Chapter 15. Computer-Aided Layout

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15.1. Introduction

Definition

Computer Aided Layout or **CAL** is the design and/or improvement of facility layouts with the help from computer programs.

Advantages of CAL

- The computational power and accuracy of the computer allow the generation and evaluation ***of many alternative layouts***.
- The computer solves each problem on its own merit following ***objective and systematic*** procedures and possibly will generate innovative or unusual layouts.
- The computer requires explicitly a ***clear problem*** and objective definition
- The computer requires a rigorous data preparation

Disadvantages of CAL

- The limitations of the current CAL programs force a ***severe simplification*** of the layout problem in order for it to be solvable.
- The computer cannot incorporate ***subjective objectives*** and/or constraints.

Evaluation of CAL usage

The CAL programs are a very useful help for the generation of many alternative and initial layouts, but they are currently unable to produce without human help and fine tuning a feasible final layout. The layouts generated by CAL programs require human interpretation and adjustment.

15.2. Spiral

General Characteristics

The **Spiral** algorithm consists of two major steps. In the first step, the fundamental principle of the **Spiral** algorithm is to grow a high weight, planar, hexagonal adjacency graph in a greedy fashion. In the second step, this graph is converted into a block layout with all rectangular departments and with material handling aisles parallel to one of the hexagon axes.

The **Spiral** algorithm grows the relationship diagram in a crystalline, spiraling fashion. The original, manual form of this algorithm was first mentioned in Reed (1967). It relies completely on the insight of the engineer. A more sophisticated version, which incorporates relationships with the outside and neighborhood improvement steps, is given in Goetschalckx (1986, 1992).

The objective is to maximize the adjacency score based on a qualitative or numerical relationship chart. Departments are represented by standard, size independent symbols such as squares or circles.

The data requirements are either a qualitative letter or quantitative relationship chart.

The spiral technique is one of the manual techniques to construct an adjacency graph or relationship diagram based upon a quantitative relationship matrix or flow matrix. The spiral technique grows the graph in a crystalline manner by adding the department, which has the highest spiral relationship next to the graph so that the graph adjacency score is maximized. As such the manual spiral algorithm is an example of a greedy, heuristic construction procedure.

The following definitions are based upon the Systematic Layout Planning method or SLP by Muther (1973). A relationship chart is the quantitative matrix containing the level of interaction between pairs of departments. The more positive the element in the matrix, the stronger two departments interact and, in general, the closer to each other they should be located. The more negative the relationship, the stronger two departments are incompatible with each other and, in general, the farther apart they should be located. A relationship diagram is a spatial arrangement of the departments to represent the relationship data in a graphical way. This diagram is also called an adjacency graph. When the space requirements for the departments are added to this relationship diagram, then a space relationship diagram has been constructed. Finally, any number of other considerations and constraints, that are not captured in the relationship data or the space data, can be incorporated in the space relationship diagram to generate a layout alternative. Hence, the spatial relationship diagram is not a layout, because it does not incorporate other considerations such as building shape and area and department shape constraints.

In the first phase, the spiral technique attempts to construct a good relationship diagram. The quality of the relationship diagram is measured by the adjacency score. Hence, the objective is to maximize the positive flow or relationships between adjacent departments and to minimize the negative flow or relationships between adjacent departments. Observe that later on the objective is to minimize the weighted distance score of the final block layout.

The data requirement for the spiral technique is the quantitative relationship chart for phase one and the department and building areas for phase two.

Spiral Procedure

Step 1.
Convert the asymmetrical relationship matrix into a symmetric matrix by adding the two corresponding elements above and below the main diagonal resulting in a single element above the main diagonal. At this time the relationship matrix is reduced to a upper triangular matrix.

Step 2.
Create a list of adjusted spiral relationships based on the size of the tuple selected. A null tuple implies a random list of departments. For the unary tuple, each department has a single spiral relationship equal to the sum of all its binary relationships. The relationships are indexed by that department. For the binary tuple, the spiral relationships are equal to the (binary) relationships in the relationship matrix. The relationships are indexed by the department pair. For the ternary tuple, the spiral relationship is the sum of the three binary relationships between the three departments in the triplet. The relationships are indexed by this department triplet.

Next, the relationships with the outside are incorporated. A department with a high positive spiral relationships will tend to be located early on in the procedure and hence on the inside of the graph. Similarly, a department with a small positive or a negative spiral relationship will tend to be located late and hence towards the perimeter of the graph. To incorporate the relationships with the outside in a consistent manner each spiral relationship is adjusted by subtracting the relationship of the departments in the tuple with the outside. For example, the adjusted unary, binary, and ternary spiral relationship (denoted by the subscript adj) are computed from the original relationships in the relationship matrix (denoted by the subscript orig) as:

$$r_{adj}(i) = \sum_{j=1}^{M} r_{orig}(i,j) - r_{orig}(i,0) \tag{15.1}$$

$$r_{adj}(i,j) = r_{orig}(i,j) - r_{orig}(i,0) - r_{orig}(j,0) \tag{15.2}$$

$$\begin{aligned} r_{adj}(i,j,k) = {} & r_{orig}(i,j) + r_{orig}(i,k) + r_{orig}(j,k) \\ & - r_{orig}(i,0) - r_{orig}(j,0) - r_{orig}(k,0) \end{aligned} \tag{15.3}$$

where M is the total number of departments in the layout and 0 indicates the artificial outside department.

Step 3.

Rank the spiral relationship by decreasing (non-increasing) value. Note that any negative relationship is smaller than all positive and zero relationships.

Step 4.

Place the departments in the relationship diagram (without regard to their space requirements) in such way that the positive relationships between adjacent departments are maximized and the negative relationships between adjacent departments are minimized. Observe that the original, not the adjusted, relationships are used to determine the best location for the department to be placed. If any location ties exist, then the list can be checked further down to break the ties. If a tie still exists at the end of the list, then it can be broken arbitrarily.

The shape and size of the departments in the relationship diagram should be independent of the true department size and shape. A neutral symbol, such as a circle or hexagon, is preferred. All relationships between department pairs of which all departments are placed can be eliminated from the list of relationships.

If more than one alternative relationship diagram is required, then step 3 can be repeated.

Evaluation Procedure

The hexagonal adjacency graph is evaluated with the adjacency score and efficiency. The adjacency score is the product of the adjacency and relationship matrices.

$$A = PA + NA \tag{15.4}$$

$$e = \frac{PA - NS}{PA + PS - NS - NA} \tag{15.5}$$

The shape distance score is the sum of the distance score and the shape penalty. The flow distance score is the product of the department centroid-to-centroid distance and the relationship matrix. The distance from a department to the outside is the smallest distance of its centroid to the building perimeter. If a department exceeds its maximum allowable shape ratio, then the excess shape ratio is multiplied by the department's shape penalty. The sum of all department shape penalties makes up the shape penalty.

$$d_{ij}^R = |x_i - x_j| + |y_i - y_j| \tag{15.6}$$

$$d_{io}^R = \min\{x + w/2, y + l/2, W - x - w/2, L - y - l/2\} \tag{15.7}$$

The total flow distance is then equal to

$$D = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} d_{ij}^R \cdot r_{ij} + \sum_{i=1}^{N} d_{io}^R \cdot r_{io} \tag{15.8}$$

The shape adjusted distance score *SD* is then equal to:

$$SD = D + \sum_{i=1}^{N} \max\{0, s_i - S_i\} \cdot p_i \tag{15.9}$$

Special Characteristics

Modern versions can incorporate relationships with the outside and have an improvement phase appended. **Spiral** is relatively user friendly, it is a third generation program.

Design of Experiments

A full factorial design of experiments to generate a relationship diagram with the **Spiral** involves:

- the selection of the seed of the random number generator
- the number of replications
- the tuple of the relationships
- the degree of graph improvements
- the node location tie breaker
- the orientation of the building
- the degree of layout improvements
- the shape penalty

Examples

Tompkins Example

Consider a layout project for a seven department facility. The space requirements and the flow from-to-chart are given below. The flow chart is based on the number of trips per day with an electric platform truck. This example was first given in Tompkins and Moore (1978) and has become the classical example to illustrate layout algorithms. The example, however, does not have any relationships with the outside, nor does it give maximum shape constraints.

Table 15.1. Departmental Data

	A	B	C	D	E	F	G	Function	Area
A		45	15	25	10	5		Receiving	12,000
B				30	25	15		Milling	8,000
C					5	10		Press	6,000
D		20			35			Lathing	12,000
E						65	35	Assembly	8,000
F		5			25		65	Plating	12,000
G								Shipping	12,000

The first step converts the asymmetric matrix into a symmetric one. The sum of all relationships is equal to 435.

Table 15.2. Symmetric Department Relationship Data

	A	B	C	D	E	F	G	Function	Area
A		45	15	25	10	5		Receiving	12,000
B				50	25	20		Milling	8,000
C					5	10		Press	6,000
D					35			Lathing	12,000
E						90	35	Assembly	8,000
F							65	Plating	12,000
G								Shipping	12,000

Step two creates the adjusted relationships, which in this case is easy since there are no outside relationships. Step three ranks the relationships by non-increasing value.

Table 15.3. Ranked Relationships

Index	Pair	Value	Index	Pair	Value	Index	Pair	Value
1	EF	90	8	BE	25	15	AG	0
2	FG	65	9	BF	20	16	BC	0
3	BD	50	10	AC	15	17	BG	0
4	AB	45	11	AE	10	18	CD	0
5	DE	35	12	CF	10	19	CG	0
6	EG	35	13	AF	5	20	DF	0
7	AD	25	14	CE	5	21	DG	0

In step four the departments are placed in the relationship diagram in such way as to maximize the sum of adjacent flows. The selection and location procedure are intermixed, because department selection depends on the current partial diagram. The selection process is essentially a greedy selection of the next department based on a list of pairwise relationships.

The flow EF is the largest, hence departments E and F are placed next to each other.

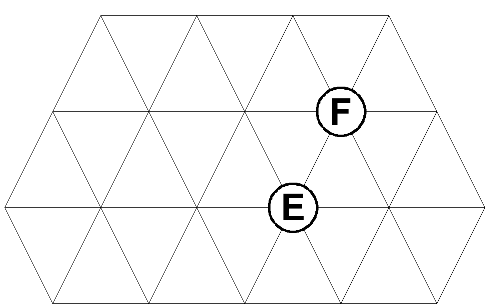

Figure 15.1. Spiral **Adjacency Graph with 2 Departments**

The largest relationship with an anchor department already located is now FG. Department G will be located adjacent to department F, but there exist alternative locations. Department G has both positive flows with departments F and E, so it is placed adjacent to both. There still exists a tie between locations left or right of departments E and F, which is broken arbitrarily.

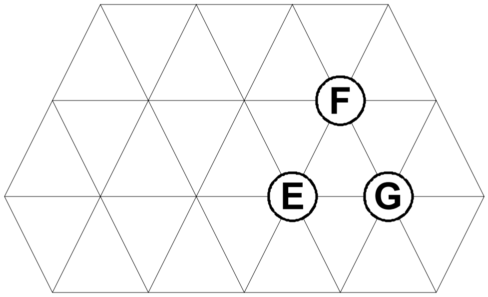

Figure 15.2. Spiral **Adjacency Graph with 3 Departments**

The next largest relationship with a department already in the layout is relationship DE. Department D will be placed adjacent to department E, but there exist alternative locations. Checking down the list shows that department D has no further relationship with any of the already located departments and the tie is thus broken arbitrarily.

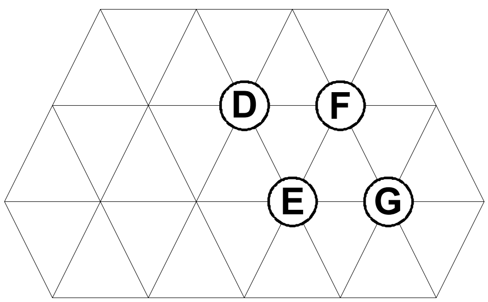

Figure 15.3. Spiral **Adjacency Graph with 4 Departments**

The next largest flow with an already located department is BD. Department B will be placed adjacent to department D. To break the tie, the first located department down the list with a relationship with B is department E. Hence department B will be located in the unique location adjacent to D and E.

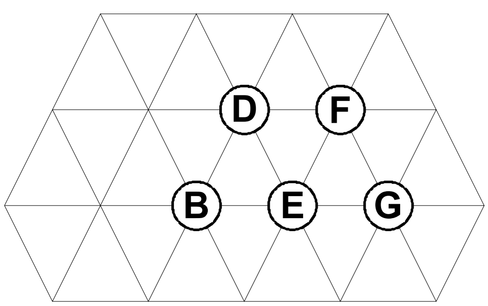

Figure 15.4. Spiral **Adjacency Graph with 5 Departments**

The largest flow is now AB. Department A has positive flows with departments B, D and E in that order. There is a single unique location adjacent to departments B and D, so department A is placed adjacent to departments B and D.

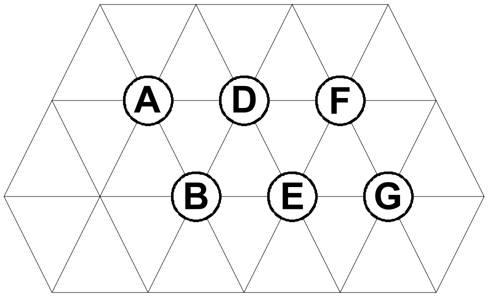

Figure 15.5. Spiral **Adjacency Graph with 6 Departments**

The largest flow is now AC. Department C has positive flows with departments A, F and E. It cannot be adjacent to A and to either F or E, so it is placed in an arbitrary location adjacent to department A.

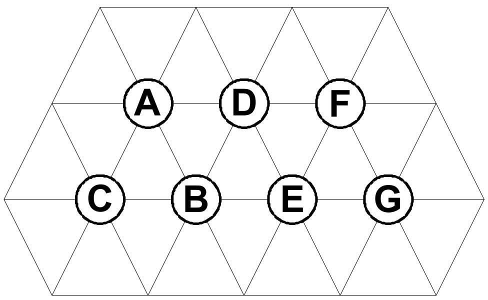

Figure 15.6. Spiral **Adjacency Graph with 7 Departments**

Since all the relationships are positive, the evaluation is done immediately with the original adjacency matrix. The adjacency matrix is multiplied element by element with the symmetric relationship matrix to generate the adjacency score.

Table 15.4. Adjacency Matrix

	A	B	C	D	E	F	G
A		1	1	1			
B			1	1	1		
C							
D					1	1	
E						1	1
F							1
G							

The adjacency score is equal to 385. The efficiency is then equal to 385 / 435 or 89 %.

If random location ties are broken differently, then the diagram of Figure 15.7 is generated. Its efficiency is equal to 405 / 435 = 93 %.

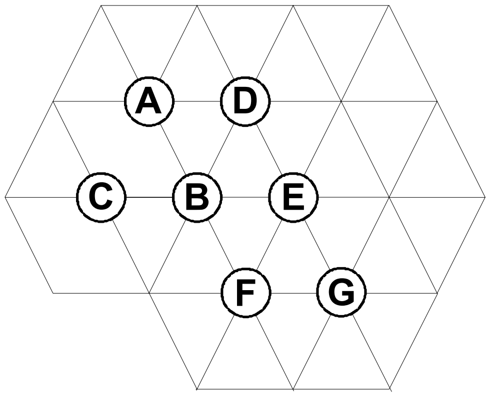

Figure 15.7. Alternative Spiral **Relationship Diagram**

In the second phase, **Spiral** converts the hexagonal adjacency graph into a rectangular block layout. The building has to be rectangular and all department shapes will also be rectangular. **Spiral** constructs the block layout based upon layers. Each layer corresponds to all departments on an axis of the hexagonal adjacency graph. Once the departments in a layer are determined, the area of this layer and the shape of each department in the layer can be computed.

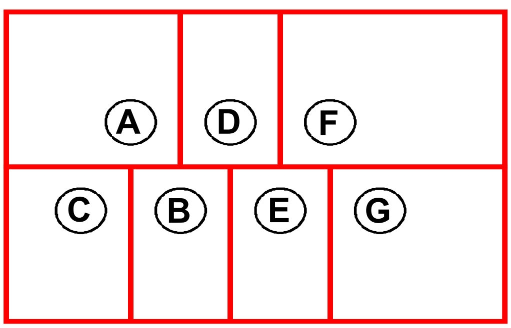

Figure 15.8. Spiral **Layout Construction Illustration**

The following graph was generated with the binary relationships and no exchange improvements and the centroid seeking tie breaker. The seed was set to 25795 and the maximum number of replications was set equal to one. The resulting adjacency score was 385 and the efficiency score was 88.5 %.

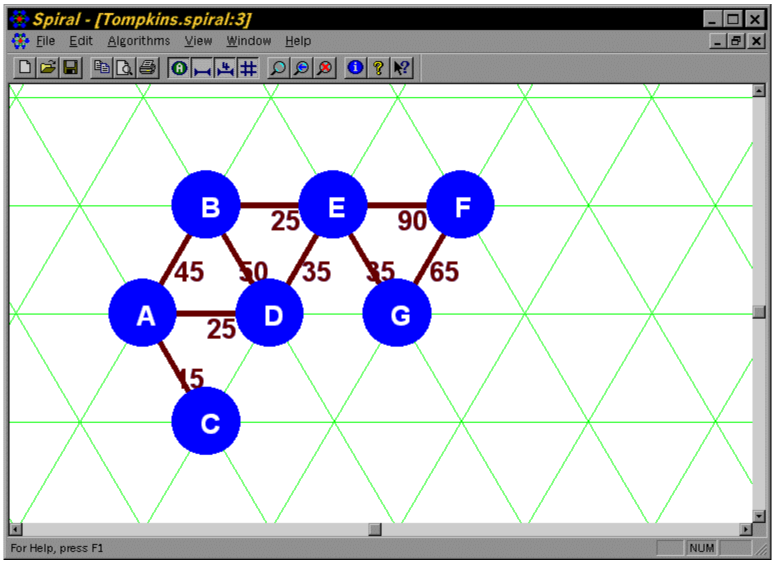

Figure 15.9. Spiral **No-Exchange Graph for the Tompkins Example**

The layout was then generated with the level building orientation, no exchange improvements, and the layered space allocation method. The maximum shape ratio was equal to 2.0 and the shape penalty was equal to 500. In the resulting layout, depament C has a shape ratio of 16.7, while all other departments have shape ratios less than two. The corresponding distance score was 9359 of which 2026 was the flow distance score and the balance of 7333 was generated by the shape penalty for department C.

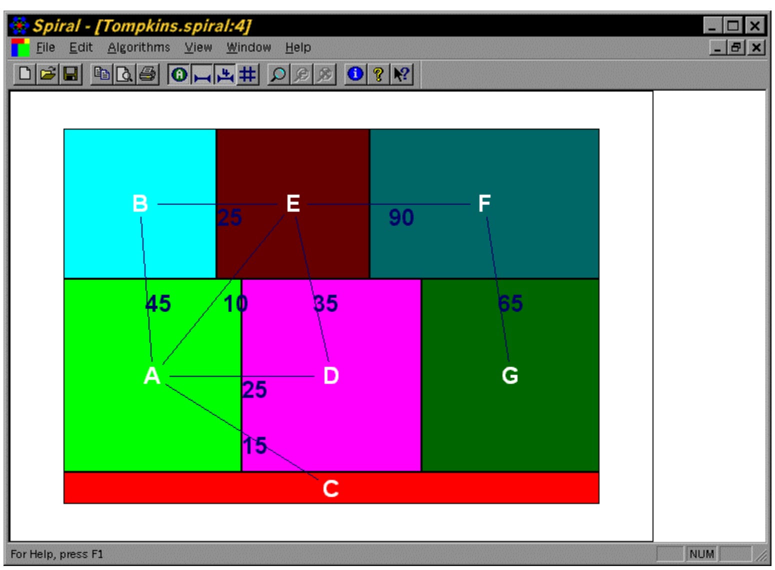

Figure 15.10. Spiral **No-Exchange Layout for the Tompkins Example**

The following graph was generated with the binary relationships and steepest descent three exchange improvements and the centroid seeking tie breaker. The maximum number of replications was set to ten. The resulting adjacency score was 405 and the efficiency was 93.1 %.

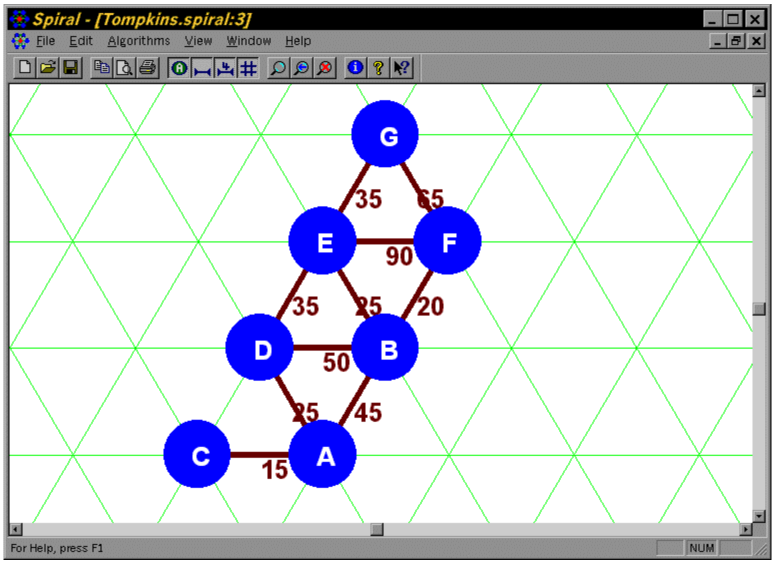

Figure 15.11. Spiral **Three Exchange Graph for the Tompkins Example**

The layout was then generated with the upwards building orientation and no exchange improvements. The maximum shape ratio was equal to 2.0 and the shape penalty was equal to 500. In the resulting layout, department C has a shape ratio of 2.41, while all other departments have shape ratios less than two. The corresponding distance score was 2164 of which 1961 was the flow distance score and the balance of 203 was generated by the shape penalty for department C.

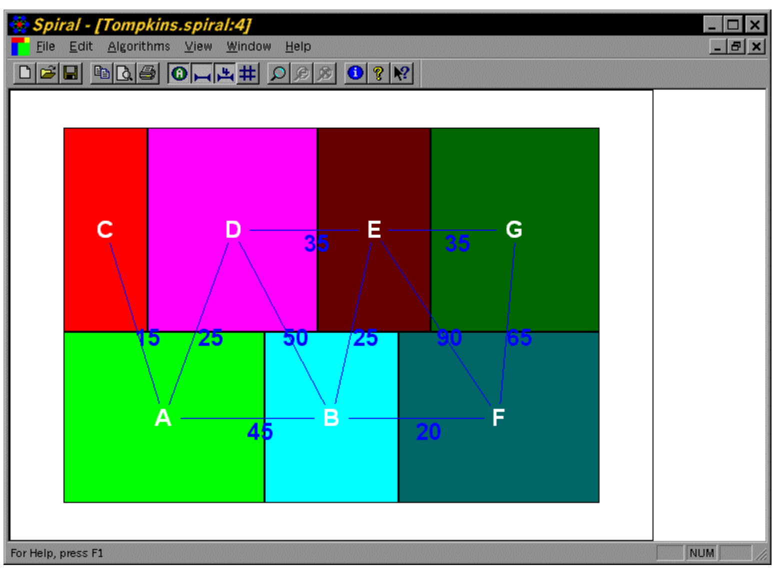

Figure 15.12. Spiral **No-Exchange Layout for the Tompkins Example**

The layout was then generated with the upwards building orientation and steepest descent three exchange improvements. The maximum shape ratio was equal to 2.0 and the shape penalty was equal to 500. The resulting distance score was 1700 and there were no shape violations.

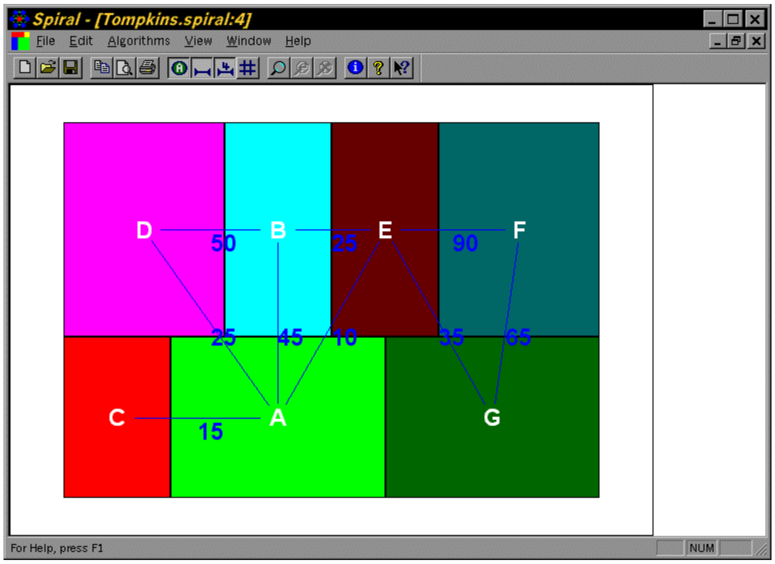

Figure 15.13. Spiral **Three Exchange Layout for the Tompkins Example**

A typical screen of **Spiral** with multiple views for the Tompkins example is shown in the next figure.

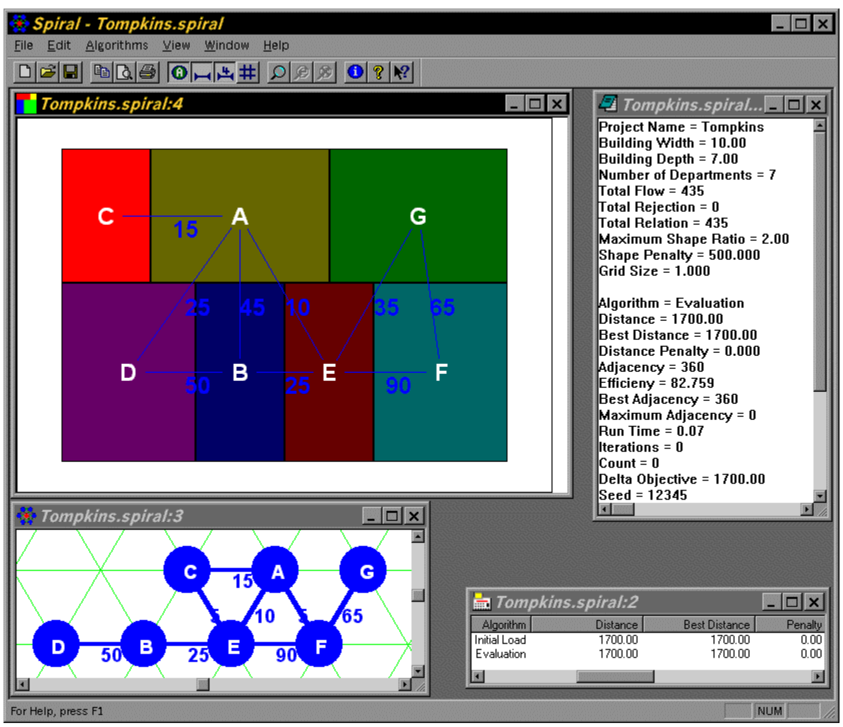

Figure 15.14. Spiral Application Tompkins Example Illustration

Autoparts Example

The Parts is Parts company has contracted you for consulting services to layout their new facility in Springfield, Tennessee. The company produces stamped metal parts in this plant from sheet metal coils to be used in automotive assembly. The plant consists of five major departments. Some of the parts may have to be treated with corrosion resistive paint and then dried in an oven. Forklift trucks are used for all material handling transportation operations in the plant. A summary of the department data is given in Table 15.5. The number of truck trips per week between each pair of departments and between each department and the outside is given in Table 15.6. The building dimensions are 200 by 120 feet.

Table 15.5. Department Data for the Parts Example

Label	Function	Area	Maximum Shape Ratio	Shape Penalty
SHI	Shipping	4,000	3.0	15,000
REC	Receiving	2,000	3.0	10,000
STA	Stamping	10,000	1.5	25,000
PAI	Painting	6,000	2.0	50,000
STO	Steel Coil Storage	2,000	4.0	10,000
OUT	Outside			

Table 15.6. Material Handling Trips for the Parts Example

	OUT	SHI	REC	STA	PAI	STO
OUT			50			
SHI	300					
REC				15		35
STA		240			60	
PAI		60				
STO				35		

Create a hexagonal adjacency graph and block layout following the Spiral methodology. For the graph construction phase, use the binary relationships, do not use improvement interchanges, and break location ties by the centroid-seeking rule. For the graph, show first the symmetrical adjusted relationships in a two-dimensional matrix. Show next the sorted list of adjusted binary relationships. Third, show the adjacency graphs after you have added each department. Finally, compute and show the adjacency and efficiency score of the final graph.

We first convert the asymmetrical material handling trips to a symmetric relationship table, where all relationships are shown above the main diagonal.

Table 15.7. Symmetric Relationships for the Parts Example

	OUT	SHI	REC	STA	PAI	STO
OUT		300	50			
SHI				240	60	
REC				15		35
STA					60	35
PAI						
STO						

Next the adjusted binary relationships are computed, that incorporate the relationships with the outside. Because several departments have positive relationships with the outside, many of the adjusted relationships are negative.

Table 15.8. Binary Adjusted Relationships for the Parts Example

	SHI	REC	STA	PAI	STO
SHI		-350	-60	-240	-300
REC			-35	-50	-15
STA				60	35
PAI					0
STO					

The adjusted binary relationships are then sorted in decreasing order.

Table 15.9. Sorted Binary Adjusted Relationships for the Parts Example

Index	Dept. 1	Dept. 2	Relation	Index	Dept. 1	Dept. 2	Relation
1	STA	PAI	60	6	REC	PAI	-50
2	STA	STO	35	7	SHI	STA	-60
3	PAI	STO	0	8	SHI	PAI	-240
4	REC	STO	-15	9	SHI	STO	-300
5	REC	STA	-35	10	SHI	REC	-350

The first two departments to enter the hexagonal adjacency graph are the two departments in the first element of the list, i.e. STA and PAI. They are placed at random in two adjacent vertices of the hexagonal grid.

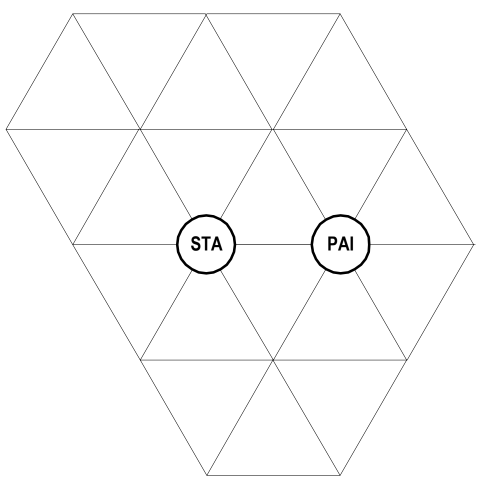

Figure 15.15. Adjacency Graph with 2 Departments for the Parts Example

The next relationship selected must have one department in the graph and one department not in the graph, called the anchor department and the new department, respectively. The anchor department also must have an open adjacent grid position. Element two of the list satisfies all those conditions:

department STA is in the graph, department STO is not, and department STA has an empty adjacent grid position. All empty grid positions adjacent to the anchor department are possible locations for the new department, and because of the relationship selection rule there exists at least one open adjacent grid position. The grid position with the highest adjacency score based on the original symmetric relationships is selected. Ties are broken by the centroid-seeking rule, i.e. the new department is located in the open grid location adjacent to the anchor department that tied for the highest adjacency score and that is closest to the centroid of the current adjacency graph. Department STO has only a relationship with department STA, and thus all open grid positions adjacent to department STA are tied. There are two grid position closest to the centroid of the graph and the one above the centroid is selected at random.

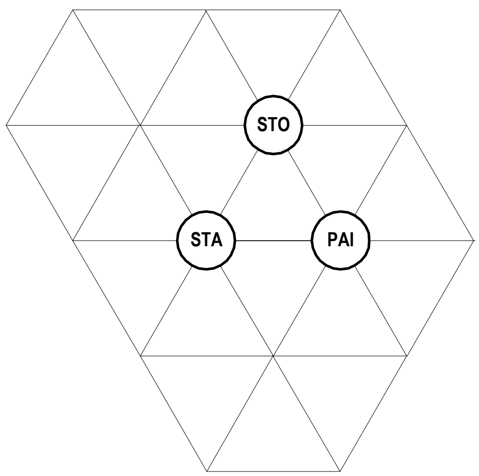

Figure 15.16. Adjacency Graph with 3 Departments for the Parts Example

Element four is the next relationship selected from the list. Department STO is in the graph, department REC is not, and department STO has an open adjacent grid position. Department REC has a positive relationship with departments STA and STO and so the open grid position adjacent to both those department is the selected location for department REC.

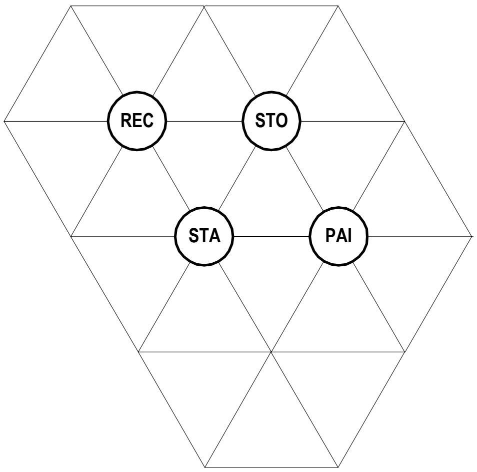

Figure 15.17. Adjacency Graph with 4 Departments for the Parts Example

Department SHI is the only remaining free department. Element seven is the next selected relationship, since department STA is in the graph, department SHI is not in the graph, and department STA has an open adjacent grid location. All open grid positions adjacent to department STA are candidate locations. Since department SHI has positive relationships only with departments STA and PAI, it will be located in the open grid location adjacent to those two departments.

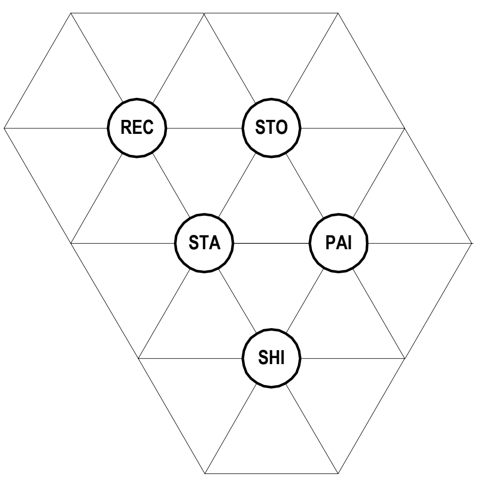

Figure 15.18. Adjacency Graph with 5 Departments for the Parts Example

To compute the adjacency score, we construct the adjacency matrix for the graph above.

Table 15.10. Adjacency Matrix for the Parts Example

	OUT	SHI	REC	STA	PAI	STO
OUT		1	1	1	1	1
SHI				1	1	
REC				1		1
STA					1	1
PAI						1
STO						

The adjacency matrix is then multiplied element by element with the symmetrical relationship matrix and the sum of the product is computed. The sum is equal to 795. Since the sum of the absolute values of all relationships is also equal to 795, the efficiency of the above graph is equal to 100 %.

For the block layout phase, use the graph axis with the most departments in your graph as the building orientation, do not use improvement interchanges, and use the layered space allocation method. For the layout phase, first show the layout drawn to scale with all departments properly dimensioned. Clearly indicated all units. Next, show all distances in a two-dimensional matrix of which you only need to fill in the upper half. Third, compute and show the inter-department distance score and the distance score with the outside. Fourth, compute and show clearly the shape penalty score for each individual department and the total shape penalty. Finally, compute and show the shape adjusted distance score.

The graph axis with the most departments is oriented downwards. The conceptual block layout with the layered space allocation method is shown in the next figure.

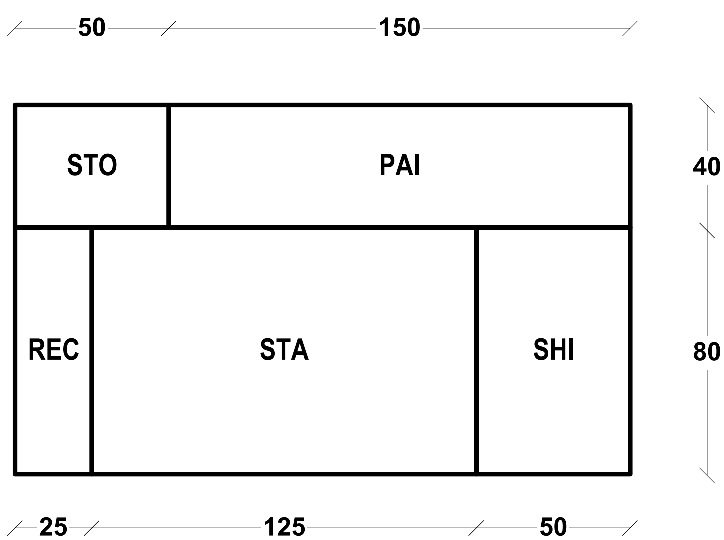

Figure 15.19. Block Layout for the Given Graph for the Parts Example

Table 15.11. Distance Matrix for the Parts Example

	OUT	SHI	REC	STA	PAI	STO
OUT		25.0	12.5	40.0	20.0	20.0
SHI			162.5	87.5	110.0	210.0
REC				75.0	72.5	72.5
STA					97.5	122.5
PAI						100.0
STO						

The distance matrix is then multiplied element by element with the symmetrical relationship matrix and the sum of the products is computed. This sum is the flow distance score and is equal to 49,525, of which 41,400 is between two departments and 8,125 is between departments and the outside.

Table 15.12. Penalty Shape Computations for the Parts Example

Dept.	Actual Shape	Maximum Shape	Delta Shape	Penalty Rate	Shape Penalty
SHI	1.6	3	0	15000	0
REC	3.2	3	0.2	10000	2000
STA	1.5625	1.5	0.0625	25000	1563
PAI	3.75	2	1.75	50000	87500
STO	1.25	4	0	10000	0

The total shape penalty is computed as the sum of the individual department shape penalties and is equal to 91,063. The total shape distance score for the layout is computed as the sum of the flow distance score and the shape penalty and is equal to 140,588.

The block layout without exchange improvements, the best block layout with the layered space allocation method, and the best block layout with the tiled space allocation method are shown in the next three figures. The distance statistics for the three layouts are shown in the next table.

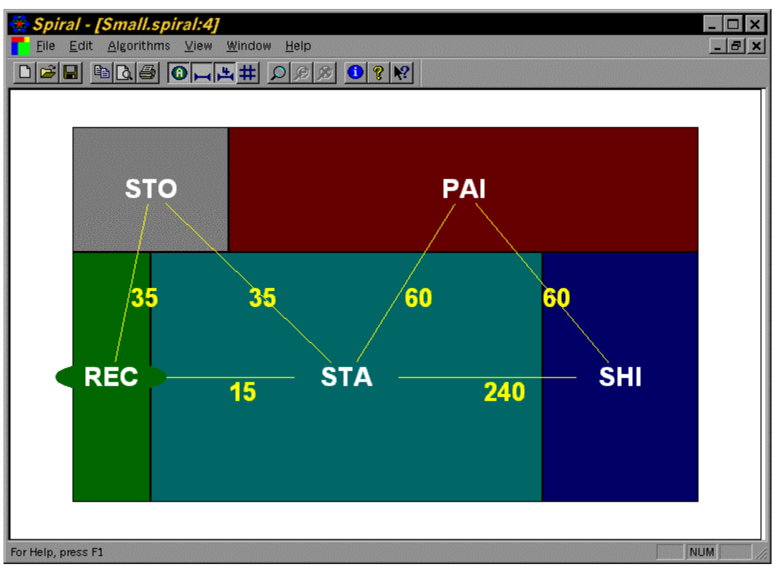

Figure 15.20. Unimproved Block Layout for the Given Graph for the Parts Example

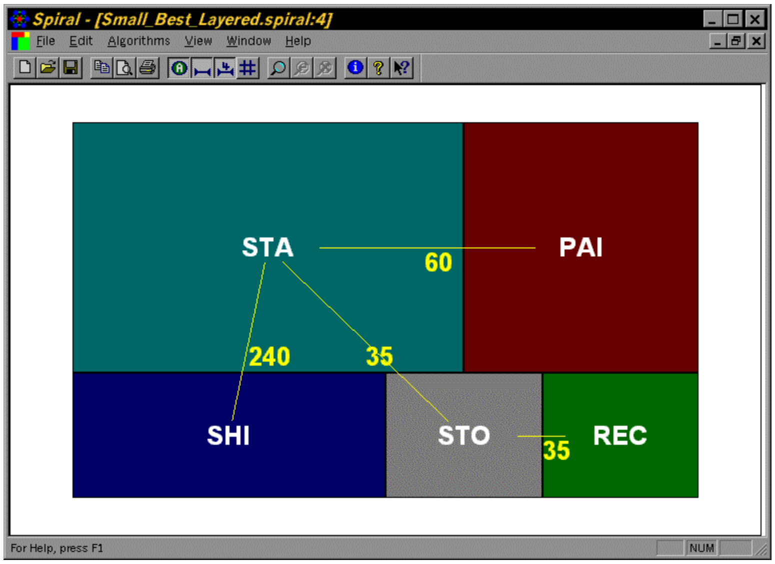

Figure 15.21. Best Layered Block Layout for the Given Graph for the Parts Example

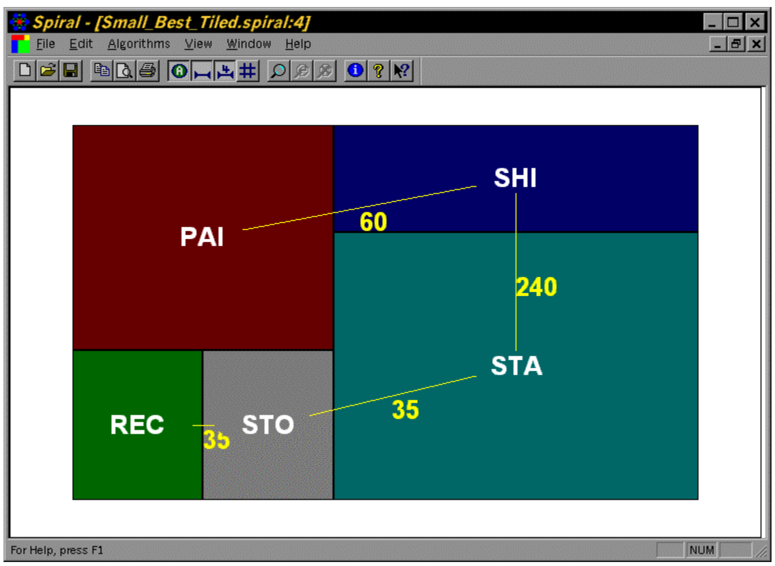

Figure 15.22. Best Tiled Block Layout for the Given Graph for the Parts Example

Table 15.13. Distance Statistics for the Parts Example

	Unimproved	Best Layered	Best Tiled
Flow Distance	49,525	49,375	43,169
Shape Penalty	91,063	1,563	6,042
Shape Distance	140,588	50,938	49,211

Furniture Example

Consider a layout project for a ten department facility. The furniture example was first published in Montreuil et al. (1987). The example used here was published in Goetschalckx (1992). The example has relationships with the outside, but it does not have maximum shape constraints.

The following graph was generated with using the ternary relationships and steepest descent two exchanges and centroid seeking tie breaker. The initial seed was 30265. The adjacency score for the graph is equal to 347. The sum of the absolute values of all relationships is 416, which yields an efficiency score of 91.6 %.

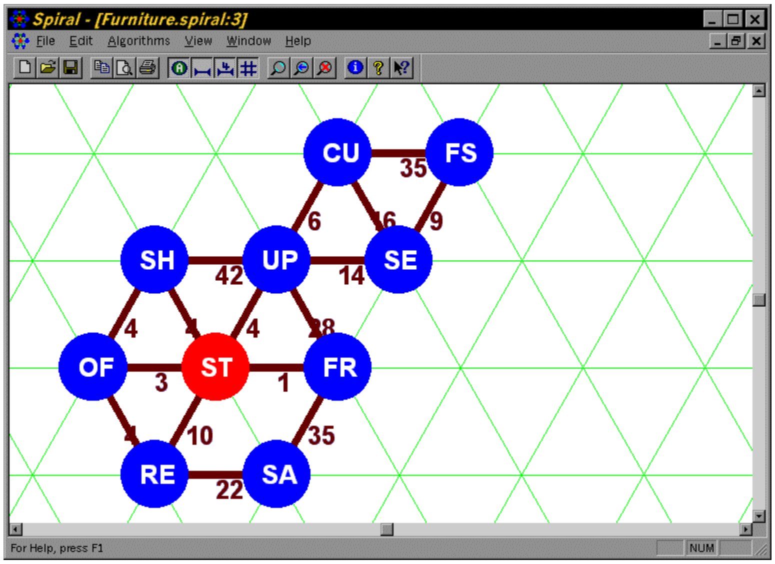

Figure 15.23. Spiral **Adjacency Graph for the Furniture Example**

The following layout was generated with the level building orientation and steepest descent three exchanges. The maximum shape ratio was set to 3.0 and shape penalty was equal to 500. The resulting distance score was equal to 607 and there were no shape violations.

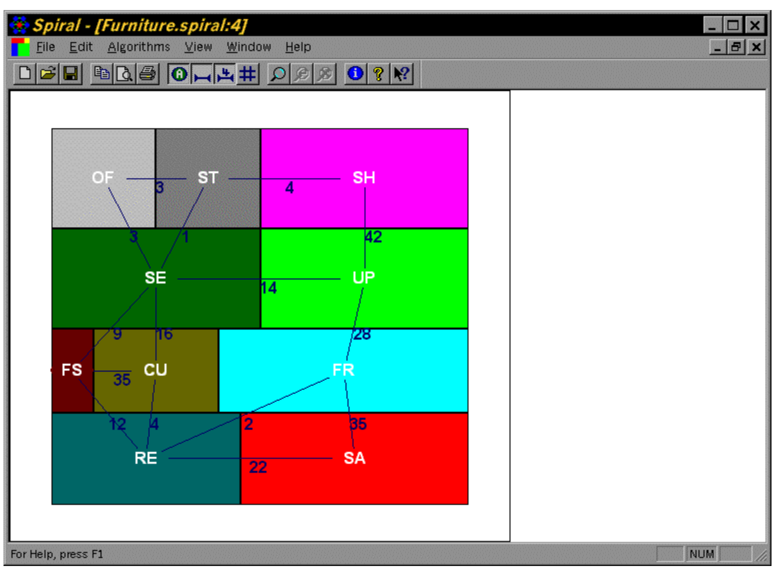

Figure 15.24. Spiral **Block Layout for the Furniture Example**

Conclusions

The first phase of Spiral has the following advantages. It generates many alternative planar adjacency graphs with very little user involvement. The graphical interface facilitates easy interpretation of the results. Spiral has the following disadvantages. The quality of each relationship diagram is rather limited. The graph can be improved by local improvement procedures such as steepest descent two exchanges and three exchanges. Hence, Spiral uses a kind of shotgun approach to design a good relationship diagram. The first phase of the Spiral technique is very a good method for visualizing and organizing the flow within a facility. It provides for an easy way to generate a first cut relationships diagram. But a high scoring graph will not necessarily lead to a high quality layout. Therefore, the quality of the final layout based upon the adjacency graph depends on the insight and persistence of the facilities planner.

The second phase of Spiral has the following advantages. It generates many alternative block layouts with very little user involvement. The layout can be improved by local improvement procedures such as two exchange and three exchange. The departments all have a rectangular shape. The layout shows natural material handling aisles. The advantages of layouts generated with **Spiral** are illustrated in Figure 15.25, which shows the layout for a facility with 37 departments. Observe the potential for east-west material handling aisles. The graphical interface facilitates easy interpretation of the results. **Spiral** has the following disadvantages. The departments might have an unacceptable shape, i.e. be very long and narrow rectangles. A maximum shape ratio can be specified, but the algorithm does not always satisfy the shape constraints. For the complex example, the shape distance score is 11,782, of which 8,981 is caused by the flow distance score and the remainder of 2,801 by the shape penalty.

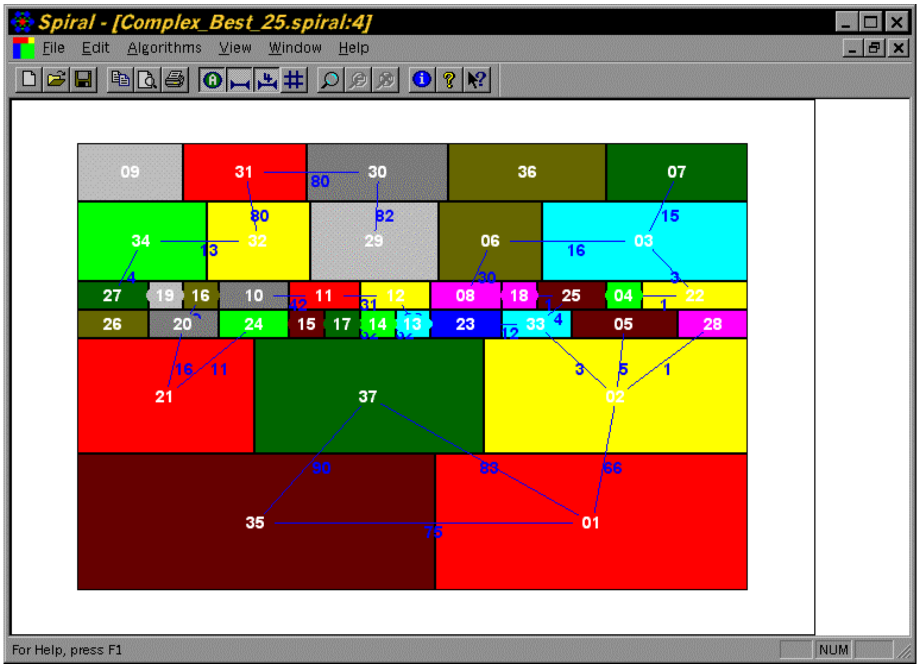

Figure 15.25. Spiral **Layout for Complex Case with Maximum Shape Factor = 2.5**

To summarize, the Spiral technique should never be used independently, but it is very helpful as a first step in the layout process.

15.3. LayOPT

General Characteristics

Discrete (Unit Squares)

Minimize Rectilinear Distance Score

Quantitative Flows

Improvement Procedure

LayOPT is based on the algorithm for the layout of multiple floors based on spacefilling curves, published by Bozer et al (1994).

Spacefilling Curve

Fractal Curve

Maps Unit Interval onto Unit Square

Close on the Curve is Close in the Layout

Finite Approximations

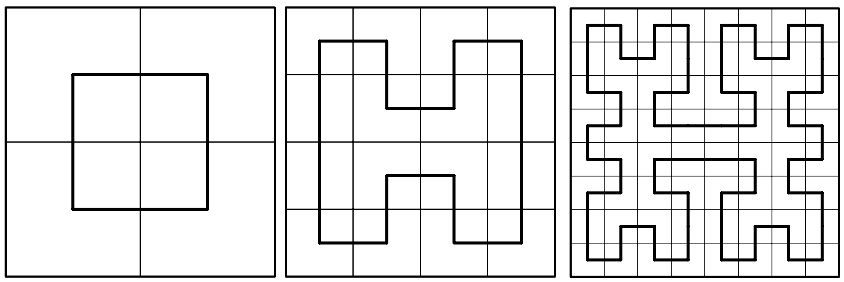

Figure 15.26. Spacefilling Curves of Increasing Approximation Levels

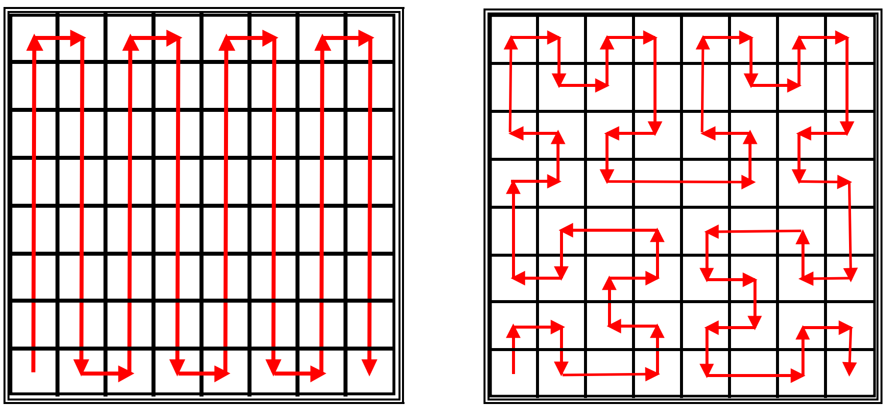

Figure 15.27. Space Filling Curve Examples (Sweep and Hilbert-19)

LayOPT Illustration

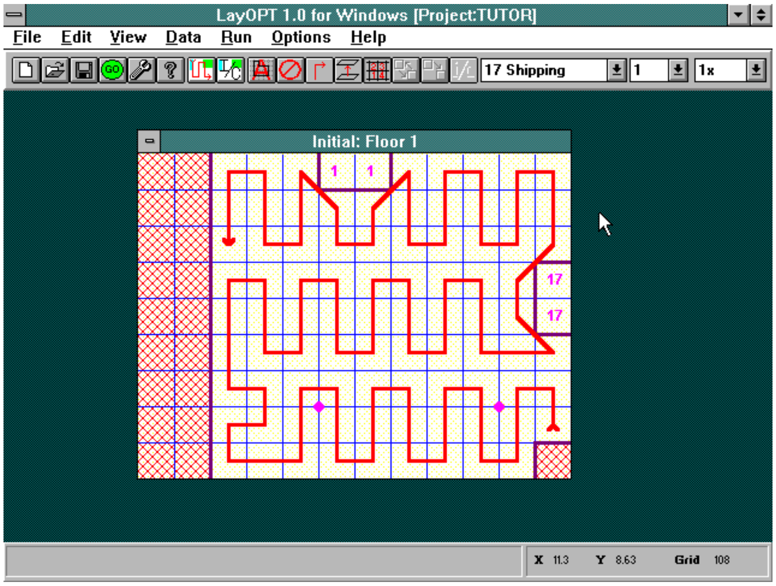

Figure 15.28. Spacefilling Curve for the Layout Example

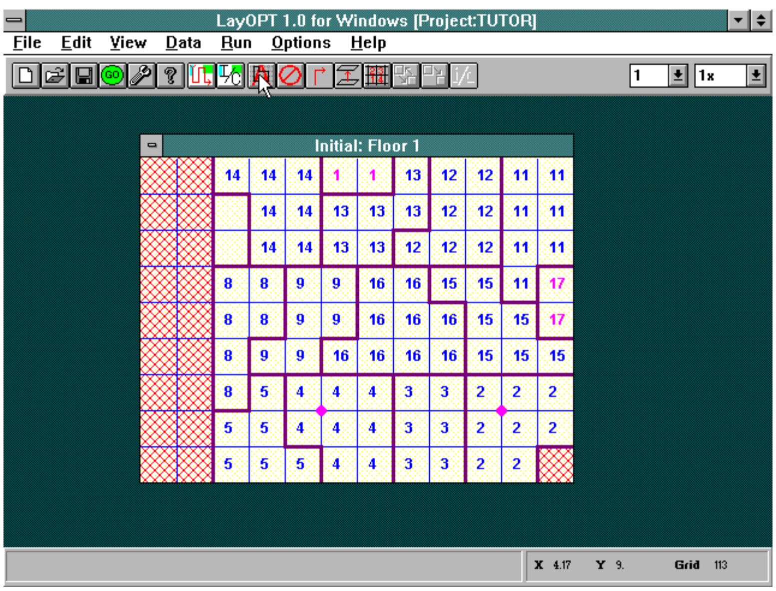

Figure 15.29. Initial LayOPT Layout

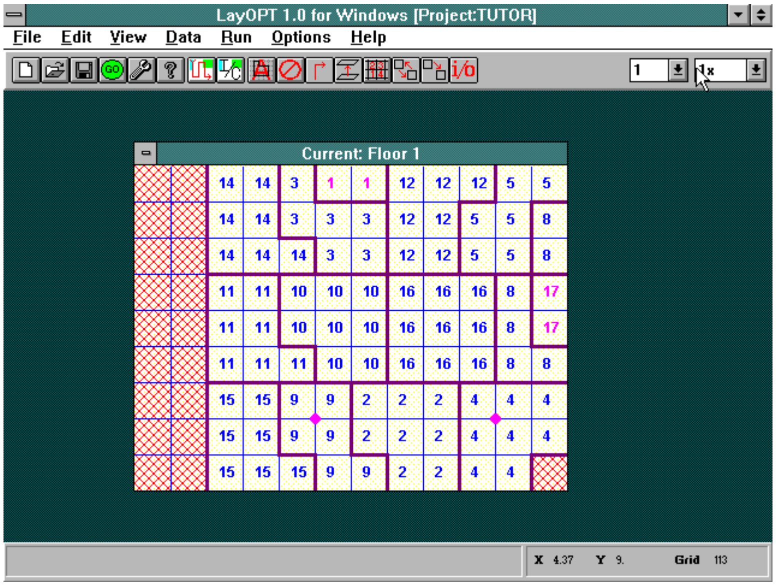

Figure 15.30. Improved Layout for the LayOPT Example

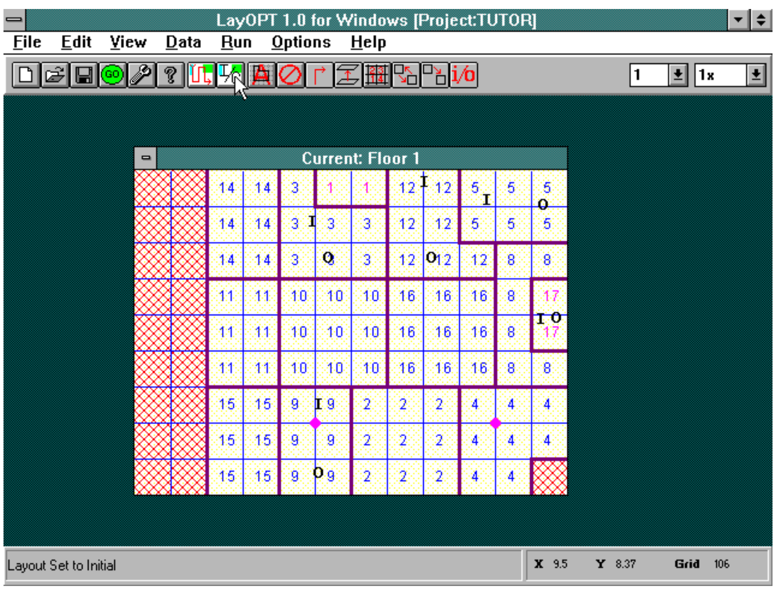

Figure 15.31. Manual Adjusted Layout with I/O Points for the LayOPT Example

Examples

Tompkins Example

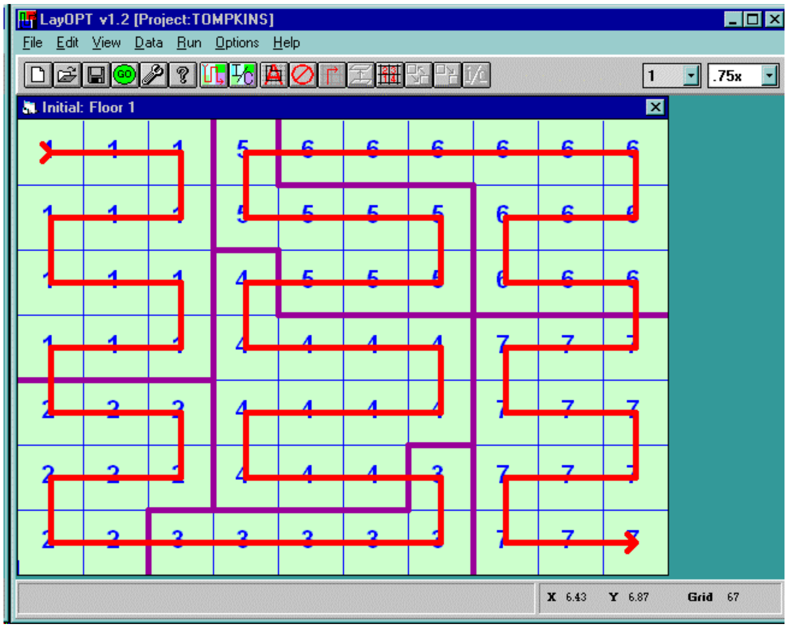

Figure 15.32. Spacefilling Curve for the Tompkins Example

The distance score of the initial layout is 2317.

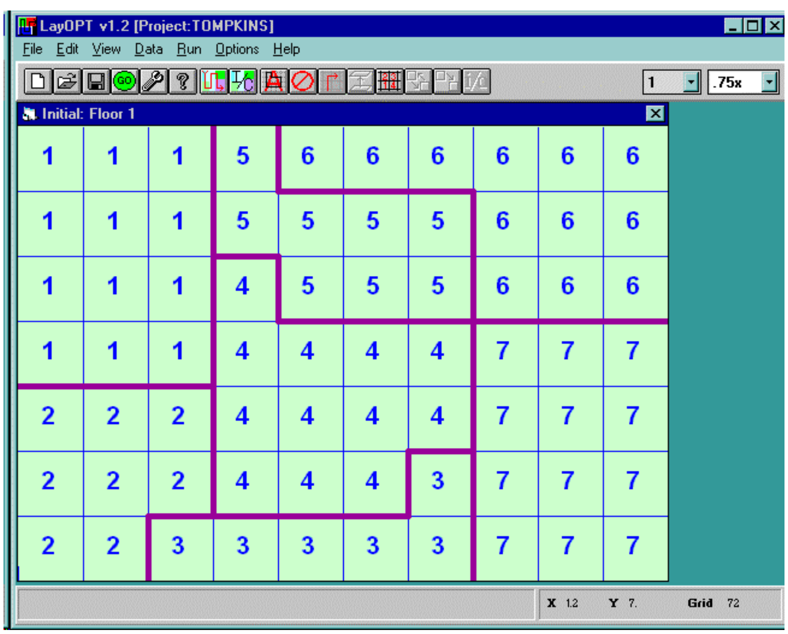

Figure 15.33. Initial Layout for the Tompkins Example

The perimeter complexity factor of all the departments was set equal to 1.43. This is equivalent to a shape factor of 6.0. Setting the perimeter complexity factor to a lower value resulted in zero improvements by the simulated annealing algorithm, i.e., the algorithm could not find a better feasible layout. The distance score of the final layout was equal to 2158.

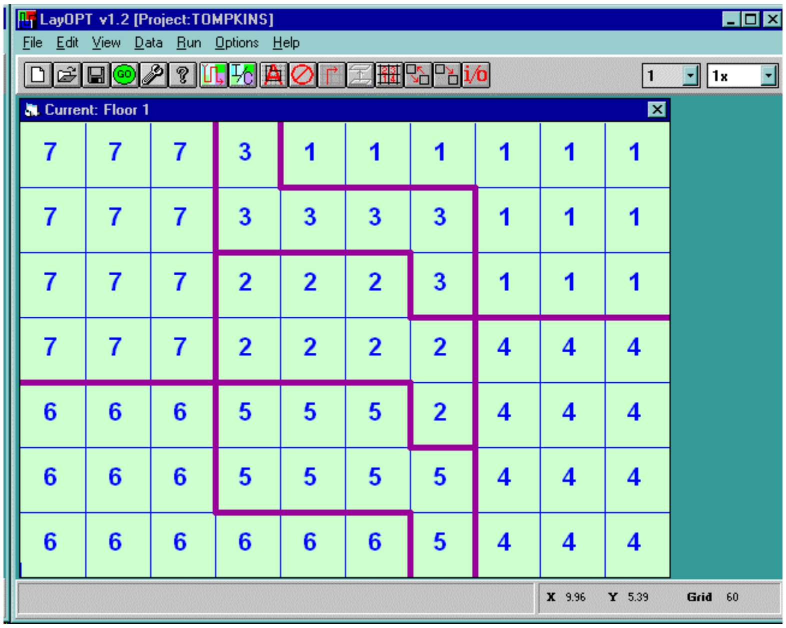

Figure 15.34. Final Layout for the Tompkins Example

Furniture Example

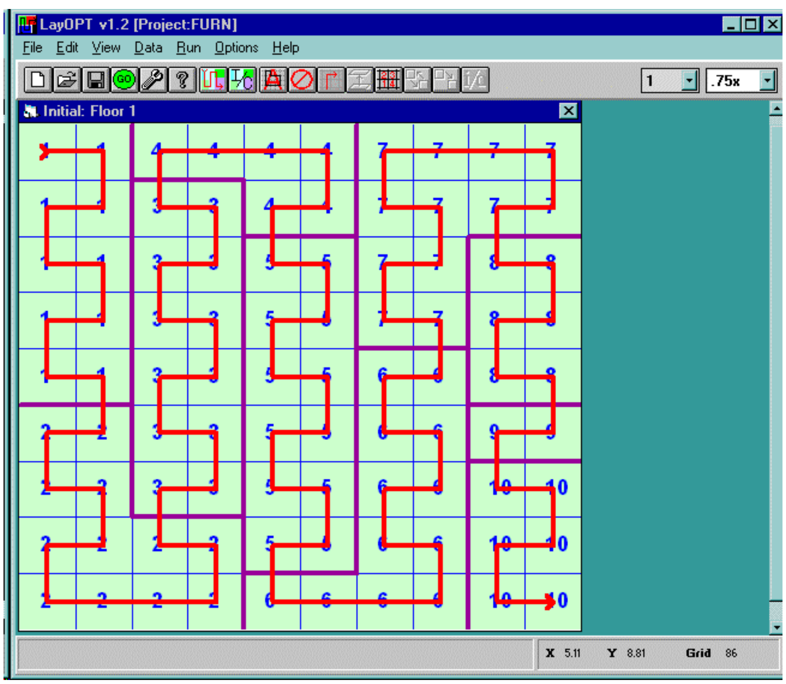

Figure 15.35. Spacefilling Curve for the Furniture Example

The distance score of the initial layout is 1040.

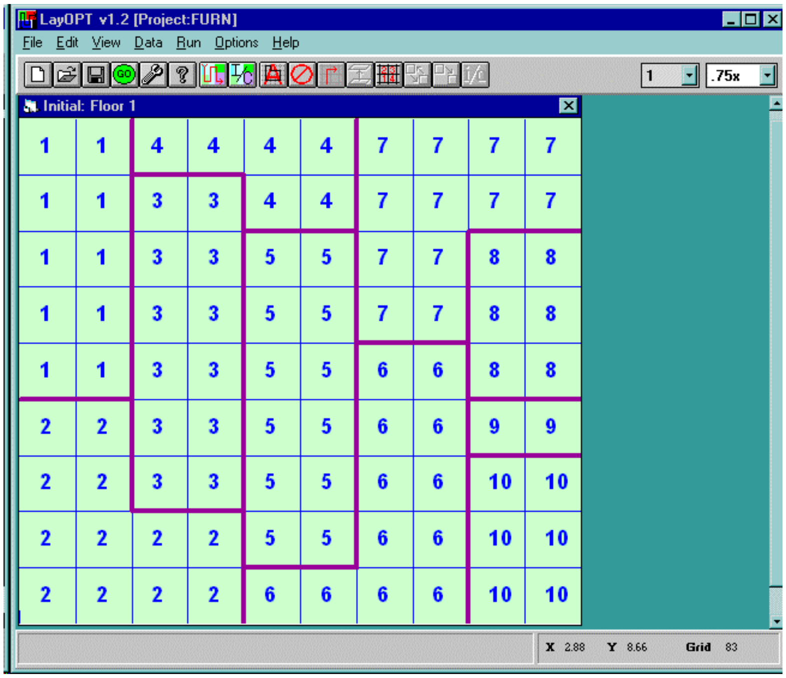

Figure 15.36. Initial Layout for the Furniture Example

The distance score for the improved layout is 781. A maximum perimeter complexity factor of 1.20 was specified, which corresponds to a shape ratio of 3.5 for rectangular departments.

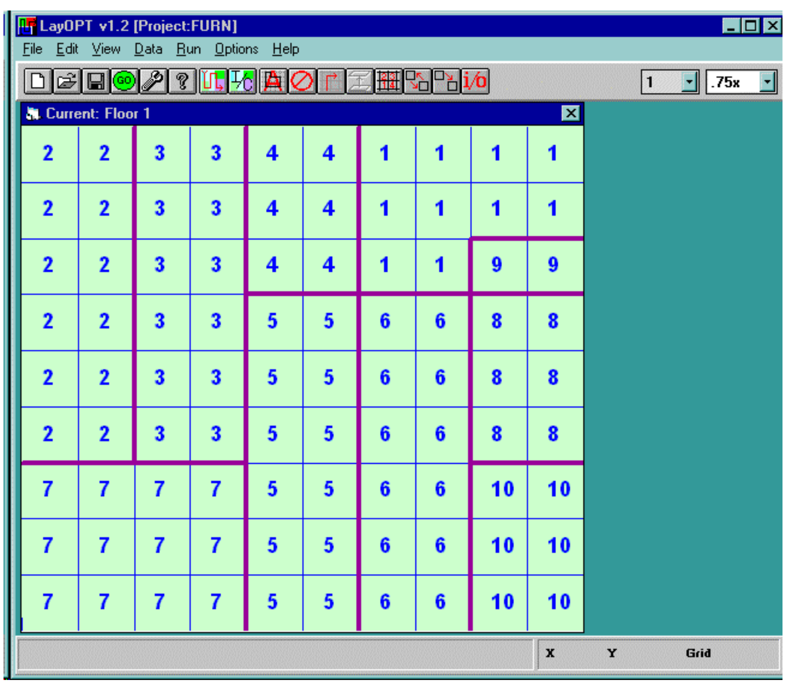

Figure 15.37. Final Layout for the Furniture Example

Design of Experiments

Scale Factor or Unit Square Size

Initial Layout

Layout Improvement Procedure

Evaluation

Modern User Interface and Easy to Use

Sometime Difficult to Create a Good Spacefilling Curve

Multiple Floors

Partial Layouts with Departments Fixed in Place

15.4. BLOCPLAN

The initial version of this facilities design software package was called BLOCPLAN. The second version was called BLOCPLAN90. The illustrations and example are based on the BLOCPLAN90 version.

Example

Table 15.14. Department Letter Relationships

	A	B	C	D	E	F	G
A		E	O	I	O	U	U
B			U	E	I	I	U
C				U	U	O	U
D					I	U	U
E						A	I
F							E
G							

The automatic search procedure generates the following layout, with a score of 1666. Observe that the algorithm does not take department shapes into consideration, so that the shape of department 4 is very long and narrow.

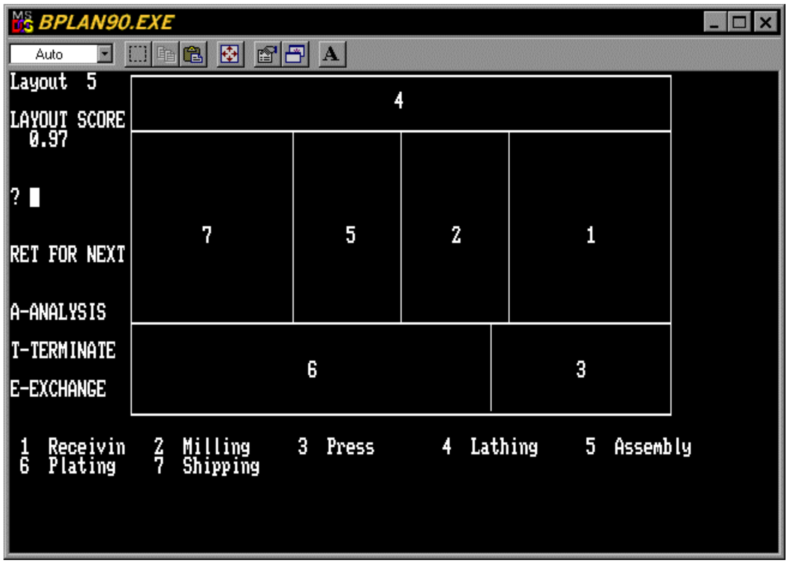

Figure 15.38. BLOCPLAN Layout for the Tompkins Example with Qualitative Data

If the number of trips are entered in the from-to matrix directly and all letter relationships are set to U, the following layout is generated by the automatic search procedure with a distance score of 2374. This score was computed outside the program, since BLOCPLAN returned a distance score of zero for this case.

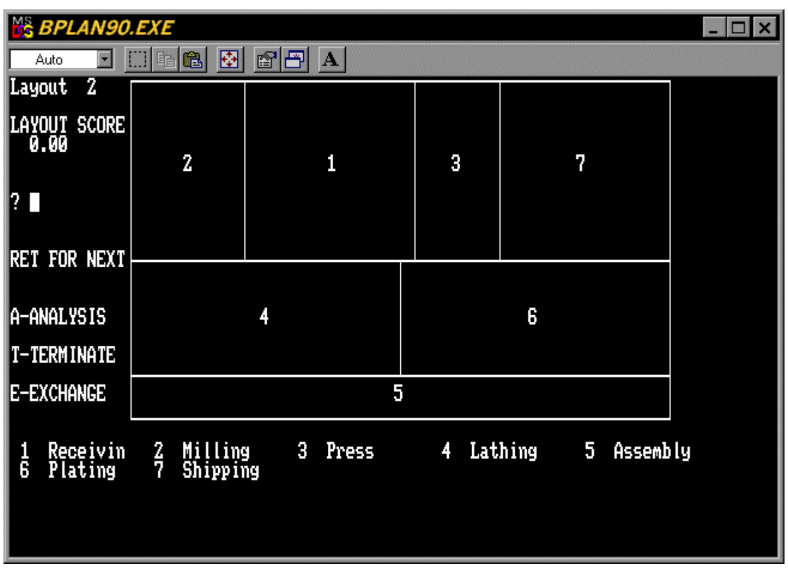

Figure 15.39. BLOCPLAN Layout for the Tompkins Example with Numerical Data

Evaluation

The BLOCPLAN software package has a keyboard-based menu structure and user interface. Its automatic search procedure is not clearly described. It has the capability of generating random layouts and then to improve them with two exchanges.

15.5. PLANOPT

The versions of this facilities design package up to version 3.0 were called LAYOPT. Because of the conflict with other facilities design software of the same name, the versions starting with version 4.0 were called PLANOPT. The illustrations are based on both the LAYOPT version 3.0 and the PLANOPT version 4.0.

Example

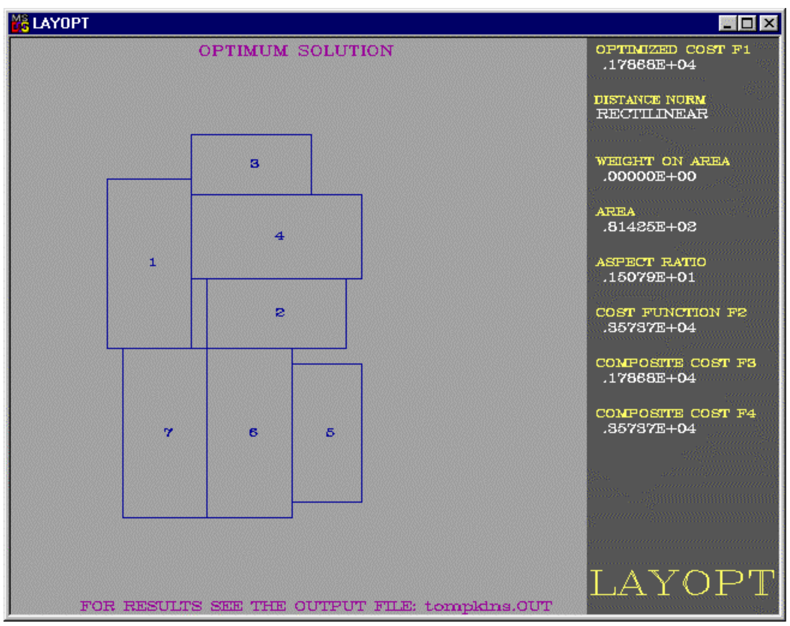

Figure 15.40. PLANOPT Layout for the Tompkins Example

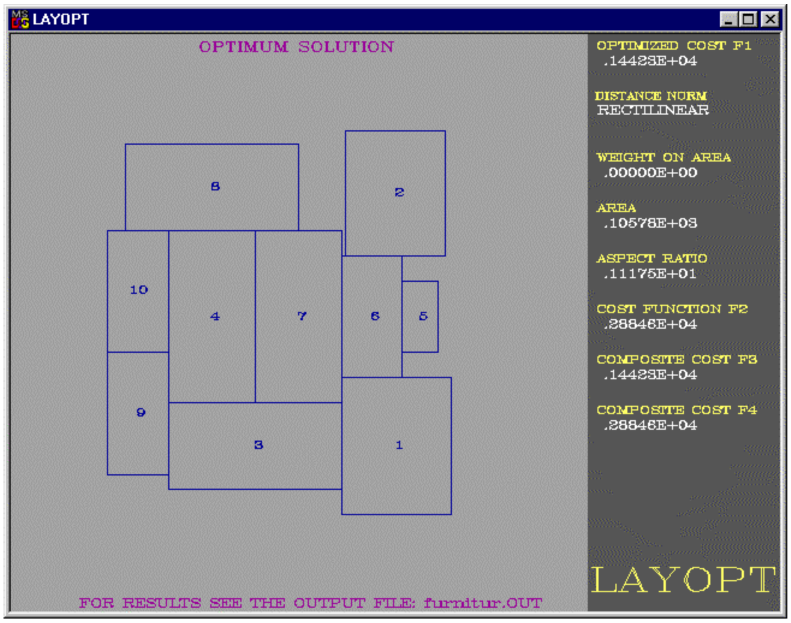

Figure 15.41. PLANOPT Layout for the Furniture Example

Evaluation

It is very difficult to compare the layouts generated by PLANOPT with the layouts generated by the previous software packages, such as Spiral, LayOPT, and BlOCPLAN, because PLANOPT does not incorporate a tight layout area constraint. Consequently the overall layout has a very irregular boundary and the distance objective function tends to be lower because of the additional flexibility. The layouts generated are similar in structure to those generated by the CORELAP facilities design software.

15.6. ALDEP

General Characteristics

The name is an acronym for **A**utomated **L**ayout **DE**sign **P**rogram. It was one of the first construction procedures, originally programmed in 1967, see Seehof and Evans (1967).

The objective is to maximize the adjacency score based on a qualitative relationship chart. The program uses computer fixed values for the different letter relationships. Two departments are said to be adjacent if at least their corners touch each other in the layout, i.e., corner adjacency is sufficient.

The data requirements are the basic department areas and the qualitative letter relationship chart. In addition, the building dimensions are required.

Selection Procedure

The fundamental principle of the ALDEP procedure is ***random selection***. The selection procedure can be summarized in the following steps:

1) Select a department randomly out of the set of all unselected departments. If only one department remains unselected, then select this last department and stop, otherwise go to step 2.

2) Construct the set of all unselected departments that have a relationship as least as high as the minimum closeness rating with the last selected department. This set can be called the set of candidate departments. If this set is empty then go to step 1, else go to step 3.

3) If the set of candidate departments is not empty, then select randomly a department out of the set. If only one department remains unselected, then select this last department and stop, otherwise go to step 2.

Location Procedure

The rectangular building is divided into vertical stripes with width equal to the sweep width. The departments are located in the order determined by the selection procedure in a serpentine manner, starting in the top left corner and weaving up and down.

Evaluation Procedure

The layout is evaluated with the adjacency score. The score is the product of the adjacency and relationship matrices. Two departments are considered adjacent if their corners or sides touch. The computer uses the following fixed values for the relationships, which follow a pattern as powers of four:

Table 15.15. ALDEP Letter Relationship Values

relationship	A	E	I	O	U	X
value	64	16	4	1	0	-1024
power of 4	3	2	1	0		5

Special Characteristics

The principal abilities of ALDEP are the ability to fix the building shape and the ability to fix the location of departments in the layout. Secondary abilities are the ability to handle multiple floors and to generate many alternatives with minimal effort. ALDEP is not user friendly, it is a first generation program.

Design of Experiments

A full factorial design of experiments to generate a layout with the ALDEP procedure involves the following primary factors:

1) seed of the random number generator
2) minimum closeness rating
3) sweep width
4) scale factor or unit square size.

There exist two schools of thought on the selection of the minimum closeness rating. One school advocates the selection of a high value, such as A or E, in order to consider only the important relationships. The second school advocates the selection of a low value such as O since otherwise important relationships, such as I, are given the same meaning or value as unimportant relationships, such as U. The problem is caused by the fact that ALDEP considers only two classes of relationships in the selection procedure (important and unimportant), divided by the minimum closeness rating, instead of the six positive classes.

A large scale factor corresponds to the case where the department areas consist of a few unit squares. This usually helps to give the departments a more regular, near rectangular shape, but it decreases location flexibility, which means usually a reduced evaluation score. A small scale factor has the opposite effect.

Evaluation of ALDEP

ALDEP has the following advantages. It generates a nice rectangular building shape and it generates many alternative layouts with the least amount of user involvement of all programs.

ALDEP has the following disadvantages. The quality of each layout is rather limited and the adjacency scoring values can not be adjusted to individual layout problems. Hence, ALDEP uses a kind of shotgun approach to design a good layout

Example

Data

The layout consists of seven departments with the following required areas:

Table 15.16. Department Functions and Areas

Department	Name	Area	Squares
1	Receiving	12,000	2
2	Milling	8,000	1
3	Press	6,000	1
4	Drilling	12,000	2
5	Assembly	8,000	1
6	Plating	12,000	2
7	Shipping	12,000	2

Each unit square has an area of 6000 square feet. The building has as dimensions 4 by 3 unit squares.

An alternative scale factor equates each unit square to an area of 2000 square feet and generates the following required number of unit squares (6, 4, 3, 6, 4, 6, 6). The building has then dimensions of 7 by 5 unit squares.

The minimum specified closeness is E and the specified sweep width is equal to one unit square.

The relationships between the departments are given in the following qualitative relationship chart:

Table 15.17. Department Letter Relationships

	A	B	C	D	E	F	G
A		E	O	I	O	U	U
B			U	E	I	I	U
C				U	U	O	U
D					I	U	U
E						A	I
F							E
G							

Selection procedure

Initial set of candidates = {1, 2, 3, 4, 5, 6, 7}

first randomly selected department = 3

Set of candidates with E or higher relation with 3 = { }

Set of candidates = {1, 2, 4, 5, 6, 7}

second randomly selected department = 7

Set of candidates with E or higher relation with 7 = {6}

third selected department = 6

Set of candidates with E or higher relation with 6 = {5}

fourth selected department = 5

Set of candidates with E or higher relation with 5 = { }

Set of candidates = {1, 2, 4}

fifth randomly selected department = 2

Set of candidates with E or higher relation with 2 = {1, 4}

sixth randomly selected department = 1

last selected department = 4

Location procedure

The following layout is generated with the serpentine location rule with a sweep width equal to one:

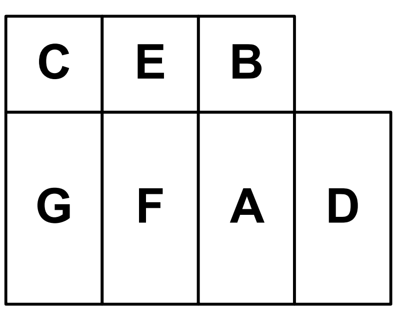

Figure 15.42. ALDEP Layout for the Tompkins Example

Evaluation procedure

Table 15.18. ALDEP Adjacency Matrix

	A	B	C	D	E	F	G
A		1	0	1	1	1	0
B			0	1	1	1	0
C				0	1	1	1
D					0	0	0
E						1	1
F							1
G							

The score is then equal to 2 (16 + 4 + 1 + 16 + 4 + 4 + 1 + 64 + 4 + 16) = 260. The efficiency of this layout is 260 / 270 = 96 %. The doubling is caused by the symmetric matrices of which only the top triangle is shown.

15.7. CORELAP

General Characteristics

The name is derived from the acronym for **CO**mputerized **RE**lationship **LA**yout **P**lanning. It is a first generation construction program, originally introduced in 1967.

The objective is to minimize the distance score. This distance score is computed based on the shortest rectilinear path between the boundaries of the departments. In other words, it is assumed that the begin and end points of the material flows into a department are located on the boundary of that department as close to the origin/destination department as possible.

The data requirements are the department areas and a qualitative letter relationship chart. The computer uses computer fixed values for the letter relationships in the selection phase, but it uses user supplied values in the location procedure. Hence, numerical values for the relationships are also required.

Selection procedure

The fundamental mechanism of the selection procedure is to ***maximize the total closeness rating or TCR***. The TCR_i for each department i is computed with the following formula:

$$TCR_j = \sum_{i=1}^{N} rel_{ij} \quad (15.$$

where the values of the relationships are determined by the computer and are as follows:

Table 15.19. CORELAP Relationship Values

relationship	A	E	I	O	U	X
value	6	5	4	3	2	1

The selection procedure has the following steps:

2) Select the department with the highest TCR from the not yet selected departments to enter first the layout. If a tie exists, select the department with the largest area. If a tie still exists, select the department with the smallest index.

3) Set the relationship that will be tested to the first (highest or A) relationship. This will be called the current relationship.

4) Set the department that will be tested to the first department in the list of selected departments. This will be called the current department.

5) Construct the set of candidate departments, which consists of all unselected departments that have the current relationship with the current department.

6) If the candidate set has one department, then add this department to the list of selected departments. If there is only one unselected department left, then select this last department and stop, else go to step 3.

If the candidate set has more than one department, select the department with the highest TCR. If a tie exists then select the department with the largest area. If a tie still exists then select the department with the smallest index. If there is only one unselected department left, then select this last department and stop, else go to step 3.

If the candidate set is empty, then if the current department is the last one in the list of selected departments, then set the current relation ship to the next lower relationship and go to step 4. Else set the current department to the next department in the list of selected departments.

This selection procedure can be summarized in the following pseudo-code algorithm:

Algorithm 15.1. CORELAP Selection Procedure

```
1. relationship loop
for relat = A downto O do
        2. selected department loop
```

```
for selected dept=1 to # selected depts do
        3. for each selected dept and relationship combination do
                construct the candidate set
                4. if cardinality = 1 then
                        select this dept
                        break to step 1
                else if cardinality > 1 then
                        pick dept with largest TCR
                        break to step 1
                else if cardinality = 0 then cycle
        next selected dept
next relation
```

Location procedure

The departments enter the layout in order of the selection procedure. For the currently entering department the location is chosen that will maximize the adjacency score with the already located departments. The user values for the relationships are used. If a tie exist, the location that has the largest boundary length with the already located departments will be selected. If a tie still exists, then the first location will be selected starting at the top left corner of the layout and moving clockwise.

Evaluation procedure

The layout is evaluated by its distance score. The distance score is the product of the distance matrix and the relationship matrix, where the computer determined numerical values are used for the evaluation. The distance between two departments is computed as the shortest rectilinear path length from boundary to boundary between the departments. The path starts and ends at the midpoint of unit square sides. The final score returned by the computer program must be multiplied by the scale factor, i.e. by the length of the side of the unit square.

Special features

CORELAP has some secondary abilities. The length to width ratio of the building can be fixed and departments can be assigned to a particular side or corner of the building. CORELAP is not user friendly, it is a first generation program, a second generation version exists nut is much less widespread.

Design of Experiment

The primary factors in a design of experiments for the CORELAP procedure are the user values for the relationships and the scale factor or unit square size.

Evaluation of CORELAP

CORELAP had the following advantages. CORELAP generates on the average departments with nice, near rectangular shapes. The user specified numerical values are used in the location procedure, which allows more flexibility and adaptation to the problem as compared to ALDEP.

CORELAP has the following disadvantages. The primary disadvantage of CORELAP is the building shape, which is irregular because of the crystalline growth of the layout.

In addition, there is no real reliable way to fix departments and the program is inconsistent if the user selected values for the relationships are different of the computer specified values. CORELAP is not user friendly, since it is a first generation program.

Example

Data

The same data as for the ALDEP example are used. The user values for the letter relationships, used in the location procedure, are the following :

Table 15.20. CORELAP User Relationship Values

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

Selection procedure

The TCR for each department is equal to:

Table 15.21. TCR Values for Example

department	1	2	3	4	5	6	7
TCR	19	22	14	19	23	22	17

Let cd stand for currently tested department and let cr stand for currently tested relationship the first selected department with highest TCR = 5

cr = A, cd = 5 : set = {6}

second selected department = 6

cr = A, cd = 5 : set = { }

cd = 6 : set = { }

cr = E, cd = 5 : set = { }

cd = 6 : set = {7}

third selected department = 7

cr = A, cd = 5, 6 : set = { }

cd = 7 : set = { }

cr = E, cd = 5, 6 : set = { }

cd = 7 : set = { }

cr = I, cd = 5 : set = {2,4}

fourth selected department with highest TCR = 2

cr = A, cd = 5, 6, 7 : set = { }

cd = 2 : set = { }

cr = E, cd = 5, 6, 7 : set = { }

cd = 2 : set = {1, 4}

fifth selected department with highest TCR = tie

fifth selected department with largest area = tie

fifth selected department with smallest index = 1

cr = A, cd = 5, 6, 7, 2 : set = { }

cd = 1 : set = { }

cr = E, cd = 5, 6, 7 : set = { }

cd = 2 : set = {4}

sixth selected department = 4

last selected department = 3

Location procedure

The first department to enter = 5 (area = 1). The second department to enter = 6 (area = 2). The third department to enter = 7, (area = 2), it has positive relationships with both departments 5 and 6 and will thus be located adjacent to both.

The fourth department to enter = 2, (area = 1), it has positive relationships with 5 and 6, but since it has area equal to 1 it can only be adjacent to one of the two. The department on the top left corner is chosen.

The fifth department to enter is 1, (area = 2), it has the highest relation with 2, hence it will be adjacent to department 2. The next highest relationship is with department 5, but it cannot be adjacent to department 2 and department 5. It has also (equal) relationships with departments 6 and 7, again the location in the top left corner is selected.

The sixth department to enter is 4, (area = 2), it has its highest relationship with department 2 and will be located adjacent to department 2. The next highest relationships are with departments 1 and 5. But it can be adjacent simultaneously with departments 2 and 1, but not with departments 2 and 5. Hence it will be located adjacent with departments 2 and 1.

The last department to enter is 3, (area = 1), it has its highest relationships with departments 1 and 6 and it can be located adjacent to those two and hence that location will be preferred.

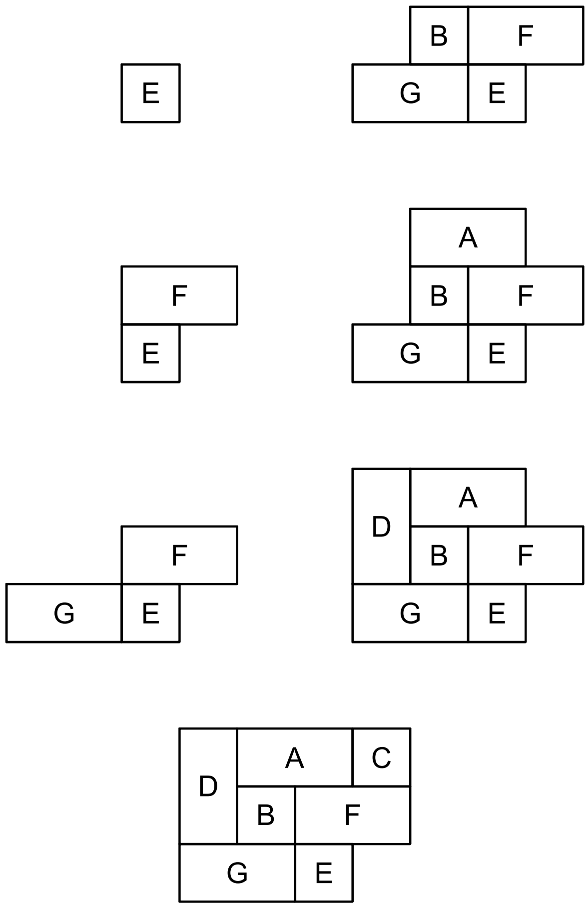

Figure 15.43. CORELAP Layout Example

Evaluation procedure

Table 15.22. CORELAP Relationship Matrix

	A	B	C	D	E	F	G
A		5	3	4	3	2	2
B			2	5	4	4	2
C				2	3	3	2
D					4	2	2
E						6	4
F							5
G							

Table 15.23. CORELAP Distance Matrix

	A	B	C	D	E	F	G
A		0	0	0	1	0	1
B			2	0	1	0	0
C				2	2	0	3
D					2	1	0
E						0	0
F							1
G							

The score is then equal to $1 \cdot 3 + 1 \cdot 2 + 2 \cdot 2 + 1 \cdot 4 + 2 \cdot 2 + 2 \cdot 2 + 3 \cdot 2 + 2 \cdot 4 + 1 \cdot 2 + 1 \cdot 5 = 42$.

This score has to be multiplied by the length scale factor, which is the square root of the unit square size.

Hence the final score is $42 \cdot \sqrt{6000} = 3253.31$.

15.8. CRAFT

General Characteristics

The name is derived from the acronym **C**omputerized **R**elative **A**llocation of **F**acilities **T**echnique. It was one of the first computer programs to help with facilities design, originally developed in 1963 by Armour and Buffa (1963,1964). It is still the most known and used CAL package. Part of the success of CRAFT is due to the fact that it is an improvement procedure, which sidesteps the difficult issues of building shape.

The objective of CRAFT is to minimize the distance score. The distance is the rectilinear distance between department centroids. The relationship matrix itself is the product of the volume or flow matrix and the cost-per-distance-unit matrix.

The data requirements are the department and building areas, an initial feasible layout and the department relationships. The relationships are given in form of two matrices, the first one is the flow from-to chart matrix, which gives the number of trips between departments. The second matrix is the unit-cost from-to chart, which gives the cost per distance unit of making the trip. This allows incorporation of the type of material handling equipment in the CAL design, e.g. for undetermined material handling equipment, set all costs equal to one, for a conveyor set the volume equal to one. The quantitative relationship from-to matrix used is equal to the product of the last two matrices.

Selection Procedure

The fundamental principle of CRAFT is distance improving two and/or three department exchanges.

Several variants of the selection procedure are possible, they are indicated by 2-way, 3-way, 2 and 3-way, 2-way before 3-way, 3-way before 2-way. The 2 or 3 refer to the number of departments that are exchanged in a single move. Assume a selection procedure variant.

The selection procedure can be divided into the following steps:

1) the initial centroids of departments and the distance matrix are constructed.

2) all departments with equal area or all departments that are adjacent are considered candidates for an exchange. The estimated savings of an exchange are computed as follows. The centroid coordinates of the departments are exchanged and the distance matrix updated by exchanging the two (or three) corresponding rows and the two (or three) columns. The new distance score is computed. If the estimated savings are positive then the actual exchange is executed. If the actual savings are positive, then the exchange is kept.

Location procedure

The departments that have to be exchanged are swapped unit square by unit square in the layout. The actual new centroid locations are computed and the distance table is updated and the actual savings are computed.

Evaluation procedure

The layout evaluation is based on the distance score. The distance score is the product of the distance matrix and the flow volume matrix and the flow unit-cost matrix. The distance is the rectilinear centroid to centroid distance.

Special Features

The most important of CRAFT's special abilities is the ability to keep the regular, rectangular building shape. This shape is determined by the initial layout and hence by the user. A secondary ability is the ability to fix departments in place. CRAFT is not user friendly, since it is a first generation program.

Design of Experiments

The three factors important in a design of experiments are the scale factor or unit square size, the different initial layouts, and the selection of the improvement algorithm(s) and their sequence.

Evaluation of CRAFT

Advantages

CRAFT is heuristic solution method of the quadratic assignment formulation of the layout problem, which is one of the fundamental approaches to the layout problem.

CRAFT keeps a regular building shape, which is determined by initial layout.

Disadvantages

The heuristic procedure in CRAFT is very dependent on the initial layout, so as many initial layouts should be tried as there are available.

CRAFT will generate irregular department shapes, especially if there are many departments consisting out of many unit squares.

CRAFT does not incorporate a ***cohesion cost*** for a department, which makes the centroid assumptions less valid. The cohesion cost is the cost that keeps unit squares belonging to the same department together and compact. In extremes, CRAFT could generate department shapes, which would all be concentric circles. See Figure 15.44 for illustrations of layouts without department cohesion costs.

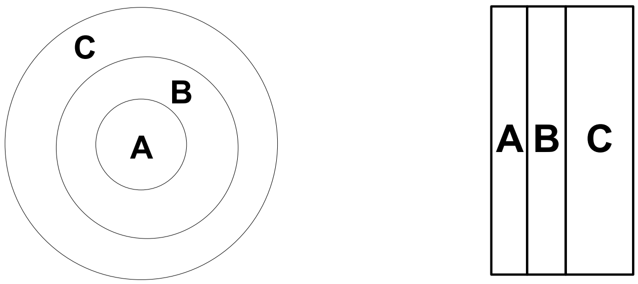

Figure 15.44. Layouts without Cohesion Costs by CRAFT

CRAFT is an improvement procedure and hence requires initial layout(s).

Example

The example is same as the one used for all the previous packages. The initial layout used was the final layout from the ALDEP procedure in Figure 15.42. The flow values are the same as for the spiral technique given in Table 15.2. The cost per unit distance was set to one for all movements.

An eighth dummy department (H) was added with zero flow to all the departments to complete the layout. CRAFT was ordered to attempt first two-way exchanges and then three-way exchanges. The distance score of the initial layout is equal to 815.

C	E	B	H
G	F	A	D

Figure 15.45. CRAFT Initial Layout from ALDEP for Example

The following two-way exchanges are tried during the first iteration and the estimated savings are listed in the last column.

Table 15.24. CRAFT Two Exchange Savings in Iteration 1

Dept. 1	Dept. 2	Est. Savings
1	2	6.00E+01
2	3	-1.60E+02
1	4	1.00E+01
2	5	-1.60E+02
3	5	-1.00E+02
1	6	-1.90E+02
4	6	-2.60E+02
5	6	1.50E+01
1	7	-1.10E+02
3	7	-1.50E+01
4	7	-1.40E+02
6	7	-7.00E+01
2	8	-4.00E+01
3	8	0.00E+00
4	8	9.00E+01
5	8	-1.90E+02

The largest estimated savings are generated by the exchange of departments 4 and 8. The estimated savings are 90.0 but the actual savings of the interchange are 60 so that the new layout score is 755.

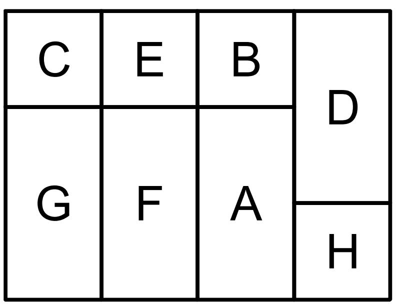

Figure 15.46. CRAFT Layout after Iteration 1 for Example

During the second iteration the savings of the following two-way exchanges are computed.

Table 15.25. CRAFT Two Exchange Savings in Iteration 2

Dept. 1	Dept. 2	Est. Savings
1	2	1.00E+01
2	3	-1.60E+02
1	4	-1.00E+01
2	4	-5.00E+00
2	5	-1.60E+02
3	5	-1.00E+02
1	6	-1.90E+02
4	6	-2.70E+02
5	6	-5.50E+01
1	7	-1.10E+02
3	7	-1.50E+01
4	7	-2.30E+02
6	7	-7.00E+01
1	8	-1.00E+02
2	8	-7.50E+01
3	8	1.50E+01
4	8	-1.15E+02
5	8	-1.50E+02

The largest estimated savings for the next iteration are generated by the exchange of departments 3 and 8. The estimated savings are 15 and the actual savings after the interchange are also 15, since the two departments have equal areas. This results in a new layout score of 740.

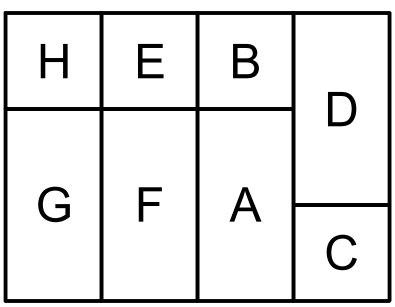

Figure 15.47. CRAFT Layout after Iteration 2 for Example

In the third iteration there is no two-way exchange which generates positive savings.

Table 15.26. CRAFT Two Exchange Savings in Iteration 3

Dept. 1	Dept. 2	Est. Savings
1	2	-3.50E+01
1	3	-5.50E+01
2	3	-6.00E+01
1	4	-1.00E+01
2	4	-5.00E+00
3	4	-1.20E+02
2	5	-1.50E+02
3	5	-1.35E+02
1	6	-2.00E+02
4	6	-2.50E+02
5	6	-7.00E+01
1	7	-1.70E+02
4	7	-2.30E+02
6	7	-9.00E+01
2	8	-1.90E+02
3	8	-1.50E+01
5	8	-1.30E+02
7	8	-4.50E+01

Hence the algorithm continues with three-way exchanges

Table 15.27. CRAFT Three Exchange Savings in Iteration 3

Dept. 1	Dept. 2	Dept. 3	Est. Savings
5	2	1	5.00E+01
6	5	2	-1.90E+02
7	6	5	-9.50E+01

The most positive estimated savings are generated by the exchange of departments 1, 2 and 5. The estimated savings are 50 but the actual savings after the exchange are zero. Hence the exchange is not executed.

In the fourth iteration there are no three-way exchanges with positive savings, hence the CRAFT algorithm terminates.

Table 15.28. CRAFT Three Exchange Savings in Iteration 4

Dept. 1	Dept. 2	Dept. 3	Est. Savings
7	6	5	-9.50E+01
8	7	6	-1.50E+01

15.9. MATCH

General Characteristics

The name is an acronym for Color graphics Interactive **Match**ing Based Layout. It was developed in 1982 at the Georgia Institute of Technology by Montreuil et al. It is a third generation construction procedure.

The objective is to maximize the adjacency score. The score of the layout is determined by multiplying the value of the relationship between two departments with their common boundary length and summing this product for all possible department pairs. The building/outside is also considered a department.

The data requirements are as usual the areas for each department and the quantitative relationship chart. The suggested (rectangular) shape for each department and the building is also required.

Selection Procedure

The Match program does not use a sequential selection procedure as all the previously discussed programs, but uses an optimal matching algorithm to find the best combination of departments. Hence, the fundamental principle of Match is the ***optimal adjacency matching***, which is a combinatorial algorithm. The perimeter length b_i of each department i is computed, based on the suggested department shape. Each department has to be adjacent exactly b_i times with other departments. The value of each of those adjacencies is given by the relationship matrix. Based on the shape of the two departments, there exists an upper and lower bound on the number of times those departments can be adjacent. Let x_{ij} be the number of times departments i and j are adjacent, let l_{ij} and u_{ij} be the lower and upper bound on the number times they can be adjacent and let c_{ij} be value for each time they are adjacent. The following matching formulation is then solved:

$$\max \quad \sum_{i=1}^{M} \sum_{j=i+1}^{M+1} c_{ij} x_{ij} \qquad (15.$$

$$s.t. \quad \sum_{j=1}^{M+1} x_{ij} = b_i \qquad i=1..M \qquad (15.$$

$l_{ij} \leq x_{ij} \leq u_{ij}$ i=1..M, j=1..M+1 (15.

$x_{ij} \varepsilon \mathbf{N}^{+}$ i=1..M, j=1..M+1 (15.

The resulting solution is usually not a feasible layout. It is the task of the human operator to impose additional constraints (by modifying l_{ij} and u_{ij}) that will force the solution to a feasible layout.

Location Procedure

The location of the departments is done interactively by the human operator on the CRT screen. As such there is no location procedure build into the program. It is possible to have an heuristic drawing method for the matching graph based on the expanded spiral technique.

Evaluation Procedure

Match evaluates the generated layout in three different ways. The adjacency score is computed as explained above, as well as the rectilinear and Euclidean distance score. The adjacency score requires a side to side adjacency. The distance score computes the distance from department centroid to department centroid. The procedure can be adapted to compute any desired evaluation score. So the user can devise its own scoring algorithm.

Special Characteristics

- ability to fix departments
- ability to fix building shape
- interactive procedure (requiring human operator)
- ability to save/load and restart solution procedures
- user friendly (third generation program)

Design of Experiments

The only important external factor in the design of experiments is the scale factor or unit square size.

Evaluation of Match

MATCH has the following advantages. Match uses a very powerful algorithm to support the layout design. It has a very user friendly color graphics interface, which allows (and requires) fast and efficient operator interaction. Match allows many, even user specified evaluation procedures

It incorporates the building/outside in the solution procedure and generates nice, near rectangular department shapes and regular building shape.

Match has the following disadvantages. It requires the constant input of a trained human operator. It requires much more expensive computer hardware, such as a powerful microcomputer. At this time it has only limited availability for industrial users.

Further information on early CAL packages can be found in the user's manual for early CAL programs by Tompkins and Moore (1978).

Exercises

Spiral Exercise 1

Consider the following layout problem consisting of seven departments. The relationships between the seven departments are given in Table 15.29. Compute the adjusted binary relationships and show them in a sorted list. Construct the hexagonal adjacency graph with the Spiral method, using the centroid seeking rule to break any ties between alternative locations. Show all the intermediate graphs with one, two, up to seven departments. Do not apply any improvement interchanges to the original adjacency graph that you have obtained. Finally, compute the adjacency score and efficiency score for this adjacency graph.

Table 15.29. Department Relationships

	A	B	C	D	E	F	G	OUT
A		10			110	30		
B			50		15	35	-10	-25
C				90		10		
D						15		
E							25	30
F								
G								

Table 15.30. Department Areas

Dept.	A	B	C	D	E	F	G
Area	8	16	8	8	8	8	8

The areas of the departments are given in Table 15.30. The building is an eight by eight square. Draw to scale the conceptual block layout following the Spiral method. Clearly indicate the dimensions. Do not apply any improvement interchanges to the original layout that you have obtained. Distances are measured centroid to centroid with the rectilinear norm. Compute the distance score and the average distance for this layout.

You should obtain an adjacency graph whose efficiency is 95.60 % and a corresponding block layout whose distance score is 1540.

Spiral Exercise 2

Consider a layout project for a facility with seven department. The space requirements and the flow from-to-chart are given below. The flow chart is based on the number of trips per day with an electric platform truck.

Table 15.31 Departmental Data

	A	B	C	D	E	F	G	O	Function	Area
A		45	15	25	10	5			Receiving	12,000
B				30	25	15			Milling	8,000
C					5	10			Press	6,000
D		20			35				Lathing	12,000
E						65	35		Assembly	8,000
F		5			25		65		Plating	12,000
G								120	Shipping	12,000
O	85								Outside	

Create the adjacency graph following the **SPIRAL** technique using ***ternary*** relationship tuples. As an intermediate result show the sorted list of ternary adjusted relationships. Draw a hexagonal grid, mark the nodes with an index, and then clearly show the sequence of steps in your graph construction procedure, i.e. show a graph after each addition of a department. Indicate for each location of a department if you needed to break location ties or not. Finally, compute and show the adjacency matrix, evaluate the graph with the adjacency score and compute its efficiency.

Spiral Exercise 3: Polymer Testing Lab

One of a major chemical company's products is green polymer, which is sold to soft drink bottle manufacturers. The polymers division superintendent has asked you to redesign the layout for one of the control laboratories. In this lab, analysts test both intermediate products and final polymer product samples. All test samples come in at the receiving station. Samples are moved from station to station on a laboratory push cart which is operated manually by the analysts. These carts require four foot aisles. After testing, waste is disposed of in the appropriate receptacle and the unused portion of the sample is placed in a storage bin. Five percent of the test results (excluding DMT Color test) are out of range. Those samples must be returned to the receiving station and retested. All samples are disposed of after 24 hours. There are five tests that are performed: Acid#DMT, DMT Color, Pellets, Glycol, and Bromides. The two DMT tests have the highest priority.

Table 15.32. Daily Number of Samples per Test

Test	Number of Samples/Day
Acid#DMT	400
DMT Color	140
Pellets	300
Glycol	100
Bromides	325

Acid#DMT

For the Acid#DMT test, the sample is crushed and measured according to procedure. The analyst adds Solvent A and stirs until the sample is dissolved. After the solution is tritated on Titrator A, the dissolved sample is disposed of as non-hazardous solvent, and the untouched sample is placed in the storage bin. Then the analyst goes to the computer center and enters the test results.

DMT Color

Samples for the DMT color test are immediately placed in the heat block. After the sample melts, the color is checked at the color station. The sample is allowed to cool at the cooling station and is disposed of in the glass waste receptacle since color samples are never retested. Then the test results are entered into the computer.

Pellets

The pellets test is performed on green and clear polymer pellet samples. The pellets are weighed, mixed with Solvent B, and melted on the hot plate. After the solution has cooled, it is titrated on Titrator B.

The polymer solution is disposed of in the receptacle for hazardous solvents, the unused pellets are placed in the storage bin, and the test results are entered in the computer.

Glycol

For the Glycol Test, a portion of the sample is weighed, heated in the oven, and weighed again to determine the percent volatile. Then the sample is diluted in Solvent C and placed in the sonic bath to dissolve. The analyst must enter the measurements into the computer in order to perform the liquid chromatography test on the dissolved sample. After liquid chromatography, the test sample is disposed of in the glass waste receptacle, the unused sample is stored in the bin, and the liquid chromatography results are entered into the computer.

Bromides

Before beginning the Bromide test, a specified volume of distilled water must be dispensed for each sample. Each sample is injected into a cup of water for testing. For each sample the analyst lowers a pair of electrodes into the solution to test bromine levels. Then the diluted samples are disposed of in the hazardous solvent receptacle, the unused sample is placed in the storage bin, and the test results are entered into the computer.

These square footage requirements for the departments are given in the next table and are approximations that include slack space for aisles. The total laboratory dimensions are 35’ x 25’.

Table 15.33. Space Requirements

Code	Lab Station	Area (square feet)
RS	Receiving Station	34
C	Crushing	17
S	Scales	25
SA	Solvent B	20
SC	Solvent C	13
St	Stirrers	25
HP	Hot Plates	18
TA	Titrator A	27
TB	Titrator B	27
LC	Liquid Chromatography	32
BrE	Bromide Electrodes	28
WD	Water Dispenser	20
Ov	Oven	15
CrS	Color Station	17
SBath	Sonic Bath	15
HB	Heat Block	15
CS	Cooling Station	17
CC	Computer Center	27
HzS	Waste: Hazardous Solvents	20
NHzS	Waste: Nonhazardous Solvents	15
G	Waste: Glass	25
StB	Storage Bin	30

Solvent B, hazardous solvent waste, the hot plates, bromide electrodes, heat block, and cooling station must all be located under a hood to reduce harmful vapors in the lab. The hoods should be located as close together as possible to reduce expense of piping in the air.

In addition, the superintendent would like to have the following support departments with their associated areas:

Table 15.34. Support Space Requirements

Code	Room	Area (square feet)
BRm	Break Room	75
RRm	Rest Rooms	50
Ad	Administrative Space	80
CRm	Conference Room	80

Design the a layout for this chemical testing lab which optimizes the material flow given the above parameters. This case was originally created by Amy Luff (1994).

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