A Review of Computer Aided Facilities Layout Packages

by

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(ABSTRACT)

The use of computers as an aide in facilities layout started with some CAFL packages in early 1960s. Over the years, with developments in software, graphics, and interactive operations, a number of computer tools have been created that assist in the design of a layout and the analysis of alternate solutions. Since the application of CAFL to the layout design process could result in improved designs, industrial engineers should be aware of the capabilities and limitations of these techniques.

In this report, significant contributions to the subject of Computer Aided Facilities Layout are reviewed. The problem formulations and solution procedures are discussed. Numerous references are cited in the body of the report as well a bibliography which lists related work not discussed in the report.

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1. Introduction

Facilities layout is the part of facilities planning involved with the arrangement of physical facilities. A facility can be a school, a manned space vehicle, a hospital, a machine tool, an industrial plant, an airport, a computer in a network, a warehouse, an office building, etc. While the general definition of a facility is quite broad, this study is limited to the layout and design of industrial facilities. The general facility design problem can be defined as that of assigning facilities to locations, under some given constraints, with an objective of efficient output of products and economic use of resources. The constraints can be physical like building structure, size and shape of locations, and operational like material flow between the facilities which defines adjacency requirements. Careful thought needs to be given to the location and design of these facilities for better space utilization and optimal material handling, keeping in mind the work flow requirements and the costs involved.

Layout design is an old engineering problem and many solution procedures have been developed over the years. Among the manual procedures, mathematical models, template generation, and graphical techniques have been used extensively. These techniques produce reasonably good results for small sized problems. As the size of problem increases, in terms of number of facilities to be located and various constraints, the time and effort required become uneconomical and act as constraints in generating and evaluating a number of alternate solutions. Additionally, the complexity of the large problems discourages the designer to depart from convention for generating new solutions. These shortcomings can be overcome by the use of Computer Aided Facilities Layout (CAFL) packages, which started in the early 1960s. As Moore, et al [79], indicate, the basic reason why a computer is helpful with the facilities layout problem is that it can perform a multitude of calculations much faster and at far less cost than manual methods.

The objective of this project was to study the concepts and applications of Computer Aided Facilities Layout packages and provide supplementary material for a course in Plant Layout. The research work was divided in three phases. Phase 1 was a study of the concepts of Plant Layout and the computerization of the various phases of layout design. The results of the study are reported here as an overview of the computer applications in layout design process.

Phase 2 was a comprehensive literature review for a limited number of Computer Aided Facilities Layout packages. These packages are reviewed here and an extensive reference list is provided. The final phase was experimentation with four CAFL packages. The solution procedures of these packages were investigated through sample problems. An example is presented here which highlights the applications and differences of the packages.

2. An Overview of Computer Aided Facilities Layout

An approach to solutions for the layout problem is by formulating mathematical models of the design problem with operations research techniques, and supplementing these with computer aids. The layout problem is frequently formulated as a quadratic assignment problem. Layout models have also been developed using simulation, artificial intelligence, and graphic techniques. Computer routines assist in the design of new facilities or the expansion of existing facility. The computer routines generate and evaluate a number of alternative solutions for these problems and select the best solution or give the user a choice for selecting one of the generated layouts. The routines frequently propose creative and unusual solutions which may be totally overlooked by manual methods.

The use of these computer routines make the various phases in the planning, design and management of facilities more productive. Facilities layout is a part of the design and management cycle. The facilities design and management cycle is a continuing loop comprising of various steps. The computer can be utilized to advantage at each of the steps, more heavily at some steps than others. The procedure for solution to the facilities layout problem can be divided into the following steps:

1. Data Preparation
2. Layout Generation
3. Comparison of Alternative Layouts
4. Data Storage

The basic data needed in the **Data Preparation** stage is the size and shape of the plant, the size, shape, and number of facilities, work flow between the facilities, some restrictions on location of facilities, and the objective of the layout design. The details on the available site and the facilities to be located vary between various techniques. The computer algorithms extract relevant information from this data for making facility location decisions.

Layout Generation was the first phase of the design cycle to be computerized. Various computer programs have been developed which generate layouts based on quantitative and qualitative design factors, such as material flow, space utilization, and inter-facility relationships. Based on the logic used to develop the block plan, the computer programs are grouped into two categories: construction algorithms and improvement algorithms.

Most construction algorithms use qualitative data like a Relationship (REL) Chart **(Figure 1)**. A Relationship Chart is a triangular matrix whose elements represent the qualitative relationships among layout facilities. Letter codes are used to indicate desirable or undesirable levels of closeness between facilities, which are then assigned numeric values to measure closeness requirements. The following six standard letter codes are used to express closeness requirements or what are termed as relationships:

	1	2	3	4	5
1	.	A	U	E	O
2		.	X	A	U
3			.	E	I
4				.	X
5					.

Figure 1. Sample REL Chart for a 5 facility layout problem

A absolutely necessary

E especially important

I important

O ordinary

U unimportant

X not desirable

Positive numeric values are assigned to A, E, I, O, and U to measure the closeness requirements and a negative value is assigned to X for establishing the "undesirability" of closely locating the facilities.

Another type of data used is material flow between the departments. From-To Charts are used which give unit flow loads for pairs of departments. This data is used to determine the relative locations of departments.

The construction procedures start from scratch and sequentially place facilities into the layout based on the contribution which each placement alternative would make to some appropriate measure of performance. Following are some of the first generation construction algorithms:

ALDEP Automated Layout Design Program
[13,21,26,29,33,63,68,81,83,99,100,104,112]

CORELAP Computerized Relationship Layout Planning
[21,26,29,33,63,65,66,68,75,80,81,83,104,112]

PLANET Plant Layout Analysis and Evaluation Technique
[1,2,26,29,63,68,75,81,104,112]

Some other construction algorithms available are:

BLOCPLAN-90 [23,24], COMPROPLAN, COMSBUL, CREATE [120], DOMINO, FATE [11], FLAG [57], FLING [8], GENOPT, INLAYT [63,88], KONUVER, LAYADAPT, LAYOUT, MAT[28,63,68], MICROLAY [118], MUSTLAP2, PLAN, RELATE, RMA-COMP I [63,68,83], SHAPE[39,40], SPACE, SISTLAP, SOM I, and SUM I.

The improvement algorithms require a feasible layout as input and use a quantitative measure like material flow cost to improve the layout. The initial layout, which can be a random layout, is scored for the total material handling cost. Alternative layouts are generated by swapping locations of facilities, to select a final layout with minimum material handling cost. Flow charts, also called From-To Charts (**Figure 2**), are used for indicating the material flow or flow costs between facilities. The flow cost between a pair of facilities, assigned to specific locations, is obtained by combining the material flow, the distance travelled, and the related material handling cost between the two.

The number of improvement algorithms developed is about half that of construction algorithms. Popular programs are:

CRAFT Computerized Relative Allocation of Facilities Technique [4,5,14,21,26,29,33,63,68,75,81,83, 87,94,98,104,112]

COFAD Computerized Facilities Design [41,63,68,93,104,105,106,107,109,110,111,112]

		To				
		1	2	3	4	5
	1	0	3	2	10	9
	2		0	5	6	8
FROM	3			0	3	10
	4				0	4
	5					0

Figure 2. Sample From-to Chart for material flow between facilities

Some other improvement heuristics available are: COSFAD [107,108], COFAD-F [101], COL [117], CRAFT-M [44,68], FRAT [59,63], H-63 [45,63,68,87], HC-66 [46,47,63,68,87,94,98], MICRO-CRAFT [49,122], MOCRAFT [102,103], MUGHAL, OFFICE, SET, SPACECRAFT [54,68], and STORM [30].

Some multiple-criteria solution procedures have been developed that combine the quantitative and qualitative approaches to facility layout.

CAFLAS, reported by Malakooti and Tsurushima [70], and a combined approach to the facility design problem developed by Rosenblatt [95] are examples of multi-criteria heuristic solutions.

The multi-criteria solution procedures assign varying weights to all the objective functions and develop a set of layouts, from which the user selects the preferred layout.

The layouts generated by the various techniques are presented to the user for clear understanding through visual displays. Computer graphics are conveniently used to draw the various layouts using predefined templates or presenting block layouts. Block layouts are commonly used in presenting layouts. However, by defining small blocks on the layout grid, the facility shapes can be approximated. Also, some detailed graphics packages, like FLAG [57], are available that have numerous templates for the various elements like machines, aisles, and structural elements, which can be used for making detailed spatial arrangements in the layout generated.

Once the alternative layouts have been generated, the designer needs to evaluate these on the basis of some measuring criteria for selecting the best alternative. The criteria for **Comparison of Alternative Layouts** can be material handling costs or some qualitative measure as sum of the closeness relationships of facilities in the final layout. Another evaluating criteria can be minimizing the difference in objectives in the multiple criteria approaches for facilities layout. The computer is useful here to make quick calculations for various alternatives and presenting results for comparison.

The final stage in the facilities design is the **Storage** of the layouts generated and the relevant data for future use. The layouts can be stored in the computer memory and are easily accessible from there for future modifications or generation of fresh layouts by using the old layouts as initial layouts. The data can be easily retrieved from the computer memory, thus speeding up the design process.

To summarize, it can be seen that computerized layout planning can significantly improve and speed up the search and development phases of layout design. New and provocative designs can be created with computerized algorithms, consequently obtaining significantly better designs than can be obtained by manual methods.

3. Computer Aided Facilities Layout packages

The emergence of the Computer Aided Facilities Layout (CAFL) packages started in the early 1960s with CRAFT and CORELAP. Over the years, with advances in the computer hardware and software technologies, a variety of layout packages have been developed. The new generation of the CAFL packages allow human interaction at various stages of the layout design process and with graphics interfaces, more realistic and presentable layouts are generated.

The following discussion covers four first-generation packages, ALDEP, CRAFT, CORELAP, and PLANET, and a limited number of the more recently developed packages. The other packages described are, BLOCPLAN-90, CAFLAS, COFAD, FLAG, FRAT, HILLIER(63), MAT, MICROLAY, SHAPE, and STORM. For each package, the discussion includes a description of the algorithm used, the input required, the output generated, and an example problem solution to illustrate the algorithm functioning. Apart from detailed descriptions of these packages, some packages using modifications of original algorithms are introduced.

3.1.1 ALDEP

ALDEP, an acronym for Automated Layout DEsign Program, is a construction type layout algorithm developed by Seehof and Evans [100]. The algorithm can be considered as an improvement algorithm also, as it compares and evaluates each layout for accepting or rejecting the solution. It has a series of subroutines, coded in FORTRAN, which aid the designer in the layout design. The programs included are:

1. Automated Inventory Program.
2. Automated Pseudo-Inventory Program.
3. Automated Layout Design Program.
4. Automated Layout-CalComp Program, and
5. Automated Layout Punch Program.

A sequential combination of these programs is used for the layout design. The objective function to be minimized is the total closeness relationships of all facilities.

The algorithm can design up to three story layouts. It allows the designer to assign facilities to specific locations and include utilities like docks, elevators, stairwells, lobbies, aisles, and dummy facilities in the layout design. It generates a pre-specified number of layouts and presents the solutions to the designer for making adjustments and developing the final layout. The layouts are scored by totalling the preference relationships of adjacent facilities. A minimum acceptable score can be specified. The layouts with scores greater than the specified minimum are printed, others are rejected. The solution procedure is described in the following steps.

Step 1. The initial data input is the facility details and the building description. The facility details are input to determine the area in square foots required by each facility. If the facility square footage is known, the Automated Layout Pseudo-Inventory Program is used to prepare an output of facility square footage. The other alternative is to use the Automated Inventory Program with input data on area requirements for equipment and personnel. The equipment area is the summation of all equipment dimensions and access areas. Aisle widths can be included in the dimensions of the equipment. The personnel area is the sum of product of number of personnel and area allocated to each personnel. Using this data, the inventory program calculates the square feet required by each facility.

The layout area is specified in unit squares which determines the number of squares for each facility. A Relationship Chart is inputted, indicating the relationships between all facilities. Additionally, any fixed locations for facilities can be specified, and the facilities can be allocated to different floors. Finally, before starting the calculations, a minimum acceptable score for the total of closeness relationships and the number of layouts desired are specified. The desired closeness is specified as given below.

A - Absolutely necessary

E - Especially important

I - Important

O - Ordinarily close

U - Unimportant

X - Undesirable

For scoring the layout, numeric values are assigned to these relationships.

Step 2. The Automated Layout Design program starts the process of locating the facilities by randomly selecting the first facility to enter the layout. For selecting the next facility, the closeness relationships of the first facility with all other facilities are determined. The facility with the highest relationship is the next to enter the layout. In case of ties and in case no facility is found with a closeness requirement, the next facility is randomly selected and the process repeated till all facilities have been selected. Some dummy facilities can be included to make the layout flexible. Additionally, blocks should be assigned for docks, elevators, lobbies, and stairwells.

Step 3. The program determines the number of unit squares for each facility, using the square footage calculated in Step 1. After selecting the order of entry for all the facilities, the placement routine locates the facilities in the layout. The routine involves placing the unit blocks of each facility in a convoluted sweep pattern. The first block, or group of blocks, is placed in the top left hand corner of the available location. The grouping of the blocks is termed as the sweep width[1], which is the number of blocks that would be placed at a time in the sweep pattern. This continues until all facilities are placed in the layout in the selected order.

Step 4. ALDEP then scores the layout by adding the closeness relationships of all the adjacent pairs of facilities. Then the Automated Layout-CalComp program is used for getting a graphic output of the layout. The program can assign areas for aisles if these have not been included in the facility dimensions. The aisles and docks can be assigned before placing any facility or after the final layout has been generated. The program will not print the layouts which have a score less than an initially input minimal score. The Automated Layout Punch Program is used to select good facility locations from the accepted layouts. These locations can be pre-assigned in subsequent runs of ALDEP.

An example problem solution, given by Tompkins and Moore [112], follows.

Example: The problem was to locate seven facilities in an area of 70,000 sq.ft. The size of the unit square was 400 sq.ft., giving the designer a total of 175 unit squares to locate the seven facilities. **Table 1** gives the specifications of the facility areas and the unit squares required. **Table 2** provides the Relationship Chart, decoded into the numeric values specified for the relationships.

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[1] The sweep width is individually assigned for each floor in multi-story layouts.

Table 1. Facility areas and unit square required

Facility	Area	Number of squares
1	12000	30
2	8000	20
3	6000	15
4	11000	30
5	8000	20
6	12000	30
7	12000	30

Table 2. Decoded Relationship Chart

	1	2	3	4	5	6	7
1	0	16	1	4	1	0	0
2		0	0	16	4	4	0
3			0	0	0	1	0
4				0	4	0	0
5					0	64	4
6						0	16
7							0

The values for the relationships were:

A	64
E	16
I	4
O	1
U	0
X	-1024

All layouts with positive scores were accepted in this example. A sweep width of 2 was assumed for all the facilities. Facility 1 was randomly selected as the first to enter the layout. The relationships of facility 1 were scanned for selecting a high relationship. Facility 2 had the highest relationship with facility 1 and was the next to enter the layout, resulting in the partial layout of **Figure** 3. Following the same procedure, the final order of the facilities to enter the layout was **1-2-4-5-6-3-7**. This placement gave a total relationship score of 242. The relationship values of adjacent facilities and the total layout score are shown in **Table 3**. The minimum acceptable score was zero, so this layout was selected. The final layout is shown in Figure 4.

Table 3. Scoring of ALDEP generated layout

Facilities	Relationship	Value	Total Value
1-2 and 2-1	E	16	32
1-4 and 4-1	I	4	8
2-4 and 4-2	E	16	32
4-5 and 5-4	I	4	8
5-6 and 6-5	A	64	128
6-7 and 7-6	E	16	32
6-3 and 3-6	O	1	2
3-7 and 7-3	U	0	0
		Total	242

```
112222
112222
112222
112222
112222
1111
1111
1111
1111
1111
```

Figure 3. Partial layout

```
112222445566667777
112222445566667777
112222445566667777
112222445566667777
112222445566667777
111144445566337777
111144445566337777
11114444556633377o
1111444455663333oo
1111444455663333oo
```

Figure 4. Final layout

3.1.2 BLOCPLAN-90

BLOCPLAN-90 is a Computer Aided Facilities Layout program which includes construction and improvement algorithms, and a random procedure, for single-story and multi-story facilities layout. Presented by Donaghey and Pire [24] it is an extension of a computer program BLOCPLAN (Block Layout Overview with Computer PLANning) created by Donaghey [23]. Created on an IBM-PC, it can generate layouts consisting of up to 18 facilities. It is a highly interactive program and allows the user to input details through a series of menus. The layouts generated are displayed on the computer screen and can be stored in files for future reference and use.

The basic input requirements are the area of the facilities, a Relationship Chart indicating the closeness desirability of pairs of facilities, and information on material flow between pairs of facilities. The facilities are represented as blocks, scaled to area requirements. The elements of the Relationship Chart are A, E, I, O, U, and X, the same as presented by Muther [84]. The relationships A, E, I, O, U are assigned positive numeric values as a measure of the desired closeness, whereas relationship X is assigned a negative value to express the desired distance between the facilities. This value is termed as the Code Equivalent Score (CES). The program offers the user an option to either enter numeric values for the ratings or use the default values of the program, which are 10, 5, 2, 1, 0, and -10, respectively.

An alternate option for inter-facility relationships is in the form of product flow through the facilities. BLOCPLAN-90 offers the option of putting in detailed product data, with a limit of 14 products. The program uses the data on unit load and sequence of flow through the facilities for each product, to generate a From-To Chart. The user can add some elements to this From-To Chart as entries in the Additions Matrix to express subjective requirements. The resulting Total Flow Matrix is used to develop a REL Chart based on product flow. The CESs for each facility are added to give an Importance Rating (IR) for that facility, which is used by the design algorithm for placing facilities.

The user has the option of using either the initially input REL Chart or the REL Chart based on Product Flow data to create single-story or multi-story layouts.

For a single-story layout, the program offers the options of generating random layouts, layouts using a construction algorithm, a improvement algorithm, or with an automatic search option. Fixed locations can be specified for facilities. The random technique generates layout with random assignments for the available facilities and scores each layout.

The construction algorithm attempts to place all the facilities with high IR scores in the center of the layout and surround these with facilities with which they have high relationships. It also attempts to maximize the distance between facilities with X ratings. The algorithm contains some random properties but produces better results than the random layouts. This random feature results in a different layout for the second run with the same data.

The improvement algorithm accepts one of the saved layouts, generated by any of the methods, as the initial layout and uses an inter-facility exchange technique for improving the layout. The program successively interchanges each pair of facilities and scores the resulting layout. Each layout is displayed and the user has the option of obtaining an analysis of each layout, which gives the detailed information on distances and flows between facilities.

The automatic search option generates good layouts and saves time by using pre-defined methods that an experienced design engineer would use while using this program.

The Layout Score presented is the quotient of sum of the relationships of facilities that share a boundary and divided by the sum of all the positive relationships between facilities. A layout score of 1.0 would indicate that all the relationships indicated in the Relationship Chart have been satisfied.

For the Multi-Story layouts, 2 to 6 stories can be defined. The program gives the user an option of partitioning the facilities between the stories or use the automatic partitioning option. This option only assigns the facilities to different stories. Detailed layout for each story is then developed as a single-story layout.

The program has two measures of effectiveness for a multi-story layout:

1. Area Difference Factor (ADF).
2. Partition Score.

ADF is a measure of the maximum deviation from the optimal story size and is calculated as:

$$\mathrm{ADF} = \mathrm{Max}\ [\mathrm{SMax}-\mathrm{SMean})/\mathrm{SMean}\ ;\ (\mathrm{SMean}-\mathrm{SMin})/\mathrm{SMean}]$$

where,

SMean = Optimum mean area for each story

SMax = Maximum story area for layout

SMin = Minimum story area for layout

The Partition Score is calculated using the REL Chart. The facilities on each floor are assumed to be adjacent, whereas those on different floors are not adjacent. For each floor, the adjacency relationships are added. The totals from each floor are summed up and divided by the sum of all the positive relationships of the REL Chart to give the Partition Score. This measures the degree to which the required facility relationships have been satisfied.

The interactive nature of the program allows the user to customize the layout to requirements.

A worked out example for the BLOCPLAN-90 solution procedure is given in chapter 4 in this report.

3.1.3 CAFLAS

CAFLAS, developed by Malakooti and D'Souza [70], is a Multiple Criteria Decision Making (MCDM) approach which considers qualitative and quantitative aspects of facilities design. It is an interactive program which allows the user to choose between different criteria for layout design or make a paired comparison of alternative plant layouts. A description of the solution procedure and an example problem solution are presented.

Step 1. The solution procedure begins by generating a set of efficient layouts. CAFLAS does not have an optimal method but uses a heuristic approach to select a set of efficient alternative layouts. A set of arbitrary layouts is generated using two construction algorithms, ALDEP and CORELAP, based on some given qualitative criteria judgements. Each alternative layout is input into an improvement algorithm, CRAFT, to generate another set of layouts based on quantitative factors. A union of these two sets is screened to obtain a set of efficient layouts. For each layout of the set, there does not exist any other alternative layout which is equivalent or better in all the five criteria and is strictly better in at least one criterion.

Step 2. A layout is arbitrarily selected as a basis of comparison with the other efficient alternative layouts. For selecting the best layout, the user defines the criteria for comparison. Multiple criteria used are the material handling cost, the production rate, flexibility of layout which measures the ease with which the layout can be modified, and some other operating criteria like safety, and manpower utilization. The utility function to be maximized is a combination of the defined criteria. The utility function is assumed to be quasi concave, i.e. if the value of each criterion is increased, the users utility will also increase. Weights, also called trade offs, are assigned to the criteria to define the relative importance.

For a given comparison between criterion **i** and criterion j, the user can express his/her strength of preference as:

- **A** - criterion **i** is Absolutely more important than criterion j
- **E** - criterion **i** is Essentially (very strongly) more important than criterion j
- **I** - criterion **i** is more Important than criterion j
- **O** - criterion **i** is Ordinarily(weakly) more important than criterion j
- **U** - criterion **i** is equally important to criterion j, or the user is Undecided or feels it Unimportant to express his/her preference.

Step 3. Based on the information provided in Step 2, some layouts are eliminated and a set of candidate layouts, with respect to the basis, are presented to the user. Paired comparisons are made between the selected basis and the candidate layouts.

Step 4. The victor, the best of the compared layouts, is then used as the basis and the user is asked to express his/her strengths of preference for the tradeoffs of all the criteria. Using this data, another set of layouts is eliminated and from the remaining layouts, candidates with respect to the basis are presented to the user. This step is repeated to find the best layout.

By the process of elimination, the procedure reduces the work of the user for making comparisons between the basis and the candidate layouts at each step.

As opposed to the solution procedures that use either the qualitative or the quantitative methods, which consider one criterion to be a sufficient guide to the closeness desirability of facilities, CAFLAS uses criteria of both kinds. By assigning different weights, the user can design a layout satisfying qualitative or quantitative requirements or one with a balanced mix of the two. An example problem solution, given by Malakooti and D'Souza [70], follows.

Example: For a manufacturing plant consisting of 10 different facilities, a layout was to be designed using the following five criteria:

C_1 - Total Materials Handling Cost (to be minimized)

C_2 - Flexibility in the Layout (to be maximized)

C_3 - Production Rate (to be maximized)

C_4 - Safety and Employee Morale (to be maximized)

C_5 - Manpower Utilization (to be minimized)

The values of these criteria were calculated based on the different matrices of material flow, production rates, and preference relationships for flexibility, safety and employee morale, and manpower utilization.

A set of 30 efficient layouts was selected from the layouts generated using some construction and improvement techniques. **Table 4** gives the listings of the efficient layouts. For the first iteration, layout #17 was selected arbitrarily as a basis of comparison. Based on the information provided on the trade offs between criteria, the objective was to:

$$\text{Maximize } U = -(C_1 - 8)^2 - (C_2 - 10)^2 - (C_3 - 20)^2 - (C_4 - 10)^2 - (C_5 - 5)^2$$

Paired comparisons of all five criteria were made between layout 17 and other layouts, utilizing A, E, I, O, and U relationships. **Table 5** presents the responses. Based on this information, the layouts #1, 5, 7, 9, 11, 18, 20, 24, 26, and 29 were eliminated. The set of candidate layouts with respect to #17, were #8, 12, 15, and 25. The user was then asked to make a paired comparison between the four and the basis of comparison #17. Layout #8 was preferred to #17, #12 to #8, #12 to #15 and #25 to #15. #25 was the best choice and the other four were eliminated. Taking #25 as the basis, a new table, **Table 6**, was created to give the strengths of preference for the tradeoffs of the five criteria.

Table 4: The set of efficient alternative layouts

Layout Design #	C1*105 Materials Handling	C2*10 Flexibility	C3 Prod. Rate	C4*10 Safety	C5 Manpower
1	-10.63	4	19.50	2	-17.08
2	-11.77	7	17.32	5	-16.29
3	-10.2	3	18.21	6	-16.82
4	-12.31	6	16.94	7	-15.97
5	-10.54	4	19.33	1	-17.20
6	-10.61	5	18.94	2	-17.12
7	-11.49	3	17.73	5	-16.56
8	-13.06	7	15.30	9	-15.08
9	-10.48	1	18.22	0	-17.29
10	-11.32	6	18.49	5	-16.64
11	-11.83	4	18.53	5	-16.20
12	-12.79	5	17.47	8	-15.27
15	-11.13	6	17.92	4	-16.78
16	-12.42	6	16.97	7	-15.53
17	-10.92	5	19.20	3	-16.31
18	-11.26	7	18.23	5	-16.73
19	-12.77	4	17.39	7	-15.27
20	-10.82	2	18.92	4	-17.03
21	-11.72	7	18.50	5	-16.31
22	-12.32	4	16.62	7	-15.96
23	-10.93	5	19.03	3	-16.91
24	-11.96	4	18.82	5	-16.13
25	-12.73	6	17.29	8	-15.29
26	-11.13	3	17.99	5	-16.79
27	-11.47	5	17.67	5	-16.52
28	-12.30	5	17.00	7	-15.98
29	-10.86	4	19.09	3	-16.99
30	-12.11	6	16.98	7	-16.02

Table 5: Priorities at layout #17

	C_1	C_2	C_3	C_4	C_5
C_1	1				
C_2	E	1			
C_3	E	I	1		
C_4	A	I	O	1	
C_5	U	E	A	A	1

Table 6: Priorities at layout #25

	C_1	C_2	C_3	C_4	C_5
C_1	1				
C_2	E	1			
C_3	A	O	1		
C_4	A	I	O	1	
C_5	U	I	A	A	1

Using this information, layouts #2, 3, 4, 6, 8, 10, 12, 14, 17, 23, 27, 28, and 30 were eliminated. The remaining candidate layouts with respect to layout #25, were layouts #16, 19, 21, and 22. After a paired comparison between the basis #25 and the four candidates, layout #25 was selected as the best candidate. The remaining layout #13 was not better than layout #25, so candidate #25 was selected as the final layout.

3.1.4 COFAD

COFAD [93], COmputerized FAcilities Design, was developed by Tompkins and Reed, as a modification of a popular algorithm, CRAFT, to allow the use of move costs for a variety of material handling equipment alternatives. The COFAD algorithm jointly considers both the layout and the material handling system. The objective is to jointly select a layout and a material handling system that approaches the minimal-cost material handling system.

The inputs required by COFAD are alternative materials handling equipment capable of performing specific moves, the costs of these alternatives, From-To Charts for each equipment alternative, and an initial layout. Various approaches to determine the alternative materials handling equipment are as discussed in Webster [121]. The From-To Charts for alternative material handling equipment are obtained using the material flow data between facilities. To estimate the costs of the alternative material handling equipment types, the equipment types are divided into fixed path and mobile. The fixed-path equipment includes conveyors, overhead cranes, and driverless tractors. All other equipment types are classified as mobile. Finally, a random initial layout is input with information of the number, area, and relative location of facilities. Fixed locations can be specified for facilities. The material movement for each material handling equipment is specified as either Rectilinear or Straight Line.
The solution procedure of COFAD is as given below.

Step 1. The first function of COFAD is to improve the initial layout by a pair-wise exchange of facility locations with the objective of reducing the transportation cost. For the initial layout, COFAD arbitrarily assigns materials handling equipment and sets all move costs equal to unity. It then calculates the initial transportation cost as the product of the entries from the From-To Material Flow Chart and the distance matrix. The distance matrix contains the distances between centroids of facility locations. The algorithm then considers pair-wise and three-way interchanges for facilities that are of equal area or have a common border in an effort to reduce the transportation cost. The search continues and is terminated when no interchanges in the layout can be found that reduce the transportation cost. The final layout of this step is used in the next step.

Step 2. For the layout developed in the first step, COFAD determines the cost of performing each move with the feasible material handling equipment alternatives. The material handling equipment costs are determined separately for the fixed-path equipment and for mobile equipment. For fixed-path equipment, the annual cost for each move is calculated as:

Move cost = {Variable cost ($/ft) * Length of move (ft/yr)}+

Non-variable cost ($/yr)

The variable costs are directly proportional to the distance. The non-variable costs are the investment cost of the drive unit required to power the fixed materials handling equipment type and the operating maintenance costs of the drive unit. For mobile equipment, the annual move costs for each move are calculated as:

Move cost = {Variable cost ($/hr) * Move time (hr/yr)} + {Non-variable cost ($/yr) * Equipment utilization (%)}

The investment cost of a mobile equipment is non-varying and operation cost is directly proportional to the time the equipment is used. The annual travel time for a move is calculated as:

$$T = (T_A + T_V + T_D + T_O)F$$

where,

T = the total annual travel time for a move

T_A = the standard time to accelerate

T_V = the standard time to travel at a constant velocity

T_D = the standard time to decelerate

T_O = the standard time to pass through an obstruction, and

F = the annual frequency of the move

These move times give the total move time for each move per year for each mobile equipment type. These times are then adjusted by the historical effectiveness of each equipment type to give the effective annual move time required to perform each move. The operating cost per unit time for each mobile equipment type is calculated as:

$$C_o = C_f + C_m + C_e + C_l$$

where,

C_o = the total operating costs defined in \$/hr,

C_f = the operating costs of fuel or power,

C_m = the operating cost of maintenance,

C_l = the operating cost of labour, and

C_e = the operating cost of equipment (depreciation) defined as the equipment cost times the hourly depreciation rate.

Step 3. COFAD's next function is to utilize the computed move costs in an effort to determine a minimal-cost material handling system. The material handling system initially selected is determined by selecting the material handling equipment alternative for each move that has the lowest move cost for that move. This follows an attempt to improve the selected material handling system.

The first improvement involves an attempt to increase the utilization of all equipment types. The utilizations for each assigned equipment type are added and rounded up to determine the required quantity of each equipment type. These round off numbers are referred to as the design equipment requirements for each equipment type. The differences between design equipment requirements and the sums of equipment utilizations are calculated and called the 'deviations' for each equipment type. Some assignments of equipment type with largest deviation are transferred to the equipment type having the smallest deviation. This continues till all deviations are minimized. In essence, the procedure exchanges assignments from well utilized equipment to equipment whose utilization is poor.

Another improvement in the material handling system is sought for each move by comparing the move cost determined initially with the allocated cost for the best existing solution. For all moves whose allocated cost is greater than the original move cost, all feasible equipment types are temporarily assigned and the total cost is recalculated. If the total cost is reduced, the temporary assignment is made permanent. This process is continued until the cost cannot be reduced further. At this point, it is concluded that the material handling system cost cannot be reduced and the minimal-cost material handling system is printed.

COFAD then compares the results of last two iterations. If the cost of the materials handling system and the number of changes in the materials handling equipment assignments varies by less than an initially input steady state percentage, no further iterations are performed to improve either the layout or the material handling system.

At this stage either the procedure is terminated or if further improvements are sought, the flow volumes within the From-To Charts are varied by an initially input percentage and the procedure is restarted. This is done to check if the steady-state solution as defined in the last step is in fact a steady-state solution and to check for flexibility of the layout.

An example problem solution, taken from Tompkins and Moore [112], follows.

Example: The layout to be designed had 7 facilities (A, B, C, D, E, F, and G) and a choice of two alternative materials handling equipment types to perform each of the required moves. The total area of the layout was 70,000 ft^2. The initial layout, as shown in **Figure 5**, consists of 20 * 20 ft unit squares of 400 ft^2 each. The layout requires 175 square units and 180 were available. A dummy facility, H, was assigned to 5 unit squares with no material flow with all other facilities. Thus, the layout to be designed was a problem of assigning 8 facilities over 180 unit squares.

The first step was applying an improvement procedure to the initial layout to determine assignment of the facilities in an effort to minimize the transportation cost. The distance matrix and material flow cost matrix for all the facilities were as shown in **Table 7** and **Table 8**, respectively. For this step, the transportation cost was unity for all the unit distances. Pair-wise interchanges between adjacent facilities or facilities with equal areas were tried in an attempt to minimize the total transportation cost. The results of the various iterations are shown in **Table 9**.

Next, COFAD searched for a minimum-cost material handling system by calculating the costs to perform each move. The alternative material handling equipment for this problem were:

```
A A A A A A A A A A G G G G G G G G
A                 A G             G
A A A A A A A A A A G G G         G
B B B B B C C C C C E E G G G G G G
B       B C       C E E E E E E E E
B B B B B D D D D F F F F F F F E E
D D D D D D     D F           F F F
D             D D F F F F F       F
D D D D D D D D H H H H H F F F F F
```

Figure 5. Initial layout

Table 7. Distance Chart for the initial layout

	A	B	C	D	E	F	G	H
A	0	6	5	6	13	16		
B		0		6	11	14		
C			0		7	10		
D		6		0	12			
E					0	3	4	
F		14			3	0	7	
G							0	
H								0

Table 8. Transportation Cost Chart for the initial layout

	A	B	C	D	E	F	G	H	TOTAL
A	.	270	75	150	130	80			705
B		.		180	275	210			665
C			.		35	100			135
D		120		.	420				540
E					.	195	140		335
F		70			75	.	445		600
G							.		
H								.	
									2980

Table 9. Results of various iterations

Iteration	Facility Interchange Selected	Estimated (Actual) Reduction	Resulting Transportation Cost
1	E & F	30(180)	2950
2	C & B	95(119.49)	2833.50
3	No further improvement in the transportation cost.		

1. Electric lift truck.

2. Electric platform truck.

The material handling data that COFAD required for each of these alternatives were the annual investment cost and the operating cost. To select the alternative with minimum material handling cost between all facilities, the move cost between pairs of facilities was compared for the two alternatives. For illustration, the move cost data for facilities A and B was as shown in **Table 10**. The electric lift truck had the lowest annual move cost for all moves between facilities A and B. Further calculations indicated the electric lift truck to be the best for all moves and was selected as the material handling equipment for all moves. The number of electric lifts was then determined by adding the utilizations for all moves. This summed up to a requirement of 1.94 electric lifts. The design equipment requirement for the electric lift truck was therefore two trucks and zero for the electric platform truck. Thus, the deviation for the electric lift truck from required to
actual was 0.06 and for the electric platform truck was 0.00.

Then COFAD tried to alter the materials handling system by reducing the assignments given to the lift truck by assigning some moves to the platform truck. However, this required acquiring a platform truck which would be poorly utilized. Thus this attempt did not result in any improvement of the layout. In the next attempt, COFAD apportioned the cost of unused capacity of the electric lift trucks to each move to get the adjusted costs for each move. These adjusted costs were compared

Table 10. Move-Cost Chart

Alternative	Pair of facilities	Number of trips	Distance	Total cost
Electric lift truck	A-B	45	96	2701
Electric platform truck	A-B	45	96	2821

```
A A A A A A A A A A G G G G G G G G
A                 A G             G
A A A A A A A A A A G G G         G
C C C C B B B B B B F F G G G G G G
C   C C B         B F F F F F F F F
C       B B B B B B F F F F F F   F
C C C C B D D D D E E E E E E F   F
D D D D D D     D E         E F   F
D             D D E E E E E E F   F
D D D D D D D D H H H H H E E F F F
```

Figure 6. Final layout

with the initially calculated annual move costs for the second least expensive equipment alternative for each move. COFAD identified the material handling system with two electric lift trucks as the best alternative at this stage.

The next step was to apportion the costs of the best material handling system established in the previous step. The apportioned cost for the electric lift truck was determined by dividing the annual cost of the electric lift truck by the quotient of the annual total number of moves and the annual total distance travelled. The apportioned cost calculated for the electric lift trucks was $0.002 per trip per foot. This cost was input into the initial improvement routine used for minimizing the transportation cost through the iterative procedure. This resulted in no further improvement and steady-state was reached. The final layout obtained is as shown in **Figure 6**.

Sensitivity analysis was performed by rerunning the model with 90% and 110% of the flow volumes. For this example there was no change noticed in the plant layout or the material handling system with the changed material flow. The program as terminated after these two reruns.

3.1.5 CORELAP

CORELAP, an acronym for COmputerized RElationship LAyout Planning, was the first construction program for the layout problem. The original version of the program was developed by Lee [66]. A modified version (version 9.3) is presented in Tompkins and Moore [112].

The solution procedure is based on a manual method presented by Muther [84]. The algorithm uses a REL (Relationship) Chart to develop schematic diagrams representing a layout. The REL Chart indicates the relationship or closeness desirability between pairs of facilities. The closeness desirabilities are defined as:

A - Absolutely necessary
E - Essentially important
I - Important
O - Ordinarily close
U - Unimportant
X - Undesirable

The ratings are given numeric values. The Total Closeness Rating (TCR) for each facility is determined by adding up the closeness ratings with all the facilities. The TCR of a facility determines the order of entry into the layout. The algorithm attempts to satisfy all the closeness relationships to produce the final layout.

The facility layout is a matrix of two digit numbers. Each number represents a unit block of area for the facility. The area of a unit block is specified, which gives the number of unit blocks for each facility area. The required input data and the CORELAP solution procedure are described in the following steps.

Step 1. The initial input consists of:

- number of facilities in the layout,
- area requirements for each facility,
- any preassigned facilities,
- the REL Chart for relationships among all facilities,
- the numeric values of the relationships A, E, I, O, U, and X, and
- the length-width ratio of the building.

The algorithm can solve problems of the size of up to 45 facilities and 990 inter-facility relationships. The material flow between pairs of facilities is assumed to be the same in either direction, which results in a symmetric REL Chart, i.e. only one half of the square matrix is used for data input in the REL Chart. The user has the option of assigning desired numeric values to the relationships, which indicate the strength of the relationship. The sum of the relationships of one facility with all other facilities gives the Total Closeness Rating (TCR) for that facility. The option of length-width ratio of the building allows the facilities to take irregular shapes.

Step 2. The program reduces the data input in Step 1 to derive reference files. Information derived in these files is used in the algorithm. The set of reference files, as given by Tompkins and Moore [112], is:

1. The total plant area
2. The size of the square building block
3. The size of layout matrix.
4. The number of building blocks/facility.
5. The Total Closeness Rating (TCR) for each facility.
6. The ranked TCRs from maximum to minimum.
7. A reordered relationship matrix for the order in which the facilities enter the layout. It helps in breaking ties when more than one facility have the same TCR and/or area.

The unit square block is input by the user. This variable allows a flexibility in the shape and dimensions of the facility. The area of a facility divided by the unit block size gives the number of blocks.

Step 3. All the unassigned facilities which are eligible for entering the layout are called Candidates. The first facility to enter the layout is the one with the highest TCR. This facility is placed in the center of the layout. Any facility which has been placed in the layout is called a Winner. Then all the candidates are tested for a facility which has an **A** rating with the first Winner. If any found, this is called the Victor and placed in the layout close to the Winner. If there are more than one candidates with an **A** rating with the Winner, the candidate with highest TCR is selected as the Victor. If this still does not break the tie, then any one of these candidates is arbitrarily selected.

For selecting the next Victor, all candidates are tested for an **A** rating with the Winner and then with the Victor. If this relationship is satisfied by any candidate, it becomes a Victor. The facility which has the required rating with the last Victor will become the new Winner. If neither the previous Winner nor any of the Victors have an **A** rating with any of the candidates, then the Winner is tested for an **E** rating with any of the candidates. If none is found, then all the Victors are tested. The process is continued checking for next rating 'I', then 'O', 'U', and finally 'X'.

The new Victor is placed in the layout close to the Winner and any other Victors with which it has a relatively high relationship. Each point around the boundary of the Winner is tested for a placement rating. Placement rating is the sum of the closeness ratings between the entering facility and its new neighbors. The entering facility is located at the point with the highest placement rating. The layout grows in the form of a crystal around every Winner. The process is continued till all the candidates have been placed.

Printouts of the layout can be obtained at each step. The printout of the final layout presents the facility areas as a group of two-digit numbers. The area of the layout not utilized by the facilities is represented as zeros.

An example problem solution, given by Lee and Moore [66] follows.

Example: The plant had 27 facilities, with respective areas and number of unit squares as indicated in **Table 11**. The unit square area assigned for the layout was 100 sq.ft. The facilities were represented as two-digit numbers from 11 to 37. The REL Chart for the relationships among pairs of facilities was as shown in **Table 12**. The values assigned to the relationships were 6, 5, 4, 3, 2, and 1 for **A**, **B**, **C**, **D**, **E** and **X** respectively. The resulting TCRs for all the facilities, in a decreasing order, are given in **Table 13**. The length to width ratio for the example problem was 4:1.

Facility 29 had the highest TCR (81) and qualified to enter the layout first. It was placed in the layout as shown in **Figure 7**. The program then checked the REL Chart for any facility with a rating **A** with facility 29. Facilities 32, 33, and 34 qualified as Candidates.

Facility 34 had the highest TCR (75) among the Candidates and qualified as the Victor. It was placed in the layout as shown in **Figure 8**. Candidate facility 32 was the next to enter followed by facility 33 with an **A** rating with the Winner 29. Next, there was no other **A** relationship for the current Winner facility 29, so the algorithm looked for an **A** relationship among the Victors. Facility 32 had an **A** relationship with facility 19, thus facility 32 became the new Winner with facility 19

Table 11. Facility dimensions

Facility	Area (sq.ft.)	Number of Unit Squares required
11	500	5
12	400	4
13	600	6
14	7000	70
15	600	6
16	400	4
17	500	5
18	400	4
19	500	5
20	300	3
21	400	4
22	1000	10
23	400	4
24	500	5
25	1100	11
26	1100	11
27	600	6
28	300	3
29	1100	11
30	400	4
31	200	2
32	400	4
33	200	2
34	1800	18
35	1200	12
36	1200	12
37	7000	70

Table 12. RELationship Chart

	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
11		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	I	E	U	U	U	I	A	A
12			A	A	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	E	U	U	U	U	U	U	U
13				A	U	U	U	U	U	U	U	U	U	U	U	I	I	U	U	E	U	U	U	U	U	U	U
14					E	U	U	U	U	U	U	U	U	A	U	U	U	E	U	U	U	U	U	U	U	U	U
15						A	U	A	I	U	U	U	I	U	X	U	U	A	I	U	U	I	U	U	U	U	U
16							I	I	U	I	O	U	O	U	X	U	U	U	U	U	U	U	U	U	O	U	U
17								A	O	O	U	O	U	U	X	U	U	X	U	U	U	U	U	U	U	U	U
18									I	O	U	O	U	U	X	U	U	E	O	U	U	O	U	U	U	U	U
19										U	U	U	U	U	X	U	U	X	E	I	U	A	A	E	I	O	O
20											U	U	U	U	X	U	U	X	U	U	U	U	U	U	U	U	U
21												U	U	U	U	U	O	U	O	O	U	O	O	O	O	O	O
22													I	U	X	U	U	U	U	U	U	U	U	U	U	U	U
23														U	U	U	I	U	U	U	U	U	U	O	U	U	U
24															U	U	U	U	U	U	U	U	U	U	U	U	U
25																U	I	X	X	X	U	X	X	X	X	X	X
26																	U	U	U	U	U	U	U	U	U	U	U
27																		U	U	U	U	U	U	U	U	U	U
28																			I	O	U	I	U	U	U	U	U
29																				I	E	A	A	A	O	O	O
30																					O	O	O	E	O	A	E
31																						U	U	O	O	A	E
32																							E	E	O	U	U
33																								A	U	O	O
34																									U	I	I
35																										A	E
36																											A
37																											

REL Codes

Code	Closeness
A	Absolutely Necessary
E	Especially Important
I	Important
O	Ordinary
U	Unimportant
X	Undesirable

Table 13. Ranked Total Closeness Rating (TCR) for facilities

Facility	TCR	Facility	TCR
29	81	31	66
16	64	30	79
36	77	12	63
34	75	21	62
19	75	28	61
15	74	23	60
37	74	17	59
32	73	27	59
14	70	24	56
18	70	22	55
33	70	26	54
35	69	20	54
11	67	25	38
13	67		

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	29	29	29	29	0	0
0	0	29	29	29	29	0	0
0	0	0	29	29	29	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Figure 7. Center location for first facility

0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	29	29	29	29	34	34	34	34	34	0	0
0	0	29	29	29	29	34	34	34	34	34	0	0
0	0	0	29	29	29	34	34	34	34	0	0	0
0	0	0	0	0	0	34	34	34	34	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 8. Partial layout with two facilities

and the Victor to enter the layout next. **Figure 9** gives the layout till 5 facilities had entered the layout. The process continued to obtain the final layout as shown in **Figure 10**. The unoccupied unit squares are represented as zeros.

The layout generated by CORELAP had an irregular shape and could be used as a starting point for the building design of a plant. Modifications to this layout would have to be made to include areas for stairs, aisles, washing rooms, and other utilities.

0	0	0	0	19	19	19	0	0	0	0	0	0
0	0	0	0	19	19	0	0	0	0	0	0	0
0	0	0	0	32	32	33	0	0	0	0	0	0
0	0	0	0	32	32	33	0	0	0	0	0	0
0	0	29	29	29	29	34	34	34	34	34	0	0
0	0	29	29	29	29	34	34	34	34	34	0	0
0	0	0	29	29	29	34	34	34	34	0	0	0
0	0	0	0	0	0	34	34	34	34	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 9. Partial layout with five facilities

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	25	25	25	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	25	25	25	26	26	26	26	26	26	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	25	25	19	19	19	26	26	14	14	14	14	14	14	14	14	14	14	0	0	0	0
0	0	0	25	25	19	19	27	27	26	26	14	14	14	14	14	14	14	14	14	0	0	0	0
0	0	21	21	0	32	32	33	27	27	24	24	14	14	14	14	14	14	14	14	0	0	0	0
0	0	21	21	0	32	32	33	27	27	24	24	24	14	14	14	14	14	14	14	0	0	0	0
0	37	37	29	29	29	29	34	34	34	34	34	30	30	14	14	14	14	14	14	0	0	0	0
0	37	37	29	29	29	29	34	34	34	34	34	30	30	14	14	14	14	14	14	0	0	0	0
0	37	37	37	29	29	29	34	34	34	34	36	36	36	13	13	14	14	14	14	0	0	0	0
0	37	37	37	37	31	31	34	34	34	34	36	36	13	13	12	14	14	14	14	0	0	0	0
0	37	37	37	37	37	37	37	37	37	37	36	36	13	13	14	14	14	14	14	0	0	0	0
0	37	37	37	37	37	37	37	37	37	37	36	36	35	35	35	14	14	14	14	0	0	0	0
0	37	37	37	37	37	37	37	37	37	37	36	36	36	35	14	14	14	14	14	23	22	22	0
0	37	37	37	37	37	37	37	37	37	37	11	11	35	35	14	14	18	23	23	23	22	22	0
0	37	37	37	37	37	37	37	37	37	37	11	11	35	35	15	15	18	17	17	22	22	0	0
0	37	37	37	37	37	37	37	37	37	11	0	35	35	35	35	15	18	18	17	22	22	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	28	28	15	15	15	16	17	17	22	22	0
0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0	16	16	16	20	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	0	0	0

Figure 10. Final layout

3.1.6 CRAFT

CRAFT, developed by Armour and Buffa [14] in 1964, is recognized as the first computerized improvement algorithm for facilities layout. CRAFT, an acronym for Computerized Relative Allocation of Facilities Technique, develops the layout with the objective of minimizing the material handling cost between all the facilities. The algorithm is programmed in FORTRAN and can design layouts with up to 40 facilities.

The algorithm takes as input a From-To Chart for the material flow load between facilities, a Move-Cost Chart indicating the cost per unit distance of handling a unit load between the facilities, and an initial layout. The product of entries in the From-To Chart and those in the Move-Cost Chart give a transportation cost matrix indicating the total cost of material handling between pairs of facilities. The Move-Cost input is unity, assuming the distance travelled to be a sufficient measure of the transportation cost. The initial layout can be the existing layout of the plant which is to be improved, or a random initial layout can be input which gives the relative location of facilities. The layout represents the facilities as blocks, which result in irregular shapes.

Dummy facilities are added to the layout to fill in the irregularities and get a rectangular configuration for the building. Using the transportation cost values and the Distance Chart, the total material handling cost is calculated for the initial layout. In an attempt to reduce the total material handling cost, possible exchanges between facility locations are tested for making the exchange that results in maximum reduction in the material handling cost. Five types of interchanges of facility locations can be tested:

1. Pair-wise interchanges,
2. Three-way interchanges,
3. Pair-wise followed by three-way interchanges,
4. Three-way followed by pair-wise interchanges, and
5. The best of pair-wise or three-way interchanges.

The interchanges are carried on until the material handling cost cannot be reduced by an interchange of facility locations. The resulting layout is the final layout.

The following steps and an example problem solution explain the CRAFT technique.

Step 1. The CRAFT solution procedure starts by calculating the centroids of the various facilities in the initial layout. The program then calculates the rectilinear distances between the facility centroids and stores these in the distance matrix. The material handling costs between pairs of facilities in the initial layout are calculated using the From-To Chart, the Move-Cost Chart, and the Distance Chart. The program then determines the total material handling cost for the initial layout.

Step 2. Pair-wise or three-way interchanges are tested for possible reduction in the material handling cost with the resulting layout. Only adjacent or equal area facilities are candidates for interchanges. Testing for a profitable interchange, the program interchanges the centroids of the candidate facilities and calculates the total material handling cost for the resultant layout. All candidates are tested for such profitable interchanges.

Step 3. The program makes the most profitable exchange calculated in Step 2 and generates the revised layout. The distances between all the facility centroids are recalculated. The product of elements of the new distance Chart and the From-To Chart, give the material handling cost for the revised layout. The process of Steps 2 and 3 is repeated until there can be no further reduction in the material handling cost. The resulting layout with the least material handling cost is presented to the designer as the final layout.

An example problem from Tompkins and Moore [112] follows.

Example: The problem was to layout seven facilities requiring a total area of 70,000 sq.ft. The facility areas were divided in unit squares of 400 sq.ft. each. The total number of squares required was 175. To get a symmetrical shape a dummy facility of 5 unit squares was added to the initial layout, resulting in 180 square units. The From-To Chart for the inter-facility material flow and the distance Chart for the initial layout were as shown in **Table 14** and **Table 15**, respectively. The move-cost was assumed unity,

Table 14. **Material Flow Chart**

	A	B	C	D	E	F	G	H
A	0	45	15	25	10	5	0	0
B		0		30	25	15	0	0
C			0		5	10	0	0
D		20		0	35	0	0	0
E					0	65	35	0
F		5			25	0	65	0
G								0
H								0

Table 15. **Distance Chart for the initial layout**

	A	B	C	D	E	F	G	H
A	0	6	5	6	13	16		
B		0		6	11	14		
C			0		7	10		
D		6		0	12			
E					0	3	4	
F		14			3	0	7	
G							0	
H								0

Table 16. **Transportation Cost Chart for the initial layout**

	A	B	C	D	E	F	G	H	TOTAL
A		270	75	150	130	80			705
B				180	275	210			665
C					35	100			135
D		120			420				540
E						195	140		335
F		70			75		455		600
G									
H									
							Total		2980

resulting in the transportation cost matrix of **Table 16**. The initial layout was as shown in **Figure 11**.

The total transportation cost for this layout was calculated to be 2980. The program then tested for pair-wise interchanges of facilities for possible reduction in the material handling cost. In the first iteration, the exchange of facilities E and F resulted in the maximum reduction of 180. Facilities E and F were exchanged to get the new layout as shown in **Figure 12**. The fresh Distance Chart and the Material Handling Cost Matrix were as shown in **Table 17** and **Table 18**, respectively. The program again checked for profitable exchanges, resulting in an exchange of location for facilities B and C. No further profitable exchanges were found. The final layout, obtained after the second iteration, is as shown in **Figure 13**.

```
A A A A A A A A A A G G G G G G G G
A                 A G             G
A A A A A A A A A A G G G         G
B B B B B C C C C C E E G G G G G G
B       B C       C E E E E E E E E
B B B B B D D D D F F F F F F F E E
D D D D D D     D F           F F F
D             D D F F F F F       F
D D D D D D D D H H H H H F F F F F
```

Figure 11. Initial layout

```
A A A A A A A A A A G G G G G G G G
A                 A G             G
A A A A A A A A A A G G G         G
B B B B B C C C C C F F G G G G G G
B       B C       C F F F F F F F F
B       B C C C C C F F F F F F   F
B B B B B D D D D E E E E E E F   F
D D D D D D     D E         E F   F
D             D D E E E E E E F   F
D D D D D D D D H H H H H E E F F F
```

Figure 12. Intermediate layout after exchange of facilities E and F

```
A A A A A A A A A A G G G G G G G G
A                 A G             G
A A A A A A A A A A G G G         G
C C C B B B B B B B F F G G G G G G
C   C C B         B F F F F F F F F
C     C B B B B B B F F F F F F   F
C C C C B D D D D E E E E E E F   F
D D D D D D     D E         E F   F
D             D D E E E E E E F   F
D D D D D D D D H H H H H E E F F F
```

Figure 13. Final Layout

Table 17. Distance Chart for intermediate layout

	A	B	C	D	E	F	G	H
A	0	6	5	6	16	13		
B		0		6	14	11		
C			0		10	7		
D		6		0	9			
E					0	3	7	
F		11			3	0	4	
G							0	
H								0

Table 18. Transportation Cost Chart for intermediate layout

	A	B	C	D	E	F	G	H	Total
A	0	270	75	150	160	65			720
B		0		180	350	165			695
C			0		50	70			120
D		120		0	315				435
E					0	195	245		440
F		55			75	0	260		390
G							0		
H								0	

3.1.7 FLAG

FLAG (Facility Layout Algorithm using Graphics), developed by Ketcham and Malstorm [57], is a set of computer assisted facility layout programs. The programs use a construction algorithm and require specific design skills for generating layouts. The extensive human-computer interface allows the user to adjust the design at each step to reflect qualitative criteria, not intrinsic to the algorithm. FLAG utilizes computer graphics to develop details, resulting in a more realistic and usable output, as compared to block layouts generated by other programs.

FLAG contains four sets of programs and four subroutine libraries. The design routine starts with developing individual facility layouts, develops facilities layout, and prints a detailed final layout. The four subroutine libraries utilized by FLAG are:

1. **IGL** - Interactive Graphics Library (IGL), is a set of PLOT 10 graphics subroutines used by the computer to generate printouts.
2. **TEMPS** - This is a series of subroutines that draw templates of machines, workbenches, pallets, and other facility fixtures. This library also contains a directory of templates.
3. **UTIL/A and UTIL/B** - They are libraries of general purpose FORTRAN subroutines that perform various tasks required in the design process.

A description of the design process follows.

Step 1. The design process starts with data input. FLOWS is the program which takes the data and creates a series of data files for use by subsequent FLAG routines. The data required is:

- name of the plant
- number and names of facilities
- number and names of separate product lines and items to be manufactured at the facility
- label or number for each distinct part that flows through the facility. The parts leaving from each facility are labeled
- list of the flow paths and the quantities of each part that comprise or are contained in each end product
- the quantity of product per unit load for each part flow path
- a move cost per foot for each part flow path.

These data are used to develop From-To Charts giving part flow data between facilities which are used to develop complete Move-Cost Tables.

Step 2. The next stage is of developing detailed facility layout. The user begins the process with WORKOUT. The program starts by asking the user the number of facilities and then works through the main program loop for each facility individually. For each facility, the program requires the number of elements, which can be machines, carts, tool racks, workbenches, pallets, and any facility fixtures to be laid out.

For developing layout of individual facilities, the program uses libraries of machine templates and templates of general geometric shapes that the user can utilize and label as required. The user develops the layout by placing the selected templates in desired locations and orientations. Once the various elements have been placed, WORKOUT draws an initial border around the facility. This border can be adjusted by the user. The last step of the WORKOUT phase is to specify the Point of Entry (POE) and Point of Departure (POD) of products along the facility border.

Step 3. In this step, the user locates the facilities in the desired locations by interacting with LAYOUT, the third FLAG program. The user is asked to specify the aisle width, or the default aisle width is used. The program then presents the user with a hypothetical plant wall.

The first two facilities to be located are Shipping and Receiving. They are placed along the wall of the plant to allow easy access to docks. A prioritized Move Cost Table is generated for all relationships of the Shipping and/or Receiving facilities with all facilities yet to be placed. Using this data, the program next places the facility with greatest move cost per foot. The POE or POD of the facility are located to minimize the move costs. The user can override the LAYOUT choice of order of placement and location of facilities. The user can experiment with alternate location of facilities and can measure the change in total move-cost.

This process is continued until all facilities have been placed and approved by the user. The final task of LAYOUT is to place the interior walls. The initial borders are automatically determined by the extreme facilities. The user can make adjustments in the exterior wall, like creating a notch from unoccupied corners. This allows the flexibility of having irregularly shaped and asymmetrical facilities.

Step 4. The last step is to generate printouts. The fourth FLAG program OUTPUT is used to obtain complete layouts, machine layout, or facility templates.

The layout generated by FLAG can be accepted as the solution, or it can be improved by stepping through the LAYOUT procedure again.

An example problem solution given by Ketcham and Malstorm [57] follows.

Example: The solution started with product information. Using the product flow data and move-cost/foot between the three facilities and Receiving and Shipping facilities a Move Cost Table was generated by the FLOW program, as shown in **Table 19**.

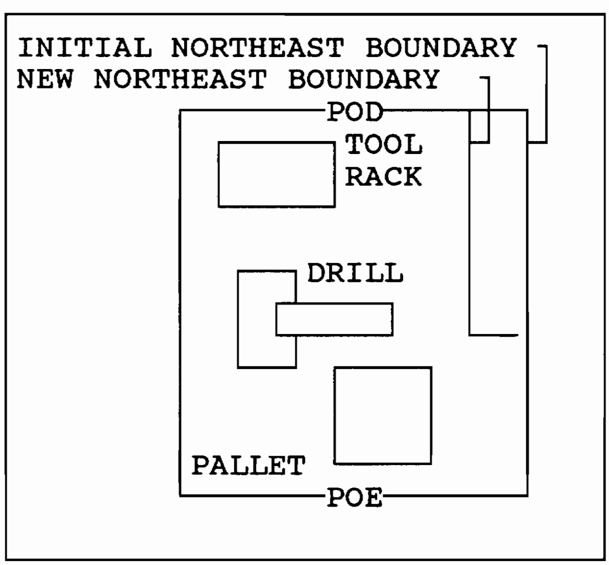
The next step was to create the facility layouts. The WORKOUT program looped through the main program for each facility. For the purpose of this example, it was assumed that the program was in its third iteration and was awaiting input for data on facility **2**. The first question asked of the user was the number of elements in the facility. WORKOUT then entered a secondary loop to place the elements

Table 19. Move-cost/foot

	Receiving	W/C 1	W/C 2	W/C 3	Shipping
Receiving	0	594	450	624	0
W/C 1	0	0	495	42	0
W/C 2	0	0	0	335	0
W/C 3	0	0	0	266	0
Shipping	0	0	0	0	0

Table 20. First iteration move-cost priority table

Departing	Entering	Move Cost Per Foot
W/C 3	Shipping	2660
Receiving	W/C 3	624
Receiving	W/C 1	594
Receiving	W/C 2	450



POD - Point of departure
POE - Point of entry

Figure 14. Final layout for facility 2

in the facility, using the subroutine libraries of templates. The various elements of the facility were placed by the user and the final shape of the facility developed, as shown in **Figure 14**.

Once all the facility shapes had been developed, the LAYOUT program started locating the facilities in the layout. The Receiving and Shipping facilities were placed along the wall of the plant to allow access for transportation. Then the next facility for placement was the one with highest priority in the move-cost priority table, or as required by the user. Facility 3 was the next to enter. **Figure 15** gives the initial placement of facility 3. For experimenting, the facility was moved and LAYOUT calculated the trade-off. The trade-off indicated a reduced material a handling cost, resulting in the final placement of facility 3 as shown in **Figure 16**. The LAYOUT program continued in this manner until all facilities had been placed and approved by the user.

Finally, LAYOUT placed the exterior walls. **Figure 17** gives the resulting final layout.

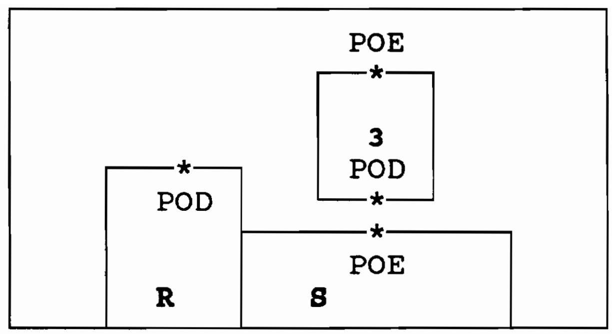


Figure 15. Initial placement of facility 3

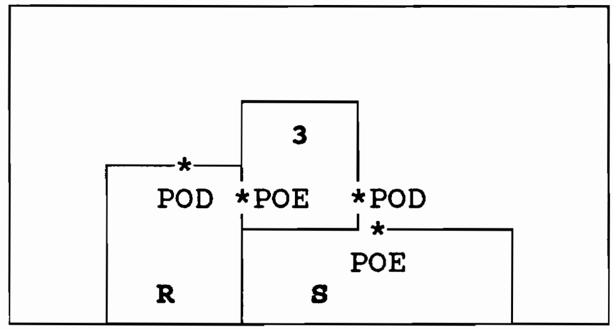


Figure 16. Adjusted placement of facility 2

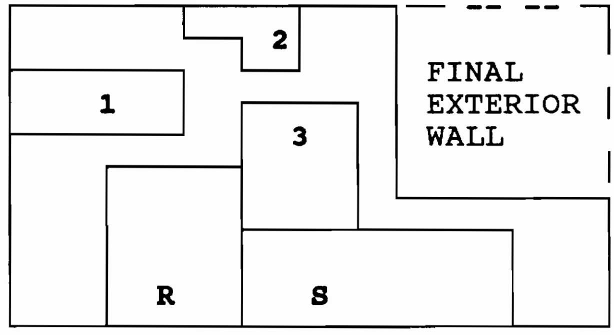


Figure 17. Final layout

3.1.8 FRAT

Facilities Relative Allocation Technique (FRAT), developed by Khalil [59], is a heuristic improvement procedure. Programmed in FORTRAN IV on an IBM 360, it is a combination of techniques suggested in models by Hillier and Connor [47], Vollmann, *et al.* [117], Armour and Buffa [14], and other well-known heuristics.

As data input, the algorithm takes number of facilities, the flow matrix and an initial layout. It generates block layouts and solves problems involving equal area facilities. The algorithm can handle both orthogonal and euclidean patterns of flow. The solution procedure is as described below.

Step 1. Given **n** facilities, the difference, **A**, of the longest and shortest distance between pairs of facilities is computed. This distance depends on the flow pattern in the plant.

Step 2. For each facility (**i**, **i** = 1, 2, 3, ..., **n**), the total cost, P_i of all possible trips of length greater than or equal to **A** is calculated. This is computed as,

$$P_i = \sum_{k \in l'} f_{ik} d_{ik}$$

where,

f_{ik} = The cost weighted flow between facilities i & k,

d_{ik} = distance between facilities i & k, and

l' is the sub-set with distance · A

Distance is taken as a measure of material handling cost.

Step 3. **M** and **N** are designated as the facilities with highest and second highest P_i values, respectively.

Step 4. Each facility location is exchanged with the location of **M** and the total flow costs are computed to make the exchange with maximum saving in the total flow cost. The step is repeated till no more saving is possible.

Step 5. Step 4 is repeated for facility **N**.

Step 6. The identity **A** is reduced by an amount **(L)** equal to the shortest distance between the centers of two facilities. The new value **A'(A'= A - L)** is used for further computations.

Step 7. Steps 2 to 6 are repeated till $A' < L$.

Step 8. Pair-wise interchanges of facilities **i** and **j** are tested for making profitable exchanges. This is repeated until $i = n-1$, $(i = 1, 2, , n-1)$ and $j = n$, $(j = 1, 2, , n)$ and no further improvement is possible. An example problem solution given by Khalil [57] follows.

Example: The problem was to locate five facilities **(1, 2, 3, 4, and 5)**, with locations in the initial layout as shown in **Figure 18**. The distance between pairs of facilities for the initial layout was as shown in **Table 21**. **Table 22** gives the material flow between pairs of

Table 21. Distance Chart

	1	2	3	4	5
1	0	5	8	10	12
2		0	3	12	8
3			0	10	5
4				0	4
5					0

Table 22. From-To Chart for material flow

	1	2	3	4	5
1	0	25	10	5	8
2		0	15	10	20
3			0	30	25
4				0	50
5					0

1	2
3	4
5	

Figure 18. Initial layout

facilities as a From-To Chart. Both charts were symmetrical about the diagonal assuming equal material flow load and distance between pairs of facilities.

From **Table 22**,

$$\mathbf{A} = 12 - 3 = 9$$

Facilities **1** and **3** had the highest(**M**) and second highest(**N**) move costs for trips of a length more than or equal to 9(**A**).

Next, checking for savings by pair-wise interchange between facility **1** and all other facilities, no savings were found. Facility **1** retained its old location. The same procedure was applied for facility 3. Switching the locations of facilities **2** and **3**, yielded the maximum saving in the cost. Facilities **2** and **3** interchanged locations. No further profitable exchanges with facility **3** were found. The value of **A** was revised, as,

$$\mathbf{A} = 9 - 3 = 6$$

Facilities 2 and **5** then had the highest and second highest material flow costs, respectively. Pair-wise interchanges between facility **2** and all other facilities were tested for any improvement. The total flow cost did not reduce. Then the process was repeated for facility **5**. No further reduction in cost was found.

The process continued till the value for **A** was less than L, the shortest distance between the locations of two facilities. This completed the first phase of the improvement procedure. From here on, pair-wise interchanges between all facilities were tested for further improvements. The program stopped when no further improvement was possible. The final layout obtained was as shown in **Figure 19**.

The FRAT algorithm is claimed to give better results as compared with CRAFT, for problems with up to 30 facilities. The computation time is also less than that required by CRAFT for the same problems.

1	3
2	5
4	

Figure 19. Final layout

3.1.9 HILLIER(63)

HILLIER(63) is an improvement algorithm developed by Hillier [45]. A layout is improved by a pair-wise interchange of facilities with the objective of minimizing the total materials handling cost between the facilities.

The material handling cost is calculated as the product of the distance between the facility locations and the material flow per unit time. Distance measure is assumed to be a good measure of the material handling cost. In case of increased material handling cost, effected by use of special equipment, it is reflected in the calculations by increasing the distance units between the related facilities. The stepwise solution procedure is as follows.

Step 1. As input, the algorithm requires a random layout, the distances between the centers of the proposed locations, and the material flow per unit time between the various facilities. The layout matrix consists of equal square areas. It is assumed that each facility will approximately fit into the allocated area.

Step 2. A Move Desirability Table is created which measures the effect on the objective function of moving a facility left, right, front, or back. For this, each facility is superimposed on an adjacent facility and the effect on the material handling cost is calculated. Positive values would indicate a desirability of relocating that facility in the related location. The facility with the highest move desirability is selected for relocation. It is superimposed onto the adjacent facility in the proposed direction of move to check a reduction in the material handling cost. If the cost is reduced, the facilities are interchanged, if not, the facility with the next highest move desirability is similarly tested for a profitable interchange.

Step 3. After two facilities are interchanged, a fresh Move Desirability Table is generated. The facility locations are tested again for profitable interchanges. This step is repeated till there cannot be any further improvement in the objective function.

Step 4. This step involves diagonal exchanges of the facility locations. From the last Move Desirability Table of Step 3, the facility with the highest move desirability is tested for profitable diagonal exchange. After the exchange, a fresh table is created and the process repeated till no further improvement in the objective function is possible.

Step 5. For attaining a still better solution, a Two-Step Move Desirability Table is computed and used for selecting a profitable interchange of locations two steps apart. This process is continued by incrementing the number of steps by one till the Maximum-Step Move Desirability Table for the given problem has been tested for possible improvement.

The final layout thus created can be tested for efficiency. This can be done by developing lower bounds for the acceptable values of the objective function. The efficiency of the final solution is computed by comparing the value of the objective function of final solution with the lower bound. If an unsatisfactory layout has been developed, different initial solutions are used to develop alternative layouts with differences in efficiency, to obtain a better layout.

Some modifications to the original procedure are suggested by Hillier and Connors [47]. One modification is to start the procedure by a Maximum-Step Move Desirability Table and proceed sequentially to One-Step Move Desirability Table, and then repeat this cycle as necessary. Second, the only interchanges that are allowed during the first cycle of the one-step moves, are those that decrease the objective function by at least a pre-specified amount; thereafter any profitable interchange is permitted. The third change is for decreasing computer storage requirement. This establishes a constraint on a facility of exchanging locations only with a facility that is on a horizontal, vertical, or diagonal line through the first center.

The following worked out example problem solution, given by Hillier [45], further explains the solution procedure.

Example: The layout problem was to assign 12 facilities, designated as 1, 2, . . . ,12, which had to be located in a large rectangular area. The material flow between the facilities was as shown in **Table 23**. The table was symmetrical about the diagonal indicating an equal material flow between pairs of facilities in either direction. The area was divided into twelve equal sized blocks to serve as locations and it was assumed that each block was large enough to locate any of the 12

Table 23. Material Flow Chart

		TO											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	1	0	5	2	4	1	0	0	6	2	1	1	1
	2		0	3	0	2	2	2	0	4	5	0	0
	3			0	0	0	0	0	5	5	2	2	2
	4				0	5	2	2	10	0	0	5	5
	5					0	10	0	0	0	5	1	1
FROM	**6**						0	5	1	1	5	4	0
	7							0	10	5	2	3	3
	8								0	0	0	5	10
	9									0	0	10	10
	10										0	5	0
	11											0	2
	12												0

facilities. The distance measure for material flow was the distance between the centroids of a pair of adjacent blocks. It was also assumed there were no subjective requirements to assign any facility to a particular location.

The objective function was to minimize

$$S = 1\backslash 2 \sum_{i,j=1}^{12} c_{ij} d_{ij}$$

where,

c_{ij} = material flow per unit time between facilities i and j, and

d_{ij} = distance between facilities i and j

The process started with a random trial solution, as indicated in Figure 20. The Move Desirability Table for the beginning trial solution was as shown in Table 24. This calculation established the desire of each facility to be moved in the given directions. For example, facility 8 was superimposed on facility 7 on its left, to check on the change in S. By moving it one block to its left, the travel loads between facility 8 and facilities 1, 3, 4, 6, 7, and 11 were reduced by 6, 5, 10, 1, 10, and 5, respectively. This reduced the objective function S by 37. Similarly, changes in the travel loads for all facilities were calculated by superimposing on adjacent facilities to the left, right, up, and down.

4	9	11	10
6	12	7	8
3	1	2	5

Figure 20. Initial Layout

Table 24. Move Desirability Table for the initial layout

Work center	Left	Right	Up	Down
1	-11	5	7	
2	5	-9	3	
3	21	11		
4		29		23
5	15		19	
6		26	-6	-6
7	-2	-8	-8	-28
8	37		-7	-15
9	-25	1		17
10	15			15
11	10	-16		-2
12	-10	-12	10	-16

In the Move Desirability Table for the first trial solution, the maximum saving in **S** could be obtained by moving facility **8** one block to the left, which was the location for facility **7**. By moving facility **8** to its left, **S** decreased by 27 and increased by 18 by moving facility **7** to its right. The net effect was a decrease of **9**. The savings of ten loads between work centers **8** and **7** that were included in the separate calculations, were not included here. Thus, the exchange was made to give the second trial solution.

The procedure for the succeeding trial solutions was the same as that for the first one. After the sixth trial solution, no further improvement was found. This was followed by diagonal interchanges and Move Desirability Tables were used to make profitable exchanges. After trial solution 9, there were no more profitable interchanges possible.

The value of **S** was reduced from 416, for the first trial solution, to 297 for the final solution. **Table 25** presents the successive changes in S, starting with the initial solution and resulting in the final layout of **Figure** 21.

9	7	11	6
12	8	4	5
3	1	2	10

Figure 21. Final layout

Table 25. Changes in the value of objective function S

Exchange	Facility initiating exchange	Other facility	Decrease in value of S
1	8	7	9
2	4	9	4
3	6	12	28
4	6	8	29
5	7	6	28
6	4	7	10
7	10	6	1
8	5	10	10

3.1.10 MAT

Modular Allocation Technique (MAT), presented by Edwards, Gillet, and Hale [28], is a construction algorithm approximating the optimal allocation of facilities to locations. For this, it uses distances between locations and flow of material between facilities as measuring elements. A facility is defined here, as a separate activity of a layout having work relationships with each of the other activities of the same layout. The MAT algorithm can solve problems with up to 40 facilities.

The input required is the number of facilities, the location matrix indicating distances between facility locations, and the load matrix for the material transported between pairs of facilities. The locations are identified as points and the program does not consider area of locations or the layout area.

Using the input data, the program enumerates various possible assignments and selects the assignment with minimum travel distance. It begins with assigning fixed locations for facilities, as required. Next, pairs of locations are listed in non-decreasing order of distances and pairs of facilities in decreasing order of loads to be transported. Successively, pairs of facilities and pairs of locations are selected for allocation, considering the available locations, unassigned facilities and feasibility of allocation. The procedure is continued to get the entire one-to-one assignment.

An improvement of the MAT assignment can be achieved by an interchanging routine. The fixed locations defined earlier are maintained and adjacent facilities are interchanged to check for an improvement. The facilities retain new locations if there is improvement or are returned to their original locations if there is no improvement. If there are **n** facilities, then after the **n***th* and **(n-1)***st* facilities are interchanged, the **n***th* facility, determined by the results of the interchanging, is assigned permanently in the location assignment array. The technique is then repeated for the **(n-1)** remaining facilities to assign the **(n-1)***st* location number in the location assignment array. The interchanging continues until all **n** facilities are permanently assigned. This interchange routine can accomplish an improvement of the MAT assignment only.

The distances between locations can be defined in two ways, one as established by user and secondly in terms of X-Y Cartesian Coordinates of the centers of the locations, which simulates aisle travel in an industrial situation. The second method, shown in **Figure 22**, can also be used tospecify distances in multi-story layouts. Each group could represent locations on a single story, and any number of groupings can be used with maximum number of total locations being 40.

The layout generated by MAT can be used as input to an improvement algorithm, like CRAFT, to significantly reduce solution times, as compared to a random initial layout.

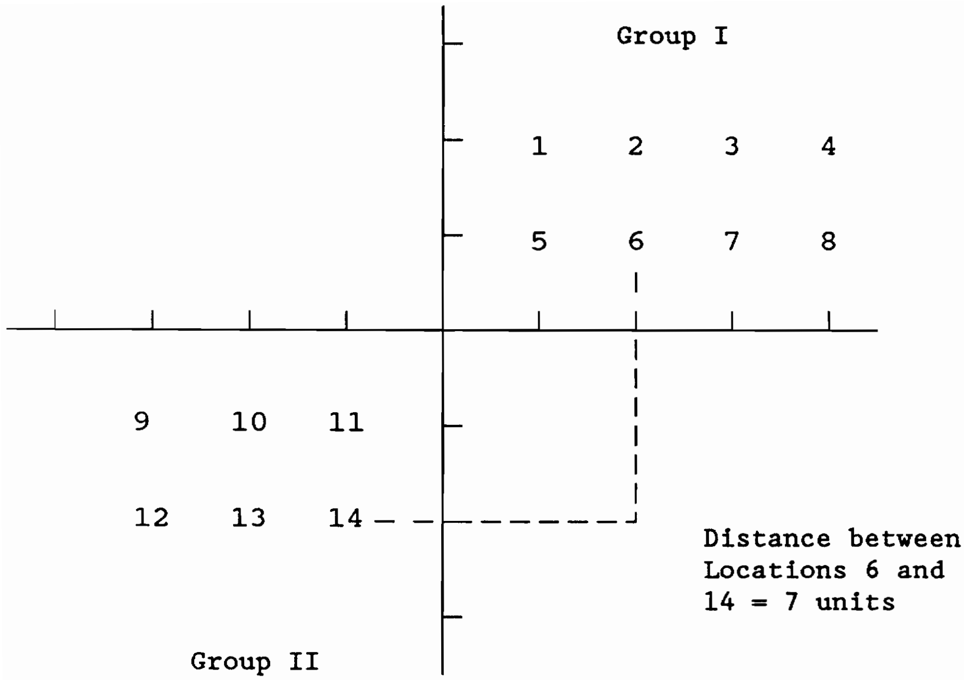


Figure 22. Method of specifying distance between locations

The following example given by Edwards, Gillet, and Hales [28], illustrates the solution procedure.

Example:

Number of facilities(**A**, **B**, **C**, **D**, **E**, **F**, & **G**)	7
Number of locations (**1**, **2**, **3**, **4**, **5**, **6**, & **7**)	7

If any facilities were to be assigned to specific locations, it was done at this stage. In the example problem, no facilities were assigned to fixed locations. The material flow between facilities was as shown in the loads matrix in **Table 26** and the distances between the locations are given in **Table 27**. The matrices were symmetrical about the diagonal indicating that the material flow and the distance travelled was the same in either direction between facilities.

Then, the flow loads between facilities were set in a decreasing order and distances between locations in an increasing order, as shown in **Table 28** and **Table 29**, respectively.

The two facilities, in the first pair **A-G**, had to be assigned to the first pair of locations, **2-3**. For this, the list was scanned for the first repetition of any one of the two facilities. Facility **A** was found repeated with facility **F**. Similarly, scanning for location, **3** was found repeated with **1**. The selections for assignment were:

Table 26. Load Matrix

	A	B	C	D	E	F	G
A	0	15	25	10	30	32	45
B		0	35	12	25	40	15
C			0	8	14	15	25
D				0	5	30	15
E					0	29	15
F						0	20
G							0

Table 27. Distance Chart

	1	2	3	4	5	6	7
1	0	15	8	25	6	10	12
2		0	5	15	10	8	9
3			0	18	35	15	8
4				0	10	20	15
5					0	25	6
6						0	15
7							0

Table 28. Material flow between facilities

Facilities	Loads
A-G	45
B-F	40
B-C	35
A-F	32
A-E	30
D-F	30
A-C	25
B-E	25
C-G	25
E-F	20
F-G	20
A-B	15
B-G	15
C-F	15
D-G	15
E-G	15
C-E	14
B-D	12
A-D	10
C-D	8
D-E	5

Table 29. Distance Chart between locations

Locations	Distance
2-3	5
1-5	6
5-7	6
1-3	8
2-6	8
3-7	8
2-7	9
1-6	10
2-5	10
4-5	10
1-7	12
1-2	15
2-4	15
3-6	15
4-7	15
6-7	15
3-4	18
4-6	20
1-4	25
5-6	25
3-5	35

Facilities	Locations
A-G	2-3
A-F	1-3

To satisfy both relationships, **A** was assigned to **3**, **F** to 1, and **G** to 2.

The remaining pairs of facilities were examined to find the first pair in which only one facility was assigned, or no facility was assigned. In case no pair was found with one facility assigned and there were more than a pair of facilities available, then the first pair of unassigned facilities was selected and the same procedure as adopted for assigning the first set of facilities is used. If there were only a pair of unassigned facilities, the two facilities would be assigned arbitrarily to the remaining

locations to retain the assignment with minimum total distance travelled.

Here, **B-F** was the next pair selected, with **F** assigned. Then, from the Distance Chart, the first pair of locations with one location assigned and the other available was **1-5**, with **1** allocated. Facility **B** was assigned to location **5**.

Since more facilities were to be assigned, the process was repeated. The next pair of facilities selected were **B-C** and the pair of locations were **5-7**. Facility **C** was assigned to location **7**. Continuing the process, the next pair of facilities were **A-E** and of locations were **2-6**.

Facility **E** was assigned to location **6**. The remaining facility **D**, was assigned to the available location **4**. In case there were two locations available, the choice would have been for the location which gave minimum total distance travelled.

Thus, the final one-to-one assignment, with total distance travelled, is shown in **Table 30**.

Table 30. Final location of facilities

Facility	Location
A	3
B	5
C	7
D	4
E	6
F	1
G	2

Total Distance Travelled = 5236 units

3.1.11 MICROLAY

MICROLAY, developed by Wascher and Chamoni [118], is an interactive computer program for factory layout planning on microcomputers. The program integrates construction and improvement algorithms as tools for supporting the planner in generating satisfactory layouts. It is designed for planning problems requiring process layouts due to a variety of products and low production volumes. The program is highly interactive, allowing the user to define absolute and relative restrictions in the layout, and to interchange locations of facilities at each stage of the design process.

All the phases of the layout process are supported by a graphic system. The graphic system, using a high-resolution monitor, allows creating and editing geometric shapes for facilities. It provides options for drawing facility shapes consisting of straight lines or circles, and duplicating, enlarging, reducing, deleting, shifting, and turning around facilities, to generate layouts.

As initial input data, the program requires dimensions of the location space, geometry of facilities, a Relationship Chart for the strength of contacts between the facilities, and absolute and relative restrictions for locating facilities. The data input can be from the keyboard or from a file, with options for correcting the input.

The initial layout construction algorithm applies a heuristic known as "circulation method". The objective function to be minimized is the sum of products of the strength of contact and distance between various facilities. The solution procedure is explained in the following steps.

Step 1. The algorithm starts with partitioning the layout space into a grid of equal sized squares. The user can choose the size of the grid squares, depending on how detailed a solution is required. For computing, each object is placed in the smallest possible rectangle it can fit into. This saves computing time and retains the shape of the facility. On the monitor, however, only the original geometry is presented.

Step 2. The first facility is randomly selected and placed in the center of the layout.

Step 3. From the set of remaining facilities, another facility is selected based on either of two rules. According to the first rule, the next facility to enter the layout is the one with minimum total strength of contacts with the remaining facilities. The second rule allows random selection of the next facility. The latter rule provides a tool to the planner to construct a variety of different solutions.

Step 4. All possible locations adjacent to the facilities already placed are determined to calculate the rectilinear distances between the possible locations and located facilities.

Step 5. Out of the possible locations, the selected facility is placed in that location which gives the minimum sum of products of strength of contact, between this facility and the facilities in the layout, and the rectilinear distance between the assigned locations and the available locations.

Steps 3-5 are repeated till either all the facilities are placed or no locations are available for the selected facility.

If no feasible layout can be created by the construction algorithm, the incomplete layout is presented to the user for manually adjusting and locating the remaining facilities.

In the layout generated, there is some unclaimed location space between the located facilities. This space can be used for traffic zones, which are not designed by MICROLAY.

The construction algorithm described is termed as an 'automatic' procedure. One of the other two options for generating an initial layout is 'manual' construction by the user. The user can locate all the facilities by placing the cursor in the desired location on the monitor screen. The last option is a combination of 'manual' and 'automatic' procedures. The user can specify location of some facilities for satisfying the absolute restrictions and subjective requirements. Then, the automatic construction program is called to locate the remaining facilities.

MICROLAY also offers an improvement algorithm to achieve suboptimal solutions for manually constructed layouts or modifications of automatically constructed layouts. As input it requires an initial layout, and strength of contacts between facilities. The improvement solution procedure involves the following steps:

Step 1. The rectilinear distances between the location centers are determined.

Step 2. A set of pairs of facilities is determined which would lead to an improvement of the objective value, if their locations were interchanged. Only such pairs are considered for exchange of their locations which would not lead to infeasible solutions. The facilities to be considered for exchange, may be unequal in size and not adjacent. To speed up calculations, it is assumed that the centers of the locations will not be affected by the interchange.

Step 3. The first pair of facilities to be exchanged is the one which improves the objective function. The user may accept the exchange or either have another pair suggested by the computer or specify one himself. Before interchanging, the program checks whether there is enough room for the larger of the two facilities at the proposed location. If not, the facilities surrounding this very location are moved grid-wise horizontally and/or vertically until the facility to be interchanged fits into it. Due to the assumption in Step 2 about the center locations, the interchange may lead to a poor or infeasible solution. For such a case, the program has the option to return to the previous layout.

Hard copies of the layouts can be obtained at all stages of the layout generation process. The layouts generated and the data files can also be stored in a file.

An example given by Wascher and Chamoni [118] is given below.

Example: The problem was to locate 11 facilities. **Table 31** gives the frequency of travel between pairs of facilities. **Figure 23** gives the shape of the facilities. The automatic construction algorithm located the facilities as shown in **Figure 24**. This layout was modified to make good use of the location space and allow room for transportation equipment. The layout was further modified t define the service areas in the facility where the transport equipment could not enter. The final layout obtained was as shown in **Figure 25**.

Table 31. Frequency of travel between facilities

	1	2	3	4	5	6	7	8	9	10	11
1		40			25			45		60	
2				50	15		60				35
3	40	80				75			30		
4	35				35		70			20	
5		15	30			45		60			
6				90	30			45			25
7	70		90					55			
8						30	45			85	
9		65					25				
10	45		35			25					70
11		65		65				60			

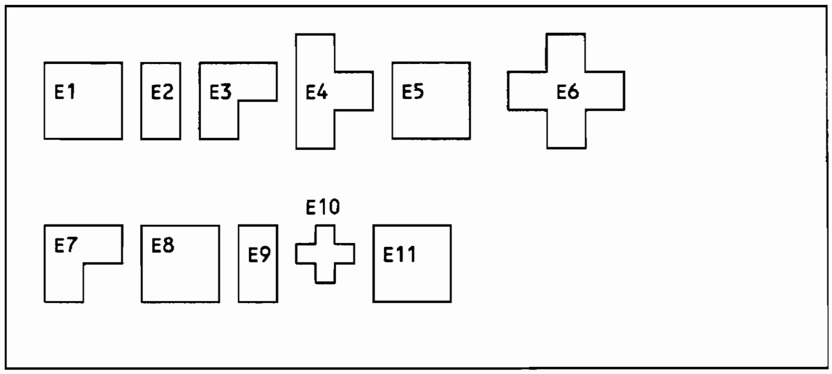


Figure 23. Geometry of Facilities

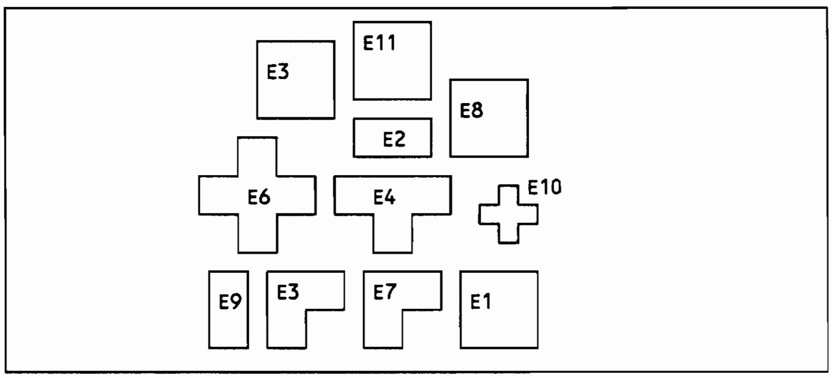


Figure 24. Initial Layout

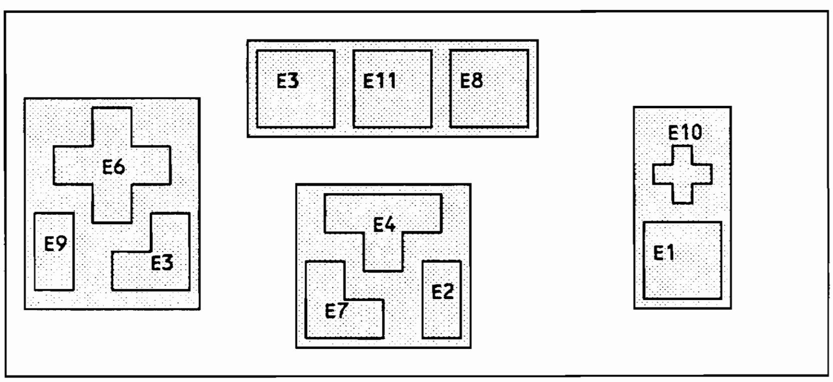


Figure 25. Final Layout

3.1.12 PLANET

PLANET (Plant Layout ANalysis and Evaluation Technique) is a construction technique for plant layout, presented by Apple and Deisenroth [1]. The algorithm allows the user to input material flow information in three alternative forms and choose one of three different construction algorithms for generating a layout. Layouts with up to 99 facilities can be designed using the PLANET algorithm.

The problem solution is obtained in three phases. The first involves the input of material flow data in any one of the three formats offered by PLANET. The second phase is the selection of the order in which the facilities would enter the layout. This is based on the material flow values from the From-To Chart or Parts-List data, or qualitative data in the form of a Penalty Matrix. The order is determined using this data and any of the three selection procedures. The objective is to minimize the material handling costs.

The final phase is the placement of the facilities in the selected order. The facilities are represented as a combination of unit blocks, which allows facilities of different shapes and areas to be included in the layout. A description of the stepwise solution procedure follows.

Step 1. The first step is the data input and the data manipulation. Two types of input data required are departmental data and material flow data. Facility data input required is facility name, area and placement priority. The placement priority determines the order in which the facilities enter the layout. The placement priorities range from 1 to 9.

Three different methods of specifying inter-facility relationships are available. The first method is to specify the flow sequence, cost per move per 100 ft, and frequency of move for each part. From-To Charts are generated by multiplying the cost per move with the frequency of move for each part and combining these costs for common flow paths. The second method to input material flow data is to directly input the From-To Chart. The third alternative is to input a Penalty Matrix which measures requirement for relative location of facilities. These penalties range from -9 to 99. A positive value indicates a desire to locate the related facilities close, whereas negative is the opposite. The numeric value gives the strength of the relationship.

PLANET converts the data input in either of the three forms to a Normalized Flow-Between Cost Chart. For this, first the From-To Chart is normalized by dividing each element in the chart by the largest element in the same chart. The normalized From-To Chart is converted to a normalized Flow-Between Cost Chart by summing up the elements in both directions in the Normalized From-To Cost Chart. This Normalized Flow-Between Chart is used by the algorithm for selecting and placing the facilities.

Step 2. The algorithm has three alternative procedures of using the Flow-Between Cost Chart to select the order of placement of the facilities. The three selection methods are classified as Selection Methods A, B, and C.

Selection Method A selects the first pair of facilities as those which are from the highest priority group and have the highest flow-between cost. The next facility to enter the layout is in the highest priority group of unselected facilities and has the highest flow-between cost with one of the selected facilities. This procedure is continued until all facilities have entered the layout.

In Selection Method B, the first pair of facilities selected is from the highest priority group and has the highest flow-between cost. The next facility to enter the layout is one of the unselected activities in the highest priority group which has the highest sum of flow-between costs with all the selected facilities. This procedure continues until all facilities have entered the layout.

The first facility selected in Selection Method C is the facility in the highest priority group that has the highest sum of flow-between costs with all other facilities. The next facility to enter the layout is the unselected facility with highest priority and highest sum of flow-between costs.

Step 3. This step is to place the facilities in the selected order. PLANET asks the user for the size of a unit block. The facility areas are represented as a combination of these unit blocks. The placement procedure then begins by placing the first pair of facilities adjacent to each other in the center of the layout grid. Each additional facilities is placed so as to minimize the increase in handling cost. Points are selected around the perimeter of the existing layouts to decide the location of the next facility. Each point is treated as the centroid of the entering facility. For the entering facility, the product of the distances and the flow-between costs are determined for each point. The minimum cost point is selected as the location where the entering facility is to be placed.

For each entering facility, the number of unit blocks are calculated and these blocks are placed in the selected location in a spiraling routine, as shown in **Figure 26**. This routine helps in obtaining relatively square areas and avoids irregularly shaped facilities.

Most layouts generated by PLANET have irregular shapes. The shapes can be modified manually to conform the layout to the site location.

A worked out example of the PLANET solution procedure is given in Chapter 5, Experimentation With Layout Packages.

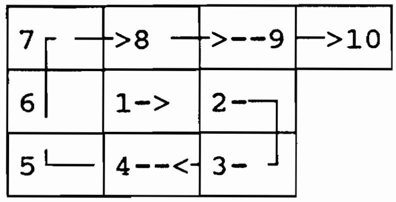


Figure 26. Spiralling routine for placing department unit blocks

3.1.13 SHAPE

The construction algorithm presented by Hassan, Hogg, and Smith [40] is part of a larger model, SHAPE (Selection of materials Handling equipment and Area Placement Evaluation) created by Hassan [39]. The objective of SHAPE is to develop a functional layout possessing minimal inter-facility movement costs. The design algorithm considers the combined effect of facility area and material flow on the shape of the facility, location and material movement cost. It attempts to determine the best arrangement and configuration of facilities.

The conceptual formulation of the solution is by constructing a layout matrix of unit squares. The user selects the size of a unit square, which approximates a common multiple of the facility area requirements or is the smallest facility area. The size of the unit square affects the overall layout resolution and the computational speed of the algorithm.

The problem solution is achieved in two phases. The first involves deciding the order in which facilities will enter the layout. This is based on the flow values from the From-To Chart. In the second phase, the facilities are placed in the selected order. The concept is to minimize the distance between the facilities with high material flow. A description of the stepwise solution procedure follows.

Step 1. The first phase of the solution procedure starts by defining a significant inter-facility flow level, which establishes a discriminatory basis for classifying the flow values. This is done by selecting a value from the From-To Chart, which can be a statistical measure of central tendency of all the entries in the From-To Chart, or determined subjectively. By selecting different values, a number of different layouts can be generated for comparison.

Step 2. The flows are classified as major if it is greater than the significant value determined in Step 1, and minor if it is less.

Step 3. For each facility, the major flows are summed up to give a measure of flow values. Also the number of major flows for each facility is listed.

Step 4. The sums obtained in Step 3 are arranged in a decreasing order. In case of ties, the greatest rank is given to the facility with the least number of large flow values. Further ties are resolved by selecting the facility with greatest total flow and remaining ties are resolved arbitrarily.

Step 5. The set of flow values obtained in Step 4 is combined with the facility relationships to decide the order of placement of facility. The second facility in the set is checked for at least one major relationship with the first facility. If one exists, the facility ranking is maintained, else, the facility is lowered down one rank. This is carried on for all facilities and the list thus obtained is the order in which facilities enter the layout.

Step 6. This is the beginning of the second phase of the solution procedure. The number of unit squares in the layout matrix is specified. The center of the layout is marked as the center of the first facility. The area of the facility determines the number of unit squares to be marked off for that facility. The squares closest to the center are marked off for the first facility.

Step 7. The true center of the placed facility is determined. If the facility has an irregular shape, its center is determined as that of the best approximating rectangle.

Step 8. For determining the location of the next facility, a set of candidate squares on all sides of the placed facilities is selected. For each side, the total move cost between the candidate squares and the placed facilities is determined. The least of these totals determines the set of squares for the entering facility.

Step 9. The total move cost is updated after each facility is placed.

Step 10. Steps 7 to 9 are repeated till all facilities are located.

The layouts generated by SHAPE ensure optimal shape for each facility, sparing the few whose shapes have been modified. The number of squares occupied by each department ensure minimal material handling cost between the entering department and the current partial layout. By providing locally optimal solutions at each stage, the algorithm ensures good solutions.

The following example problem given by Hassan, Hogg, and Smith [40] further explains the solution procedure.

Example: Five facilities, 1, 2, 3, 4, and 5, with areas 2, 3, 3, 4, and 4, respectively, had to be located. The From-To Chart for the material flow was as shown in **Table 32**.

To distinguish between the major and minor flows, the significant flow value was 5. The sum of major flow values of the facilities were 35, 25, 23, 39, and 14, respectively. Based on these values, the order of placement was **4-1-2-3-5**. Next, the flow relation between consecutive facilities was tested. The order of placement remained the same.

The layout matrix was assumed to consist of 10 rows and 10 columns. The set of squares selected for the first entering facility, 4, were 45, 46, 55, and 56 out of the grid matrix of 100 squares. For the next entering facility, 1, all four sides of the occupied area were tested **(Figure 27)**. Side 1 was arbitrarily selected as line of expansion as all the sides were equivalent. The candidate squares were 34, 35, 36, and 37, with move costs 36, 24, 24, and 36, respectively.

The move-cost between facilities 1 and 4, for location at squares 35 and 36 was 24 ((24 + 24)/2) and for squares 34 and 37 was 36 ((36 + 36)/2). Squares 35 and 36 were selected for locating facility 1 **(Figure 28)**.

Additional iterations followed the same pattern, yielding the final layout as shown in **Figure 29**.

Table 32. Material Flow From-To Chart

		TO				
		1	2	3	4	5
	1	0	9	9	12	5
	2	0	0	6	10	3
FROM	3	0	0	0	8	4
	4	0	0	0	0	9
	5	0	0	0	0	0

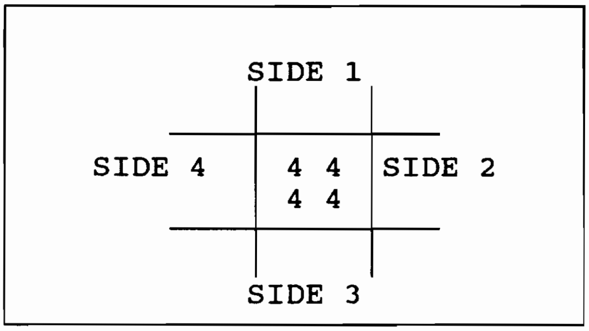


Figure 27. Location of first facility

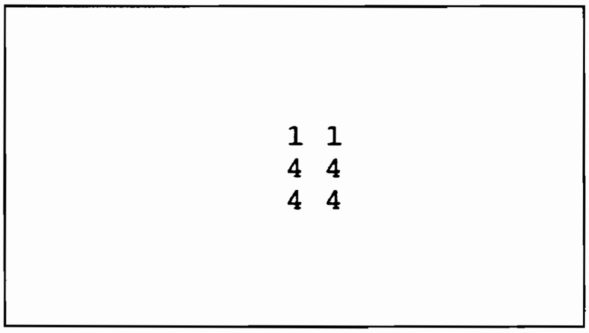


Figure 28. Partial layout with two facilities

5	3	3	3
5	1	1	2
5	4	4	2
5	4	4	2

Figure 29. Final layout

Sequence of entry: 4, 1, 2, 3, and 5
Objective function value: 192

3.1.14 STORM

STORM [30] is an improvement type CAFL program which uses a modified steepest descent pairwise interchange method (SDPIM). The complete SDPIM method considers every possible pairwise exchange of department locations. It then exchanges the pair that yields the greatest cost improvement and then it restarts the whole move evaluation cycle. STORM allows the user to define the number of successful evaluations to be found before it goes ahead and makes the best exchange it has discovered so far. This modification results in lower computation times and the option can be used to generate a number of heuristic solutions by changing the number of successes allowed.

The layout generated is an equal area block layout (**Figure 30**), with each block representing a department. The program can be cheated into solving unequal area department problems. This can be done by defining a small block size and representing a department as a number of small blocks. One of the blocks for a department can be used to define flows with other departments. To keep the blocks of the same department packed together, high flow values should be defined between these blocks. Then, to get the true value of the objective function, the hypothetical flow values can be deducted from the objective function of the final layout.

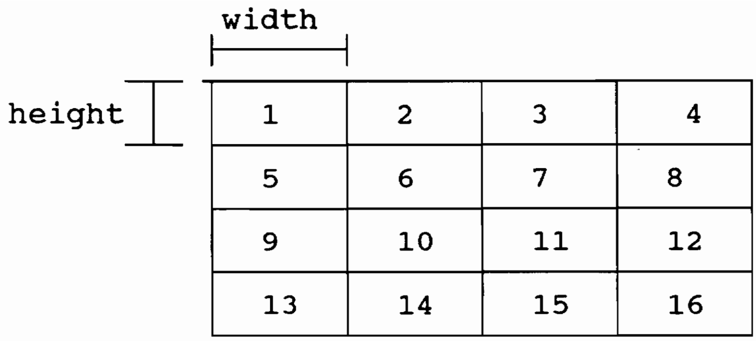


Figure 30. Layout with unequal area departments

The solution procedure and the algorithmic functioning are explained in the following steps.

Step 1. The data entry starts with basic problem definition. The data elements are:

- title
- number of departments
- number of departments down
- department height
- department width
- distance (eulc/rect)
- symmetric matrices
- successful evaluations

After the title for the problem and the number of departments in the layout, the next entry allows the user to customize the layout boundary. By specifying the number of departments down, the user defines the number of departments to be placed from top to the bottom of the entire layout area. The number of departments divided by the number of departments down, gives the number of departments across the layout area. If the result of this division is not an integer, it is rounded up to the next integer value. This results in a greater number of blocks than departments. The empty blocks can be defined as dummy departments or STORM assigns the unused locations around the edge of the layout and moves them around if doing so improves the layout.
The department height and width are measured in distance units as shown in **Figure 30**. The program calculates the center of departments using

these dimensions. Material flow is assumed to be between centers of departments. The distance measure can be defined as either euclidean, that is diagonal, or rectilinear, that is along the X-Y axes.

The cost and flow matrices can be defined as either symmetric or non-symmetric about the diagonal. A symmetric matrix would indicate equal values for flow or cost between two departments in either direction.

The number of successful evaluations informs the program to make the most profitable exchange after the defined number of profitable exchanges have been determined.

Step 2. Here, the layout details are entered. The user has an option of declaring fixed locations for departments, which is followed by an optional user solution for the remaining departments. If the user does not provide an initial solution, STORM generates a random solution, maintaining the defined fixed locations.

Unit loads per unit time are entered in the flow matrix to give a measure of department relationships. Similarly the cost matrix is declared for the unit material handling costs. Each of these matrices can be either symmetrical or non-symmetrical, as declared earlier.

Step 3. STORM takes the data entered and the initial solution (if provided) or its own, and tries to improve on it by moving departments around in the layout. The objective function is to minimize the total interaction value. STORM calculates the interaction value for a department as the product of material flow and flow cost between this department and all other facilities. The program gives an option for observing the solution after each iteration or it will give the final local optimum solution, if so directed. The output generated can be directed to three sources; screen, printer, and an output file.

Step 4. The program gives several options for post-solution analysis. These are,

- draw layout
- department interaction values
- objective function by department
- generate random initial solution and resolve
- perform user defined exchanges
- restart solution process from current solution
- save best solution found as user solution

The user can experiment with alternate solutions using these options.

An example problem solution using STORM is presented in Chapter 5 of the report.

3.2 Summary

In this report, various features of 14 CAFL packages were discussed. The discussion included formulations of the layout problem and the algorithms used. Illustrative examples were included to further explain the solution procedures used. A summary of the various features, regarding input, algorithm used, and output generated for each package is given in **Table 33**. This table provides a means of comparison between the packages.

Table 33. **Summary of CAFL Packages**

NAME	YEAR	DATA		ALGORITHM	OBJECTIVE	LAYOUT	# OF FLOORS
		QUALITATIVE	QUANTITATIVE				
ALDEP	1966	REL Chart		Construction	Maximize total Relationship Score	Matrix of facility identifiers; unequal area; alternate layouts	3
BLOCPLAN-90	1990	REL Chart	Product Flow	Construction, Improvement, & Random	Maximize Adjacency Score	Block layout; unequal area; alternate layouts	6
CAFLAS	1984	REL Chart	Initial layout and material handling cost	Improvement	Maximize the multi-criteria utility function	Block layout; unequal area; one layout	1
COFAD	1975		Initial layout; From-To Chart; Move-Cost Chart	Improvement	Minimize total material handling cost	Block layout; unequal area; one layout	1
CORELAP	1966	REL Chart		Construction	Maximize sum of Relationships	Block matrix of facility identifiers; unequal area; one layout	1
CRAFT	1964		Initial layout; From-To Chart; Distance Matrix	Improvement	Minimize flow distance	Block matrix of facility identifiers; unequal area; one layout	1
FLAG	1984		Product Flow & Move Cost Chart	Construction	Minimize move costs	Block layout; unequal area; alternate layouts; details developed with templates	1
FRAT	1973		Initial Layout; From-To Chart; Distance Chart	Improvement	Minimize flow distance	Block layout; equal area; one layout	1
HILLIER-63	1963		Initial layout; From-To Chart; Distance Chart	Improvement	Minimize flow distance	Block layout; equal area; one layout	1
MAT	1970		From-To Chart	Construction & Improvement	Minimize flow distance	Point locations for facilities; one layout	40
MICROLAY	1987	REL Chart		Construction & Improvement	Minmize product of REL Chart and Distance Chart	Block layout; unequal area defined shaps for facilities; one layout	1
PLANET	1967	Penalty Matrix (REL Chart)	Parts List and From-To Chart	Construction	Minimize normalized flow-between cost	Matrix of facility identifiers; unequal area; set of three layouts	1
SHAPE	1986		From-To Chart	Construction	Minimize flow distance	Block matrix of facility identifiers; unequal area; one layout	1
STORM	1989		Initial layout; flow loads; flow costs	Improvement	Minimize product of flow loads & flow costs	Block layout; equal area; one layout	1

4. Modifications of Original Algorithms

This section introduces some algorithms which are modifications or extensions of the original layout algorithms. The modifications use the same basic algorithms with changes to accommodate various applications. A summary of the modified algorithms follows.

1. **Interactive CORELAP**. Interactive CORELAP[80] is also a construction type algorithm based on the original algorithm. The original CORELAP algorithm has a batch processing type solution procedure. It generates a layout with a one time data input. The interactive CORELAP program has some additional features with user-interaction, allowing the designer to customize the layout and compare alternative layouts. These are:

    1. Interactive CORELAP solves both, new plant and existing plant problems.
    2. It permits fixed locations for facilities.
    3. It scores any layout, i.e. partial or complete.
    4. It simplifies the procedure for modifying adjustments to layouts.

These additional features allow the user to customize the layout and compare alternative layouts.

2. **COFAD-F**. The COFAD improvement algorithm develops layouts for a standard product flow volume, with consideration to the type of material

handling system used. COFAD-F [101] adds a flexible routine to the solution procedure by considering various product mixes and flow volumes. It considers different product mixes and develops a layout which has least expected cost penalties for a combination of the product mixes and the material handling systems. The facility layout having the least cost penalty is said to be the most flexible facility.

3. **COSFAD**. This algorithm incorporates plant safety factors in the COFAD improvement algorithm. The objective of COSFAD [107] is to determine a material handling system for a plant layout that has minimum handling cost with minimal total-system risk. Total system risk is calculated by quantifying safety factors in the plant operations.

4. **CRAFT-M**. This is a modification of one of the improvement algorithms, CRAFT. CRAFT-M [44] incorporates the cost of moving the department with the material handling improvement factors in the decision logic of CRAFT. The layout developed by CRAFT-M would pay for the cost of moving the required facilities, within an estimated lifetime of the rearrangement.

5. **MOCRAFT**. This is a Multi Objective CRAFT method. MOCRAFT [103] incorporates the capability to use both, quantitative and qualitative data, in the CRAFT solution procedure. It can generate layouts which are simultaneously based on both cost-flow and REL data.

6. **MICRO-CRAFT**. MICRO-CRAFT [122] is another adaptation of CRAFT. A number of assumptions are made in the program to allow using the

pairwise exchange method on the micro-computer, as well as to produce a graphical representation on the screen. The program accepts an initial arrangement of the departments in a plant, as well as material flow data (From-To Chart), material handling cost, and departmental areas. The user can define fixed locations for departments. The program produces a sub-optimal arrangement of the departments in the layout with respect to total material handling cost.

7. **SPACECRAFT**. This is an improvement algorithm for multi-story layouts. The solution procedure is based on the single story CRAFT heuristic. The main difference between CRAFT and SPACECRAFT [54] is the consideration of different costs of movement between floors. SPACECRAFT checks all routes and uses the fastest round trip route. Also, SPACECRAFT can specify restrictions on facility locations between floors or on the same floor.

8. **HILLIRER-CONNORS 1966 (HC-66)**. HC-66[47] is a modified version of H-63, which is a heuristic deterministic improvement procedure. H-63 improves a layout by pair-wise interchanges of adjacent facility locations. HC-66 incorporates a modification in the exchange routine. The modified procedure allows interchanges of non-adjacent facilities also. Another modification is the criteria for interchanges. In HC-66 the only interchanges of facilities that are allowed in the first round are those which decrease the objective function by at least a pre-specified positive amount. Thereafter, any interchange that decreases the objective function value is permitted.

5. Experimetation with CAFL packages

This chapter is a report on the application of four Computer Aided Facilities Layout (CAFL[2]) packages to a plant layout design problem. The packages under study were:

1. BLOCPLAN 90
2. MICRO-CRAFT
3. PLANET
4. STORM.

A hypothetical plant layout problem was created and the related data entered into the layout packages for generating layouts. The objective was to highlight the capabilities of the packages in terms of data input required, the solution procedure used for generating layouts, and the quality of the layout generated. The basic data regarding the layout specifications and material flow was common or similar for the four packages. This data is given below. Additional data used, specific to different packages, is given as the packages are covered.

5.1 Example Problem Statement

The test problem was to develop a layout for a Machine-Tool manufacturing plant. The departmental specifications were as shown in Table 34. The area for aisles and loading and unloading zones was included in the departmental areas. The DUMMY department was added to

[2] Here, a department in the plant is referred to as a facility.

Table 34. Departmental information

NUMBER	NAME	IDENTIFIER	AREA(sq.ft.)
1.	RECEIVING	RE	1800
2.	SHIPPING	SH	1800
3.	STORAGE	ST	1200
4.	MACHINING	MA	600
5.	DRILLING	DR	600
6.	GRINDING	GR	600
7.	ASSEMBLY	AS	600
8.	PAINTING	PA	600
9.	TOOLING	TO	600
10.	DUMMY	DU	1200
		TOTAL AREA	9,600

Area of plant floor = 11,000 sq.ft.

Table 35a. Product Flow Chart

NUMBER	SEQUENCE OF FLOW THROUGH DEPARTMENTS	NUMBER OF DEPARTMENTS	FREQUENCY OF MOVE/ UNIT LOAD	MOVE COST ($)
1.	1-3-4-8-6-3-5	7	70	2
2.	2-3-6-5-4-3-2	7	40	2
3.	1-3-6-4-8-9-3	7	30	2
4.	1-6-5-4-6-7-3-2	8	80	2
5.	6-3-4-7-8-3-2	7	40	2
6.	1-3-4-5-7-6-3-2	8	100	2
7.	2-5-8-9-2	5	80	2
8.	1-5-7-4-9-2	6	100	2
9.	3-5-6-2	4	60	1
10.	3-5-7-8-9	5	30	1

Table 35b. Product Flow Chart for qualitative requirements

NUMBER	SEQUENCE OF FLOW THROUGH DEPARTMENTS	NUMBER OF DEPARTMENTS	FREQUENCY OF MOVE/ UNIT LOAD	MOVE COST ($)
11.	1-2	2	300	1
12.	6-9	2	300	1
13.	5-9	2	-120	1

include area for utilities like stairwells, restrooms, etc. The total area required by the departments was less than the plant floor area allocated, providing space for structural entities like doorways, ramps, etc.

Quantitative data on material flow used for establishing the interaction between departments was given in the form of a Product Flow Chart (**Table 35a** and **Table 35b**). This Chart was used to determine relative locations of departments based on material flow. The sequence of flow gave the order of flow through departments, frequency of move was the unit loads per unit time that the part traveled between the departments, and the move cost was cost of transporting a unit load of material between the facilities.

The relative location of various departments depended on this flow data. Any two departments with high flow values needed to be close to each other so as to minimize the total move cost. In addition to the requirements due to the product flow, there were subjective requirements for relative location of departments.

Departments **1 & 2** and **6 & 9** were required to be close to each other. Hypothetical product flows were used to express this. A negative flow was used to express the requirement of not placing departments 5 and 9 close to each other. Only M-CRAFT and PLANET accepted the negative flows and this requirement could not be expressed while using the BLOCPLAN-90 Product Flow REL Chart and STORM. These requirements, expressed as product flows are shown in **Table 35b**. This data was used to generate a From-To Chart. This chart, **(Table 36)** gives weighted flows between pairs of departments.

The From-To Chart was the alternate form of quantitative data input. The entry of -120 for flow between departments 5 and 9 was an expression of not locating these two close together. The requirement of closeness for departments 1 & 2, and 6 & 9 was expressed by adding positive flow values. Again, the negative flow value was accepted only by M-CRAFT and PLANET. The symmetric From-To Chart obtained from **Table 36** was as shown in **Table 37**.

The objective of the layout design was to minimize, within constraints, the total material handling cost.

The qualitative data used was the REL Chart of **Table 38**, which gives the closeness relationships between the various departments. This chart was generated with the flow

Table 36. From-To Chart

FROM \ TO	1	2	3	4	5	6	7	8	9	10
1	0	300	400	0	200	160	0	0	0	0
2	0	0	80	0	160	0	0	0	0	0
3	0	520	0	420	230	140	0	0	0	0
4	0	0	80	0	200	160	80	200	200	0
5	0	0	0	240	0	60	430	160	-120	0
6	0	60	420	60	240	0	160	0	300	0
7	0	0	160	200	0	200	0	110	0	0
8	0	0	80	0	0	140	0	0	250	0
9	0	360	60	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0

Table 37. Symmetric From-To Chart

FROM \ TO	1	2	3	4	5	6	7	8	9	10
1	0	300	400	0	200	160	0	0	0	0
2		0	600	0	160	60	0	0	360	0
3			0	500	230	560	160	80	60	0
4				0	440	220	280	200	200	0
5					0	300	430	160	-120	0
6						0	360	140	300	0
7							0	110	0	0
8								0	250	0
9									0	0
10										0

Table 38. REL Chart

	1	2	3	4	5	6	7	8	9	10
1	.	I	E	U	O	O	U	U	U	U
2		.	A	U	O	U	U	U	I	U
3			.	A	O	A	O	U	U	U
4				.	E	O	I	O	O	U
5					.	I	E	O	X	U
6						.	I	O	I	U
7							.	U	U	U
8								.	I	U
9									.	U
10										.

information provided by the From-To Chart. To define the relationships based on the flow between pairs of departments, six intervals were created, and a REL code assigned to each interval. REL codes were assigned based on flow values and the intervals for the relationships. Equal intervals were created by dividing the highest flow value by 5 and assigning the REL codes as shown in **Table 39**. The weights assigned to the codes are given in **Table 40**. The relative locations of departments were to be decided based on the flow data or the REL Chart. In addition to these requirements, the location of three departments was pre-determined based on factors that could not be quantified. The locations of Receiving and Shipping departments were fixed on the periphery, for easy access to roads and rail tracks, and the Storage department was assigned a fixed location in the center of the layout to facilitate product flow.

The data given above was the core data used for the problem. The four packages used different combinations of the core data provided. In addition to this data, different details were specified by each package for customizing the layout and evaluating it under various conditions. Such data is given in the worked out example solutions that follow.

Table 39. REL codes for flow intervals

Flow	REL code
600 - 480	A
480 - 360	E
360 - 240	I
240 - 120	O
120 - 0	U
0 - -120	X

Table 40. REL code equvalent values

REL code	Numeric Value
A	91
E	71
I	51
O	31
U	11
X	-9

5.2 BLOCPLAN-90

BLOCPLAN 90 [24] is a CAFL package which uses a construction algorithm for generating layouts. Layouts can be developed with the layout algorithm, a random procedure, an improvement algorithm, and an automatic search option. For any of the four options, fixed locations can be defined in any of the 18 zones available for location. The layouts developed are block diagrams of different area rectangular blocks. The size of the block is in proportion with the area of the department it represents. The user can define the Length and Width ratio of the layout outline.

BLOCPLAN 90 is the only one among the four packages under study, that develops multi-story layouts. The multi-story option partitions the departments in up to 6 stories, giving the department numbers and the covered area on each floor. Each of these partitions can be stored in a separate file. Detailed layouts for each story are developed by using each partition file as data input in the Single-story option.

5.2.1 Example Problem Solution

Input: The area requirements for the departments were as shown in Table 34. The layout outline shape was specified as a Length/Width ratio of 100/110[3], where Length was the boundary wall along the X-axis and Width along Y-axis.

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[3]. The program offered four standard ratios to choose from and a fifth option where the user can specify the ratio desired.

The program had options for qualitative and quantitative data input. Qualitative data was input in the form of the REL Chart of **Table 38**, with weights for the codes as indicated.

Quantitative data used was the Product Flow Chart. The unit loads and sequence of operations for the 10 products were entered as given in **Table 35a**. The program extracted a From-To Flow Chart from this data, giving the flow loads between pairs of departments. In addition to the product flows, there was an option for expressing subjective requirements for the relative location of departments. This was accomplished by entering flows between departments other than the product flow. These flow values were entered in the Additions Matrix, as shown in **Table 41**. Only positive values were accepted here and the desire to keep departments **5** and **9** apart could not be expressed while using this option for data input.

The program combined the From-To Chart and the Additions Matrix into a Total Flow Chart to generate the Product Flow REL Chart. The codes were generated by creating intervals in the Flow Chart. The highest value in the chart, 600, divided by 5, resulted in the interval width of 120. For product flows between 480 and 600, the departments were assigned an 'A' relationship, 'E' for the interval 360-480, 'I' for the interval 240-360, 'O' for the interval 120-240, and a 'U' relationship for the interval 0-120. The Product Flow REL Chart so obtained was as shown in **Table 42**.

Table 41. Additions Matrix

		TO									
		1	2	3	4	5	6	7	8	9	10
	1		300								
	2										
	3										
	4										
FROM	5										
	6									300	
	7										
	8										
	9										
	10										

Table 42. Product flow REL Chart

	1	2	3	4	5	6	7	8	9	10
1	.	I	E	U	O	O	U	U	U	U
2		.	A	U	O	U	U	U	I	U
3			.	A	O	A	O	U	U	U
4				.	E	O	I	O	O	U
5					.	I	E	O	U	U
6						.	I	O	I	U
7							.	U	U	U
8								.	I	U
9									.	U
10										.

Output: Two sets of single-story layouts were generated, alternatively using the directly input REL Chart and the Product Flow REL Chart. For each set, 20 layouts[4] were developed using a combination of the following options:

1. Automatic Search
2. Manually Insert Departments
3. Random Layout
4. Layout Algorithm
5. Improvement Algorithm

The automatic search option is offered to save time. It uses pre-defined procedures that an experienced BLOCPLAN user would apply to develop good layouts. Ten layouts were developed using this option by manually locating departments 1, 2, and 3 in fixed locations and allowing the program to locate the other departments. There were 9 zones available for placing departments, as shown in **Figure 31**. Each of the zones was further divided into Left and Right wings, resulting in a total of 18 locations. The three departments were assigned fixed locations in zones A(Left), C(Right), and E(Left), respectively.

Ten more layouts were developed by using the layout algorithm and the random layout options, with the same fixed locations for departments 1, 2, and 3. Out of the 20 saved layouts, 5 layouts with the least layout scores were deleted.

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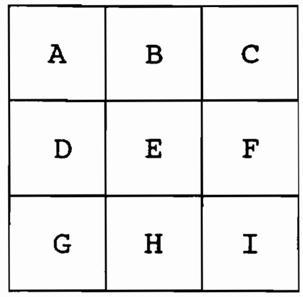
[4]. A maximum of 20 layouts can be saved as solutions to one probem. Any further layout saved replaces the 20th layout.



Fixed locations defined:
1. Receiving zone A, left
2. Shipping zone B, left
3. Storage zone C, right

Figure 31. Zones for manually locating departments

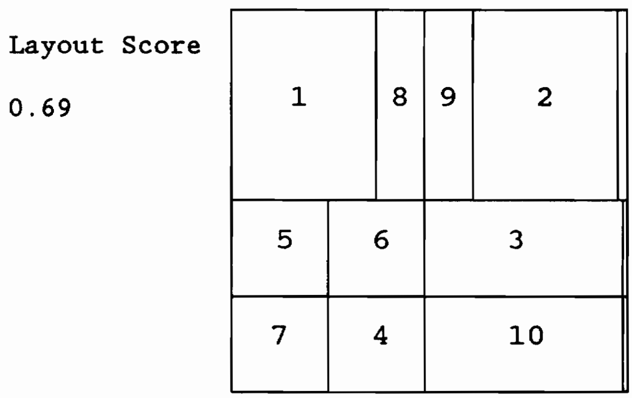


Figure 32. Layout developed with Product Flow REL Chart

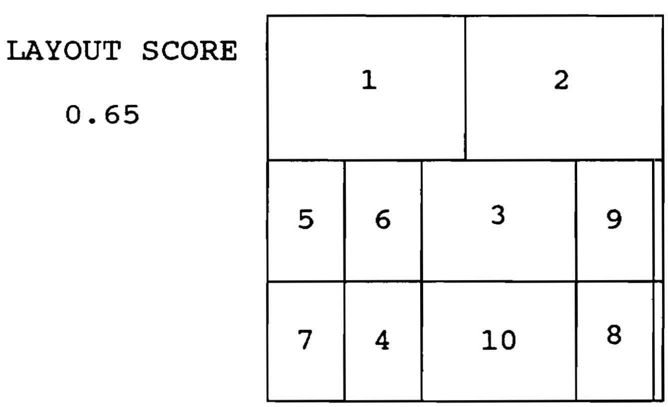


Figure 33. Layout developed with directly input REL Chart

From the remaining 15 layouts the best 5 were used as basis for the improvement algorithm in an attempt to improve the Layout Score.

The improvement algorithm accepted any saved layout as input and tried to improve the layout through an iterative procedure. For the example problem, with 3 departments in fixed locations, there were 21 iterations[5]. With no locations fixed, the number of iterations would be 45. For all the 21 layouts that were generated in the iterations, the program had options for analysis, exchanging departments, and saving the layout. Through various iterations, the layout with the highest layout score and lowest Total Product Movement was saved as an improved layout. The final layouts accepted as solutions, using the two types of data input, were as shown in **Figure 32** and **Figure 33**.

The measures of a good layout were the Layout Score, the Total Product Movement, and the REL-DIST score. Of the 20 saved layouts, the layout with the highest Layout Score, lowest Total Product Movement, and lowest REL-DIST score was accepted as the problem solution. For this layout, the locations of some departments were exchanged to check the effect on the Layout Score. Layout Score decreased in each case, so the departments were relocated.

The program tabulated the Adjacency Score, R-Score, REL-DIST Score, and the Product Movement for all saved layouts. For the layout developed with Product Flow REL Chart, the sum of satisfied adjacencies (962),

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[5]. The number of iterations depends on the number of departments to be located. With 3 fixed locations, 7 departments are to be located.

divided by the sum of all positive adjacencies in the REL Chart, (1395), gave the Adjacency Score of 0.69, which was also used as the Layout Score.

The REL-DIST scores were obtained by the sum of products of relationship and distance between pairs of departments in the layout. The layout had a REL-DIST score of 76028. Similarly, the Total Product Movement (363093) was calculated as the sum of product of flow loads and distance between all pairs of departments. In contrast, the layout solution with the directly input REL Chart had a Layout Score of 0.65, a REL-DIST score of 71018, and the Total Product Movement of 358799.

The variation in the layouts developed with the two types of data reflects the effect of difference in information that was provided as quantitative data or as qualitative data.

Analysis: For analysis of the layout, the program provided a set of charts. One REL Chart was presented, with a listing of the satisfied and unsatisfied adjacency relationships. This chart helps in determining the quality of the layout. For layout details, it presented the centroids for all the departments as X-Y locations, considering the lower left corner of layout as (0,0).

Another chart gave the Distance Matrix for distances between departments and the REL-Distance score for the layout. It gave the upper and lower bounds for the possible REL-Distance scores for given data. These were calculated as:

$$\text{Lower bound} = D_x S_1 + D_{x-1} S_2 + \ldots\ldots + D_1 S_x$$

$$\text{Upper bound} = D_1 S_1 + D_2 S_2 + \ldots\ldots + D_x S_x$$

where,

D is a vector of the distances between the departments, and S is a vector of the relationship scores, both vectors arranged in an ascending order of values for the given data, and x is the number of elements in each vector.

For the layout selected while using Product Flow input, the vectors were:

D = 2,2,3,3,3,3,3,3,3,3,4,5,5,5,5,5,5,5,5,6,6,6,6,6,
6,7,7,7,7,8,8,8,8,8,8,9,9,10,10,10,11,11,11,13,13.

S = 11,11,11,11,11,11,11,11,11,11,11,11,11,11,11,11,11,
11,11,11,11,11,31,31,31,31,31,31,31,31,31,31,51,51,
51,51,51,51,51,71,71,71,91,91,91.

The bounds were used to give the **R-Score**, which is a measure of the quality of the layout. This was calculated as:

$$\text{R-Score} = 1 - (\text{REL-DIST Score} - \text{Lower bound})/(\text{Upper bound} - \text{Lower bound})$$

$$= 1 - (76028.21 - 62763.84)/(118057.7 - 62763.84)$$

$$= 0.76$$

An **R-Score** of 1 would be a perfect score.

Multi-Story layout

BLOCPLAN 90 had an option of partitioning the layout in up to 6 stories. The user could partition the layout through the Manual Partition option to decide which departments were to be placed on every floor or through the Automatic Partition option, let the program place the departments on different stories. In the Automatic Partition option, the user could give the desired ADF (Area Difference Factor, between 0 and 1) score, which is the allowed difference in the area of stories. The higher the allowed ADF, the more flexibility the program had to place the departments.

The Multi-Story option was used to develop partitions. The departmental information and the flow data used were the same as for Single-Story Layout with Product Flow data.

For the Manual Partition option, departments 1, 2, and 8 were placed on Story 1 and departments 3, 4, 5, 6, 7, 9, and 10 on Story 2. For this partition, the actual ADF was 0.125, with a Partition Score of 0.67, as given in **Table 43a**. With the Automatic Partition option, the partitioning for departments and the Partition score, varied with the ADF. **Table 43b** gives the partitions obtained with different ADF values. ADF was a measure of the maximum deviation in the area of the two stories, which could come out to be less than permitted, as was evident from the results.

All departments on one story were considered adjacent whereas departments on different stories were not adjacent. The sum of

Table 43a. Multi-Story manual layout partition

ADF (Actual)	Departments on Story-1	Departments on Story-2	Partition Score
0.125	1,2,8	3,4,5,6,7,9,10	0.67

Table 43b. Multi-story layout partitions with different ADF values

ADF		Departments	Departments	Partition
Desired	Actual	on Story-1	on Story-2	Score
0.1	0.0	1,2,10	3,4,5,6,7,8,9	0.67
0.5	0.5	8,9,10	1,2,3,4,5,6,7	0.70
1.0	0.5	8,9,10	1,2,3,4,5,6,7	0.70

relationships of the adjacent departments, divided by the total sum of all the positive relationships gave the Partition Score. Partition Score was a measure of satisfied adjacencies.

While developing Multi-Story layouts, data on each story was saved separately in a file. Each of these files could be treated as a single-story layout to develop layouts for that story. For the current problem, only partitions were created to display the ability of the program to develop Multi-Story layouts.

5.2.2 Observations

BLOCPLAN 90 is a comprehensive package for developing plant layouts, given quantitative or qualitative data. The basic principal behind the algorithm is to develop a number of good layouts as options for the designer to make the final choice, in contrast with the other three packages under study which try to develop an optimal layout. While working with BLOCPLAN 90 for solution to the layout problem, following observations were made which highlight the strengths and weak points of the package.

1. BLOCPLAN 90 had good user interaction. Any data entry errors could be easily corrected. Additionally, it allowed changes in the data at every stage for observing the resultant effect on the layout.

2. Due to somewhat random placement routine of the Layout Algorithm, the program did not generate the same layout for the same data in different runs. This weakness was offset by generating a number of layouts, saving only good layouts, and leaving it on the designer to select the best layout.

3. The options for quantitative or qualitative data input make the program flexible for application to different problems. Also, a combination of quantitative data, in the form of Parts-List and qualitative data, as Additions Matrix, allowed to express relations other than actual flow values. However, only positive relations, expressed as hypothetical flows, were accepted as entries to the Additions Matrix.

4. For layouts without the hypothetical flow values in the Additions Matrix, there was noted difference in the relative location of the concerned departments, e.g. departments 6 and 9 were not essentially placed close to each other. The relative location of departments 1 and 2 was not effected as their locations were fixed.

5. While developing layouts using either the directly input REL Chart or the Product-Flow REL Chart, the program automatically developed layouts under the second option also, using the respective REL Chart. This was a handicap, as any previously saved layouts under the second option were overwritten with fresh layouts. Additionally, while saving the data file, the option for using directly input REL Chart had to be restored or else the layouts developed with the Product-Flow REL Chart were saved under both the options. This is an error in the code and the authors are in the process of rectifying the error. To overcome the problem, two different files were created to develop layouts with the two types of data input.

6. Under the Single-Story Menu, when the Automatic Search option was used, the program erased all saved layouts and saved only the fresh layouts. To overcome this problem, this option was used first to develop layouts and then the other options of random layout, layout algorithm, and improvement algorithm were used.

7. The program did not have any option for obtaining a hard copy of the layout and the analysis charts. For obtaining hard copies, the GRAPHICS

file from DOS was loaded before loading the program. Subsequently, any desired hard copies were obtained using the 'Print Screen' key on the Keyboard.

8. In the graphical representation of the layout, the total bay area occupied by the departments was dependent on the departmental areas and the L/W ratio specified. Some area was left unoccupied in a bay, depending on the departments placed in that bay.

9. The program offers an option to make changes in the REL Chart developed with product flow information. However, this option did not work and did not allow any changes to the REL Chart.

5.2.3 Remarks

BLOCPLAN-90 can be used as a tool for generating good quality layout alternatives. The flexibility and details of data input, combined with the variety of algorithms used, allow the user to generate a number of alternative solutions for one problem. The program then provides various measures for scoring and comparing the alternate layouts, assisting the user in selecting the best solution. However, the somewhat random nature of the solution procedure does not guarantee an optimal solution. It is concluded that BLOCPLAN-90 can be used to generate a number of alternate layouts, for the user to select the most acceptable solution.

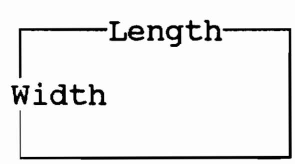
5.3 MICRO-CRAFT

MICRO-CRAFT [122] is a micro-computer version of the improvement algorithm CRAFT. It uses quantitative data for solving the layout problem. The objective of the algorithm is to minimize the cost of material handling between the departments, where cost is expressed as a linear function of the distance travelled between departments. Given an initial layout, the program tests for profitable pair-wise exchanges between department locations, i.e. exchanges which reduce the material handling cost, to make the most profitable exchange. It also provides graphical representations and an option for obtaining hard copies, of the data and layout. The program can develop layouts with up to 40 departments.

5.3.1 Example Problem Solution

Input: Data input could be through keyboard or through data files. Data files stored from previous runs could be input for modifications and developing fresh layouts. The first time data input was through keyboard.

The data input started with dimensions of the layout. The Length (100) and Width (110) were specified as:



The plant floor was divided into 4 bays and the departments entered the layout along the bays as shown in **Figure 34**. One department could occupy area over more than one bay. With the same material flow data, the layout varied with the number of bays specified. A smaller number of bays resulted in more rectangular shapes as compared to a large number of bays. This also effected the total move cost between the departments, e.g. the Total Cost with 5, 10, and 20 bays was $ 356178.3, $ 322013.9, and $ 1.457723E+07, respectively. The layout with 5 bays was accepted as the solution because of a relatively low cost and more rectangular shapes for the departments.

For departmental relationships, two forms of quantitative data input were allowed with the IIE package containing the MICRO-CRAFT program, either the product flow data in the From-To Chart generator, or a direct From-To Chart. For the first option, the product flow data would be input in the From-To Chart generator which would generate the From-To Chart and store it as a data file. Subsequently, the MICRO-CRAFT program could accept this data file as flow data and the flow costs would be entered. Alternately, the MICRO-CRAFT program would accept the From-To Chart for material flow and move costs as data input. Here, the first option was used and the output from the From-To Chart generator was input in the MICRO-CRAFT program.

For the product flow information, the quantity, batch size, and sequence of operations were as shown in **Table 35a** and **Table 35b**, except the negative flow entry between departments 5 and 9. The frequency of move

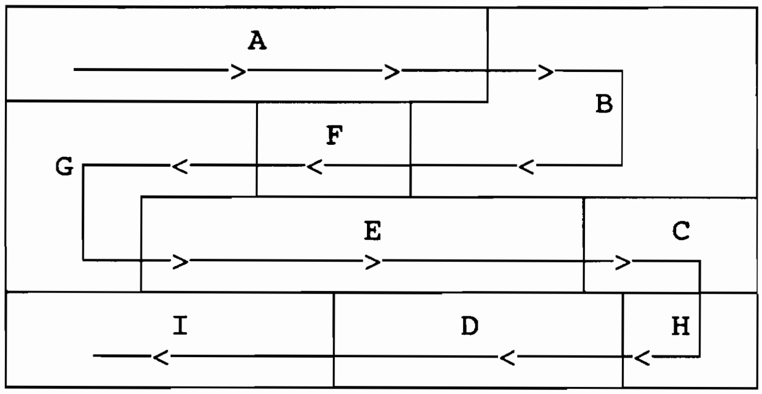


Figure 34. Spiralling routine followed for placing departments

for a product was calculated as the quotient of quantity divided by batch size. A unity batch size was assumed.

For calculations, the program required an initial sequence for the entry of the departments in the layout. The departments were placed in the layout in that sequence in a spiraling routine, as shown in **Figure** 34. The initial sequence was used by the program as the basis for the improvement algorithm. The quality of the layout developed was sensitive to the initial sequence and this was used as a method of developing alternate layouts.

For the example problem the following two initial sequences were tried.

a) 1-2-4-5-3-6-7-8-9-10, and

b) 1-2-10-9-3-8-7-6-5-4,

with fixed locations for the Receiving(1), Shipping(2), and the Storage(3) departments. The layout obtained with sequence **a** had a lower material handling cost and was selected as the initial sequence.

The fixed locations ensured that the order of entry of these departments would not change in the process of exchange of departmental locations. However, the fixed locations so defined did not ensure fixed shape or geometrical locations for these departments.

The last entry before calculations started, was the distance measure for travel between departments. The product movement was considered to be between the centroids of the departments and RECTILINEAR distance measure was used. This measured the distance for travel between the department centroids, in straight lines parallel to the layout axes. The other option was to use EUCLIDEAN distance measure, which would be the shortest straight line distance between the department centroids.

Output: The program then started the iterative procedure to make the most profitable exchanges between department locations, other than departments 1, 2, and 3, which had fixed locations. The objective was to minimize the material handling cost. The process continued till there were no further improvements in the material handling cost. The initial layout with 5 bays had the Total Material Handling Cost of $ 429855.8, which reduced to 356178.3 in 7 iterations. When the program could make no further reductions in the cost it stopped the calculations and declared the last layout sequence as the final solution.

The program had an option to stop calculations after any iteration by hitting any key on the keyboard. This option was provided to save time in case the desired layout sequence was obtained or the total cost was within acceptable limits. For big problems, the program took considerable amount of time to test for all profitable exchanges, e.g. for the 10 department problem with 5 bays, the program took about 5 minutes for 7 iterations.

The last solution was saved with the problem data. The final sequence for the layout mentioned above, was: 1-2-9-8-3-6-7-5-4-10, with fixed locations for departments 1, 2, and 3. Thus from the various iterations, this was the only sequence that was saved for subsequent analysis, and became the default initial sequence for the next run.

A graphical screen display and a hard copy for the final layout was generated. The output consisted of graphical representation of the layout, the sequence in which departments were placed, the total material handling cost, layout dimensions, and the material flow data for the problem. The layout created with 5 bays was as shown in **Figure 35**. Each department was represented by the department number. Departments 1 to 10 were represented as sets of 1, 2, 9, and A. The unoccupied space in the layout was represented with 0. The unoccupied space was always placed last by the spiralling routine.

Analysis: For post-solution analysis, the options were:

1. GRAPHICAL REPRESENTATION OF LAYOUT AND PRINTED OUTPUT
2. INPUT NEW INITIAL SEQUENCE
3. MODIFY DATA
4. INPUT DESIRED FINAL SEQUENCE (OTHER THAN THE BEST ONE SHOWN)

The outputs generated and printed were as described before. The final layout varied with the initial sequence entered. Thus, a number of layouts could be generated for analysis by the designer by using different initial input for the same set of data. Similarly, the option for data modification allowed the user to generate various layouts and

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11111111111111111111111111111112222222
11111111111111111111111111111112222222
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88889999999999222222222222222222222222
88889999999999222222222222222222222222
88889999999999222222222222222222222222
88889999999999222222222222222222222222
88888833333333333333333333366666666667
88888833333333333333333333366666666667
88888833333333333333333333366666666667
88888833333333333333333333366666666667
AAAAAAAAA4444444444555555555577777777
AAAAAAAAA44444444445555555555777777777
AAAAAAAAA44444444445555555555777777777
AAAAAAAAA44444444445555555555777777777
AAAAAAAAAAAA00000000000000000000000000
AAAAAAAAAAAA00000000000000000000000000
AAAAAAAAAAAA00000000000000000000000000
AAAAAAAAAAAA00000000000000000000000000
```

Department Sequence of Entry:
1** - 2** - 9 - 8 - 3** - 6 - 7 - 5 - 10

Total Cost: $ 356178.3

Initial Sequence:
1** - 2** - 4 - 5 - 3** - 6 - 7 - 8 - 9 - 10

**Designates Departments With Fixed Sequence

Figure 35. Layout generated with 5 bays

perform sensitivity analysis for changes in data, e.g. the same data set was used with different number of bays, 5, 10, and 20.

With the input of the desired sequence, the program gave a graphical representation and material handling cost of the layout. This could be used for comparison with different layouts generated by the program.

5.3.2 Observations

The following points highlight some qualities of the MICRO-CRAFT program.

1. MICRO-CRAFT takes a considerable amount of time to generate layouts e.g., for the example problem, with 10 bays and no fixed locations, it took 15 minutes on the AT&T 6286, to generate the final layout. The time taken also depends on the speed of the computer. For the same problem, the time taken on an IBM PC was between 20 to 40 minutes.

2. The program could not graphically represent a problem size of more than 10 departments. For number of departments between 3 and 40, the program generated the order of entry and calculated the Total Cost but would not produce a graphical output.

3. The qualitative data included in the form of hypothetical product flows had an effect on the relative location of the departments. The additional positive flow between departments 6 and 9, brought them closer, and the non-positive flow between 5 and 9, separated them. There was no effect on the relative location of departments 1 and 2, because their locations were fixed.

4. For the graphical representation, the layout was presented as a set of numbers, laid across the various bays, with each set representing one department. The total number of rows in the layout and the number on rows in each bay, varied with the number of bays, the length/width ratio of the layout, and the number of departments. For the example problem,

the total number of rows in the layout with 3, 5, and 15 bays, was 21, 20, and 15, respectively. The maximum number of rows possible for graphical representation was 22.

5. The only way an old layout could be reviewed was by running the whole program with the same data, as there was no separate output file generated. This acted as a handicap while reviewing old layouts.

5.3.3 Remarks

MICRO-CRAFT accepts only quantitative data for departmental relationships. This somewhat limits its application to improving existing layouts. For creating new layouts, material flow values and departmental relationships have to be predicted accurately. However, the option for defining initial sequenc provides the flexibility to generate alternate layouts, for the user to select the best solution. MICRO-CRAFT can also be used for deciding an optimal location for a new department in an existing layout.

5.4 PLANET

PLANET [2] is classified as a construction type algorithm for developing facilities layouts. It allows data input in three different forms, and has three types of selection routines for placing the departments in the layout. Depending on the type of problem data available, the program can be used for varied applications.

The PC version of PLANET used for this project is programmed to develop layouts with up to 99 departments. It develops layouts with different area departments and the placement routines generate different shapes of the departments. The solution procedure involves a one time data input and places the output in an output file PLT.OUT.

The program accepts data from the keyboard or from a disk file. The data input through the keyboard is stored as a data file, named SCREEN.DAT. For input from disk, the data file is copied to a file PLT1.DAT[6].

5.4.1 Example Problem Solution

Input: The departmental data used was as given in **Table 34**. A Priority Rating of 1 was established for all the departments. The Priority Rating gave the order in which the departments enter the layout. The same rating for all the departments ensured that the selection and placement of departments was based only on either the material flow data

6. In either case, the program requires a resident file PLT1.DAT on the disk.

or the departmental penalties/relationships. The location of Receiving, Shipping, and Storage departments could not be fixed in desired locations as the program did not have an option for the same.

Each department was built up as a set of unit blocks, with a common unit block size for all the departments. The unit block size specified for the example problem was 100.

Output: With the above basic data, three sets of layouts were created, one each using the three types of input data for departmental relationships. The program had the options of presenting layouts after each department was added to the layout or to present only the final layout. Only the option for final layouts was used here. Two types of quantitative data and one type of qualitative data were used to express the closeness requirements of departments.

One type of data used was product flow information in the form a Parts List. The product data specified was frequency of move, move cost\ft., and flow sequence through departments as given in **Table 35a** and **Table 35b**[7]. All but one entries given in the tables were used here. The relation between the Drilling and Painting departments was expressed as a hypothetical product flow of -99, which expressed the requirement of

---

7. This includes 3 hypothetical parts with flows of -99, 300, and 300 with unity move-cost, between departments 5-8, 1-2, and 6-9, respectively. This is done to express the qualitative requirement for the relative location of these departments.

not to locating these departments close together. -99 was the maximum negative flow accepted[8].

The program converted this information into a From-To Cost Chart for cost of material flow/ft between pairs of departments. A Normalized From-To Chart was then obtained by dividing each element by the highest element of the chart, giving the flow cost per unit travel between the departments. The data was further reduced to obtain a symmetric chart by adding the flow costs in either direction between pairs of departments. The resulting Normalized Flow-Between Cost Chart was used by the selection procedures to select the sequence of entry of departments in the layout.

All three selection procedures, A, B, and C, were used to obtain the final layout using the Parts List data. The layouts obtained are as shown in **Figure 36, Figure 37,** and **Figure 38,** respectively. The sequence of entry and the Layout Cost are given with the layout.

The second set of layouts was created using the From-To Cost Chart as the other type of quantitative data input. The From-To Chart of **Table 36** was used here. The relation between the Drilling and Painting departments was expressed as a negative flow of -120, which expressed the requirement of not locating these departments close together.

---

8. However, this did not give the full qualitative measure for the relative location of the two departments.

```
   RE RE RE RE RE
   RE RE RE RE RE TO TO
   RE RE RE RE RE TO TO TO
      RE RE RE GR GR GR TO
SH SH SH SH SH GR GR GR
SH SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST PA
         DR DR MA MA MA PA PA
         DR DR MA MA MA PA PA
         DR DR AS AS AS PA
               AS AS AS DU DU DU
                        DU DU DU
                        DU DU DU
                        DU DU DU
```

Order of Placement:
SH-ST-GR-MA-DR-AS-RE-TO-PA-DU

Layout Cost: 69

Figure 36. Layout with Selection Method A using Parts List data

```
            RE RE RE RE RE
            RE RE RE RE RE
               RE RE RE RE
               RE RE RE RE
SH SH SH SH SH RE RE RE RE
SH SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST
   TO TO DR DR GR GR GR AS AS
   TO TO DR DR GR GR GR AS AS
   TO TO DR DR MA MA MA AS AS
         PA PA MA MA MA
         PA PA PA
         PA    DU DU DU
               DU DU DU
               DU DU DU
               DU DU DU
```

Order of Placement:
SH-ST-RE-GR-DR-MA-AS-TO-PA-DU

Layout Cost: 65

Figure 37. Layout with Selection Method B using Parts List data

```
                        AS AS AS
                        AS AS AS
               MA MA MA DR DR DR
RE RE RE RE RE MA MA MA DR DR DR PA PA
RE RE RE RE ST ST ST ST GR GR GR PA PA
   RE RE RE ST ST ST ST GR GR GR PA PA
   RE RE RE ST ST ST ST SH TO TO
   RE RE RE SH SH SH SH SH TO TO
               SH SH SH SH TO TO
               SH SH SH SH
               SH SH SH SH
               DU DU DU
               DU DU DU
               DU DU DU
               DU DU DU
```

Order of Placement:
ST-GR-MA-DR-SH-AS-TO-RE-PA-DU

Layout Cost: 64

Figure 38. Layout with Selection Method C using Parts List data

Similarly, a hypothetical flow of 300 between departments
the requirement of not locating these departments close together. Similarly, a hypothetical flow of 300 between departments 1-2 and 6-9 was entered to express the requirement of locating these departments close together. The program then generated a Normalized From-To Chart and a Normalized Flow-Between Cost Chart from the given data. The resultant layouts were as shown in **Figure 39**, **Figure 40**, and **Figure 41**.

The third set of layouts was created using qualitative data input for closeness relationships between departments in the form of a Penalty Matrix. The 'penalties' were a measure of the closeness desirability for departments. Higher the penalty, higher the cost of locating the departments far apart, e.g. the value of 51 between the Receiving and Storage departments and of 11 between the Receiving and Drilling departments was an expression of a strong requirement to closely locate the first pair of departments and not so strong a requirement for the second pair.

The Penalty Matrix data used was the decoded REL Chart of **Table 39**. The values assigned to the REL codes were as given in **Table 41**. The program generated a Normalized Flow-Between Cost Chart from the Penalty Matrix and three layouts were developed using this data and the three selection methods. The resultant layouts were as shown in **Figure 42**, **Figure 43**, and **Figure 44**.

```
   RE RE RE RE RE
   RE RE RE RE RE TO TO
   RE RE RE RE RE TO TO TO
      RE RE RE GR GR GR TO
SH SH SH SH SH GR GR GR
SH SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST PA
         DR DR MA MA MA PA PA
         DR DR MA MA MA PA PA
         DR DR AS AS AS PA
               AS AS AS DU DU DU
                        DU DU DU
                        DU DU DU
                        DU DU DU
```

Order of Placement:
SH-ST-GR-MA-DR-AS-RE-TO-PA-DU

Layout Cost: 69

Figure 39. Layout with Selection Method A using From-To Chart

```
            RE RE RE RE RE
            RE RE RE RE RE
               RE RE RE RE
SH SH SH SH SH RE RE RE RE
SH SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST
   SH SH SH SH ST ST ST ST
   TO TO DR DR GR GR GR AS AS
   TO TO DR DR GR GR GR AS AS
   TO TO DR DR MA MA MA AS AS
         PA PA MA MA MA
         PA PA PA
         PA    DU DU DU
               DU DU DU
               DU DU DU
               DU DU DU
```

Order of Placement:
SH-ST-RE-GR-DR-MA-AS-TO-PA-DU

Layout Cost: 65

Figure 40. Layout with Selection Method B using From-To Chart

```
               AS AS AS
               AS AS AS
PA PA MA MA MA DR DR DR
PA PA MA MA MA DR DR DR
PA ST ST ST ST GR GR GR
PA ST ST ST ST GR GR GR RE RE
   ST ST ST ST SH RE RE RE RE
TO SH SH SH SH SH RE RE RE RE
TO TO SH SH SH SH RE RE RE RE
TO TO SH SH SH SH RE RE RE RE
TO    SH SH SH SH
               DU DU DU
               DU DU DU
               DU DU DU
               DU DU DU
```

Order of Placement:
ST-GR-MA-DR-SH-AS-RE-TO-PA-DU

Layout Cost: 65

Figure 41. Layout with Selection Method C using From-To Chart

```
            DU DU DU DU
            DU DU DU DU
            DU DU DU DU PA
   MA MA MA DR DR PA PA PA
   MA MA MA DR DR PA PA RE RE
ST ST ST ST GR GR GR RE RE RE RE
ST ST ST ST GR GR GR RE RE RE RE
ST ST ST ST SH AS AS RE RE RE RE
SH SH SH SH SH AS AS RE RE RE RE
   SH SH SH SH AS AS
   SH SH SH SH TO TO
   SH SH SH SH TO TO
               TO TO
```

Order of Placement:
ST-GR-MA-SH-DR-AS-RE-TO-PA-DU

Layout Cost: 84

Figure 42. Layout with Selection Method A using Penalty Matrix

```
   SH SH SH SH SH
   SH SH SH SH SH       DU DU DU
   SH SH SH SH DR DR DR DU DU DU
   SH SH SH SH DR DR DR DU DU DU DU
TO TO MA MA MA AS AS AS PA PA DU DU
TO TO MA MA MA AS AS AS PA PA
TO ST ST ST ST GR GR GR PA PA
TO ST ST ST ST GR GR GR RE
   ST ST ST ST RE RE RE RE
            RE RE RE RE RE
               RE RE RE RE
               RE RE RE RE
```

Order of Placement:
ST-GR-MA-AS-DR-SH-RE-TO-PA-DU

Layout Cost: 80

Figure 43. Layout with Selection Method B using Penalty Matrix

```
            DU DU DU DU
            DU DU DU DU
            DU DU DU DU    PA
   MA MA MA DR DR DR PA PA PA
   MA MA MA DR DR DR PA PA RE RE
ST ST ST ST GR GR GR RE RE RE RE
ST ST ST ST GR GR GR RE RE RE RE
ST ST ST ST SH AS AS RE RE RE RE
SH SH SH SH SH AS AS RE RE RE RE
   SH SH SH SH AS AS
   SH SH SH SH TO TO
   SH SH SH SH TO TO
            TO TO
```

Order of Placement:
ST-GR-MA-DR-SH-AS-RE-TO-PA-DU

Layout Cost: 84

Figure 44. Layout with Selection Method C using Penalty Matrix

The layouts generated using the two types of quantitative data were identical in selection, placement, and cost. However, these layouts were different from the layouts generated using the qualitative data, for the same problem. This was due to the subjective nature of Penalty Matrix. The strength of the relationships of departments due to flow values, could not be expressed in the Penalty Matrix. Thus, the departmental relationships expressed with penalties were not the same as those with quantitative data[9]. The quality of the layouts generated by using the Penalty Matrix depends on the ability of the designer to express relationships in the form of qualitative data.

The layouts varied with different scales of the penalties, with different values for the lowest penalty, and with the interval between the penalties. This added to the sensitivity of qualitative data.

For analysis of a layout, the program provided the Layout Cost, which was the cost of material handling for all moves between the departments. Lower the Layout Cost, better the layout. Also, the Normalized From-To Chart and the Normalized Flow-Between Cost Chart could be used to check the layout for whether or not the departments with high flow costs were placed close together. The option for output after every department entered the layout gave the user a tool to study and modify the relative location of departments by changing input data.

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[9]. The quality of the layouts generated by using the Penalty Matrix depends on the ability of the designer to express relationships in the form of qualitative data.

5.4.2 Observations

The flexibility in data input makes the PLANET program applicable to a variety of layout problems. The PC version of PLANET under study had certain other strengths and weak points which effected the layout solutions. These are briefly discussed below.

1. PLANET requires a block data input which limits user interaction. This proved to be a handicap if any incorrect entries were made, or any changes were desired. The data entry process was not flexible and in case of any incorrect entries, the program would terminate, and the data entry process would have to be restarted.

For data input from disk-file, a previously saved data file would be copied onto a resident file PLT1.DAT. For any changes in the problem data, the effect on the layouts generated were observed by editing the file through the Edlin editor and opting for data input through file. However, this was a time-consuming process and acted as a handicap in generating alternate layouts by modifying parts of the data.

2. The shape and size of the departments varied with the unit block size specified. Also, the placement of the departments varied with change in unit block size, while the order of entry or the selection of the departments remained the same for different block sizes. This gives the user a flexibility of developing alternate layouts for comparison.

3. The program develops layouts for different area departments. This gives the actual layout outline, with relative locations of departments.

4. The program did not have an option for assigning fixed locations for departments. However the required location of departments could be approximated by defining different priorities, e.g. an alternate layout was developed by assigning different priorities for departments as shown in **Table 44**. Priority 1 for Storage department ensured that it was the first to enter the layout and was placed in the center of the layout, with other departments being placed around it. The least Priority, 3, for Receiving and Shipping departments ensured that these were the last to enter the layout, and hence were placed along the boundary of the layout. This partially fulfilled the requirement for placing the Storage department in the center and the Receiving and Shipping departments along the border of the plant.

5. The program did not offer any options for analysis of the generated layout, e.g. exchanging a pair of departments.

5.4.3 Remarks

In PLANET, the variety of data input provides the user flexibility in defining departmental relations. The variety of data and the algorithms used, provide good quality layout alternatives, and extend applications to different types of layout problems. However, the block data input, limits user interaction and discourages the user to check the effect of modifications in input data. Additionally, the layouts generated do not have a pre-defined outline and require modifications for final shape.

Table 44. Different Priority Ratings for departments

Department	Priority
Receiving	3
Shipping	3
Storage	1
Machining	2
Drilling	2
Grinding	2
Drilling	2
Assembly	2
Painting	2
Tooling	2
Dummy	2

5.5 STORM

STORM [30] is an improvement type layout algorithm which uses a CRAFT like procedure to develop layouts. The PC-program develops layouts with up to 25 departments. It uses a modified SDPIM (Steepest Descent Pair-wise Interchange Method) procedure for developing layouts. The SDPIM procedure tests for all profitable pair-wise exchanges of department locations to make the most profitable exchange. A profitable exchange, termed as a successful evaluation, is any exchange in departmental locations, that reduces the objective function value function. The objective function is to minimize the total interaction cost between departments, the interaction cost being the product of material flow and the cost per unit move for a pair of departments.

The user can define the number of successful evaluations, to be tried before making the most profitable exchange. This option can reduce the computation time and generate a local optimal solution, not very different from the one that the SDPIM procedure would generate. Another benefit is that it allows the user to develop a number of layouts by defining different number of successful evaluations. If the number of successful evaluations asked for is more than the number of such evaluations obtained, the program makes the most profitable of these evaluations and continues with the iterations. The user can see the layout developed after every iteration or obtain the final layout in one step.

The layouts developed are equal area block layouts, with each block representing a department. The block size depends on the department width and height specified. The objective is to obtain relative location of departments to help the designer in developing detailed layouts.

5.5.1 Example Problem Solution

Input: The names and dimensions of the 10 departments of the plant were as given in **Table 34**. The program did not require department areas and treated these as equal area departments and a common height/width ratio of 110/100 was specified for the departments.

A RECTILINEAR distance measure was used for product movement between departments, with the assumption that material flow was in aisles parallel to the axes of the plant floor. An entry for Number of Departments Down allowed the user to adjust the number of departments along the length and width of the layout. Four Departments Down were specified. Thus, the number of departments along the vertical axis was 4 and along the perpendicular axis was 3, resulting in the block layout of **Figure 45**. This resulted in two empty blocks, which were placed in the last two available locations. A specification of 5 departments down would result in a layout similar to the one shown in **Figure 46**.

The From-To Chart of **Table 37** was used as flow matrix. The flow and the cost matrices were declared symmetric, indicating that the material flow and the material handling cost between pairs of departments were the same in both directions.

DEPT 3	DEPT 5	DEPT 6
	DEPT 2	DEPT 1
DEPT 10	DEPT 9	DEPT 7
	DEPT 4	DEPT 8

Figure 45. Block layout for 10 department problem with 4 departments down

DEPT 1	DEPT 2
DEPT 3	DEPT 4
DEPT 5	DEPT 6
DEPT 7	DEPT 8
DEPT 9	DEPT 10

Figure 46. Block layout for 10 department problem with 5 departments down

The subjective requirement for departments 1-2, and 6-9 to be close had to be expressed as hypothetical flow. With the addition of a flow of 300 units between departments 6-9, and 1-2, departments 6 and 9 were placed close together but there was no effect on the location of departments 1-2 as these were in fixed locations. The requirement of not placing departments 5-9 close together could not be expressed, as negative flows were not accepted.

A $1 material handling cost was entered between all departments, with the assumption that the same material handling equipment would be used between all departments.

The number of successful evaluations entered was 20, allowing the program to make a sufficient number of checks before exchanging departments.

Before starting the calculations, the program allowed an option for entry of initial layout with fixed locations. Alternately, the program would generate a random initial layout with the defined fixed locations. For initial layout and fixed locations, the block number for each department was entered. The locations of departments 1, 2, and 3 were fixed in blocks 1, 3, and 5, respectively and the initial layout entered was as shown in **Figure 47**. The final solution was sensitive to the initial layout, so a number of layouts could be generated for the same data set, by changing the initial layout entered.

DEPT 1*	DEPT 4	DEPT 2*
DEPT 5	DEPT 3*	DEPT 6
DEPT 7	DEPT 8	DEPT 9
DEPT 10		

* Designates fixed locations

Figure 47. Initial layout with fixed location for departments 1, 2, and 3

DEPT 1*	DEPT 5	DEPT 2*
DEPT 6	DEPT 3*	DEPT 9
DEPT 7	DEPT 4	DEPT 8
DEPT 10		

* Designates fixed locations
Total objective function value = 1251800

Figure 48. Final layout

The calculations were started by punching the function key F7. Once storm obtained the local optimum, i.e. it could not reduce the objective value function any further, the best solution was saved on a disk file.

Output: The program had an option in the configuration menu to direct the output to various destinations. The option for output devices was set as a file and the computer screen. A third option of directing the output to the printer was also available.

The final layout obtained was as shown in **Figure 48**. The Total Objective Function value of 125180 was the sum of products of material flow, flow cost, and distances, between all departments.

Analysis: For post solution analysis, the program presented a list of options after generating the final layout. These were:

1. **Draw layout.** This was used to create an output of the layout on the computer screen. It presented the block layout of the best solution with the Total Objective Function Value, as shown in **Figure 48**. It gave the final locations of the 10 department blocks and two empty blocks, and the total move cost.

2. **Department interaction values.** This chart provided the interaction values between all pairs of departments, listed in a decreasing order, e.g. the interaction value between departments 2 and 3 was \$ 600. This was obtained as the sum of product flow of (80) from department 2 to 3 with unity move cost and a product flow of 520 from department 3 to 2

with unity move cost. This chart could be used to examine the layout to see if departments with high interaction values were placed close together, and if not, appropriate changes would be made.

3. **Objective function by department**. This was a list of the total contribution of each department to the objective function value. It could be used to ascertain if the departments with high total are more centrally located and those with low are more on the periphery.

4. **Generate a random initial solution and resolve.** The option for generating random initial solution was used to create various layouts with different initial assignments of the departments, except for the fixed location assignments. Thus, a number of layouts could be generated to choose from.

5. **Perform user defined exchanges**. To experiment with the solution generated, department locations could be interchanged to see the effect on cost, e.g. a switch of locations for departments 5 and 6 increased the objective value by $ 10600, and they were returned to their original locations. A second switch was tested between departments 4 and 5. It increased the objective value by $ 55000, so the departments were returned to original locations. This option could be used to satisfy any requirement for relative location of departments. The change in objective value would measure the benefit of loss and help make the decision.

6. **Restart solution process from current solution.** This option provided a means of generating a number of layouts for comparison. The

program took the most recent layout as the basis for the solution process and generated another local optimum solution.

7. **Save best solution found as user solution.** The program remembered the best solution generated during the whole process and updated the record for the same. At the end of the session, the best solution was saved with the layout data on the disk file. For the next run of the program, if this file were used as input data, the saved solution would be the default initial solution.

Unequal Area Department Problem

The program could also treat the departments as unequal area departments. For this, each department is broken down to a number of equal area blocks. High flow values are entered between the blocks of the same department. These high flow values ensure that blocks of one department remain tied together. One block of each department is used to define material flow with other departments, whereas the rest of the blocks for the same department have '0' flow with other departments. The hypothetical flow values would be subtracted from the final flow value to give the actual material flow between departments.

The example problem solved as an unequal area department problem resulted in the layout as shown in **Figure 49**. The smallest area, 600 here, was taken as a unit block for dividing departments with higher

DEPT 1	DEPT 2	DEPT 4	DEPT 5
DEPT 3	DEPT 7	DEPT 8	DEPT 6
DEPT 9	DEPT 10	DEPT 11	DEPT 14
DEPT 13	DEPT 12	DEPT 15	DEPT 16

Total objective function value = 3519300

Figure 49. Final layout for unequal area departments

area. As a result, the Receiving department was represented as DEPT 1, DEPT 2, and DEPT 3, and similarly the other departments with area greater than 600 units were represented as more than one department. The resulting layout constituted 16 departments. STORM allocated one block to each of the real and also the hypothetical departments. High flow values of 2000 each were defined between blocks of the same department for keeping them together. DEPT 2, DEPT 4, DEPT 6, and DEPT 15 represented the actual flow values between the respective departments and other departments in the layout.

The total objective function value for the final layout was 3519300. The hypothetical flows were deducted from the this to give the actual value. Hypothetical flow values were calculated by multiplying the false value with the unit distance between the respective departments, e.g. for DEPT 1 and DEPT 2 as it was 200000 (2000*100) and for DEPT 1 and DEPT 3 it was 220000 (2000*110). The total contribution of these hypothetical totalled up to 2080000, giving an actual objective function value of 1439300 (3519300 - 2080000) for the final layout.

5.5.2 Observations

Some strengths and weak points of STORM, as observed in the example problem solution, are highlighted below.

1. Data input in STORM was in stages and could be revised at any time during the input process or for observing the effect on layout of any changes. This allowed ample interaction with the program to ensure correct data input and to customize the layout. Data input could be through screen or directly from files created in previous runs.

2. The option to define symmetric or non-symmetric flow and cost matrices let the user enter different material flows and flow costs between departments for either direction.

3. By varying the department height/width ratio and the number of departments down, the layout outline can be customized as needed. Additionally, by varying the number of departments down, alternate layouts can be developed for comparison.

4. The post solution analysis give the user options for comparing alternate layouts and customizing locations for departments with high flows and interactions.

5. In general, the equal area block layout provides only relative locations for departments and does not give a true outline for the actual layout.

4.5.3 Remarks

The data input required is quantitative flow data which limits the use to improving existing layouts. For generating new layouts, the user has to accurately predict/define material flows and a random layout has to be used as the seed. The layout outline can be specified but the assumption of equal area departments limits the use to developing relative locations of departments. The different tools for layout analysis can be effectively used to compare alternatives and select a good solution.

6. Evaluation of CAFL packages

The four packages used for experimentation with the example plant layout problem had different capabilities regarding types of data input required, the solution procedure used, and the resulting outputs generated. Consequently, the application of any one of the packages depends on the problem data and the required outputs.

To evaluate the strengths and weak points of the four packages, the following criteria were used.

1. Computer resources required
2. Data input
    i) Qualitative or quantitative
    ii) Fixed locations
    iii) Move/costs
    iv) Symmetric flow charts
    v) Data storage
3. User interaction
4. Output
    i) Hard/soft copy
    ii) Contents
5. Quality of output
6. Analysis of the layout
7. Multi-story layout
8. Solution times

1. **Computer resources required.** Any of the four packages under study could be run on a PC with a RAM of 640K. The time taken for generating layouts depended on the hardware used. The AT&T 6286 PC with a 80286 micro-chip resulted in speedy calculations. The IBM PC with the 8086 processor took more time for computing the results. The monitor used for each package was a CGA or a monitor with higher resolution.

2. **Data input**

i) Qualitative or quantitative. The data for defining inter-departmental relationships can be broadly classified as qualitative or quantitative. Qualitative data is in the form of a REL Chart which defines the closeness requirements between department locations. This is subjective data and relies heavily on the layout engineer's ability to define actual relationships between departments. The quantitative data input involves information like product flow between departments and move-costs for various product flows, which provides a better measure for defining relationships. This data is reduced to departmental relationships by the layout algorithm. The layouts developed with quantitative data are likely to be closer to the actual requirements, than with qualitative data.

BLOCPLAN 90 had options for both types of data input. This gives BLOCPLAN 90 the flexibility to be used for problems with either kind of data available.

MICRO-CRAFT took quantitative data input only. For expressing any qualitative information, hypothetical product flows had to be entered.

However, a requirement of not placing any two departments close together could not be expressed because negative flows were not accepted.

PLANET was the most flexible of the four packages in terms of kinds of data input. Two types of quantitative data and one type of qualitative data input options were available. Either of the three data input formats could be used to solve layout problems. While using the quantitative data input, any qualitative information had to be expressed as hypothetical flows between the concerned departments.

STORM used quantitative data only. Here again, the qualitative requirements had to be expressed as hypothetical flows between the concerned departments. However, a requirement for placing departments not close together, could not be expressed because negative flows were not accepted.

ii) Fixed locations. In a plant, locations for some departments are determined by criteria other than the flow criteria, like building structure and location of facilities like rail-tracks and roads, or subjective requirements. For example, the Receiving and Shipping departments needed to be located on the periphery of the layout and near rail-track or road locations, and the Storage department in the center of the layout to minimize material flow. To satisfy such requirements, specific locations are fixed for some departments while the algorithm decides the locations of other departments.

BLOCPLAN 90, MICRO-CRAFT, and STORM allowed the user to define fixed locations, e.g. locations of Receiving, Shipping, and Storage were fixed. The PLANET algorithm did not have an option to declare fixed locations but by defining different placement priorities, the locations could be approximated. If a department had to be located in the center it would be given the highest priority and for departments that are required to be on the periphery, lower priority ratings would be declared.

iii) Move-costs. The cost of transporting material between the departments is used as a measure for relative locations of departments. Some algorithms assume a unity cost for all moves between departments, assuming the same material handling system for all moves and thus changing the objective to be minimizing the flow distance or flow loads between departments. If different material handling systems are used, different move-costs have to be specified.

BLOCPLAN 90 did not allow any move-cost input for the product flow data, and developed layouts with the objective of minimizing the total movement between departments. This could be an unrealistic assumption if different material handling systems are being used, resulting in varying transportation costs between departments. MICRO-CRAFT, PLANET, and STORM allowed the user to input different material flow costs between departments.

iv) Symmetric flow charts. Some algorithms assume the data matrices to be symmetric along the diagonal. This implies that a entry for flow between a pair of departments on one side of the matrix represents the total flow between the two departments and the entry for cost represents move-cost in either direction.

The REL Chart is always a symmetric chart, as in BLOCPLAN 90 and PLANET. STORM gave the user an option of entering either symmetric flow and cost charts, i.e. only the elements on one side of the diagonal, or charts with different elements on either side of the diagonal. MICRO-CRAFT required entries for all the elements of the Flow Chart and the Cost Chart.

v) **Data storage**. Data for a plant layout problem can be stored on disk files for revisions or generating layouts. BLOCPLAN 90, MICRO-CRAFT, and STORM had the option to load data from disk files for modifications and for developing fresh layouts. The program for PLANET had the option to load data from a disk file but only for the purpose of generating a copy of the layout. It did not have an option for modifying old data files. The data file to be input had to be loaded under the name PLT1.DAT. As soon as the option for data entry through disk file was chosen, the program started calculations and the user was not given any option to revise the data. For any modifications or changes in a PLANET data file, the Edlin editor has to be used.

3. **User interaction**. The User-interaction of a program is measured in terms of style of data input and various options for modifying data for observing the effect of the changes. For good user interaction, the data input would be in stages, with the option of revising data at every

step. The other type is block data input with low user interaction not allowing revisions.

BLOCPLAN 90, MICRO-CRAFT, and STORM have good user interaction capabilities and allow the user to review and revise the data at every step. The current PLANET program has low user interaction for data entry and making any modifications in the layout.

4. **Output**

i) Hard/soft Copy. The option for a printout of the layout produced is helpful for developing details of layout and visually comparing various layouts. Among the four packages, M-CRAFT and STORM had an option within the program for generating a hard copy output. BLOCPLAN 90 developed screen outputs of the layout and for generating hard copies, the Graphics file of DOS had to be used. MICRO-CRAFT generated graphical representation of the layout on the screen and the program offered an option to get a printout of the layout and the data used. STORM had a option of directing the output to three sources: screen, disk file, and a printer. The layout displayed on the screen could be printed through the Print Screen key or all displays on the screen could be directed to the printer and a report file. The outputs generated could be saved in the report file for future reference. PLANET placed the output generated in a file under the filename PLT.OUT. A graphical screen image could be created by the 'Type filename' command and a hard copy could be obtained by the printing the file. Different layouts could be stored by renaming the PLT.OUT file for every output.

ii) Contents. The contents of the output generated could be the layout and measures like layout score, distance between departments, satisfied adjacencies, etc. This data helps in analysis, generating alternate layouts, and developing detailed layouts. Each of the four programs provided different details.

BLOCPLAN 90 generated screen outputs for the total REL Score for each department, the block layout, and the Layout Score. A set of four more charts was presented. One chart gave X-Y coordinates of centers of departments and a REL Chart gave the satisfied adjacencies. Two other charts gave the product movement and flow distance between departments. All these details give a good measure of the layout generated and provide data for developing details.

MICRO-CRAFT presented the layout, layout dimensions, sequence of entry of departments into the layout, the cost of the layout, and a summary of the movement between departments. The STORM output was the block layout with the objective function value for the layout. Two other charts were given with STORM layout, one with departmental interaction values between pairs of departments and the other with a list of the contribution of each department towards the objective function value. PLANET output file had the layout input data including dimensions and flow information, the Normalized From-To Chart for material flow, the Normalized Flow-Between Cost Chart, and the layout with the layout cost.

The output provided by MICRO-CRAFT, PLANET, and STORM, gives reasonable measures of the quality of the layout generated and data for analysis, but not as much data to help develop layout details.

5. **Quality of output**. The layouts generated are either block layouts or layouts with different shapes of departments, not restricted to a defined boundary. The layout generated by BLOCPLAN 90 was a block layout of different size blocks. The size of the block depended on the area of the department it represented. Thus, the layout gave the relative location and size of departments which helps the user in developing details. This type of presentation is better than the equal area block layouts generated by some packages, e.g. STORM. The equal area block layout are good only for determining relative locations of the departments.

The layouts developed by MICRO-CRAFT and PLANET represented departments as a grid of the department number or identifier. The size of the grid for each department was representative of its area. For the MICRO-CRAFT generated layout the shape of the department varied with the number of bays in the layout. A small number of bays, e.g. 5, resulted in rectangular shapes for departments, whereas a higher number of bays, e.g. 20, resulted in departments spread out along the length of the layout. For PLANET, the outline boundary of the layout was not defined and restricted to any shape. The departments had irregular shapes which resulted in an irregular outline for the layout. Thus the layout would have to be modified to conform to the actual plant outline.

6. **Analysis of layout**. For analysis of the layout generated, the packages present charts and tables, which can be used by the designer to compare different layouts or develop details. BLOCPLAN 90 offered a comprehensive analysis for any layout. The first table presented the location of the centroid of every department in the X-Y plane. This could be used for measurements while developing details of the layout. A second table gave a REL Chart indicating the satisfied adjacencies, which gives a measure of the quality of the layout. Two charts gave the product movement and distance between departments. The program measured the quality of layout by calculating the Layout Score, the REL-DIST score, and the Total Product Movement between departments. Additionally, there was an option for exchanging locations of pairs of departments to satisfy requirements or check the effect on the quality of the layout.

MICRO-CRAFT offered one option for analysis. Any sequence of entry of departments could be input to obtain the layout for comparing it with other layouts developed by the program. The measure for comparison was the Total Cost of the layout.

PLANET did not have any option for analysis of the layouts developed. The layout cost could be used as the quantitative measure for comparing different layouts.

STORM offered good options for post solution analysis[10], which could be used for evaluating and comparing different layouts.

7. **Multi-story layout.** BLOCPLAN 90 was the only one of the four packages that develops multi-story layouts. However, it was limited to partitioning the departments into various stories. The departmental locations for each story had to be developed under the single-story option.

8. **Solution time.** The time taken to develop the layouts varies between the four computer algorithms. For the 10 department example problem solution, the time between the last entry of the input data and when the final layout was developed by the program, was measured using a Stop-watch. The solution times recorded for runs on the AT&T 6286 terminals were:

BLOCPLAN 90	-	less than 2 seconds for single-story layouts with REL Chart or with Product Flow REL Chart
MICRO-CRAFT	-	173 seconds for layout with 5 bays.
	-	287 seconds for layout with 10 bays.
	-	521 seconds for layout with 20 bays.
PLANET	-	between 7 to 10 seconds for generating the output file
STORM	-	less than 2 seconds.

[10]. A description of the options is given with the example problem solution.

7. Conclusions

Facilities layout is an age-old industrial engineering problem. The research on the subject has involved modelling the facilities layout problem using mathematical techniques and computer muscle, resulting in a number of layout packages. The software review represents the variety of Computer Aided Facilities Layout packages developed over the years.

The layout packages approach the problem from different perspectives, with a common goal of generating layouts that satisfy qualitative or/and quantitative criteria. The speed and computational power of the computer helps in different stages of generating layouts. The packages differ in terms of the data required, the algorithm used, and the type of layout generated, as summarized in **Table 33**. The different approaches used by the packages make them usable for different kinds of problems.

For expressing departmental relations, the packages use qualitative data, quantitative data, or a combination of the two. Further, the options for layout specifications, like fixed locations, shape of facilities, etc., vary between packages. For new layouts it is easier to express departmental relations using qualitative data, whereas for improving existing layouts either of the two types of data can be obtained. The qualitative data used in the REL chart divides the relations between departments in a maximum of six levels. This limits the users ability to finely distinguish between departmental relations and relative locations desired, in the absence of quantitative data.

The computer packages try to overcome the handicap of limited data by allowing the user to easily generate layout alternatives. However, the choice for the best, or the most acceptable, layout is left to the user because of the limited measures provided to score the layouts.

Most of the construction and improvement algorithms used in the packages discussed here, use a single criteria objective function. Commonly used criteria are material flow cost and departmental relations. A limited number of packages use an objective function which includes a weighted sum of various criteria. Such an objective function allows the user to include details to develop good layouts.

The algorithms used consider the effect of change in locations of two departments at a time. A more comprehensive method can be to check the effect of changing locations of three (or more) departments at a time. However, such calculations would require high speed computers for obtaining solutions in acceptable limits of time.

The packages have limited graphic capabilities for representing departments. The layouts generated are either equal, or unequal, area block layouts or layouts with areas represented as matrices of departmental identifiers. The layouts generated do not necessarily provide the final shape of departments and leave the details to the user.

Experimentations with the four CAFL packages helped in understanding the process of layout design and the capabilities of the packages available.

The example problem solution presented here verifies the features of layout packages discussed above. This endorses the observation that a layout package can be used to prepare good outlines for layouts and decisions for the final layout and layout details are left for the user.

From the above discussion, it is concluded that good CAFL packages should

: accept both, quantitative and qualitative data

: provide the user flexibility in data input for layout specifications like fixed locations, facility shapes, etc.

: have a multiple-criteria objective function

: use a combination of construction and improvement algorithms

: be able to generate layouts with equal or unequal area facilities

: generate and compare alternate solutions

: have an ability to evaluate solutions using different measures with an eye towards practical applications.

: have graphical capabilities of generating facility and layout details

: have low memory and computation time requirements

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