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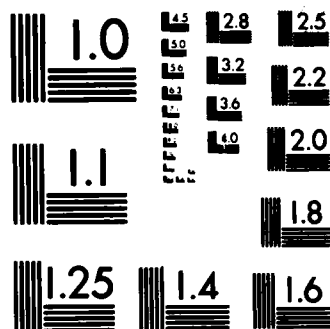
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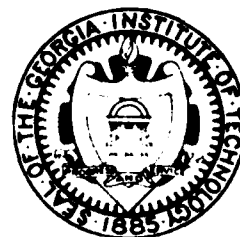


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by

Leon F. McGinnis[†]

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COMPUTER AIDED LAYOUT PROGRAMS:
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ABSTRACT

Widely available facility layout programs are discussed. The program logic, data required, scoring methods and limitations are evaluated for both construction and improvement programs. Implementation technology and other areas of improvement are discussed.

INTRODUCTION

One of the problems commonly addressed by industrial engineers is the physical arrangement, or layout of facilities. Practical guidelines and systematic procedures for layout analysis are one of the fundamental subjects of industrial engineering education. It is widely recognized that layout analysis is probably closer to "art" than to "science" because of the number of complex interrelationships which must be considered.

Beginning about 1960, procedures were described for systematizing some of the steps in the process of layout analysis [13]. Shortly thereafter, computer aided layout programs began to appear in the literature. A synopsis of several of the more widely available procedures is presented by Tompkins and Moore [18]. In spite of the early enthusiasm, computer aided layout does not appear to have had a revolutionary impact on the solution of layout problems.

In order to understand why this is so, it will be necessary to explore in some detail the currently available computer aided layout programs. In particular, concern must be focused on the assumptions, either implicit or explicit, embodied in these programs, and on the implementation methods used in the programs themselves.

Figure 1 presents a categorization of computer aided layout programs. There are two fundamentally different types of layout programs, referred to as improvement programs and construction programs. Improvement programs require the analyst to present, in addition to problem data, an initial layout. The program then attempts to modify the initial layout in such a way as to improve some measure of performance. Construction programs, on the other hand, require only the problem data, and through various algorithms, develop a layout solution.

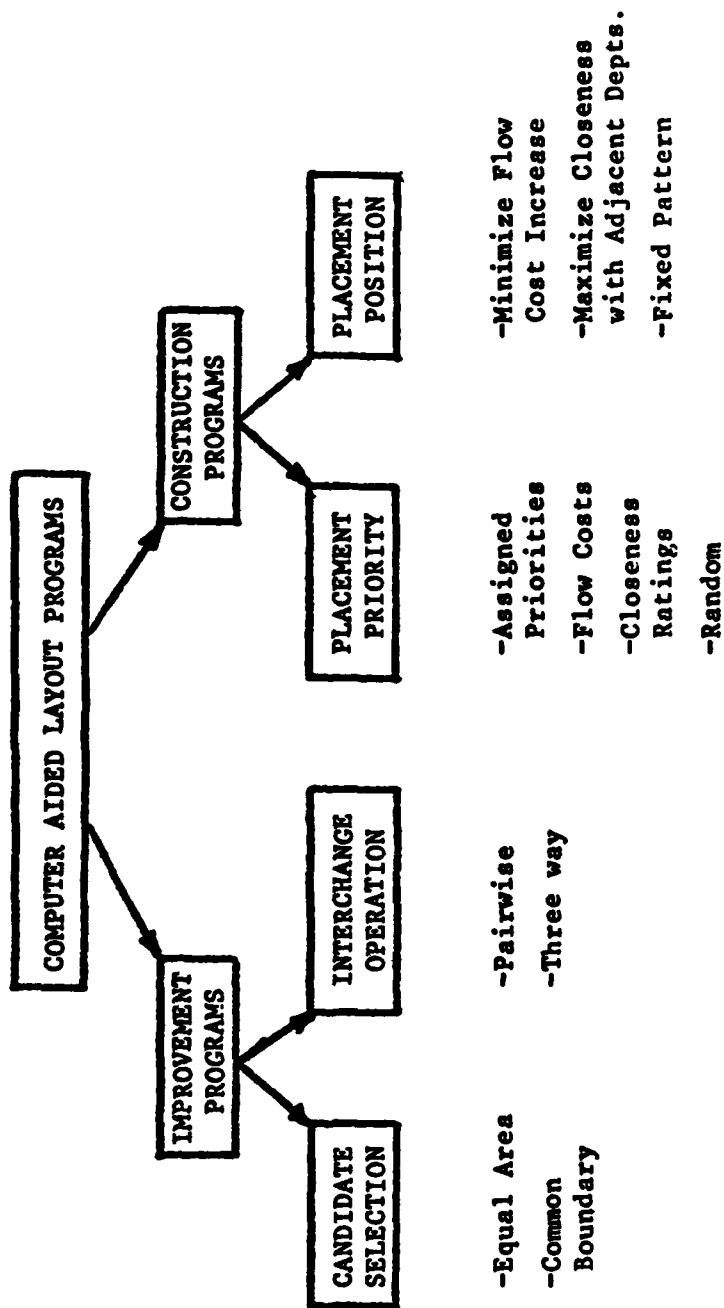


Figure 1. Categorization of Computer Aided Layout Programs

PROBLEM DATA

Computer aided layout programs require certain information describing the layout problem. All procedures discussed below require a listing of the departments to be located and their area requirement. Additional information is required to establish the relationships between departments that will guide the layout design. Two types of relationship data may be required. The first is a REL chart [11], which provides a qualitative description of the importance of having two departments adjacent or close to one another. The second type of relationship information is the FROM-TO chart, which describes, in quantitative terms, the volume of flow between departments. It is also common to include some sort of cost of flow information with the FROM-TO chart.

CONSTRUCTION PROGRAMS

Construction programs, as the name implies, use the problem data to construct a layout. Existing programs utilize a number of algorithms for arriving at a solution, and incorporate a number of different assumptions about the department and facility configurations. As indicated in Figure 1, however, all the construction programs involve two distinct phases, or decisions. These are the order in which departments are added to the layout and the position of the departments when they are added. The following discussion will focus on just three of the many construction programs that have been developed. Hopefully, these three are representative of the many variations on the basic theme.

CORELAP: This is the oldest of the construction programs, having been developed in 1966 by Lee [9], and described in the open literature in 1967 by Lee and Moore [10]. CORELAP uses the REL chart data both for determining

the placement priorities and for determining the placement location for departments entering the layout.

The placement order is determined by first computing the "total closeness rating," or TCR, for each department. This is done by assigning numerical values to the qualitative relationship descriptions (A=6, E=5, I=4, O=3, U=2, X=1), and then summing the resulting "closeness ratings" for each department. The department with the highest TCR is the first one to enter the layout. The order in which departments enter the layout is important, since it is used to determine which department not already in the layout will enter next.

At any point in the process, the "next" department to enter the layout is determined by considering the departments already placed, in the order in which they entered the layout. Each one is considered in turn until one is found which has an A rating with a department which is not currently in the layout. This department, then, is the next one to enter the layout (ties are broken on the basis of largest TCR). If no A rating is found, then the process is repeated, looking for an E rating, and so on, until all departments have been placed.

As departments are entered into the layout, their placement position must be determined. This is done by determining the location which will result in the highest "placing rating." The placing rating is determined by trying each possible position and computing the sum of the weighted closeness ratings (using user-specified weights) with adjacent departments. Ties are broken by choosing the location giving the longest common boundary.

In placing the departments, some variation in the dimensions are allowed, although an essentially rectangular shape is maintained. No constraint on the building configuration is assumed. The evaluation of the resulting layout is

essentially a distance weighted closeness rating. For each pair of departments, the shortest distance between department boundaries is determined, where the distance metric is the unit area (or grid square) used in presenting the layout. Each of these shortest distances is multiplied by the corresponding numerical closeness rating and the sum of the products is the layout's score. Note that the score is obviously a function of the scale chosen for the final layout, so some care is required in any attempt to interpret the score or to compare scores from different layouts.

The particular limitations of CORELAP which should be recognized by its users are [18]:

- building shape cannot be specified
- only REL chart type data can be used in the layout
- flow between departments is assumed to follow the shortest path
- material handling costs are not explicitly considered
- departments cannot be fixed
- limited to 45 departments.

ALDEP: Although ALDEP [17] appeared soon after CORELAP, it is based on a somewhat different philosophy. Whereas CORELAP attempts to duplicate (to some extent) the steps that would be taken by a human layout analyst, ALDEP, on the other hand, attempts to generate a number of layouts on a somewhat random basis, in the hope that at least one of them will be "good." One unique feature of ALDEP is that it can handle up to three floors in the layout.

The first department placed in the layout by ALDEP is chosen at random. Subsequent departments are placed by considering the "last" (most recent department placed in the layout. Among all departments not already in the layout, and having a closeness rating at least as great as the minimum rating

specified by the user, one is chosen at random to enter the layout. If there are none having the required closeness rating, one is selected at random from among all the remaining departments.

ALDEP has a greatly simplified method for determining the placement of the entering department, which allows it to construct many layouts in a relatively short time. In essence, the placement is fixed, a priori. Beginning in the upper left hand corner of the layout, ALDEP "sweeps" the layout in vertical paths, inserting the departments in the order described above. The width of the sweep can be controlled by the analyst, leading to different configurations for the departments.

For each of the layouts generated, ALDEP computes a score, and only those layouts whose score exceeds a user-specified minimum are displayed. The score is the sum of the numerically weighted closeness ratings between adjacent departments where the ratings are: A=64, E=16, I=4, O=1, U=0, and X=-1024.

In contrast to CORELAP, ALDEP allows the building configuration to be specified and also allows departments to be fixed in the layout. The limitations of ALDEP which should be recognized are:

- X relationships may not be honored (although this may lead to having none of the layouts displayed)
- scoring method ignores relationships between non-adjacent departments
- mandatory space configurations not taken into account
- movement costs are not explicitly considered
- limited to 53 departments

PLANET: The PLANET [3], program is more recent in origin, and is more comprehensive in its treatment of the layout problem. The approach is concerned primarily with the costs of flow between departments, and the program allows

several methods for describing this flow. The flow between the departments may be described by means of a parts list, where each of the manufactured items is listed, along with its move frequency and the sequence of departments. Alternatively, a standard FROM-TO chart may be used, or the analyst may use a "penalty" chart, which contains values between -9 and 99, indicating the desirability of locating the departments close to one another.

The first step in the PLANET program is to convert the FROM-TO chart or the parts list or the penalty chart to a "flow-between cost" or FBC chart. This chart gives a per unit distance "cost" for the flow between departments. PLANET uses the FBC chart, along with a user-specified placement priority, to determine the order in which the departments will enter the layout. PLANET has three procedures for determining the order--the one to be used is chosen by the analyst.

Selection method A considers all unplaced departments in the highest selection priority group. The department chosen next is the one which has the highest FBC with an already placed department. Selection method B is very similar, except that the department chosen is the one having the highest sum of FBC for all of the previously placed departments. Selection method C also considers the unplaced departments in order of priority group, placing all from a given priority before going to the next lower priority. Within a priority group, the departments are chosen in order of their total FBC with other departments, regardless of whether or not they are already placed.

Once a department is chosen, PLANET determines its placement in the layout on the basis of minimal material handling costs between the entering department and those already placed. Material handling cost is computed as the product of the rectilinear distance between department centroids and

FBC. Because the centroid of the incoming department cannot be determined without actually placing the department (a time-consuming operation), an approximation to the material handling cost is determined as follows.

Each grid square on the boundary of the already placed departments is considered as a potential location for the incoming department centroid. For each of these potential locations, the material handling cost is computed and the one having the smallest cost is chosen. Now the incoming department is located about the selected grid square. It is not clear how this is done and, in fact, the actual location of the incoming department's centroid could be quite different from the selected potential location, resulting in significantly different costs.

PLANET considers explicitly the material handling costs associated with the layout and displays the computed cost for each flow between departments as well as the total material handling cost. Although it is considered to be the most powerful of the construction procedures, there are some points to be considered when using PLANET:

- all flows are between department centroids
- the direction of flow is not important (the FROM-TO chart is converted to a triangular array by adding the directed flows)
- move costs are linear with the distance of the move
- no control over resulting shape of the layout
- no control over department shapes (departments are "spiralled" around the selected centroid location)
- cannot handle an "X-type" relationship, i.e., closeness undesirable.

A common complaint about the construction programs is that they do not allow the building shape to be specified, except, of course, with ALDEP.

Even with ALDEP, however, the price for having a specified building shape is the arbitrary location of the departments in the layout. The question is, "Why is there no construction program having the capability to accept a specified building outline without also having an arbitrary placement of the departments?"

The answer is that to build in such a capability in the construction framework would be incredibly difficult. This is not an obvious conclusion and requires some explanation. Consider a very simple version of the layout problem. In this simplified problem the relative location of the departments is of no concern, i.e., any layout will be satisfactory. There are exactly n departments to be located, each having a given area requirement. The building is rectangular and its area is equal to the sum of the areas of the departments to be located.

How does one construct a feasible layout? The problem, of course, is trivial if there are no restrictions on how small a dimension is allowed for the departments. Note, however, that as soon as a lower limit on the department dimensions is specified, the problem becomes vastly more difficult to solve. The next step would be to allow the departments to take other than rectangular shapes, which again, makes the problem trivial, in the absence of a criterion based on relative location.

Just to indicate the difficulties that can arise if the departments are initially placed in the layout on the basis of the relative location based criterion, consider the following. The departments enter the layout as in, say, CORELAP or PLANET. As more departments are added to the layout, the "middle" of the layout starts to fill up. Soon, the layout is divided into three parts. The middle part, which contains the departments already placed

in the layout, separates two disjoint areas remaining to be filled. Now, how can one guarantee that these two areas can accommodate the remaining departments without having to split one of them between the two areas? This is not easy to do, and perhaps indicates why such programs have not been developed.

IMPROVEMENT PROGRAMS

The basic idea behind the improvement programs for layout is to use the computer's enormous capacity for rapid calculation to permit examination of many variations of a given, or initial, solution. Essentially, these programs operate by interchanging the locations of two or more departments and checking to see if the change produces a better layout.

A number of improvement programs appeared in the literature, beginning about 1963. A few of the better known of the programs are: CRAFT [2], MAT [4], HC66 [7], TSP [8], and Biased Sampling [14]. It should be pointed out that the majority of these programs address only a special case of the general layout problem, since they assume that all departments have the same area requirement. This special case is also referred to as the quadratic assignment problem, and there is a vast literature dealing with its solution.

The quadratic assignment problem addresses the assignment of departments to specific locations where there are not infeasibilities caused by a mismatch between the department's area requirement and the area available at the location. Because of this very special structure, the solution to the problem may be presented in the form of an assignment matrix, (x_{ij}) , where $x_{ij} = 1$ if and only if department i is assigned to location j . Thus, there will be exactly a single "1" in each row and column of the matrix.

For the quadratic assignment formulation, there is no difficulty in swapping the locations of two or more departments, since this will not lead to any area infeasibilities. In fact, this type of "interchange" or neighborhood search" heuristic is quite intuitive for the quadratic assignment problem (although it has also been suggested for a number of similar difficult combinatorial problems). For an early example, see [5].

For the more general layout problem, however, the straightforward interchange idea will have to be modified to take into account the possible differences in the areas of the departments being interchanged. To our knowledge, only CRAFT incorporates the logic necessary to allow unequal department areas. CRAFT allows interchanges to take place between departments which:

- a) have the same area requirement,
- b) have a common boundary, or
- c) two departments each boarder on a common third department

Both pairwise and three-way interchanges are permitted.

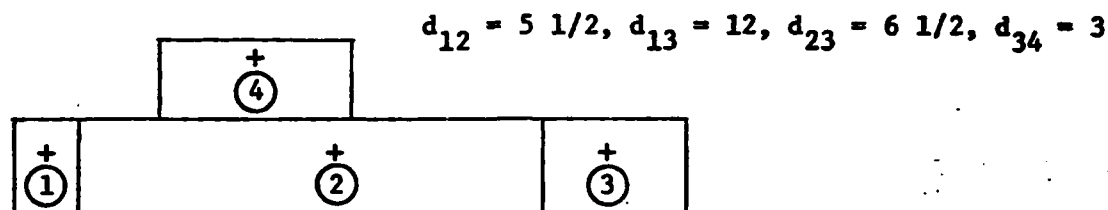
To determine whether or not a particular interchange will improve the layout, CRAFT performs the following evaluation. It is assumed that the centroids of the departments being interchanged will simply swap locations. (Note that especially for unequal sized departments, this could be a crude approximation.) The criterion is the transportation cost of inter-department flows, where flows are assumed to occur between centroids, and distance is rectilinear. If the interchange is evaluated positively, then the swap is carried out and the actual impact on transportation cost is determined.

There is no guarantee that the actual impact on transportation costs will be a decrease, as is illustrated in Figure 2. With the flows as indi-

FROM-TO CHART				
	1	2	3	4
1	-	5	5	0
2		-	10	5
3			-	0
4				-

MOVE COST CHART				
	1	2	3	4
1		1	1	
2			1	1
3				
4				

INITIAL LAYOUT



$$\text{SCORE} = 5(5 \frac{1}{2}) + 5(12) + 10(6 \frac{1}{2}) + 5(3) = 167 \frac{1}{2}$$

INTERCHANGE CENTROIDS FOR 1 AND 3.

THE ESTIMATED SCORE IS:

$$5(6 \frac{1}{2}) + 5(12) + 10(5 \frac{1}{2}) + 5(3) = 167 \frac{1}{2}$$

NEW LAYOUT

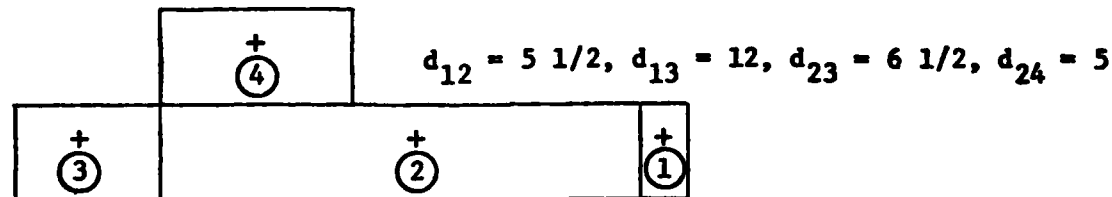


FIGURE 2. CRAFT INTERCHANGE HEURISTIC

cated in the FROM-TO chart, CRAFT would evaluate an interchange of departments 1 and 3 as favorable. In fact, however, such an interchange leads to an increased transportation cost, because it also shifts the centroid of department 2, thus increasing the distance between departments 2 and 4.

Biased Sampling [14] is a variant of CRAFT which attempts to increase the number of solutions generated by "randomizing" some of the decisions made by the CRAFT algorithm. In particular, instead of selecting an interchange which has a positive evaluation, Biased Sampling assigns to it a probability. Among the favorable interchanges that are identified, one is selected at random, with the probability of any interchange being selected assigned as above.

Evaluations of improvement programs have been conducted by Nugent, Vollmann, and Ruml [14], Edwards, Gillett, and Hale [4], Ritzman [15], Hitchings and Cottam [8], and Scriabin and Vergin [16]. Unfortunately, all of these studies dealt with the quadratic assignment formulation, so the results have little bearing on the general layout problem. It can be concluded, however, that CRAFT is competitive with other programs for this special version of the layout problem, and that Biased Sampling is superior to CRAFT, but requires substantially more computing effort.

SCORING LAYOUTS

Table 1 summarizes the layout evaluation procedures used in the layout programs discussed above. Note that the procedures used by CRAFT and PLANET are based on quantitative relationship information, while the procedures used by CORELAP and ALDEP are qualitative in nature. None of these programs is capable of explicitly treating more than one criterion or objective.

TABLE 1. LAYOUT SCORING PROCEDURES

LAYOUT PROGRAM	SCORING PROCEDURE
CRAFT	Based on total transportation costs using FROM-TO trip data, MOVE COST per unit distance (rectilinear) between department centroids.
PLANET	Essentially the same as CRAFT, except that it is called material handling cost. The criterion is used in the placement phase of the algorithm, but no score, <u>per se</u> is reported.
CORELAP	Based on total distance weighted closeness rating using A=6, E=5, I=4, O=3, U=2, X=1, and the number of unit squares on the shortest path between department boundaries. (Note that the score is scale dependent.)
ALDEP	Total closeness rating for adjacent departments using A=64, E=16, I=4, O=1, U=0, and X=-1024.

IMPLEMENTATION CONSIDERATIONS

All of these layout programs produce a block diagram of the layout. In addition, they all have a similar mechanism for representing the block diagram. A matrix is used, for which each cell represents a particular area in the layout, and all cells (or unit areas) have the same dimension. Thus, the layout can be displayed simply by displaying this matrix, where the contents of each cell indicate the department which will occupy the corresponding area in the building.

While this is a very intuitive method for representing the layout, it does create some problems. The first problem arises in converting the department area requirements into equivalent unit areas. If the requirement for a particular department does not equal an integral number of unit areas, then it will have to be rounded, either up or down. The department will therefore occupy either more or less area in the block diagram (proportionally) than it will in the actual layout. The degree of error introduced by

rounding will depend on the scale chosen, the number of dependents, and their sizes.

The second problem with the matrix representation is that it is very wasteful of computer memory. Suppose, for example, that each department is required to have no more than twelve corners in the final solution. Since each corner is common to at least two departments, there are at worst $6n$ corners, or distinct points, in the layout. If each department were described simply by listing the coordinates for its corners, this would require at most $24n$ data elements, or computer memory words. In contrast, CRAFT uses a 30×30 matrix, and CORELAP uses a 39×39 matrix. According to Moore [12], this is typical.

The third, and possibly most difficult, problem caused by the matrix representation is the complex program logic required to manipulate departments having more than one grid square. Not only must all the grid squares for a given department be in contiguous locations, but their configuration must not be too extreme, or the resulting layout will require extensive manual adjustment.

The manipulation of areas and adjustment of configurations seems to be the element of the solution process which is most capably handled by the human analyst. It is interesting (perplexing might be a better description) to note, however, that not one truly interactive layout program has been developed to exploit this observation.

SUMMARY

While a number of computer aided layout programs have been developed, they each have some more or less serious limitations. In general, the shortcomings of layout programs are:

- (1) either can't specify building shape, or get stuck with arbitrary department location algorithm
- (2) there are scale problems caused by the matrix representation of the block diagram layout
- (3) there is no true interaction by the analyst which exploits his visual-spatial capabilities.

What is needed is a new attack on the problem of computer aided layout analysis. Key elements in this new attack would be: a rethinking of the method used to represent the layout in an effort to avoid some of the problems associated with the matrix representation; an attempt to develop construction algorithms which will accept a specified building shape and still allow a "thoughtful" placement of the departments; and finally, the development of truly interactive procedures which exploit the human's natural abilities. In this latter regard, it seems that there are two types of research problems. One has to do with the mechanics of computer graphics, i.e., how will the analyst interact with the computer and specifically, how can block layouts be modified, e.g., with a light pen? The second type of research problem has to do more with how to present the information that the analyst will need in order to decide how to modify the current layout or how to add the next department to the current partial solution.

There is no doubt that worthwhile research remains to be done in the area of computer aided layout. The field has lain dormant now for the past four or five years. Hopefully, the time has come for a new surge of interest and for new advances in computer aided layout programs.

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