Dornbos	.89	7
Elliot	.87	5
Green	.82	1
Kent	.86	4
Moore	.85	3
Ottati	.87	5
Payne	.84	2
Pitman	.85	3
Smith	.90	8
Spence	.84	2
Sturdivant	.89	7
Sweet	.85	3
Williams	.87	5
Young	.90	8

Final Specification

Layout Performance	Score
Over .908	9
.897 to .907	8
.886 to .896	7
.875 to .885	6
.864 to .874	5
.853 to .863	4
.842 to .852	3
.831 to .841	2
Under .831	1

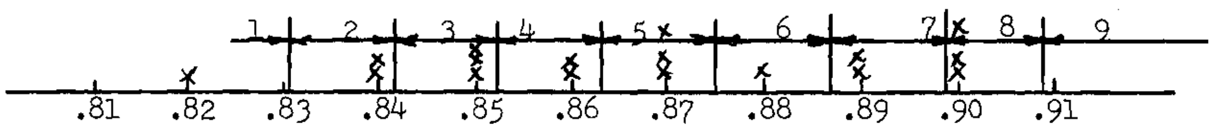


Figure 5-8. The Scoring Function for Production Methods

Criterion No. 5: Expandability

Measure of Performance: Number of Dimensions Expandable

Data

Name	Performance	Score
Bertz	2D	3
Brown	2D	3
Dean	3D	9
Dornbos	3D	9
Elliot	$2\frac{1}{2}$D	6
Green	2D	3
Kent	3D	9
Moore	3D	9
Ottati	3D	9
Payne	2D	3
Pitman	$2\frac{1}{2}$D	6
Smith	3D	9
Spence	3D	9
Sturdivant	3D	9
Sweet	2D	3
Williams	3D	9
Young	3D	9

Final Specification

Layout Performance	Score
3 Dimensions	9
	8
	7
$2\frac{1}{2}$ Dimensions	6
	5
	4
2 Dimensions	3
	2
	1

Figure 5-9. The Scoring Function for Expandability

Criterion No. 6: Flexibility

Measure of Performance: Work Station Flexibility Index

Data

Name	Performance	Score
Bertz	.741	6
Brown	.550	2
Dean	.722	6
Dornbos	.600	3
Elliot	.746	6
Green	.528	2
Kent	.491	1
Moore	.667	5
Ottati	.830	9
Payne	.679	5
Pitman	.600	3
Smith	.789	7
Spence	.700	5
Sturdivant	.825	9
Sweet	.613	4
Williams	.786	7
Young	.762	7

Final Specification

Layout Performance	Score
over .820	9
.801 to .820	8
.751 to .800	7
.711 to .750	6
.658 to .710	5
.605 to .657	4
.552 to .604	3
.499 to .551	2
under .499	1

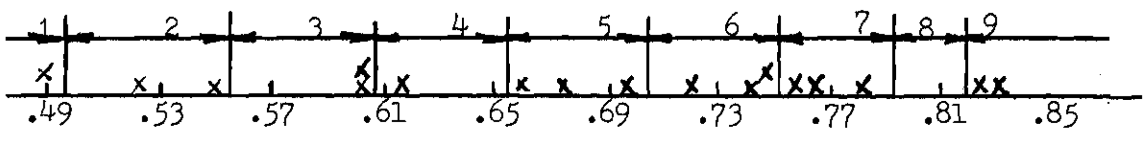


Figure 5-10. The Scoring Function for Flexibility

Criterion No. 7: Offices and Services

Measure of Performance: Survey of Characteristics

Data

Name	Performance	Score
Bertz	.88	7
Brown	.84	3
Dean	.83	2
Dornbos	.87	6
Elliot	.91	9
Green	.87	6
Kent	.88	7
Moore	.88	7
Ottati	.79	1
Payne	.88	7
Pitman	.88	7
Smith	.87	6
Spence	.82	1
Sturdivant	.85	4
Sweet	.87	6
Williams	.85	4
Young	.85	4

Final Specification

Layout Performance	Score
over .899	9
.888 to .899	8
.877 to .887	7
.866 to .876	6
.855 to .865	5
.844 to .854	4
.833 to .843	3
.822 to .832	2
under .832	1

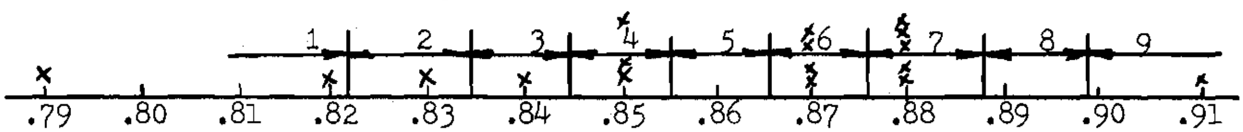


Figure 5-11. The Scoring Function for Office and Services.

The Step 5 is to interrelate the scoring functions for the criteria with their corresponding relative weights into an evaluation model. The matrix notation introduced in this chapter will be used to present the evaluation model and the calculation of the overall layout scores. The model is formed as the combination of the Criteria Value Matrix, Table 5 - 1, and the Relative Weight Matrix of the criteria weights determined in Chapter IV:

Layout		Criteria Value Matrix								Relative Weight Matrix		Total
Bertz		4	6	9	4	3	6	7		.143		5.859
Brown		1	1	4	6	3	2	3		.179		3.357
Dean		6	3	3	8	9	6	2		.250		5.210
Dornbos		4	2	1	7	9	3	6		.214		3.854
Elliot		8	4	8	5	6	6	9	x	.071	=	6.322
Green		4	9	1	1	3	2	6		.107		3.290
Kent		3	3	3	4	9	1	7		.036		3.570
Moore	=	3	4	8	3	9	5	7				5.213
Ottati		6	5	8	5	9	9	1				6.461
Payne		5	8	9	2	3	5	7				5.825
Pitman		5	8	6	3	6	3	7				5.288
Smith		8	4	3	8	9	7	6				5.926
Spence		8	7	8	2	9	5	1				6.035
Sturdivant		8	7	4	7	9	9	4				6.641
Sweet		2	1	7	3	3	4	6				3.714
Williams		8	5	4	5	9	7	4				5.641
Young		4	9	1	8	9	7	4				5.677

In completing the construction of the evaluation model, the inclusion of constraints to criteria score values must be considered. Upon discussion with the decision maker the following constraints were established: 1) a flow of materials distance greater than 3300 feet was unacceptable, and 2) an office-survey index below .83 was unacceptable. Formally, these are represented as $C_{i3} \geq 3$ and $c_{i7} \geq$ in the completely structured evaluation model. Based on these constraints the Ottati, Spence, Young, Dornbos, and Green layouts were withdrawn from further consideration. In addition, the Smith layout was arbitrarily eliminated as being "too tight" for production to be carried on. This situation is discussed further in Chapter VI.

CHAPTER VI

VERIFICATION AND ANALYSIS

For an evaluation model to have any true meaning, it must be verified before it can be confidently used. This means that its practicability and especially its results must be substantiated or proven to be accurate within reasonable limits within the actual situation it is modeling. The determination of this accuracy for the evaluation model is accomplished by first creating a logical basis for the test statistic, Kendall's τ, and then applying the measure to the output rankings of the evaluation model and some other method of ranking the layouts. Once the model has been validated, the engineer must analyze his results, not only for the best layout, but also for weaknesses, strengths and opportunities for combining features of several layouts to yield a better layout. If the model is not validated on the first test, four suggestions are included to help in the authentication. The test and analysis methodology developed here are applied to the Toy Train layouts for illustrative purposes.

A logical basis for testing the output of the evaluation model is to compare its results with some other layout evaluation model that is valid and accepted by the decision maker. Specifically, a base is required that will serve to evaluate layouts in such a manner that an ordering from the best to worst layout will result. This would make it possible to test the effectiveness of the evaluation model over the entire range of quality of alternatives. Once the two rankings are available, a comparison between the two orderings follows logically as a means of verification or an indication of adjustments that should be made in the evaluation model to attune it to the base. If the engineer could prove that the model's alignment is the same as the other methods with only minor chance variations, then it would be possible to conclude that the model has been correctly tuned, is representative of the decision process, and would generally rank any layouts in the same manner as the base.

However, a problem exists in that such a quantitative model to serve as a time has not been developed for general use in the plant layout field at this time. In its place a method must be found that will provide the necessary rankings, and still be fairly reliable. One possibility is to have the decision maker informally and subjectively rank the alternative layouts. Admittedly, the validity of such a method is questionable, but it is the best that can be done under the circumstances. One good feature of this method is that the decision maker may change his ranking at any time, and the analyst must closely interact with the decision maker throughout the verification process. Summarized, the objective of the verification process in this research will be to align the model and the subjective ranking first by making structural changes in the evaluation model, and, second, interacting with the decision maker to make changes in his ranking if necessary, so that the model is representative of the selection process.

Since it would be improbable that both orderings would choose the same layout as best, it would be more feasible to compare the overall rankings of the two, and leave to the analysis phase to glean what information it can and make the necessary adjustments from the results. A statistic must be found, then, that gives a relative indication of the degree of closeness and its significance of the two layout rankings relative to each other. Also, it must be able to serve as an indicator of when the two are fairly well aligned after changes have been made, so that the engineer can begin his analysis of the output of the evaluation model. Such a measure is Kendall's τ used in rank correlation analyses.

Kendall's τ

In psychological work the problem of comparing two different rankings of the same set of individuals is often solved by the rank correlation coefficient, Kendall's τ. Specifically, it quantitatively shows the compatibility of the rankings of, or n individuals layouts in this research from one to n, according to some designated characteristic, by m observers. Because of its definition, this statistic has found wide application in other fields, and can easily be adapted to the comparison of two rankings of alternative plant layouts. It is the best test statistic for such a comparison between a small $(10 < n \leq 20)$ number of individuals. It has some validity over the range, $5 < n \leq 10$, but Spearman's is better for $n > 20$. For a more detailed discussion the reader should see Kendall (17).

The rank correlation coefficient is +1 only when the two rankings are perfectly aligned, and -1 when the rankings are exactly inverted. For intermediate values it provides a satisfactory measure of correspondence between the two rankings. In the case where either of the rankings may be taken as the objective ranking, as in this research, τ measures how accurate either ranking would be if the other were the objective, or it measures thee <u>compatibility</u> of the two rankings. The verification of the model consists of calculating the value of τ as defined below, and a test of significance statistic to disprove the hypothesis that the two rankings are unrelated, which leads to the conclusion that the two methods order layouts in the same manner, and that the model is valid.

Definition of Tau

The following definition of Tau and much of its related material is taken from Kendall's Rank Correlation Methods (17) where the interested reader will find a more detailed presentation of the calculation of this measure. The definition of Tau is more easily comprehended if an example is worked out before a general statement of how it is calculated is made.

Consider a set of layouts, numbered from 1 to 10, whose objective order is 1, 2, 3, . . ., 10, and consider another arbitrary ranking of the same layouts such as:

3 7 1 10 2 6 8 1 4 9.

Consider the order of the nine pairs obtained by taking the first number 4, with each succeeding number. The first pair, 4 7, is in the correct order (sequenced 1, 2, . . ., 10), and it is given a score of +1. The second pair, 4 2, is in the wrong order and is score -1. The third pair is scored +1, and so on, the nine scores being:

+1 -1 +1 -1 +1 +1 -1 +1 +1 = +3.

Performing a similar analysis with the second number, 7, and its eight succeeding numbers the scores and total would be:

-1 +1 -1 -1 +1 -1 -1 +1 = - -2.

Proceeding with each number, the nine scores are as follows:

+3, -2, +5, -6, +3, 0, -1, +2, +1.

are totaled to yield a score of +5.

The maximum score, obtained if the numbers are all in objective order

(1, 2, . . ., 10), is 45. The rank correlation coefficient between a variable ranked in objective order and a variable ranked in the order above is:

$$\text{Tau} = \frac{\text{Actual Score}}{\text{Maximum Possible Score}} = \frac{5}{45} = 0.11.$$

Generally, if there are n layouts, the maximum score, obtained if and only if they are all in objective order is $(n-1) + (n-2) + \ldots + 1 = \frac{n(n-1)}{2}$. Denoting the sum of actual scores for any given ranking by S, this measure of rank correlation, τ, may be calculated as:

$$\tau = \frac{2S}{n(n-1)} .$$

In the case of ties, where two layouts receive the same score from the same model, a more complex form a τ may be calculated or some arbitrary rule may be established for breaking ties (17). The latter approach will be used for the example problem.

<u>Test of Significance</u>

After the τ has been calculated, its value or its related quantity S, (which is just a multiple of Tau) must be tested for significance before any tangible conclusions may be drawn about the correlation between the two rankings of layouts. A test of significance is a test which, by use of a test statistic, purports to provide a test of an hypothesis that a certain effect is absent. The strategy recommended by Kendall is to assume that no relationship exists between the two orderings or that τ and S are zero and calculate a test statistic, based on a property of S to prove or disprove this supposition.

Kendall has demonstrated that for a sample size of n greater than 10, the variable S is satisfactorily approximated by a normal distribution with mean of zero and standard deviation of one. Further, it was shown the variance of S is: Var $S = s^2 = \frac{1}{18}(n)(n-1)(2n+5)$. However, since a continuous distribution is being used to approximate a discrete one, a compensating correction in the test statistic must be made. It is assumed that instead of having frequencies at S, as in a discrete distribution, that the frequencies are spread out uniformly over the interval S - 1 to S + 1, so that a continuous distribution has been approximated. In comparing the areas under the normal curve, one will be subtracted from the observed S before it is expressed as a multiple of the standard deviation, and this is known as the correction for continuity.

The hypothesis to be tested is that the two rankings are independent indicating that there is no real relationship between them, versus the alternate that the two rankings came from the same source or model. The following criterion will be adopted for testing this: if it is very improbable that the observed value of S, or greater in absolute value, could have arisen by chance, the hypothesis will be rejected. In other words, if the observed S lies in the "tails" of the distribution away from the mean, the hypothesis will be rejected. The five percent level of significance will be used in this research to specify this chance occurence, though other values might prove more suitable to another analyst. An illustration, taken from Kendall, will prove useful in understanding this test.

Example 6 - 1[1]

In a pair of rankings of 20 the value of S was observed to be 58 and Tau was found to be 0.31. Is this significant?

$$\text{Tau} = \frac{2S}{n(n-1)} = \frac{2(58)}{20(19)} = 0.31.$$

$$s^2 = \text{Var } S = \frac{1}{18}(20 \times 19 \times 45) = 950$$

$$s = 30.82.$$

Making the correction for continuity, S becomes 57, and

$$S = \frac{57}{30.82/s} = 1.85 \text{ s}.$$

From the normal tables, the probability of a deviation less than 1.85 s is about 0.9678. The probability that 1.85 s is obtained or exceeded in absolute value is 2(1 - 0.9678) = 0.064. This is small, but not small enough to reject the hypothesis. If the observed S had been equal to or larger than 1.96 s or 61, the hypothesis would have been rejected, and it could be assumed that the two rankings came from the same source.

Analysis

Analysis of the results is the last and most important step in this methodology. After the layouts that have violated constraints have been thrown out, the engineer must calculate the value of τ and its significance as in the previous section to see if the model that has been constructed conforms to the base ranking. If the value of τ is significant, then the analyst should study the output for useful information as recommended in Section A below. If τ is not significant, then he should return to some

[1]Kendall (17)

of the diagnostic suggestions of Section B to see if improvements in the correlation of the two orderings can be made. If this fails also, then the analyst should interact with the decision maker to see if a change in the ranking of layouts is in order, or if he can give some insight as to where the output of the model might be in error.

Section A. A Significant Tau

If the observed τ is found to be significant, the researcher can conclude that his model and the base method of ranking will coincide with only small chance variations and that a representative model has been built. He can then analyze its output. In addition to finding the best alternative layout, a more extensive study should be made of other layouts, finishing close to the top as well as those which did best under each criterion, so that opportunities for improvement and combinations of layouts for producing a better overall layout will not be overlooked.

The discovery of the best alternative was one of the primary objectives of this research. The layout selected should represent the best compromise of the weighted criteria set, optimizing each criterion in accordance with the objectives of all other criteria. It will consistently score high for each criterion, because it has the best combination of elements uniform with the criteria set used to evaluate it. If a layout must be selected from the competing set of alternatives, this is the one that should be suggested to the decision maker.

Nevertheless, greater opportunities exist when the close finishers, the second or third or fourth best layouts, are also studies. After careful circumspection, it might be possible to discover ways to combine one or several of these with the best layout or with each other to form an even better layout. For example, maybe a certain machine arrangement in the fourth best layout could be used to improve a weakness or poor criterion score in the second best layout to yield a new alternative that might be better than the number one layout. A large number of opportunities for improvement exists from following this pattern.

Finally, the engineer should consider the layouts which had the best score in a particular criterion, but which did not finish high in the overall rankings. A vast reservoir of ideas for improving the top layouts can come from this source. If one of the top layouts did poorly in this category, the ideas or even that part of the layout with the lower total score, but with the highest score related to that criterion could prove useful in correcting the weakness or alleviating the problem in the higher ranked layout, thus improving it some more.

All that is hoped for in this analysis stage is that the engineer will not just choose the best, but will look into the wealth of information and the vast opportunities for implementation of ideas from lower ranked layouts. The model itself should not be discarded after the analysis, either, for it could serve as a screening device so that insteadof giving the decision maker seventeen layouts from which to choose the best, the engineer could present only the top five "scorers" from the model. Among other uses, the model should give some insight to the decision maker about how alternative layouts are evaluated and selected, what criteria are most important, and how they are weighted in reaching the final selection.

Section B. A Non-Significant Tau

If the value of Tau is not significant, the two rankings have no relation to each other and the model's structure must be rechecked.

Diagnostic action should begin with any discrete criterion scoring functions, then progress to the scoring functions for the other criteria, and, last, to the measures of performance chosen for the criteria. The ultimate goal of this trouble shooting is to improve the consistency between the model's and the base method of ranking by adjusting scoring intervals within each scoring function. It should be re-emphasized that the other source is not to be taken as the absolute correct ranking and the model must be changed to suit it, but that the other is a base which the model should try to emulate as much as possible. Also, the analyst should always interact with the decision maker to see if he prefers the results obtained.

The first thing to check is the scoring functions used for discrete criteria. Other class intervals beside the equi-spacing used in the previous chapter might be tried in the hope that the changes produced in the rankings may bring the model closer into alignment with the base. The scores should be assigned higher or lower to see if this will improve the correlation statistic.

Next, the other scoring functions should be rechecked to see that the proper amount of discernment is achieved at <u>all scoring levels</u>. The researcher might check those scoring functions with large ranges of values, expanding the scoring intervals around the tails, while being careful not to alter those in the middle of the distribution. Another common problem is groups of points with very similar values falling into the same interval; here greater attention should be paid to contracting these intervals to increase discrimination power in that part of the distribution, while trying not to disturb the more effective of the remaining scoring intervals. Again, all changes should be tried and the ones that improve correlation should be implemented.

Finally, the measures of performances themselves should be challenged to see that they really meet all the characteristics described in Chapter III. It is entirely possible that an invalid measure has been used or that the measure selected has failed to properly discriminate levels of performance, and a better one should be found. For example, the engineer should suspect that a measure is not discriminating properly when performance results similar to survey results of the survey in Figure 5-11 appear. In such cases he should look for another measure of performance. The reliability of the measure should be examined over the entire range of performance to see that it has given consistent results. Also, the measure might have been misapplied or misunderstood in its application, and this should be investigated.

As a last resort, the engineer should take several of the best ranked layouts from the base method of ranking, and compare to see where or why they did poorly in the evaluation model. Possible areas of improvement are indicated by this approach which might have been overlooked in the previous refinements. If not he should then confront the decision maker with the results, and see if the decision maker should make alternations in his rankings. If changes in order are made then the analyst should repeat the above process.

After each change has been made, another Tau and significance test should be run. If the Tau is significant, the researcher should proceed as in Section A. If not, more refinements should be made. If all else fails the engineer must be satisfied with some generated data of unknown value and look over the suggestions of Section A, while being careful not to draw any real conclusions about his model. In other words, his model hasn't satisfactorily approximated the base, and it is possible that such an evaluation model will not be applicable to the layout problem before analyst.

Verification and Analysis in the Example Problem

The evaluation model output was analyzed and verified according to the procedures presented in this chapter for the Toy Train layouts. No major adjustments were required in the verification step, for the calculated Tau was significant on the first trial. As an example of what the analysis phase might include, an attempt was made to improve one of the best layout's weaknesses by combining it with another layout.

Verification

Step 6 of the proposed methodology is to verify the model by tuning it to a valid base. Since such a base was not available, the decision maker's judgment ranking of the layouts was used. Structural changes in the intervals of the scoring functions, and decision maker changes in the judgment rankings are made until the correlation coefficient, Kendall's Tau, indicates that there is agreement between the orderings. Once this agreement has been achieved the researcher analyzed the alternatives not only for the layout with the highest score, but also other alternatives in an effort to make a combination leading to an even better layout.

First, the decision maker ranked the seventeen Toy Train layouts from best to worst. These rankings were then added to the model output of Table 5 - 1 to form Table 6 - 1.

After removing the layouts that have violated constraints, a Kendall's τ was calculated and tested at a significance level of five percent. The computed value was significant and indicated that the model had sufficiently

Table 6 - 1

Layout	Criterion 1	2	3	4	5	6	7	Score	Rank	Judgment Ranking
Sturdivant	8	7	4	7	9	9	4	6.641	1	1
Ottati*	6	5	8	5	9	9	1*	6.461	2	11
Elliot	8	4	8	5	6	6	9	6.322	3	6
Spence*	8	7	8	2	9	5	1*	6.035	4	13
Smith**	8	4	3	8	9	7	6	5.926	5	15
Bertz	4	6	9	4	3	6	7	5.859	6	2
Payne	5	8	9	2	3	5	7	5.825	7	7
Young*	4	9	1*	8	9	7	4	5.677	8	9
Williams	8	5	4	5	9	7	4	5.641	9	5
Pitman	5	8	6	3	6	3	7	5.288	10	3
Moore	3	4	8	3	9	5	7	5.213	11	12
Dean	6	3	3	8	9	6	2	5.210	12	14
Dornbos*	4	2	1*	7	9	3	6	3.854	13	4
Sweet	2	1	7	3	3	4	7	3.714	14	17
Kent	3	3	3	4	9	1	7	3.570	15	8
Brown	1	1	4	6	3	2	3	3.357	16	10
Green*	4	9	1*	1	3	2	6	3.290	17	16

Constraints: $C_{i3} > 3$ $C_{i7} > 2$

* Violated constraint
** Eliminated by the decision maker

approximated the decision maker's ranking, and that it would probably rank any alternative layout something like the decision maker with only minor variations. The computations were as follows:

Layout Rankings

Evaluation Model:	1	2	3	4	5	6	7	8	9	10	11
Judgment Ranking:	1	6	2	7	8	5	3	9	4	10	11

$S = 10 + 1 + 1 + 0 + 1 + 4 + 1 + 2 + 1 = 29$

$$\text{Tau} = \frac{2S}{n(n-1)} = \frac{2(29)}{11(10)} = .527$$

$$s^2 = \frac{1}{18}(11)(10)(27) = 165, \quad s = 12.84$$

Making the correction for continuity, S becomes 28, and

$$S = \frac{28}{12.84/s} = 2.18 \text{ s.}$$

From the normal tables, the probability of a deviation less than 2.18 is about 0.9851. The probability that 2.18 s is obtained or exceeded in absolute value is 2(1 - 0.9851) = 0.030. This is small enough to reject the hypothesis that the two rankings are unrelated. Therefore, the analyst can conclude the rankings came from the same source, of that the model has sufficiently approximated the decision maker's selections and ordering.

Since Tau was significant on the first try, no further changes are necessary in the model. However, if τ had not been significant, the changes in the scoring functions suggested in the section "A Non-significant τ" would have been made until it became significant.

Analysis

The Sturdivant layout was the best alternative in terms of achieving the highest overall score, but the analyst should not stop there. The Sturdivant layout has weaknesses, as evidenced by low criteria values, for "Flow of Materials" and "Offices and Services". To indicate how an analyst might go about combining layouts to generate a better overall layout, the Bertz layout which scored higher than Sturdivant in the criterion "Flow" will be combined with the Sturdivant layout.

A rearrangement of the Sturdivant machines, Figure 6 - 1, to fit the Bertz flow of materials pattern, Figure 6 - 2, was attempted to generate a better layout, Figure 6 - 3. No other changes were made. Other combinations and improvements are possible, but will be left to future efforts in this area.

Figure 6 - 1. The Sturdivant Layout

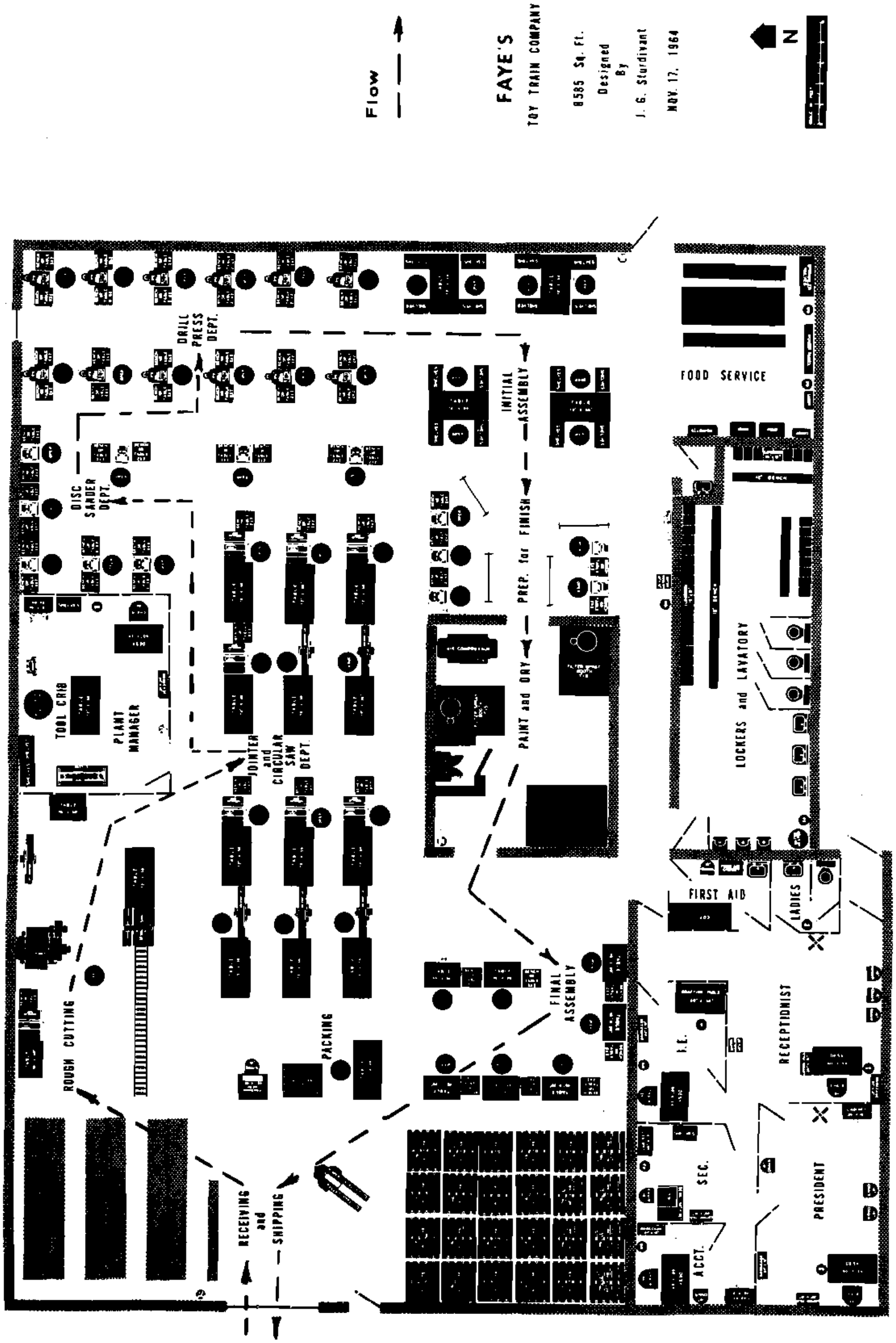


Figure 6 - 2. The Bertz Layout

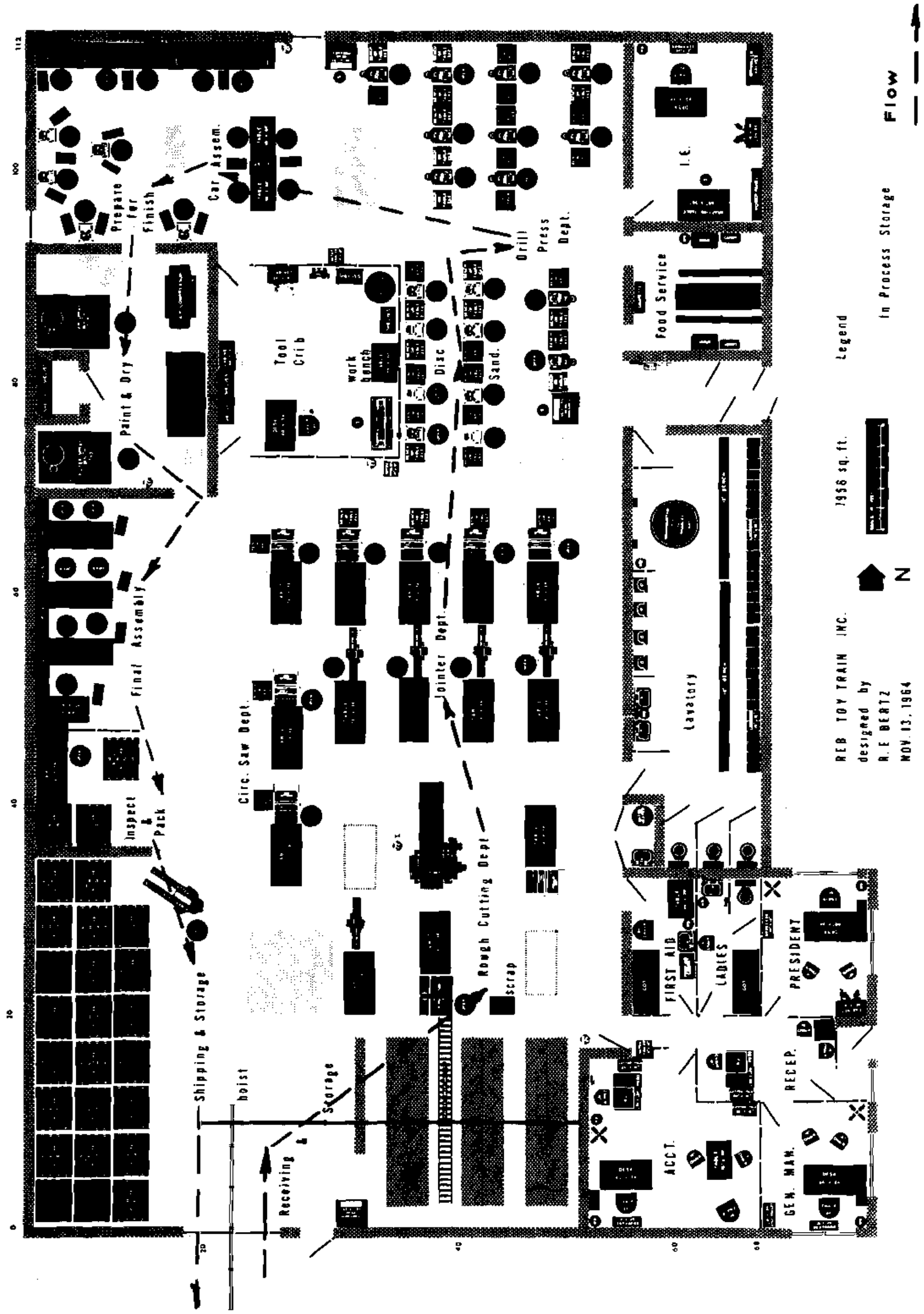
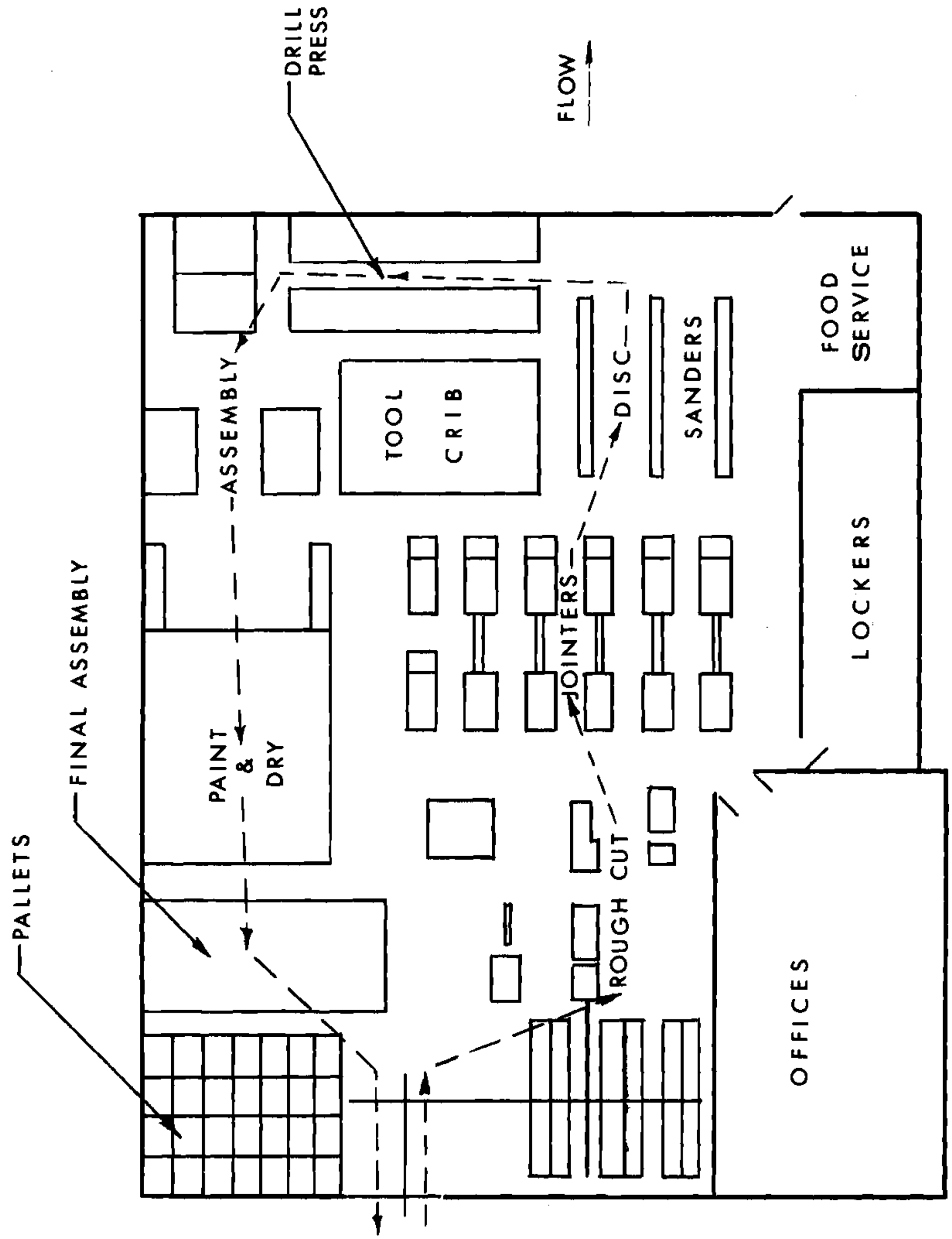


Figure 6 - 3. The Sturdivant Layout Combined with the Bertz Flow of Materials



CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The primary goal of this research has been to develop a workable methodology for quantitatively evaluating a set of alternative plant layouts to determine the best. In this final chapter, a summary of the method is presented, then conclusions originating from this research are drawn, and recommendations and extensions for further research are made.

Summary

The quantitative method proposed by this research for evaluating alternative plant layouts of the same production facility consists of six steps. It has solved the problems of uniqueness, singularity and the proper place of judgment. These steps are:

1) Select from five to ten criteria from a list of objectives to be accomplished by the final plant layout. Three possible sources of this list are management directives and desires, engineering checklists, and a composite list of plant layout objectives derived from the literature.

2) Choose a measure of performance to indicate the degree of goal accomplishment for each criterion must be chosen. For criteria derived from the composite list of objectives, a master list of factors that could conceivably serve as quantitative measures was developed. To establish factors for criteria taken from the other two sources, the analysis technique used to develop factors for the composite list was suggested.

3) Calculate a relative weight for each criterion, since not all

members of the criteria set will have the same significance in the selection of the best alternative. Four of many possible methods were presented in Chapter IV for computing these weights.

4) Specify scoring functions for the distribution of performance results of the measures selected in Step 3. Although the process of specification is primarily one of interaction between the analyst and the decision maker, a definition and a procedure for constructing a scoring function is included to make this process more systematic.

5) Interrelate the scoring functions for the criteria with their corresponding relative weights into an evaluation model. A possible form for this model for evaluating alternative layouts was developed in Chapter V, and emphasized the necessity for and the role that scoring functions play in the model.

6) Verify the model by tuning it to a valid and accepted base. Since such a base was not found, a judgment ranking of questionable validity might be used. Structural changes in the scoring functions and changes in the judgment ranking as suggested by the decision maker are made until the rank correlatinn coefficient, Kendall's Tau, indicates that there is substantial agreement between the two orderings. The analyst then must not only select the best layout, but look for combinations of layouts that might produce even better alternatives than those presently in the set.

An example problem consisting of seventeen alternative layouts for a Toy Train factory is included to illustrate each of these steps and the concepts presented within them.

Conclusions

The following conclusions result from this research:

(1) There is a deficiency of quantitative techniques and evaluators for specific plant layout objectives other than Materials Handling and Flow of Materials.

(2) The decision theory approach is both applicable and readily adaptable to the alternative plant layout selection problem. There was very little trouble in adapting that methodology to this research.

(3) The model form evolved from the analyst's conception of the layout selection problem and decision theory methodology is but one of many possible formulations. However, the summation approach has been demonstrated to be effective in another research, and is probably the easiest form for a decision maker to comprehend.

(4) By combining the best aspects of several layouts, as indicated by their high scores from criteria scoring functions, an opportunity to have an even better alternative layout can be created. This was illustrated by the combination of alternatives produced for the example problem.

(5) A set of layout alternatives can be evaluated by the proposed method. Based on its application to the example problem, the method is workable and practical. However, more research is needed to improve the method in the areas of: scoring function specification, establishment of quantitative factors, and additional applications to determine and correct flaws not apparent in the example used in this research.

<u>Recommendations and Extensions for Further Research</u>

In the process of developing this quantitative method, several related problems were recognized by this researcher, but time did not permit resolving them. Areas for possible further efforts include:

(1) The redevelopment of a better and more extensive list of plant

layout objectives; factors that could serve as possible evaluators for each; and improvement of the master list presented in Chapter III.

(2) Determine better measures of performance, so that less emphasis will be placed on the definition and survey methods of evaluating performance.

(3) More work should be done on the validity and the reliability of the survey approach. Psychological testing should be performed to increase its acceptability as a measure and improve its format for future applications in evaluating alternative plant layouts and other fields.

(4) The decision theory research needs to be expanded and detailed in simpler terms so that it will be more accessible for use by engineers. The methodology has the potential for becoming a powerful management and engineering tool.

(5) The number of alternative layouts to be evaluated as been tacitly assumed to be higher than ten. More work should be done to discover what affect the number of alternatives has open the workability of the proposed method, especially with less than 10.

(6) Finally, more work should be done in the areas of combining the best parts of the seventeen Toy Train layouts to see if a better combination or combinations than the one included in Chapter VI can be generated.

Possible extensions of this effort relate to the alternative evaluation problem and to application of the methodology to other areas. The method developed in this research might prove useful in formulating a base model to be used to test other optimal plant selection formulations, for example, Mitchell's (22) untested linear programming model. Other areas where the method might be applicable are plant site location and the problem of selecting of the best material handling equipment.

APPENDIX I

THE TOY TRAIN PROBLEM

Purpose

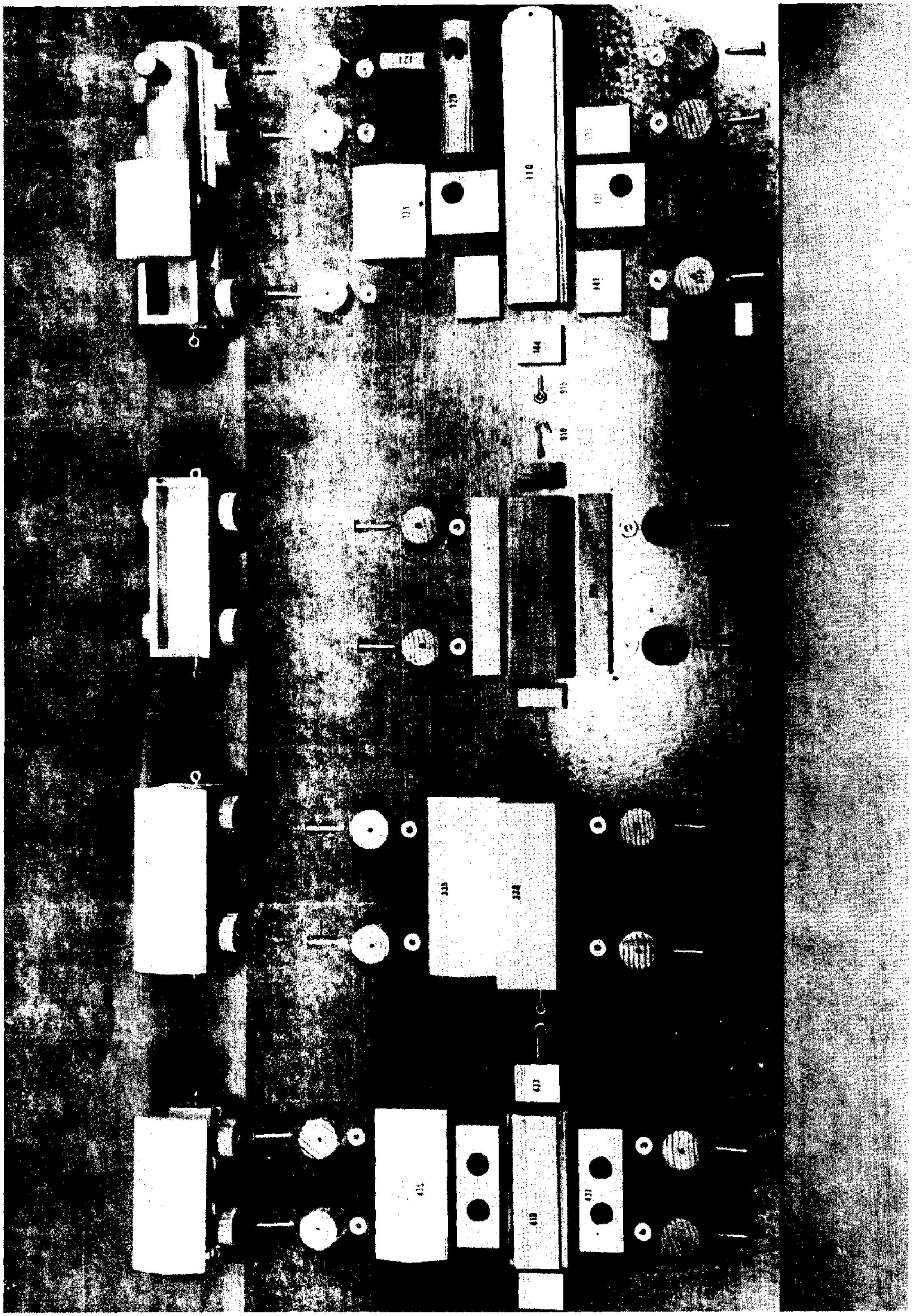
The purpose of this appendix is to familiarize the reader with the details of the toy train problem used as an example throughout this research. The problem originated as a course requirement for I. E. 447. Each student was given the problem of designing a plant layout which was to accomplish several requirements as listed below. Seventeen layouts of toy train factories from the Fall of 1964 class became the raw data for this study. The numerical grades assigned to them by Professor Apple became the benchmark to which the scoring model rankings were compared to test the reliability of the evaluation model.

Product

The basic product is a wooden toy train consisting of three cars and an engine hooked together by screw hooks and eyes (see diagram 1). It is to be made from #1 Poplar lumber and painted. The features are sturdy and safe for normal child's use. It will sell for approximately $5 on the retail market.

Production

The proposed plant is to produce toy trains at the rate of 50 per hour or 100,000 per year. All operations on the rough lumber received are done in the plant, including painting and packaging. Only the wheels, coupling hooks and eyes, wood bead, string, carton, liners, tape, and labels are purchased.



Plant Facilities

Size and Construction

The building to house the plant must be constructed of cement block with concrete floor, tar and gravel "flat" roof, and a front of brick.

Production

The production sequence to make the toy trains is as follows:

1. After the boards are received, they are cut into four to six foot lengths and are planned to the proper thickness and cut to the proper width.

2. Part Fabrication: The necessary cutting to length, jointing, drilling, and handing is done to make the individual parts.

3. Assembly: The various parts are assembled, and glued or nailed together, placed on racks to dry. Final sanding is done after drying.

4. Painting and Finishing: Two coats of paint are applied in a paint booth and dried in an oven. When dry each item is inspected; wheels, and hooks and eyes are then put one. A string and bead are attached to the engine, and the whole assmelby is inspected again and packed in a carton.

Offices

Approximately 1000 square feet of total office area is required for the President, the Industrial Engineer, Production Manager, Accountant, and Secretarial help.

Other Facilities

Food services in some form must be provided. A tool room and tool crib to do the simple repairs and tool sharpening are necessary. First aid station(s) and toilet facilities must be provided.

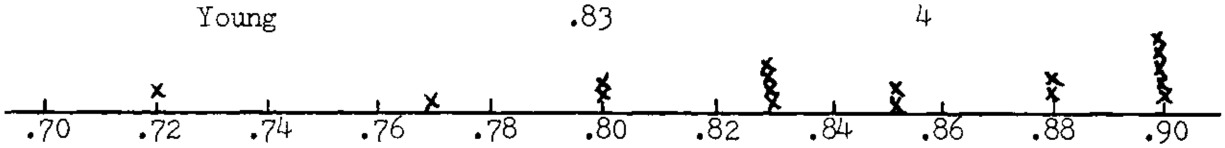
APPENDIX II

Criterion No. 1: General Appearance

Measure of Performance: Survey of Characteristics

(1) Gather data:

Layout	Performance	Score
Bertz	.83	4
Brown	.72	1
Dean	.88	6
Dornbos	.83	4
Elliot	.90	8
Green	.83	4
Kent	.80	3
Moore	.80	3
Ottati	.88	6
Payne	.85	5
Pitman	.85	5
Smith	.90	8
Spence	.90	8
Sturdivant	.90	8
Sweet	.77	2
Williams	.90	8
Young	.83	4



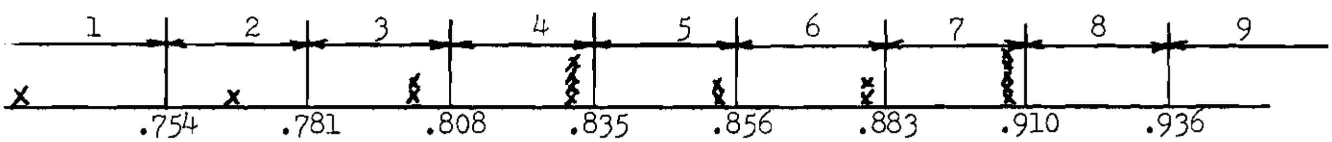
(2) Determine parameters:

Mean = .845; Standard Deviation = 0.052.

(3) Set up initial intervals:

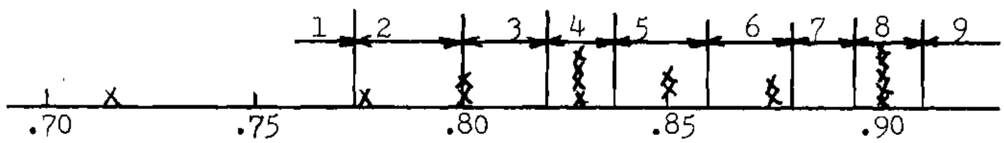
Performance	Value	Score
over m + 1.75 s	over .936	9
m + 1.25 s to m + 1.75 s	.910 to .936	8
m + .75 s to m + 1.25 s	.883 to .909	7
m + .25 s to m + .75 s	.856 to .882	6
m - .25 s to m + .25 s	.835 to .855	5
m - .75 s to m - .25 s	.808 to .834	4
m - 1.25 s to m - .75 s	.781 to .807	3
m - 1.75 s to m - 1.25 s	.754 to .780	2
under m - 1.75 s		1

(h) Assign Scores:



(5) Contract and adjust intervals for final specification:

Value	Score
over .905	9
.895 to .905	8
.884 to .894	7
.863 to .883	6
.842 to .862	5
.821 to .841	4
.800 to .820	3
.769 to .799	2
under .769	1

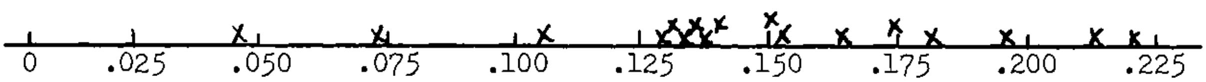


Criterion No. 2: Adequate Aisles

Measure of Performance: Aisle Space Index

(1) Gather data:

Layout	r	q	r/q	Score
Bertz	1220	7956	.153	6
Brown	350	8080	.043	1
Dean	1075	8400	.128	3
Dornbos	888	8160	.109	2
Elliot	1104	8285	.133	4
Green	1674	7515	.223	9
Kent	1052	8192	.128	3
Moore	1103	8400	.131	4
Ottati	1290	8500	.152	5
Payne	1532	8514	.180	8
Pitman	1603	8200	.195	8
Smith	1123	8100	.139	4
Spence	1460	8640	.169	7
Sturdivant	1504	8585	.175	7
Sweet	618	8340	.074	1
Williams	1628	11200	.145	5
Young	1992	9052	.220	9



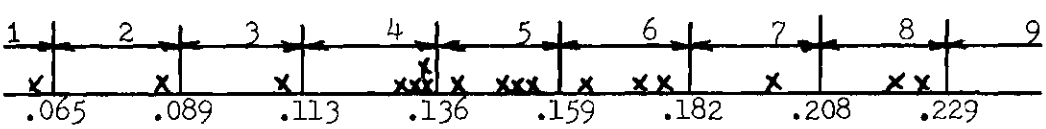
(2) Determine parameters:

Mean - .147; Standard Deviation - .047

(3) Set up initial intervals:

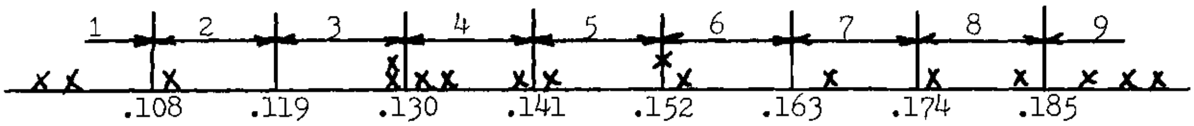
Performance	Value	Score
under m - 1.75 s	under .065	1
m - 1.75 s to m - 1.25 s	.065 to .088	2
m - 1.25 s to m - .75 s	.089 to .112	3
m - .75 s to m - .25 s	.113 to .135	4
m - .25 s to m + .25 s	.136 to .158	5
m + .25 s to m + .75 s	.159 to .181	6
m + .75 s to m + 1.25 s	.182 to .207	7
m + 1.25 s to m + 1.75 s	.208 to .229	8
over m + 1.75 s	over .229	9

(4) Assign scores:



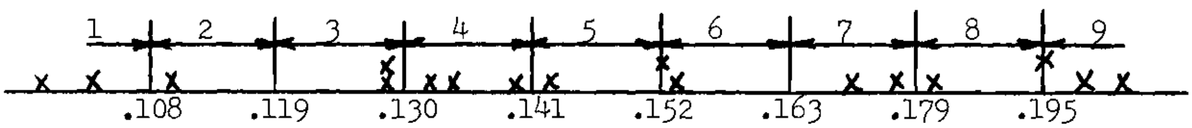
(5) Contract intervals:

Value	Score
over .186	9
.175 to .185	8
.164 to .174	7
.153 to .163	6
.142 to .152	5
.131 to .141	4
.120 to .130	3
.109 to .119	2
under .108	1



(6) Final Specifications:

Value	Score
over .196	9
.180 to .196	8
.164 to .179	7
.153 to .163	6
.142 to .152	5
.131 to .141	4
.120 to .130	3
.109 to .119	2
under .108	1

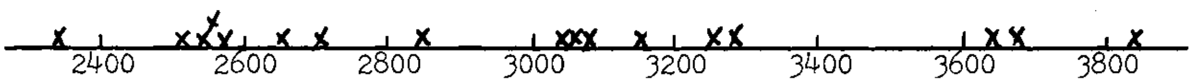


Criterion No. 3: Flow of Materials

Measure of Performance: Travel Chart

(1) Gather data:

Layout	Distance Traveled	Score
Bertz	2451	9
Brown	3116	8
Dean	3225	3
Dornbos	3629	1
Elliot	2635	8
Green	3677	1
Kent	3234	3
Moore	2525	8
Ottati	2523	8
Payne	2366	9
Pitman	2874	6
Smith	3168	3
Spence	2510	8
Sturdivant	3097	4
Sweet	2709	7
Williams	3054	4
Young	3836	1



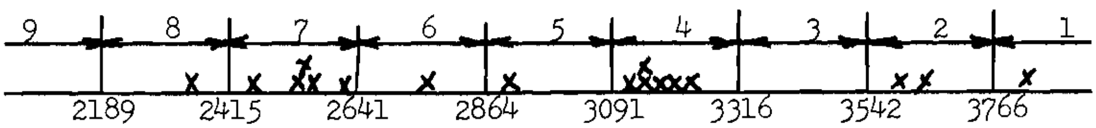
(2) Determine parameters:

Mean = 2978; Standard Deviation = 451

(3) Set up initial intervals:

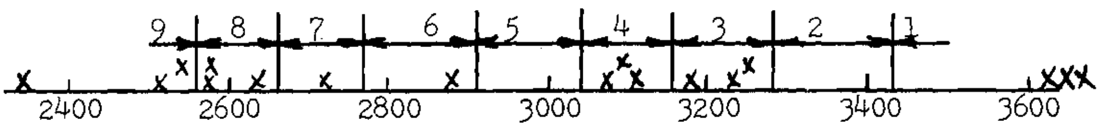
Performance	Value	Score
under m - 1.75 s	under 2189	9
m - 1.75 s to m - 1.25 s	2189 to 2414	8
m - 1.25 s to m - .75 s	2415 to 2640	7
m - .75 s to m - .25 s	2641 to 2865	6
m - .25 s to m + .25 s	2864 to 3090	5
m + .25 s to m + .75 s	3091 to 3315	4
m + .75 s to m + 1.25 s	3316 to 3541	3
m + 1.25 s to m + 1.75 s	3542 to 3766	2
over m + 1.75 s	over 3766	1

(4) Assign Scores:



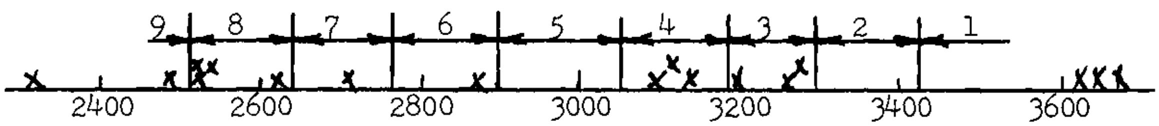
(5) Contract intervals:

Value	Score
under 2527	9
2527 to 2653	8
2654 to 2779	7
2780 to 2905	6
2906 to 3031	5
3032 to 3157	4
3158 to 3283	3
3284 to 3409	2
over 3284	1



(6) Final specification:

Value	Score
under 2501	9
2501 to 2653	8
2654 to 2779	7
2780 to 2905	6
2906 to 3031	5
3032 to 3157	4
3158 to 3283	3
3284 to 3409	2
over 3284	1

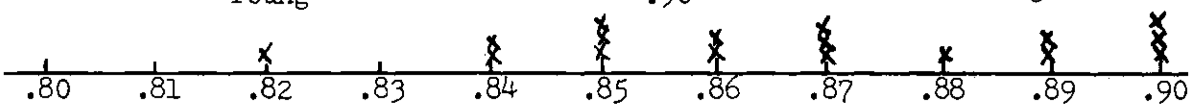


Criterion No. 4: Production Methods

Measure of Performance: Survey of Characteristics

(1) Gather data:

Layout	Performance	Score
Bertz	.86	4
Brown	.88	6
Dean	.90	8
Dornbos	.89	7
Elliot	.87	5
Green	.82	1
Kent	.86	4
Moore	.85	3
Ottati	.87	5
Payne	.84	2
Pitman	.85	3
Smith	.90	8
Spence	.84	2
Sturdivant	.89	7
Sweet	.85	3
Williams	.87	5
Young	.90	8



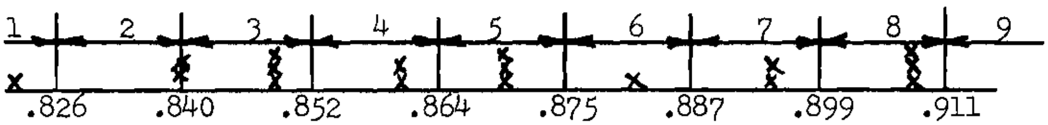
(2) Determine parameters:

Mean = .869; Standard Deviation = .024

(3) Set up initial intervals

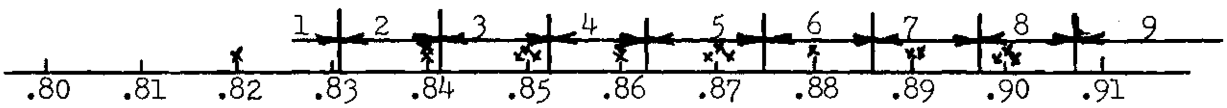
Performance	Value	Score
over m + 1.75 s	over .911	9
m + 1.25 s to m + 1.75 s	.899 to .910	8
m + .75 s to m + 1.25 s	.887 to .898	7
m + .25 s to m + .75 s	.875 to .886	6
m - .25 s to m + .25 s	.864 to .874	5
m - .75 s to m - .25 s	.852 to .863	4
m - 1.25 s to m - .75 s	.840 to .851	3
m - 1.75 s to m - 1.25 s	.826 to .839	2
under m - 1.75 s	under .826	1

(4) Assign scores:



(5) Contract intervals and final specification:

Value	Score
over .908	9
.897 to .908	8
.886 to .896	7
.875 to .885	6
.864 to .874	5
.853 to .863	4
.842 to .852	3
.831 to .841	2
under .831	1

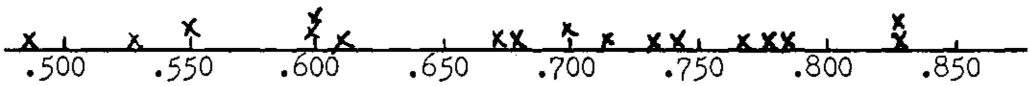


Criterion No. 6: Flexibility

Measure of Performance: Work Station Index

(1) Gather data:

Layout	Work Stations Flexible	Total Work Stations	Ratio	Score
Bertz	40	54	.741	6
Brown	33	60	.550	2
Dean	39	54	.722	6
Dornbos	33	55	.600	3
Elliot	47	63	.746	6
Green	28	53	.528	2
Kent	28	57	.491	1
Moore	40	60	.667	5
Ottati	49	59	.830	9
Payne	38	56	.679	5
Pitman	36	60	.600	3
Smith	45	57	.789	7
Spence	42	60	.700	5
Sturdivant	47	57	.825	9
Sweet	38	62	.613	4
Williams	44	56	.786	7
Young	48	63	.762	7



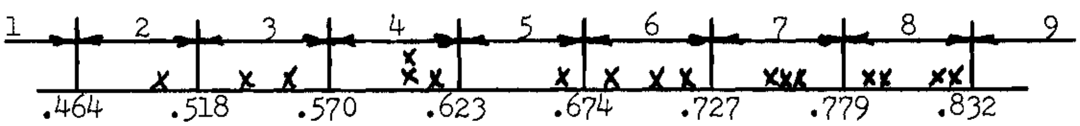
(2) Determine parameters

Mean = .684; Standard Deviation = .105

(3) Set up initial intervals

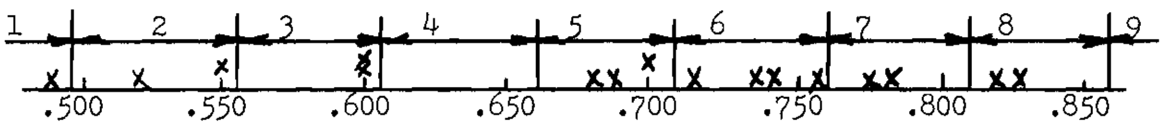
Performance	Value	Score
over m + 1.75 s	over .832	9
m + 1.25 s to m + 1.75 s	.779 to .832	8
m + .75 s to m + 1.25 s	.727 to .778	7
m + .25 s to m + .75 s	.674 to .726	6
m - .25 s to m + .25 s	.623 to .673	5
m - .75 s to m - .25 s	.570 to .622	4
m - 1.25 s to m - .75 s	.518 to .569	3
m - 1.75 s to m - 1.25 s	.464 to .517	2
under m - 1.75 s	under .464	1

(4) Assign scores:



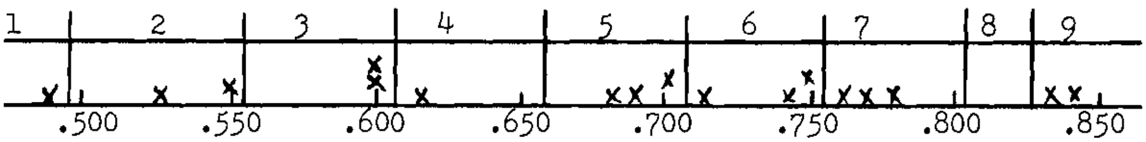
(5) Contract intervals:

Value	Score
over .868	9
.816 to .868	8
.763 to .815	7
.710 to .762	6
.658 to .709	5
.605 to .657	4
.552 to .604	3
.499 to .551	2
under .499	1



(6) Adjust four top intervals for final specification:

Value	Score
over .820	9
.801 to .820	8
.751 to .801	7
.710 to .750	6
.658 to .709	5
.605 to .657	4
.552 to .604	3
.499 to .551	2
under .499	1

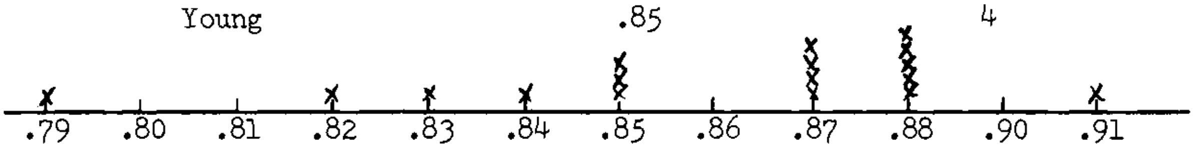


Criterion No. 7: Offices and Services

Measure of Performance: Survey of Characteristics

(1) Gather data

Layout	Performance	Score
Bertz	.88	7
Brown	.84	3
Dean	.83	2
Dornbos	.87	6
Elliot	.91	9
Green	.87	6
Kent	.88	7
Moore	.88	7
Ottati	.79	1
Payne	.88	7
Pitman	.88	7
Smith	.87	6
Spence	.82	1
Sturdivant	.85	4
Sweet	.87	6
Williams	.85	4
Young	.85	4



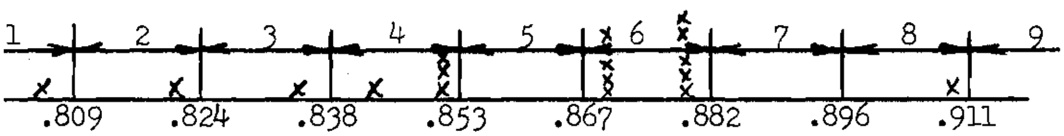
(2) Determine parameters:

Mean - .86; Standard Deviation - .029

(3) Set up initial intervals:

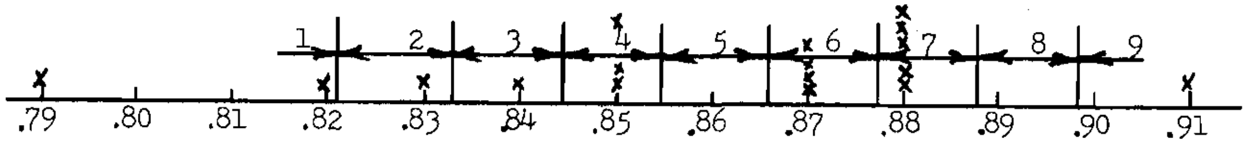
Performance	Value	Score
over m + 1.75 s	over .911	9
m + 1.25 s to m + 1.75 s	.896 to .911	8
m + .75 s to m + 1.25 s	.882 to .895	7
m + .25 s to m + .75 s	.867 to .881	6
m - .25 s to m + .25 s	.853 to .866	5
m - .75 s to m - .25 s	.838 to .852	4
m - 1.25 s to m - .75 s	.824 to .837	3
m - 1.75 s to m - 1.25 s	.809 to .823	2
under m - 1.75 s	under .809	1

(4) Assign scores:



(5) Expand intervals and Final specification:

Performance	Score
over .899	9
.888 to .898	8
.877 to .887	7
.866 to .878	6
.855 to .865	5
.844 to .854	4
.833 to .843	3
.822 to .832	2
under .821	1



NAME Sturdivant

Criterion: Production Methods

Characteristics percent:	0	10	20	30	40	50	60	70	80	90	100
1. General Work Place Layout										✓	
a. Adequate Operator Space										✓	
b. Adequate Material Space										✓	
c. Individual Work Areas Coordinated .										✓	
d. Material Handling indicated, compat										✓	
e. Access for repair and maint.,adjust										✓	
2. Specific											
a. Finishing operations indicated . .									✓		
b. Packaging operations specified . .									✓		

Evaluation

Item	(%) Performance	(%) Weight	Product
1. General work place layout	___	___	___
a. Adequate Operator Space	90	15	.14
b. Adequate material space	90	10	.09
c. Individual work areas coord.	90	30	.27
d. Material Handling indic., compat.	90	20	.18
e. Access for repair and maint., adjust	90	5	.05
2. Specific	___	___	___
a. Finishing operations indicated	80	10	.08
b. Packaging operations specified	80	10	.08
Measure of Performance: .89		100%	.89

NAME Sturdivant

Criterion: General Appearance

Characteristics	percent:	0	10	20	30	40	50	60	70	80	90	100
1. Neatness											✓	
2. Crowdedness											✓	
3. Excess Space											✓	

Evaluation

	(%) Performance	(%) Weight	Product
1. Neatness	90	30	.27
2. Crowdedness	90	50	.45
3. Excess Space	90	20	.18
		100%	.90

Measure of Performance: .90

NAME Sturdivant

Criterion: Offices and Services

Characteristics: percent:	0	10	20	30	40	50	60	70	80	90	100
1. Service areas close to areas served .											
a. Maintenance and tool room										✓	
b. Locker							✓				
c. Food							✓				
d. First aid						✓					
2. Utilities										✓	
3. Adequate fire equipment,sprinkler outside wall										✓	
4. General office appearance											
a. Crowded										✓	
b. Traffic										✓	
c. Aisle									✓		
d. Interrelationship										✓	
e. Cluttered										✓	
5. Entries--front, plant, office to plant									✓		
6. Toliets, locker room										✓	

Evaluation

Item	(%) Performance	(%) Weight	Product
1. Service areas close to areas served			
a. Maintenance	90	7.5	.07
b. Locker	60	7.5	.05
c. Food	60	7.5	.05
d. First aid	50	7.5	.04
2. Utilities	90	10	.09
3. Adequate fire equipment, sprinkler	90	10	.09
4. General office appearance			
a. Crowded	90	5	.05
b. Traffic	90	5	.05
c. Aisle	80	5	.04

Evaluation (continued)

Item	(%) Performance	(%) Weight	Product
d. Interrelationship	90	5	.05
e. Cluttered	90	5	.05
5. Entries--front, plant, offices to plant	80	10	.08
6. Toliets, locker room	90	15	.14
		100%	.85

NAME Sturdivant

TRAVEL CHART — FROM \ TO	1 Rough Cutting	2 Jointer and Circular Saw	3 Disc Sander	4 Drill Press	5 Initial Assembly	6 Prepare for Finish	7 Paint and Dry	8 Final Assembly	9 Packing	10	TOTALS
1 Rough Cutting		22 42									924
2 Jointer and Circular Saw			8 47	5 54	9 62						1204
3 Disc Sander				4 28	5 50						362
4 Drill Press			1 28		8 40						348
5 Initial Assembly						4 16					64
6 Prepare for Finish							4 15				60
7 Paint and Dry								4 28			112
8 Final Assembly									1 23		23
9 Packing											
10											
TOTALS		924	404	382	1128	64	60	112	23		3097 3097

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