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REALIZATION OF A REGULAR FACILITY BLOCK PLAN FROM AN ADJACENCY GRAPH USING GRAPH THEORETIC BASED HEURISTICS

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REALIZATION OF A REGULAR FACILITY BLOCK PLAN FROM AN ADJACENCY GRAPH USING GRAPH THEORETIC BASED HEURISTICS

by

Lawrence George McJannet

A Thesis Submitted to the Faculty of the

Department of Systems and Industrial Engineering

In Partial Fullfillment of the Requirements
For the Degree of

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In the Graduate College

THE UNIVERISITY OF ARIZONA

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STATEMENT BY AUTHOR

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

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Assistant Professor

04/30/86
Date

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ABSTRACT

This thesis presents two workable heuristics which provide useful Block Plans for a single story facility based on a given Relationship Chart. Both of the heuristics are in the form of a two phase Graph Theoretic Approach and are implemented without the need for planarity verification. These heuristics can be applied in such a way as to conform to a predetermined structure or, as originally intended, they can themselves develop a preferred structure shape. The heuristics are intended to provide a spatial framework rather than an actual floor plan but an extension to practical/actual layouts and computational experience is reported. Justification of a heuristic solution for Facility Layout Problems and an analysis of current topical literature are included.

CHAPTER 1

INTRODUCTION

In this chapter we will explain the purpose of this thesis and the specific problem we are addressing. Included also is an explanation of the layout of the thesis along with some terminology and definitions.

1.1 The purpose of this thesis

The purpose of this thesis is to explore two heuristic solution approaches to a natural group of Facility Layout Problems which require solutions of geometrically regular shape. It is felt that, in consideration of recent advancas in the application of graph theoretic techniques, the development of heuristics which produce solutions in a workable form, of measurable efficiency, is appropriate. In the following chapters we will discuss the currently available theoretical techniques, why we feel that these current techniques may not always be useful and show how they can be used to determine the efficiency of the heuristics which we develop. We will then present the heuristics which we have developed and some examples of their application. Finally we will close with some remarks which indicate not only the positive accomplishments of the thesis but also some areas where more work is required.

1.2 Organization of this thesis

This thesis is divided into six parts:

1. the first part is the lead pages consisting of the acknowledgements, abstract and index,
2. the second part is the introduction, which gives some insight into the 'raison d'etre',
3. the third part explains the current state of work in this area and the justification of the heuristics which are presented,
4. the fourth part explains in detail the heuristics presented,
5. the fifth part presents some example problems and their solutions as found using the heuristics, and
6. the last part consists of appendices which detail some computer programs used in support of the heuristics.

1.3 Terminology and Definitions

In this section we will present the graph theoretic terminology and relevant definitions that will be considered innate. Except where noted we have attempted to follow the conventions used by Harary (1969) and Giffin (1984). Entries will be listed alphabetically except where grouped to facilitate commenting.

Definition 1.3.1 The term Block Plan is used to describe the final product of either heuristic. This Block Plan must be, to the extent possible, a regular shape. Usually an output of Phase 2 of the heuristics.

Definition 1.3.2 'E' will denote the total number of edges found on a graph.

Remark 1.3.3 As a consequence of Euler (1752) it can be proven that $|E| = 3|V| - 6$, if $G = (V,E)$ is a planar graph.

Definition 1.3.4 If the edge E(Vi,Vj) exists then;

(i) Vi and Vj are adjacent, and

(ii) Vi and Vj are incident with edge E(Vi,Vj).

Definition 1.3.5 The term euclidean distance is used to refer to the 'straight-line distance' between the centroids of respective sections.

Definition 1.3.6 The term rectilinear distance is used to refer to the distance between the centroids of respective sections if that distance is travelled on a rectilinear set of paths. ie. all path intersections are perpendicular.

Remark 1.3.7 Both rectilinear and euclidean distances are approximations when applied to block plans since they are cognizant only of centroid location and they are not affected by the circulation paths which will eventually be incorporated.

Definition 1.3.8 The faces of a planar graph are the regions bounded by the edges of the graph. All faces of a maximally planar graph are triangular.

Definition 1.3.9 The term flow dominance is used to describe how the required sequencing of operations within a facility determines the pattern of section locations within the facility.

Remark 1.3.10 The prefixes 'High' and 'Low' are added to flow dominance to imply either that the required sequencing of operations is such that a distinctive pattern of adjacencies is necessitated (high flow dominance) or that the lack of required sequencing of operations is such that no distinctive pattern of adjacencies is obvious (low flow dominance).

Definition 1.3.11 The term function is used to imply an A Programming Language (APL) programming code.

Remark 1.3.12 The reader may think of the various 'functions' that are presented throughout this thesis as they would think of a 'program' in most common computer languages. We may interchange the term function with program or code throughout.

Definition 1.3.13 The geometric rectangular dual of a planar graph in the sense of Whitney (1931) is a representation of that graph where the edges have been transformed into partitions separating centroids associated with adjacent vertices. Two Sections are considered adjacent and are depicted as having positive boundary lenghts if and only if their corresponding vertices are connected. See Figure 1.3.1 for a pictorial representation.

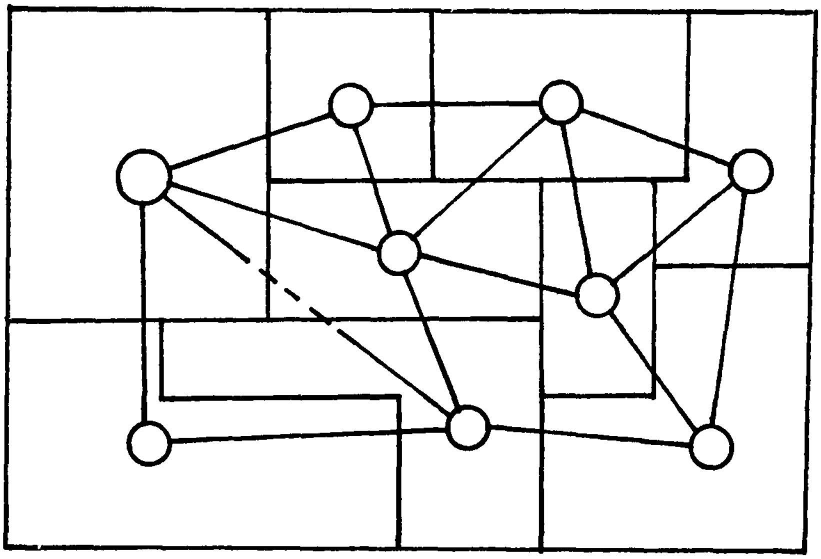


Figure 1.3.1 A Planar Graph and a Corresponding Geometric Rectangular Dual (Excluding edges relative to the exterior face)

Definition 1.3.14 A *pseudo-geometric rectangular dual* of a planar graph is an approximation of the geometric rectangular dual which may fail to represent all of the edges found on the original graph. Pseudo-geometric rectangular duals are useful when the geometric rectangular dual has properties unsuited to the desired purpose.

Remark 1.3.15 We will use the terms 'dual' and 'pseudo-dual', throughout this thesis when we are referring to the geometric rectangular dual and the pseudo-geometric rectangular dual respectively.

Definition 1.3.16 A *relationship chart*, is a matrix whose elements $W_{i;j}$ represent a pairwise adjacency score rewarded for having vertices V_i and V_j connected by an undirected edge (v_i,v_j) on the corresponding adjacency graph. We will refer to the elements of the relationship chart as REL_chart scores.

Definition 1.3.17 The term *greedy* will be used whenever a selection /decision is made by choosing the option which will have the highest immediate return.

Definition 1.3.18 The term *heuristic* is used to refer to a solution technique which does not necessarily return an optimal solution but which has been formulated in such a manner as to return a near optimal solution for most applications.

Definition 1.3.19 A graph is *maximally planar* if no edges may be added without violating planarity.

Remark 1.3.20 The maximum number of edges that can be embedded on the plane and associated with a planar graph is $|E| = 3|V| - 6$.

Definition 1.3.21 'N' will denote the total number of sections represented on the REL chart. As a result of Remark 1.3.20 above $N = V - 1$.

Definition 1.3.22 A planar graph is one which can be drawn in a plane in such a way that no edges intersect geometrically except at a vertex.

Definition 1.3.23 A Graph $G = (V,E)$ for the purposes of this thesis is defined as an ordered pair of sets where 'V' exists and is finite, and 'E' is a set of selected pairs of elements of 'V'. The elements of 'V' represent the Sections of the Facility and are called vertices on the Graph. The elements of 'E' denote adjacency within the facility and are called edges on the Graph.

Definition 1.3.24 The term Raw Block Plan is used to describe any interim block plan which has not been regularized; these are an output of Phase 1 of both heuristics presented.

Definition 1.3.25 The term REG'D' is the identifier applied to the deltahedron based heuristic which is presented in this thesis.

Definition 1.3.26 The term REG'T' is the identifier applied to the Triangulated Graph based heuristic which is presented in this thesis.

Definition 1.3.27 The term regularize and its derivatives are used to describe any process which transforms a Raw Block Plan into a Block Plan.

Remark 1.3.28 The regularity of a Block Plan is very much an arbitrary concept. We have decided that for this thesis a regular shape is one which is rectangular for interior sections and the overall exterior be at worst in an 'L' shape.

Definition 1.3.29 The term section is used to describe a unit work area.

Remark 1.3.30 A section could comprise a large area of similar or related functional tasking, such as 'the machine shop' or it could be a single identifiable unit such as 'a wave soldering machine'.

Definition 1.3.31 A Triangulated Graph has all interior faces triangular and it is planar. It is usually not maximally planar.

Definition 1.3.32 'V' will denote the total number of sections which are to be incorporated into the resultant block plan.

Remark 1.3.33 We will for all examples be considering the exterior to be part of the facility represented as a section on the REL_chart and assumed to be enclosing the facility on the block plans.

Definition 1.3.34 The valency (degree) of a vertex is the number of edges incident to that vertex.

1.4 The problem to be studied

Earlier we have referred to 'a natural group of Facility Layout Problems'. It is a fundamental premise of this thesis that most Facility Layout Problems require more than that the sections of the resultant facility be laid out in an optimal manner with respect to maximization of relative adjacencies or minimization of material transportation costs or any of the other parameters by which layouts are conventionally evaluated. They also require that the sections be of reasonable shapes and that the accredited adjacencies be of useful dimension. We feel that this 'natural group' is extensive and in fact represents the main body of Facility Layout Problems for which solutions are sought. To this end we present this thesis as a method of accommodating both an academic desire for 'optimality' and an intuitive need for practicality in the solution of Facility Layout Problems.

CHAPTER 2

FACILITY LAYOUT PROBLEMS

In this chapter we will explain relevant background of the facilities layout problem (FLP). This will include discussion of its justification, its nature, a brief review of the attempts that have been made to solve the problem, and a presentation of the deltahedron approach which we feel produces useful solutions.

2.1 The Nature of the Problem

In this section we will discuss the evolution of the FLP.

2.1.1 Justification of Study

Every year millions of dollars are spent by businesses throughout the world in an attempt to optimally arrange sections of their facilities. It is felt that a significant amount of money is wasted each year as a result of operating facilities which are not optimally arranged. The preeminent task of many Industrial Engineers is the solution of FLPs in one form or another.

This task is not only academically very challenging but it is intuitively interesting.

2.1.2 The Objective of the Study

The objective in solving the class of FLPs which we will be considering is quite specific - to arrange various sections or units within the area of a facility in an optimal manner. The objective of this thesis is to present a method which develops a spatial block plan consisting of regularly shaped sections arranged in a near optimal manner. Perhaps the largest problem in solving the FLP we face is the subjectiveness of the term 'OPTIMAL'. This problem will be addressed in several of the following sections and will be part of the underlying discussion throughout this paper.

2.1.3 Previous Solution Formulation Attempts

There have been many approaches to quantifying the FLP starting with Beckmann and Koopmanns (1957) who developed the FLP as a Quadratic Assignment Problem (QAP). With respect to the overall approach to real world FLPs, we consider the Systematic Layout Approach, developed by Muther (1961), to be a good one. His Systematic Layout Approach is one, of very few, that address all aspects of the FLP including the development of relationship values between sections. The layouts developed are not based on a planar block plan and he makes extensive use of physical models to develop his solutions. The approach is good as a general overview methodology, but in light of the recent advances in the application of Graph Theoretic techniques we feel that better solutions are readily available. Work was done by many trying both algorithmic and heuristic solutions to the FLP-QAP. The underlying problem was that the FLP QAP was eventually proven to be NP-complete (Lenstra (1976), Giffin (1984)).

2.1.4 General Heuristics for Solving Facility Layout Problems

Development of heuristics to find near optimal solutions to NP-complete problems has become a norm. Foulds (1983) discusses heuristic approaches to problem solving in general. The theory of NP-completeness in fact shows the necessity to use heuristics when solving problems of reasonable size.

Early heuristic approaches to the FLP were the normal relaxations applied to QAPs' which hopefully transformed the problem in such a way as to make it simpler to solve. Industry standards such as CRAFT (Buffa et al. (1964)), CORELAP (Lee and Moore (1967)) and ALDEP (Seehof and Evans (1970)) were developed using various heuristic approaches. We will compare the approach and results of the REG heuristics to CORELAP with respect to seven sample problems in Chapter 4. In innovative approach, the application of graph theory to the FLP was suggested by Levin (1964).

2.1.5 The Graph Theoretic Approach

The usefulness of the graph theoretic approach (GTA) can be envisioned if one thinks of the undirected connected graph G(V,E) as realization of adjacencies. If one maximizes the adjacencies represented in the graph, while maintaining planarity, and then transforms this maximal planar graph to its dual, the result will be an optimal realization of the pairwise adjacencies of the REL_chart. We call this a Block Plan. This Block Plan is 'optimal' with respect to the information reflected in the REL_chart. Note that it may not be possible to have as much information about the Facility operation in the REL_chart as would be available when using a QAP approach and therefore the respective optimal solutions would vary.

The graph theoretic approach has certain advantages over the QAP approach (see Giffin (1984), and see Chapter 4 for an enumerative comparison of the REG heuristics with CORELAP on five sample problems). In theory the QAP and GTA will accommodate any shape of an individual section or overall facility. We say 'in theory' since clearly there are practical restrictions on the final layout which must be taken into consideration (see the Section 2.5.3 'Utility in Design').

The problem of NP-completeness is not avoided by utilization of GTA. Giffin (1984) showed that in fact the FLP remains NP-complete even when restricted to the GTA. This implies that again one is forced to use heuristics to formulate a near optimal solution to the FLP.

2.1.6 Graph Theoretic Approach Based Heuristics for Solving the Facility Layout Problem

Hammouche and Webster (1985) succinctly review the various attempts to utilize GTA in solving the FLP. In the late 1970's two GTA heuristics were presented which give nearly optimal planar graphs. The first, Carrie, Moore, Rocziak and Seppanen (1978), involves a complicated GTA . The second heuristic, Foulds and Robinson (1978) is, we feel, more straight forward and does not need the complicated string processing representation and manipulation of the graph that the previous work requires. That is the Deltahedron Heuristic with which a maximally planar graph is created by successive embedding of 3-connected vertices into an initial tetrahedron. Without further comment on these varied methods the remainder of this paper will be devoted to an extension in one case and a variation in another case to the deltahedron heuristic approach which we consider the most practical. It is the spatial relationship which the deltahedron conceptualizes and that we use to realize the regular block plan for the FLP.

All of the GTA approaches mentioned have had the common trait that they claimed that a 'desired block plan' could be developed from the dual of the maximally planar graph which they produced. The problem was that no one had actually devised a method to produce a rectangular dual to the maximally planar graph and so the desired block plan remained elusive. Giffin (1986) is considered to be the first to take the concept developed by Foulds and Robinson (1978) and show how it was possible to algorithmically produce a rectangular dual of the maximally planar graph of which the deltahedron is a form. It was this step, the production of a rectangular dual to the planar deltahedron, which has opened the door to the realization and evaluation of workable regular block plans from the deltahedron heuristic.

Keenan (1986) has implemented Giffin's (1985) method of attaining the dual of the deltahedron including the actual floor area requirements of the sections involved. His work comprises a complete automation of the layout process and provides an exact realization of the

REL_chart scores, which are represented by the deltahedron, by producing an actual rectangular dual of the deltahedron. Keenan's method has application in many specialized areas. The heuristics which we will be explaining produce regular Block Plans which we feel have application for FLPs involving the traditional Plant, Office or similar types of facilities.

2.2 Formulation of the Facility Layout Problem

In this section we will discuss the decisions which must be made before attempting to find a solution to a FLP. We will describe the decisions we made and discuss their importance with respect to the type of FLP which we are addressing.

2.2.1 What to Optimize

When trying to optimize FLPs there are many different values which may be considered. For facility layout the concept of intra section distances may be considered the central issue. That is to say the distance between sections within a facility is the key to accounting for the cost of utilizing the facility. The distance could be translated into travel cost of moving material around the facility, or time cost of supervisors moving around the facility or penalty costs for having undesirable adjacencies within the facility.

Distance within a facility is usually measured using a rectilinear or euclidean norm. We will consider in fact neither of these for this thesis. The formulation of the REL_charts will be considered to have been done in such a manner that the objective is to maximize the sum of the pairwise adjacency scores listed. Therefore the concepts of rectilinear or euclidean distances are not considered explicitly. The fundamental assumptions of the deltahedron heuristic and the Triangulated Graph heuristic, as we will use them, are that only adjacency counts and that all adjacencies are equivalent and non adjacencies are also equivalent.

These assumptions become very critical when one actually draws the Floor Plan for a given facility. The problem that we are attempting to handle is the production of a Block Plan. The major difference is that the block plan will show spatial rather than detailed layout. We are assuming that adjacency is found whenever two sections are placed side by side, which is reasonable when dealing with a block plan, but may not be attainable when producing the equivalent floor plan.

Giffin and Foulds (1985) relate the concept of the 'umbrella' effect which appears when 'popular' sections have high REL_chart scores with many other sections. This umbrella effect must be arbitrarily curtailed to ensure legitimate adjacencies are attained in the block plan. The curtailment can take place either within the deltahedron formulation phase or during the block plan realization phase. For both of our heuristics we have decided to curtail valency at the block plan realization phase. This makes it possible for us to greedily decide on which adjacencies will be preferred. The curtailment at the planar graph formulation phase can cause highly scored REL_chart adjacencies to be overlooked since the insertion order into the planar graph is typically based on the:

$$\sum_{i=1}^{v} \text{REL\_chart Scores}$$

and therefore could cause curtailment of possibly higher individually scored adjacencies. This might happen if a high pairwise adjacency score was assigned to an otherwise lowly scored section. That section would be considered for embedding into the planar graph late in the process and by that stage the desirable adjacency may not be available. The heuristics which we present are cognizant of all scores until every section has been included in the block plan. It is therefore possible at any time to 'optimize' specific adjacencies associated with each section as it is considered for positioning in the Block Plan. Thereby we may perhaps improve the overall score accredited to the block plan.

The entire concept of Optimization is vague when attempting to produce Block Plans which eventually will have application via transformation into Floor Plans. Certainly purists could argue that there is no vagueness about the problem once defined. We do not disagree. We do point out however that the definition phase can be manipulated so that it is difficult to know when the 'optimal' solution is attained. The approaches we present for solving the FLP are considered pragmatic. We will develop two heuristics both of which will produce an aesthetically pleasing block plan constructed of regularly shaped sections which we feel will represent a high REL_chart score summation based on these restrictions.

2.2.2 Selection of Relationship Chart Entries

The assumption that only actual adjacency should be considered is important and it demands that the formulation of the REL_chart be done in an exact manner. The formulation must be done in consideration of the method which will be used to optimize the FLP.

There has not been a significant amount of work published which deals specifically with the problem formulation of REL_charts. Throughout this thesis we will approach the solution of the FLP with the intention of maximizing the total of credited REL_chart scores. The term credited is meant to imply that if two facilities are 'adjacent' in the resultant block plan then the indicated REL_chart score will be included in the summation. For the remainder of this thesis consider the REL_chart simply to exist. The REL_chart will be thought to have been created in consideration of the goals which we have just stated.

2.2.3 Human vs Computer Solutions

The heuristics which we will present in this paper have been formulated in such a manner that the human ability to evaluate a developing layout aesthetically is fundamental. As will be seen the heuristics use a computer code which has been formulated to carry out the development of the planar graph but the realization of the block plan is created by hand. This craftsmanship is not hindrance since the final solutions have been found attractive with respect to achieved scoring, appeal of the layout and even solution time, if one considers the post optimal activities required of most computer based programs to achieve comparable results.

2.3 The Deltahedron Heuristic Approach

In this section we will discuss the deltahedron heuristic which we use in support of the REG'D' heuristic. We must know and understand how the heuristic allows us to attain our goals and the price we will be paying when we use the heuristic. Finally in this section we will present the mechanics of forming the deltahedron and discuss the computer code we have developed to produce it in a form we need.

2.3.1 Advantage of the Deltahedron Approach

Computationally the most time-consuming and difficult part of solving the FLP using GTA in earlier works was the requirement for planarity checks. Clearly via Whitney's [1931] characterization of geometric duality it was considered that the resultant maximally weighted graph must be planar in order that the associated dual represent a feasible ie. planar block plan. Foulds and Robinson (1978) have shown that construction of a deltahedron is such that it remains planar throughout. This then removes the requirement for continual planarity checks. For an excellent review of the structure of combinatorial deltahedra, see Foulds and Robinson (1979).

2.3.2 The Cost of using the Deltahedron Heuristic

By definition the use of a heuristic approach to solving any problem means that one is not guaranteed to attain the 'optimal' solution. The so-called optimal solution is not identified by the deltahedron approach either. This means that we will not know the quality (in terms of the total possible score) of the solution that the deltahedron finds. Dyer, Foulds and Frieze (1985) have analysed the performance of several heuristics used to create a deltahedron. Dependent on the technique used the Deltahedron Heuristic guarantees, in worst case ratio sense as little as zero and high as one third of the potential optimal, (see worst case ratio in Terminology and Definitions section). This is a worst case analysis which involves pathological examples designed specifically to cause poor performance. In realistic applications and in randomly generated applications the Deltahedron Heuristic has been shown (see Giffin, 1984) to perform very well. The worst result found when the Deltahedron Heuristic was applied to randomly generated problems was reported to be ≈ 87%. For problems with $N \leq 12$ there are programs available which will find the numerical optimal value, using a branch-and-bound scheme with an embedded planarity testing routine. This value is not necessarily attainable via the Deltahedron Heuristic but as we discussed before, the optimal solution, especially in realistically sized problems is disproportionately expensive to attain or effectively impossible to attain.

The cost of the Planarity requirement is that only 3V-6 of the REL_chart scores are attainable. This is since the construction of the block plan is such that the plane will only accommodate that number.

Depending on the particular type of facility we are working with, it may be possible to effectively achieve credit for more than 3V-6 REL_chart scores. This would be done by the addition of facilities (with zero area) at the intersection points within the block plan. This then actually increases the size of the FLP since 'N' would be increased and therefore the problem has been changed. While the 3V-6 planarity restriction is valid in applications which demand planarity in the adjacencies themselves, we feel that in applications, such as offices and many plant environments, the block plan should be credited with adjacencies around the 'courtyard'. The courtyard concept is discussed by Baybars (1982), and an example is shown Figure 2.1. The applications to which, we feel, the heuristics of this thesis are addressed are such that we will consider the 'courtyard' to be present at all intersections involving more than 3 sections. This is contrary to the idea of maximal planarity since it in effect allows edges to intersect at a point other than at a vertex. This is why the courtyard concept is appealing in that the courtyard acts as the vertex at the intersection of the edges and thereby permits the illusion of planarity. We accept the fact that the planarity of the block plans produced via our heuristics is somewhat illusionary and as discussed, in Section 2.5.2, we have made accommodations in scoring rules so that various plans developed may be compared as a strictly planar plan and in consideration possible courtyard intersections. This narrows the scope of application by excluding facilities that have a planarity in their adjacencies. However such facilities are considered extremely rare in 'real life'. Purists may insist that every eventuality be considered while non academics prefer to solve 'real world' problems.

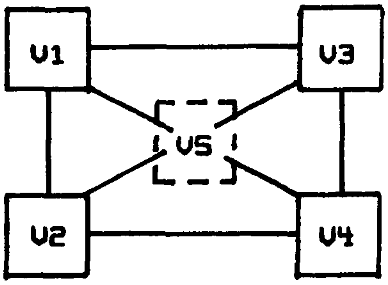


Fig. 2.1 Block Plan with Courtyard

Note that the section labelled V5 is the so called courtyard. V5 is in effect the vertex at which edges E(V1,V4) now E(V1,V5) - E(V5,V4) and E(V2,V3) now

E(V2,V5 T) - E(V5,V3) intersect. Therefore all edges intersect at a vertex as required by planarity.

For purposes of comparison, we will refer to NORMAL SCORING RULES (NSR) and COURTYARD SCORING RULES (CSR). The NSR will reflect only three adjacencies possible at any intersection while the CSR will reflect three or four adjacencies at any intersection.

2.3.3 Creation of the Deltahedron

The method for creating the deltahedron was introduced by Foulds and Robinson (1978). For a detailed understanding of the concepts and mathematics involved see Foulds and Robinson (1978 and 1979).

The approach is conceptually and computationally simple. We have changed it only slightly from the original presentation. The change is in the handling of the embedding of the outside or exterior of the facility. Foulds and Robinson (1978) created the deltahedron within an initial triangle one vertex of which was considered to represent the exterior of the facility in question. The heuristic which we use to produce the block plan is not affected by the handling of the exterior except that the exterior be considered and presented as a section of the facility. The embedding process differences themselves are not significant since it has been shown Foulds and Robinson

(1979) that any deltahedron can be transformed into any other on the same vertices through a sequence of elementary edge exchange operations.

2.3.4 Selection of Adjacencies

The construction of the deltahedron can be done in consideration of many different factors. We have chosen to construct the deltahedron semi-greedily. The computation of a Semi-Greedy Deltahedron without valency constraints has been shown to be simple enough, see Atrek and Fifield (1985). We have processed problems with up to 100 sections on an AT&T 6300. The solution begins to appear 'instantly' and the only time restriction seems to be the scroll rate of the screen on which it is presented. Since there is not a practical restriction on the size of the problems considered nor the time required to produce the deltahedron information we will leave the discussion of the mechanics of computer code (WORKDELTA) and its output for the interested reader in Appendix 1.

The development and physical representation of the deltahedron as a maximally planar graph is not considered a part of the deltahedron based heuristic (REG'D') which we are presenting in this thesis. Rather that development is considered to be a fundamental precursor to the heuristic. We do not have to actually draw the deltahedron physically. It is enough that we know that it exists and can conceptualize the essence of its structure. Specifically we keep in mind the 'umbrella' formations and the fact that we are not restricting the valency of any vertex.

2.3.5 The Physical Representation of Deltahedra

For completeness we will present a brief explanation and demonstration of the physical creation of the deltahedron. As we have discussed, the first and most critical part of the operation is the development of the REL_chart. We assume this has been done; see Table 2.1. You will note that the REL_chart is presented in the form of a square matrix rather than the more conventional '>' shape which the reader may be more familiar with. This presentation accommodates the computer codes which both heuristics incorporate.

Table 2.1 REL_chart for Example #1

	S1	S2	S3	S4	S5	S6	S7	S8	EXT
SECTION 1	0	0	16	16	16	16	16	16	64
SECTION 2	0	0	16	16	16	16	16	16	64
SECTION 3	16	16	0	64	0	0	0	0	0
SECTION 4	16	16	64	0	64	0	0	0	0
SECTION 5	16	16	0	64	0	64	0	0	0
SECTION 6	16	16	0	0	64	0	64	0	0
SECTION 7	16	16	0	0	0	64	0	64	0
SECTION 8	16	16	0	0	0	0	64	0	0
EXTERIOR	64	64	0	0	0	0	0	0	0

The approach we present here is a well established one which we include solely in the interest of completeness. There are only three basic steps.

1. The first step is to identify the insertion order. This is simply a ranking in order of the sum of available pairwise adjacency scores from the REL_chart. Giffin (1984) has extensively tested several variations of techniques to determine the insertion order. He could not justify the additional computations required when using the Greedy method. We have decided that, for the examples we will be presenting, the summation ranking method will suffice for determination of the insertion order. The insertion order for Example #1 is, 1-2-4-5-6-7-8-3-9.
2. The next step is to form an initial triangulation using the first four sections listed in the insertion order. In this example they are 1-2-4-5. See Figure 2.2.

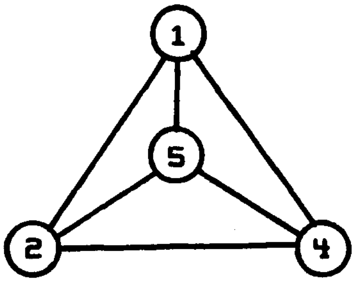


Fig. 2.2 Initial Tetrahedron for Example #1

3. The third step is repeated until all sections have been included in the deltahedron. That is; select the next entering section from the insertion order and Greedily assess into which triangle the new section should be embedded in order to maximize achieved adjacency scores. See Figure 2.3 for a pictorial presentation of the process.

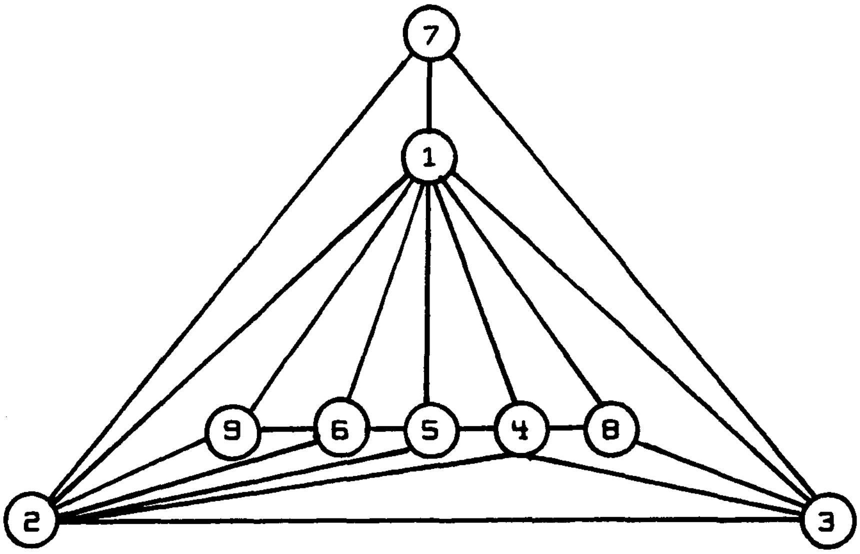


Fig. 2.3 Deltahedron - Maximally Planar Graph Example #1

2.4 The Triangulated Graph Heuristic Approach

In this section we will discuss the features, advantages and disadvantages of the Triangulated Graph heuristic approach used in support of the REG'T' heuristic.

Again it is necessary that we understand why this approach allows us to attain our goal and what the potential costs associated are. We will not include a discussion of the mechanics of formulating the 'Triangulation' as that is discussed in detail in the REG'T' section.

2.4.1 What is the Triangulated Graph Approach

The Triangulated Graph Approach is one which takes advantage of the fact that a Graph which has all of its interior faces made up of triangles is a PLANAR GRAPH. It is not necessarily maximally planar but, fortunately, maximal planarity is not essential to finding a highly weighted planar graph. Basically the Triangulated Graph approach involves an initial triangle of vertices onto which vertices are added adjacent to two vertices which are themselves adjacent. Note that for the Deltahedron formulation, vertices are embedded into the graph while for the Triangulated Graph vertices are appended to the exterior of the graph.

2.4.2 Advantages of the Triangulated Graph Approach

The first advantage which we have just shown is the fact that as for the Deltahedron approach there is no requirement for planarity checks. In addition, as we will show, a highly weighted triangular graph which is not maximally planar is very easily transformed into a regular rectangular pseudo-geometric dual and in some cases an actual rectangular geometric dual. Whether a pseudo or geometric dual is produced seems to be a factor of the relative valency of the various sections. The last and perhaps most significant factor is that the Triangulated Graph is computationally easy to handle. The scores associated with the Triangulated Graph have been found in some cases to be as high as the results of the deltahedron despite the fact that the Triangulated Graph has 'V' fewer edges (see below).

2.4.3 Disadvantages of the Triangulated Graph Approach

Although we have not experienced a case in the applications we have attempted, it is felt that pathological examples may exist where the pseudo-dual produced from the Triangulated Graph would be so misshaped that regularization could not be achieved without loss of significant adjacencies. Where as the deltahedron is maximally planar with 3V-6 edges, the Triangulated Graph will have only 2V-3 edges. (This may be proven by induction on V). This difference is narrowed via the formulation of the associated block plan since more adjacencies can be represented on a planar block plan than are on the Triangulated Graph and in most cases for the deltahedron based heuristics fewer adjacencies are eventually represented to eliminate extreme irregularities in the shape of some sections.

2.4.4 The physical representation of the Triangulated Graph

As we discussed, in the introduction to this section, the details of the formation of the Triangulated Graph are found in the REG'T' section. However to be consistent with our coverage of the Deltahedron we will provide the Triangulated Graph of the current example. Figure 2.4 shows the initial triangle.

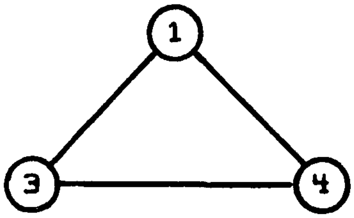


Fig. 2.4 Initial Triangulated Graph for Example #1

This triangle represents the most highly weighted combination of three incident vertices found in the REL_chart. The completed Triangulated Graph is shown in Figure 2.5.

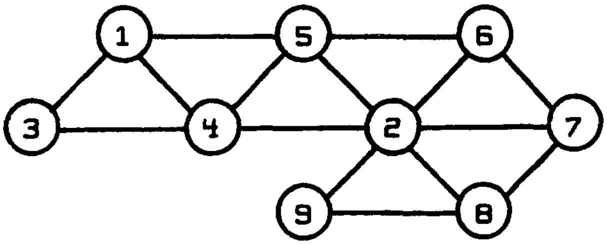


Fig. 2.5 Triangulated Graph for Example #1

Each of the vertices has been inserted in a semi-greedy fashion which ensures that the Triangulated Graph is highly weighted. The semi-greedy implementation of the embedding process will be discussed in the section dealing with the REG'T' heuristic.

2.5 The Block Plan

In this section we will discuss the Block Plan. This discussion will include what we mean by the term 'Block Plan', and brief overview of others' attempts to realize a block plan from a graph, planar or non-planar. We will review in some detail the successful work in this area by Giffin (1986) and continue the discussion of useful block plans which leads to the presentation of the concept of pseudo-duals to the adjacency graphs.

2.5.1 Understanding the Block Plan

Most readers will already have a preconceived notion of what a block plan is, what it is for and what it should look like. We have already, in Section 1.3 (para. 1.3.1) given a brief definition of a Block Plan, however we have introduced several concepts in this thesis which narrow the definition of the term as we will be using it. To ensure a complete appreciation of the REG Heuristics we will briefly highlight certain aspects which may help the reader understand the objective of the study and the REG'D' and REG'T' heuristics' handling of the REL_chart entries.

The Block Plan which the REG'D' Heuristic creates is a regular realization of the dual of the maximally planar adjacency graph or deltahedron. Similarly the Block Plan which the REG'T' creates is a regular realization of the dual of the highly weighted planar adjacency graph or Triangulated Graph. Both are in the form of a spatial representations of the selected adjacencies.

The reader will note that most of the examples which are presented do not take into consideration the required area of the section involved. That is because the REL_chart scores, that we are assuming to have been formulated, CANNOT logically incorporate area considerations. That is not to say that other types of REL_chart scores cannot incorporate areas. The reader will recall however that in Section 2.2.1 the notation of 'rectilinear or euclidean distance' was discussed and dismissed for the purposes of the problem which we have addressed. To accommodate that decision one may wish to realize that the handling of distances is usually in terms of inter section centroid dispersion. We suggest that it is possible to allow for such considerations by simply creating all sections of 'unit' size.

The unit size concept, while greatly enlarging the problem, has some advantages. Firstly, it avoids the problem we earlier referred to as 'equality of adjacencies'. Secondly, it eliminates the concept of size from the Block Plan solution and therefore makes that solution easier to transform into an equivalent Facility Plan. The unit size concept does not extend to account for the 'near adjacency concept'. For complete coverage of the primary deltahedron formulation techniques see Giffin (1984).

The Block Plans which the REG'D' and REG'T' heuristics create are of Regularly shaped and equally sized blocks. While we can theoretically support the decision to not incorporate the area of sections into the heuristics it has been found that in 'Real World' problems, which we have solved, area incorporation has not caused loss of significant adjacencies. Obviously it is possible to pathologically create problems for which this would not be true; such problems we would solve using Keenan's (1986) method since pathological examples do not require REGULARLY SHAPED BLOCK PLAN SOLUTIONS and his method provides an adequate solution for such examples.

Since we have found that the REG'D' and the REG'T' heuristics secondarily accommodate section area we have not pursued that aspect of the problem in depth. Inclusion of area is, for purposes of this thesis, considered to a problem associated with the drawing of a Facility Plan which is an architectural function which must incorporate many considerations outside the scope of the REL_chart which we have defined. We also have not considered it necessary to use the Unit size concept in formulating the problem but, if impelled, may use that concept to overcome problems which conceivably if not practically could arise. We have included an example, based on actual data, which incorporates area, see Section 3.3.1

2.5.2 Previous attempts to find the Dual of an Adjacency Graph

Levin (1964) suggested the use of the GTA for solving the FLP. He did not however address the problem of transforming the maximally planar adjacency graph into a block plan. Hashimshony, Roth and Wachman (1982) have effectively reviewed most of the various attempts to solve this problem.

The various attempts all seem to have common traits. These are:

1. they are difficult to conceptualize, or
2. they are difficult computationally, or
3. they are not repeatable.

Giffin and Foulds (1986) have successfully solved the problem of creating the rectangular dual of a maximally planar adjacency graph (for the class of graphs constructable by the insertion operation). Their solution is elegant in concept, easily applied and repeatable. For an excellent presentation of the solution including an extension to accommodate relative areas of sections see Keenan (1986). Since their solution represents the actual dual to the maximally planar adjacency graph, all of the 3V-6 adjacencies represented on the Deltahedron will be realized in the block plan which they produce.

This information is invaluable to the evaluation of the heuristic which we will be presenting in the following sections. We can now use a Relationship Ratio which is based on the Deltahedron achieved score and refer to this as the REL-Rd. This ratio will be found by;

REL block plan /REL deltahedron.

We will use this REL-Rd as a performance measure since its value is easily calculated for all sizes of problems within the scope of this thesis. REL-Rd then represents a standard of performance measure which is itself easy to understand, easy to calculate and repeatable.

2.5.3 Utility in Design

Clearly in consideration of the Deltahedron Heuristic approach, Giffin has effectively solved the problem of finding a near optimal solution for the FLP using the GTA. Academically the game is in a sense over; a workable solution to a described problem is in hand. Now let us consider the original goal of the FLP. That is to 'arrange the various sections of a facility in an optimal manner'. Once again we must consider the word optimal.

Academically an optimal solution is only found if the maximum feasible number of the REL chart pairwise adjacency scores have been realized in the resultant block plan. MacGregor Smith and Pelosi (1984) refer to a concept they term as 'Utility of Place', their idea being that if a block plan is to have practical application, then the adjacencies represented must be utilizable and the shapes of the various sections represented must also be useable. That is not to imply that odd shaped sections or minimal adjacencies are always impractical, it is just that we are interested in the more general applications which require conventional (for the most part regular) section layouts. We have already discussed the fact that the use of the Deltahedron Heuristic approach forfeits the utopian optimum for an attainable optimum. The application of the heuristics we are presenting here MAY cause us to relinquish the attainable optimum so that we have a block plan which represents a workable solution.

It is also important that the Block Plan produced actually bear some resemblance to the workable Floor Plan which is the next phase in the FLP solution process. While outside the scope of this thesis, we feel it necessary to always be cognizant of the global application. For example consider the block plan which is found by taking the actual dual of the deltahedron of Example #1, see Figure 2.6

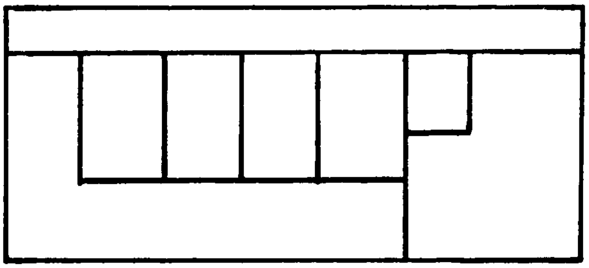


Fig. 2.6 Block Plan for Example #1 (Giffin/Foulds Method)

The adjacency REL chart for this example is based on a multi unit drive thru automobile servicing operation an admittedly trivial example but the actual dual of the maximally planar adjacency graph is not a reasonable block plan. This small example serves to demonstrate the idea that the Block Plan must be transformable into a Floor Plan. Consider the complications involved in a large FLP. Finding a near optimal Block Plan is not finding a near optimal solution to the FLP if a useable Floor Plan is not easily derivable from that Block Plan. Because of the aesthetic input of the human operator in the heuristics which we are presenting, the Block Plans which are produced can be easily envisioned as Floor Plans. For example consider the Block Plan which the REG heuristics produced, see Figure 2.7. We refer to both heuristics since they both, in this simple application, produced the same block plans.

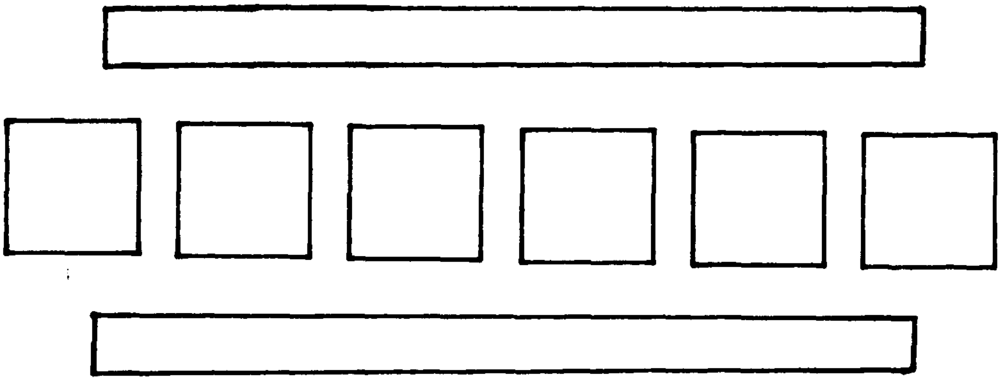


Fig. 2.7 Block Plan for Example #1
(REG Heuristics)

The pattern is recognizable and with very little effort the transformation is made to the Facility Plan shown in Figure 2.8

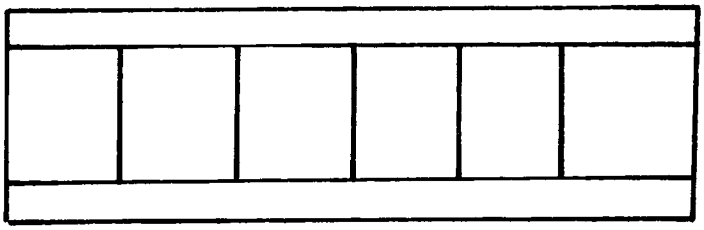


Fig. 2.8 Potential Facility Plan for Example #1

The following example is one which more clearly demonstrates the potential of the Giffin and Foulds method, while at the same time demonstrating the potential aesthetic advantages of the REG heuristics. This problem is not a trivial example; containing twenty sections including the exterior it is larger than any complete example we have seen in publication. The REL_chart was developed using random numbers. This randomization of REL_chart scores induces an atypically low flow dominance which induces poor performance of the REG heuristics if one is interested in a 'highly scored' Block plan. We feel that both the REG heuristics will perform 'better' with respect to the REL-Rd on more realistic problems. So that the reader will be fully cognizant of the potential of the Giffin/Foulds approach we present this more comples example.

The REL_chart, Table 2.2, has been transformed into the deltahedron shown Figure 2.9 and the corresponding Triangulated Graph shown Figure 2.10. The resultant block plan of the Giffin and Foulds approach is shown Figure 2.11 the resultant Block Plan of the REG'D' heuristic is shown in Figure 2.12 and the resultant block plan of the REG'T' heuristic is shown in Figure 2.13. We will use this example in the following chapter to explain in detail the development of a Block Plan using both REG heuristics.

These Block Plans are scored as follows. The Giffin/Foulds Block Plan Figure 2.8 scores 4184 which is 100% of the deltahedron representing pairwise adjacencies. The REG'D' heuristic scores NSR 4031 (with 54 adjacencies counted) which implies a REL-Rd of 97% and CSR 4580 (with 68 adjacencies counted) which implies a REL-Rd of 108%. The REG'T' heuristic scores NSR 4060 (with 54 adjacencies counted) which implies a REL-Rd of 97% and CSR 4491 (with 67 adjacencies counted) which implies a REL-Rd of 107.3%. Notice that the block plans presented Figure 2.12 and Figure 2.13 are labelled as being in their 'RAW' state. In Chapter 3 we will show how these block plans can be made rectangular and still for CSRs maintain a REL-RdT in excess of 100% and regularity of sections. Having a REL-RdT in excess of 100% is a phenomenon of the REG Heuristics; it is not considered a feature since the heuristics do not guarantee that result.

Table 2.2 REL_chart for Example #2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	EX	20
S1	0	88	43	37	52	9	65	70	86	88	27	49	21	12	71	93	93	53	2	10
S2	88	0	20	34	88	63	42	5	99	95	67	29	81	6	19	34	6	64	40	23
S3	43	20	0	97	69	99	85	77	78	62	53	86	90	17	13	24	80	29	68	1
S4	37	34	97	0	27	39	99	99	88	30	98	2	71	82	75	36	91	93	46	50
S5	52	88	69	27	0	69	1	36	23	0	5	20	10	60	70	16	51	96	57	11
S6	9	63	99	39	69	0	6	56	13	81	30	65	8	46	39	80	17	52	39	1
S7	65	42	85	99	1	6	0	86	32	58	60	99	42	88	97	7	92	41	55	53
S8	70	5	77	99	36	56	86	0	76	28	59	6	25	13	58	85	48	30	95	60
S9	86	99	78	88	23	13	32	76	0	91	53	55	12	5	81	61	30	48	85	20
S10	88	95	62	30	0	81	58	28	91	0	33	99	77	49	83	63	49	36	39	11
S11	27	67	53	98	85	30	60	59	53	53	0	56	56	68	71	76	34	2	93	1
S12	49	29	86	2	20	65	99	6	55	99	56	0	53	47	66	39	2	25	30	64
S13	21	81	90	71	10	8	42	25	12	77	56	53	0	79	56	44	42	27	99	79
S14	12	6	17	82	60	46	88	13	5	49	68	47	79	0	6	5	16	97	46	11
S15	71	19	13	75	70	39	97	58	81	83	71	66	56	6	0	35	79	26	91	58
S16	93	34	24	36	16	80	7	85	61	63	76	39	44	5	35	0	30	57	98	69
S17	93	6	80	91	51	17	92	48	30	49	34	2	42	16	79	30	0	17	27	63
S18	53	64	29	93	96	52	41	30	48	36	2	25	27	97	26	57	17	0	91	82
EXT	2	40	68	46	57	39	55	95	85	39	93	30	99	46	91	98	27	91	0	41
S20	10	23	1	50	11	1	53	60	20	11	81	64	79	11	58	69	63	82	41	0

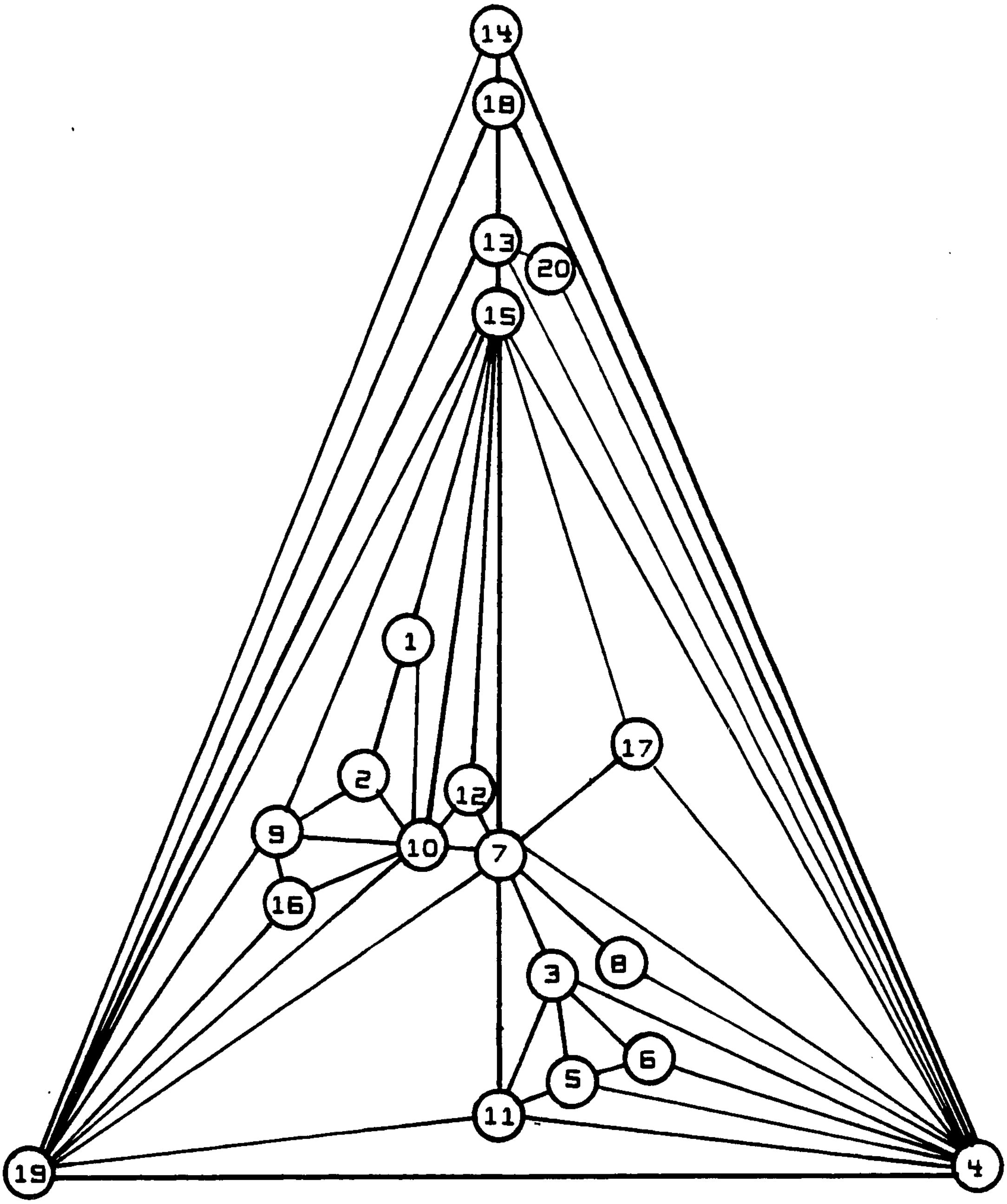


Fig. 2.9 Deltahedron for Example #2

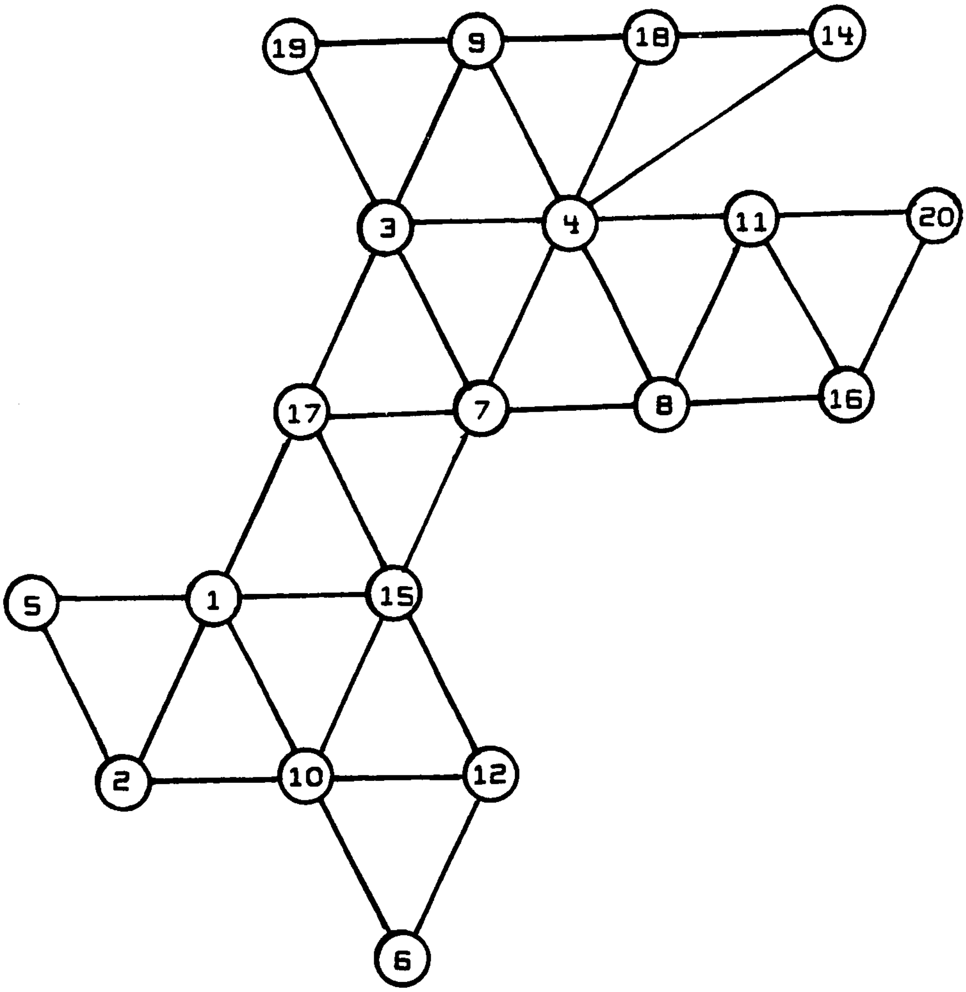


Fig. 2.10 Triangulated Graph for Example #2

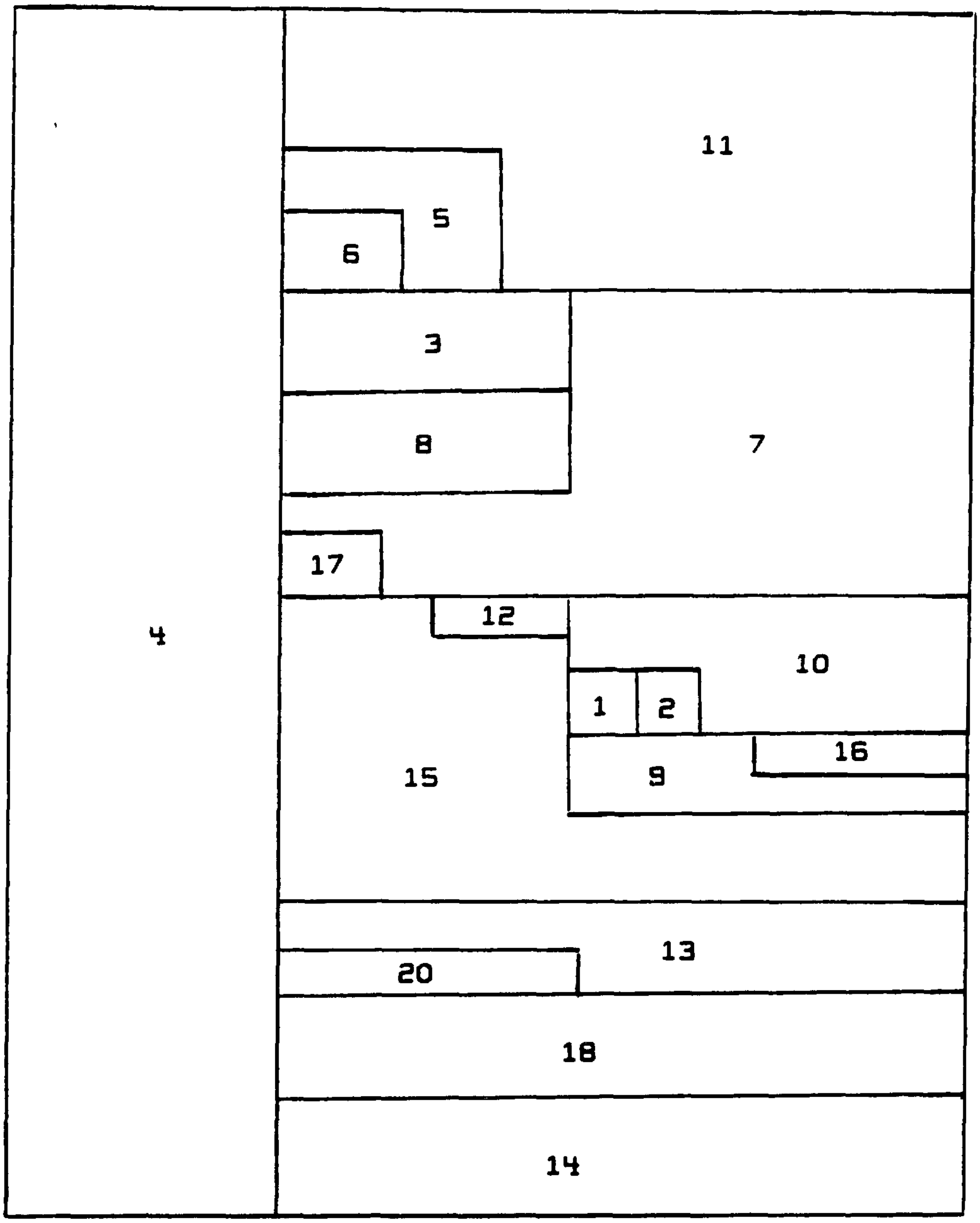


Fig. 2.11 Block Plan for Example #2
(Giffin/Foulds method)

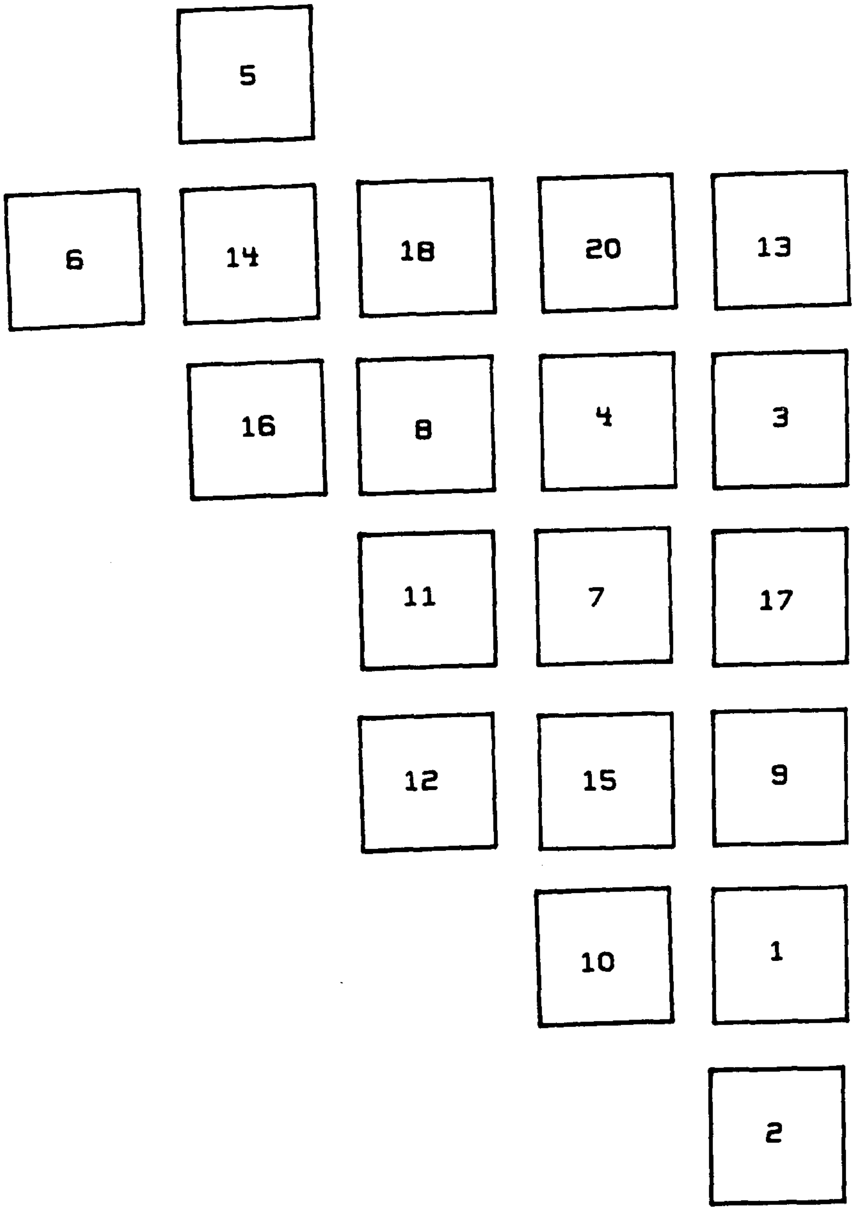


Fig. 2.12 Raw Block Plan for Example #2
(REG'D' method)

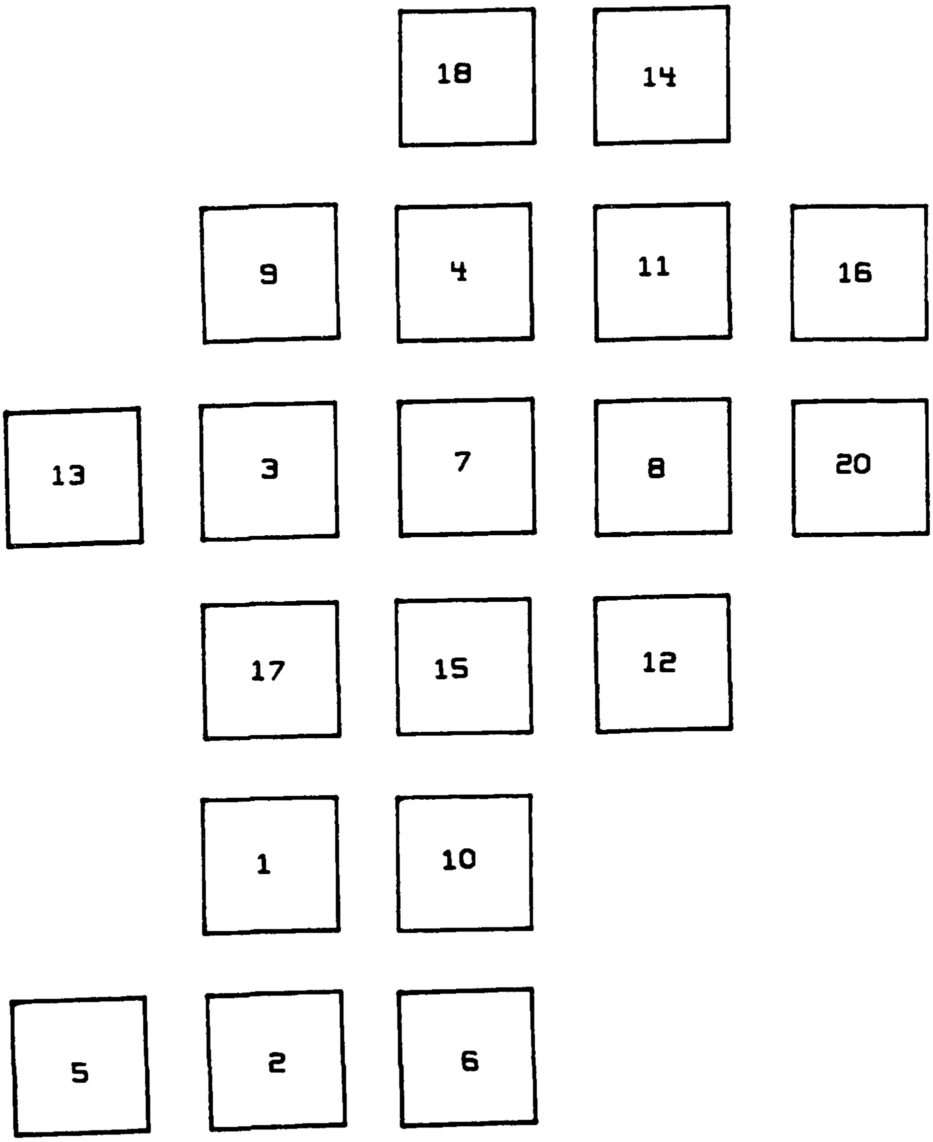


Fig. 2.13 Raw Block Plan for Example #2
(REG'T' method)

2.5.4 Pseudo-Duals of an Adjacency Graph

Having established that for some applications the actual geometric dual of the maximally planar adjacency graph does not meet all of the requirements for the solution of a FLP, we use the REG heuristics to effectively find pseudo-duals to the planar adjacency graphs. The pseudo-duals are hopefully good representations of the planar adjacency graphs actual duals which optimizes those graphs potential to form a Block Plans. The main problem with the approach of finding a pseudo-dual is that of repeatability.

Heuristics must have a certain degree of repeatability if they are going to find any acceptance. In the case of a pseudo-dual we must set out very precise guidelines, within the heuristics, to ensure a reasonable amount of repeatability. Because there exist a large number of alternative pseudo duals and because the heuristics themselves are to some extent aesthetically oriented, a delicate balance of regulation versus creative freedom must be established.

CHAPTER 3

PRESENTATION OF THE HEURISTICS

In this chapter we will present the REG'D' and REG'T' heuristics. This presentation will include an explanation of their derivation, some examples of their application, discussion of their apparent shortcomings and an example of their application involving section areas. The sections on the heuristics evolution are presented separately as they were not developed as alternatives. We will however present all of the other examples using both heuristics in tandem. This will avoid duplication of effort with respect to problem descriptions.

3.1 The REG'D' Heuristic

In this section we will explain the evolution and application of the REG'D' Heuristic.

3.1.1 The Evolution of the REG'D' Heuristic

The REG'D' Heuristic was developed as a method to exploit the work of Giffin (1986). He presented a method of finding the rectangular geometric dual of a maximally planar adjacency graph (in the form of a deltahedron) but his result when used as a block plan was not considered to be useful in all applications. It was felt, as we have discussed earlier, that for many applications a more regular rectangular block plan was required. Hence the REG'D' Heuristic was formulated.

The deltahedron methods developed by Foulds and Robinson (1978) are considered an excellent starting point. This is especially practical in consideration of Giffin's work. Characterizable construction properties mean that deltahedra are a very well suited form of a maximally planar graph if the goal is to find a rectangular dual. We found that deltahedra were also a good structure with which to work finding a 'PSEUDO-DUAL' of suitable form for use with transformation as a BLOCK PLAN.

The REG'D' heuristic is based on determination of which adjacencies on the deltahedron should be honored and which should be sacrificed for the sake of regularity. Consideration of computerization of the entire heuristic was made but decided against as it was not our intention to develop an expert system, we felt that an expert system would be required to accommodate the aesthetic based decisions which the heuristic requires of the user.

3.1.2 The REG'D' Heuristic Phase 1

The REG'D' Heuristic is extremely simple to apply. It does require that the user have a reasonable understanding of the goal. As will be seen, the block plan which the 'Phase One' of the heuristic develops is what we refer to as the 'Raw Block Plan' and is made mostly of square boxes of equal area. These boxes are a physical representation of a conceptual entity. They represent the relative spatial location of the various sections making up the facility. The open areas have been left between the boxes because in the Block Plan stage of the solution to a FLP adjacency is not 'real'. Adjacency is real when it has been achieved in the final facility plan. The NSR and CSR adjacency scores which we claim have been achieved are for the BLOCK PLANS and as we discussed earlier may not be realizable in the final facility. They do however represent at least one measure with which we can evaluate the efficiency of our heuristics and the Block Plans which they produce.

The REG'D' Heuristic

1. Use WORKDELTA function to provide details of the deltahedron.
2. Draw initial four sections, if exterior is one of the initial four sections do not represent it as a box, simply take it that

the exterior surrounds the perimeter of the Raw Block Plan.

3. Draw subsequent boxes (sections) in the appropriate location as directed by the preferred adjacencies listed by the WORKDELTA function.
4. If there is a conflict such that a section can not be located as directed, then evaluate the adjacencies of all sections involved, i.e. including the sections already located which inhibit the location of the entering section as directed, and rearrange the adjacencies in a greedy manner.

We initialize the heuristic by creating the DELTAHEDRON. Foulds and Robinson (1978) detail the construction procedure. We have used a variant of the Atrek and Fifield (1985) code which we call WORKDELTA. WORKDELTA returns the insertion order and embedding incidence listing. By embedding incidence listing we refer to the list of preferred adjacencies (3) for each of the entering sections. See Figure 3.1 for an example of the output in the form in which we use it.

```
INITIAL DELTAHEDRON  4 19 7 11

THE TRIANGLE INSERTION ORDER IS   4 19 7 11 15 3 10 9 8 13
1 18 16 2 12 17 5 6 20 14

INTO TRIANGLE  4 19 7 INSERT SECTION  15

SECTION 15  HAS REL SCORE TO SECTION   4 OF 75
SECTION 15  HAS REL SCORE TO SECTION  19 OF 91
SECTION 15  HAS REL SCORE TO SECTION   7 OF 97
```

Fig. 3.1 WORKDELTA output for Example #2
(partial)

NOTES FOR FIGURE 3.1: The first line lists the sections involved in the Initial Deltahedron. The next line lists the entire insertion order, i.e. the order in which the sections will be considered for embedding onto the adjacency graph. In Figure 3.1 we have only shown the output with respect to the first embedding sequence.

The next step is to draw the initial 4 sections (as squares) on the raw block plan. For ease of insertion of subsequent sections we list on the raw block plan the value of respective adjacencies, see Figure 3.2.

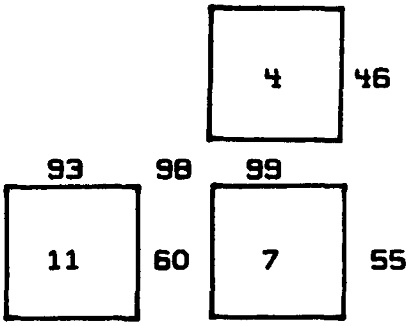


Fig 3.2 Initial Raw Block Plan REG'D'
Example #2

NOTES FOR FIGURE 3.2: The most evident feature of this FOUR SECTION block plan is that there are apparently only THREE SECTIONS represented. The fourth section represented is Section 19, which for this example happens to be the exterior and is accepted as all area surrounding the peripheral sections. Also note the fact that we draw all adjacencies as if CSR (Court Yard Scoring Rules) are in effect. Therefore we have four corner intersections. Here one may, if familiar with the Giffin/Foulds method, note a significant departure. Specifically, the rectangular geometric dual which they produce has only two corner intersections which involve three sections of the facility. We feel that even if one restricts the scoring of adjacencies to NSR (Normal Scoring Rules) the resultant Block Plan will be more regular by convention ie. having normal intersection patterns. Notice also that there are 2 scores recorded at the four corner intersection, for NSR only one of these may be counted. The choice is made greedily.

The next and most important step is the iterative process of entering all the remaining sections onto the raw block plan. It is simply a matter of drawing the representative square in an area adjacent to the sections which WORKDELTA has listed as preferred. In cases where such adjacency will cause irregularity in the form of the raw block plan we must curtail such adjacency. Curtailment is made in consideration of two very simple rules:

1. the resultant raw block plan must have a 'Regular' appearance, and
2. when the indicated adjacency must be curtailed, other potential adjacencies must be evaluated so as to GREEDILY locate the entering section.

While it may appear that the curtailment operation would be a cumbersome effort, we have found that in practical applications it is not. In fact even when solving what are considered very large problems the computations are trivial.

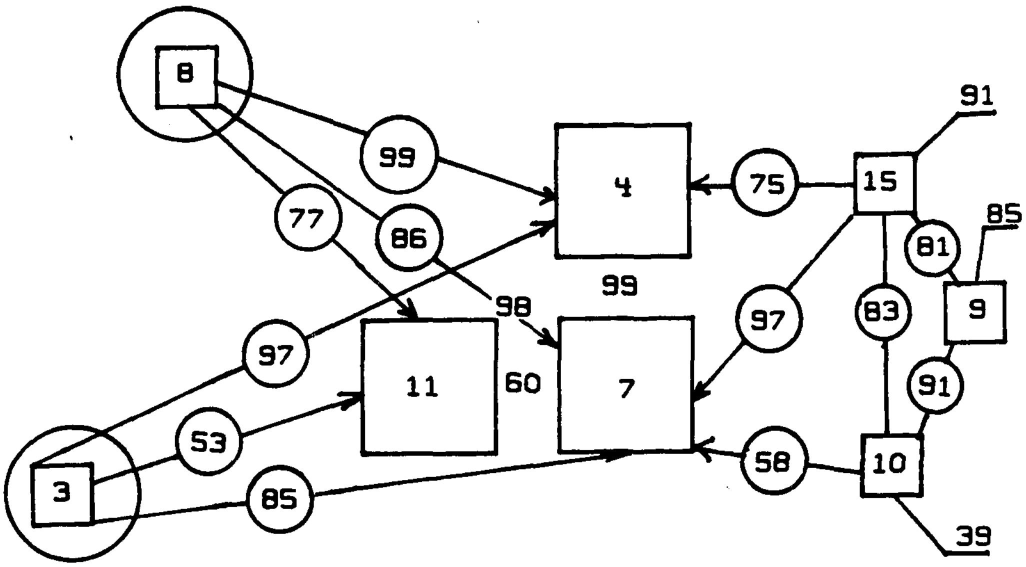
Consider Example #2 from Section 2.5. The REL_chart is listed Table 2.2. We will now work through the entire formulation procedure using the REG'D' heuristic method.

STEP 1 Use WORKDELTA to provide the insertion order and preferred incident list. The listing Figure 3.1 is for this example.

STEP 2 Draw the initial raw block plan using the first four sections and listing all adjacencies, see Figure 3.2.

STEP 3 Locate the next entering section listing all adjacencies, see Figure 3.3. Note that entering sections are represented as smaller more disjoint boxes until the plan is periodically redrawn.

STEP 4 Locate subsequent sections as above. We have found it unnecessary to redraw the raw block plan for each addition. As a rule we do not redraw until a curtailment is required or the number of new sections cause the diagram to become awkward, see Figures 3.4a and 3.4b.



```
INTO TRIANGLE  4 19 7  INSERT SECTION  15
        SECTION 15  HAS REL SCORE TO SECTION   4  OF 75
        SECTION 15  HAS REL SCORE TO SECTION  19  OF 91
        SECTION 15  HAS REL SCORE TO SECTION   7  OF 97

INTO TRIANGLE  7 11 4  INSERT SECTION   3
        SECTION  3  HAS REL SCORE TO SECTION   7  OF 85
        SECTION  3  HAS REL SCORE TO SECTION  11  OF 53
        SECTION  3  HAS REL SCORE TO SECTION   4  OF 97

INTO TRIANGLE 19 7 15  INSERT SECTION   10
        SECTION 10  HAS REL SCORE TO SECTION  19  OF 39
        SECTION 10  HAS REL SCORE TO SECTION   7  OF 58
        SECTION 10  HAS REL SCORE TO SECTION  15  OF 83

INTO TRIANGLE 15 10 19  INSERT SECTION  9
        SECTION  9  HAS REL SCORE TO SECTION  15  OF 81
        SECTION  9  HAS REL SCORE TO SECTION  10  OF 91
        SECTION  9  HAS REL SCORE TO SECTION  19  OF 85

INTO TRIANGLE  4 3 7    INSERT SECTION  8
        SECTION  8  HAS REL SCORE TO SECTION   4  OF 99
        SECTION  8  HAS REL SCORE TO SECTION   3  OF 77
        SECTION  8  HAS REL SCORE TO SECTION   7  OF 86
```

Fig. 3.3 Partial Worksheet for Example #2

NOTES FOR FIGURE 3.3: This figure includes at the bottom the output from WORKDELTA as it applies to the sections being inserted at this stage. The drawing of the Raw Block Plan appears as it would on a work sheet which one uses to develop the interim Raw Block Plans when using the REG'D' heuristic. The work sheet presentation Figure 3.3 is to facilitate reader understanding of the development process. Of interest is the listing of entering sections along with their preferred pairwise adjacencies and the REL_chart score associated with those adjacencies. If curtailment is required, the adjacency which is not honored or which is forfeited is referred to as a SACRIFICE. In the case of Entering Section 8 we can not honor all of Section 8's preferred adjacencies with the Block Plan in its' current configuration, so a GREEDY evaluation is made, (see Section 3.1.2a for an explaination of the GREEDY evaluation.)

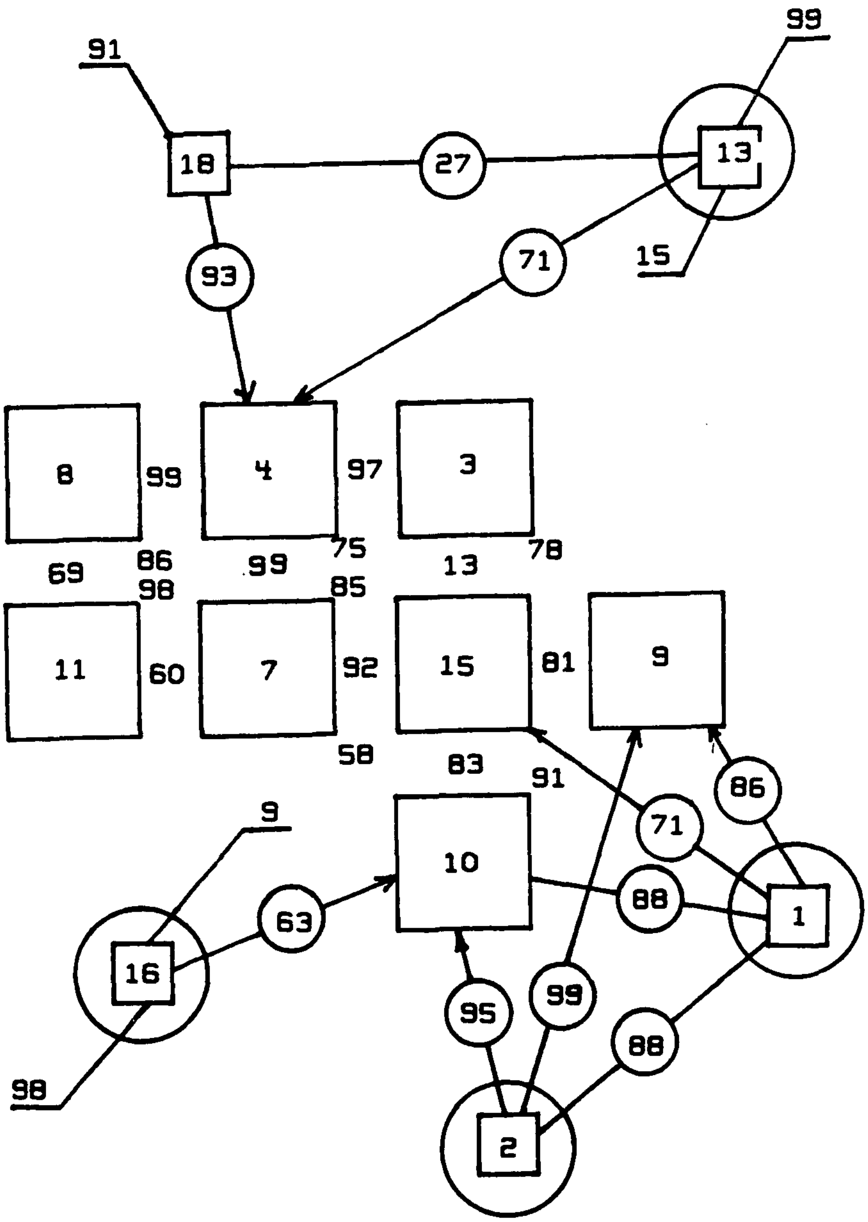


Fig. 3.4a Interim Raw Block Plan for Example #2
(REG'D' method)

NOTES FOR FIGURE 3.4a: It is the intermediate raw block plans which must be closely monitored for aesthetic quality. This is when creativity is a part of the development and therefore where the repeatability of the heuristic may be infringed upon.

```
INTO TRIANGLE  15 4 19   INSERT SECTION  13
     SECTION  13  HAS REL SCORE TO SECTION 15  OF  56
     SECTION  13  HAS REL SCORE TO SECTION  4  OF  71
     SECTION  13  HAS REL SCORE TO SECTION 19  OF  99

INTO TRIANGLE  9 15 10   INSERT SECTION  1
     SECTION   1  HAS REL SCORE TO SECTION  9  OF  86
     SECTION   1  HAS REL SCORE TO SECTION 15  OF  71
     SECTION   1  HAS REL SCORE TO SECTION 10  OF  88

INTO TRIANGLE  4 19 13   INSERT SECTION 18
     SECTION  18  HAS REL SCORE TO SECTION  4  OF  93
     SECTION  18  HAS REL SCORE TO SECTION 19  OF  91
     SECTION  18  HAS REL SCORE TO SECTION 13  OF  27

INTO TRIANGLE 10 19 9    INSERT SECTION 16
     SECTION  16  HAS REL SCORE TO SECTION 10  OF  63
     SECTION  16  HAS REL SCORE TO SECTION 19  OF  98
     SECTION  16  HAS REL SCORE TO SECTION  9  OF  61

INTO TRIANGLE 10  1 9    INSERT SECTION  2
     SECTION   2  HAS REL SCORE TO SECTION 10  OF  95
     SECTION   2  HAS REL SCORE TO SECTION  1  OF  88
     SECTION   2  HAS REL SCORE TO SECTION  9  OF  99
```

Fig. 3.4b WORKDELTA Output for Example #2

NOTES FOR FIGURE 3.4b: For each Section we have noted which edges from the adjacency graph are required to be sacrificed. As the Raw Block Plan increases with respect to the number of sections involved, especially in cases which exhibit low flow dominance, sacrifices must be made frequently. The greedy decision process is simple. We will expound on the problem of 'low flow dominance' in Section 3.1.4 REG'D' Shortcomings. It is important to recall that the greedy decision making process is aided by the lookahead ability the operator has due to the WORKDELTA function. An experienced operator is able to be cognizant of conflicts with respect to sections which will be entering and also with respect to potentially awkward shapes in the developing block plan. Understanding of the limitations of the WORKDELTA function is also important since it is often the case when only one of the preferred adjacencies is available that there are other locations with higher associated adjacency scores. This is due to the WORKDELTA function only evaluating the triangles of the deltahedron while the operator can evaluate other potential locations evident on the interim Raw Block Plan.

The series of figures 3.4-c,-d and -e show the final development of the Raw Block Plan. Admittedly the process can appear, to the uninitiated, as intricate. Actually if one follows the structure as it develops, the greedy insertion of sections is very straightforward.

Again it is important to note that the low flow dominance associated with randomly generated problems makes it more difficult to apply the heuristic. As noted at the beginning of this section, Example #2 is not trivial. We can now see that it is difficult not only because it involves a relatively large number of sections but also because of the method of REL_chart formulation.

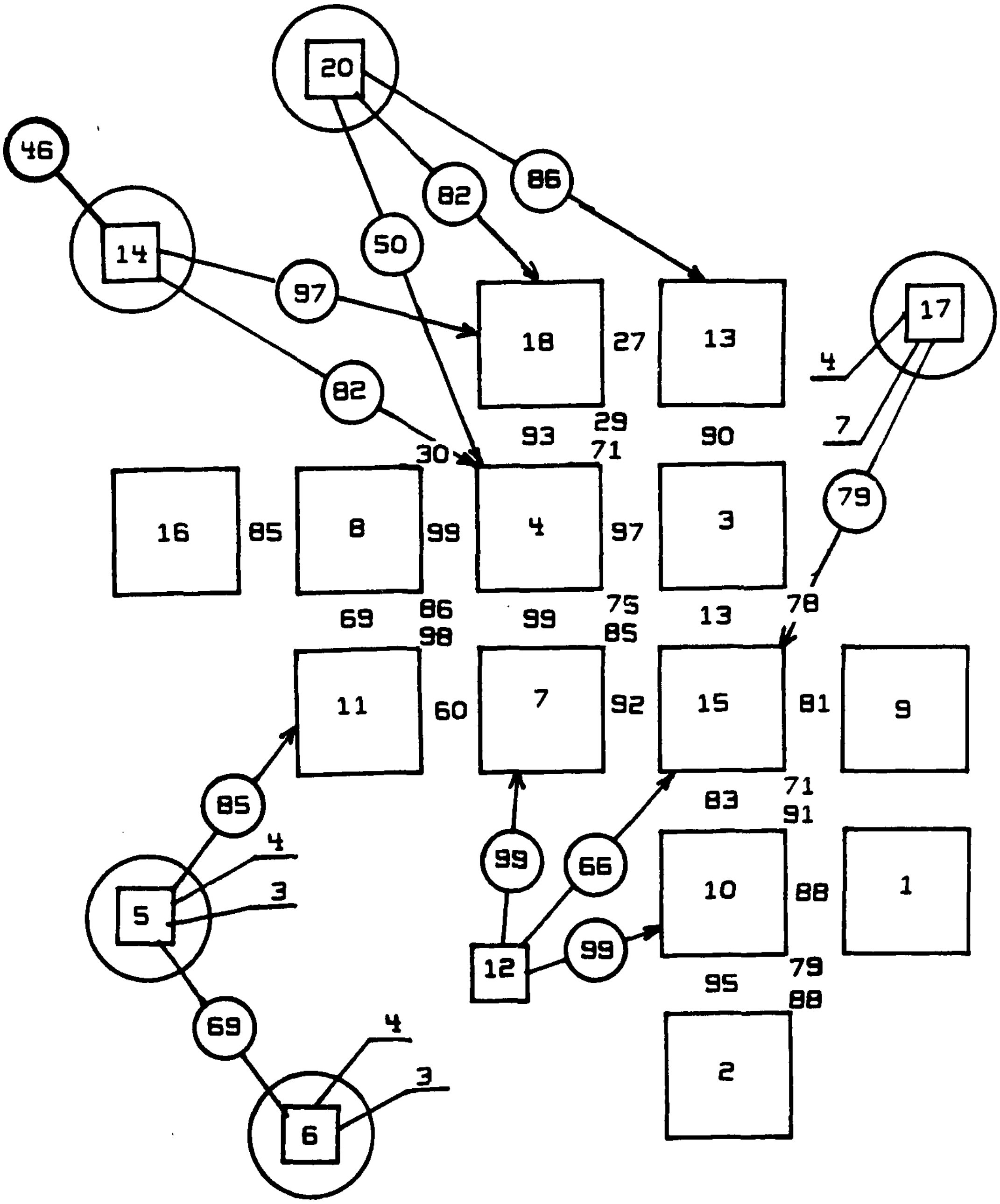


Fig. 3.4c Interim Raw Block Plan for Example #2
(REG'D' method)

```
INTO TRIANGLE  7 15 10  INSERT SECTION  12
     SECTION  12  HAS REL SCORE TO SECTION  7  OF  99
     SECTION  12  HAS REL SCORE TO SECTION 15  OF  66
     SECTION  12  HAS REL SCORE TO SECTION 10  OF  99

INTO TRIANGLE  7 15  4  INSERT SECTION  17
     SECTION  17  HAS REL SCORE TO SECTION  7  OF  92
     SECTION  17  HAS REL SCORE TO SECTION 15  OF  79
     SECTION  17  HAS REL SCORE TO SECTION  4  OF  91

INTO TRIANGLE 11  4  3  INSERT SECTION   5
     SECTION   5  HAS REL SCORE TO SECTION 11  OF  85
     SECTION   5  HAS REL SCORE TO SECTION  4  OF  27
     SECTION   5  HAS REL SCORE TO SECTION  3  OF  69

INTO TRIANGLE  4  3  5  INSERT SECTION   6
     SECTION   6  HAS REL SCORE TO SECTION  4  OF  39
     SECTION   6  HAS REL SCORE TO SECTION  3  OF  99
     SECTION   6  HAS REL SCORE TO SECTION  5  OF  69

INTO TRIANGLE 13 18  4  INSERT SECTION  20
     SECTION  20  HAS REL SCORE TO SECTION 13  OF  79
     SECTION  20  HAS REL SCORE TO SECTION 18  OF  82
     SECTION  20  HAS REL SCORE TO SECTION  4  OF  50

INTO TRIANGLE 18  4 19  INSERT SECTION  14
     SECTION  14  HAS REL SCORE TO SECTION 18  OF  97
     SECTION   4  HAS REL SCORE TO SECTION  4  OF  82
     SECTION  19  HAS REL SCORE TO SECTION 19  OF  46
```

Fig. 3.4d Portion WORKDELTA Output For Example #2

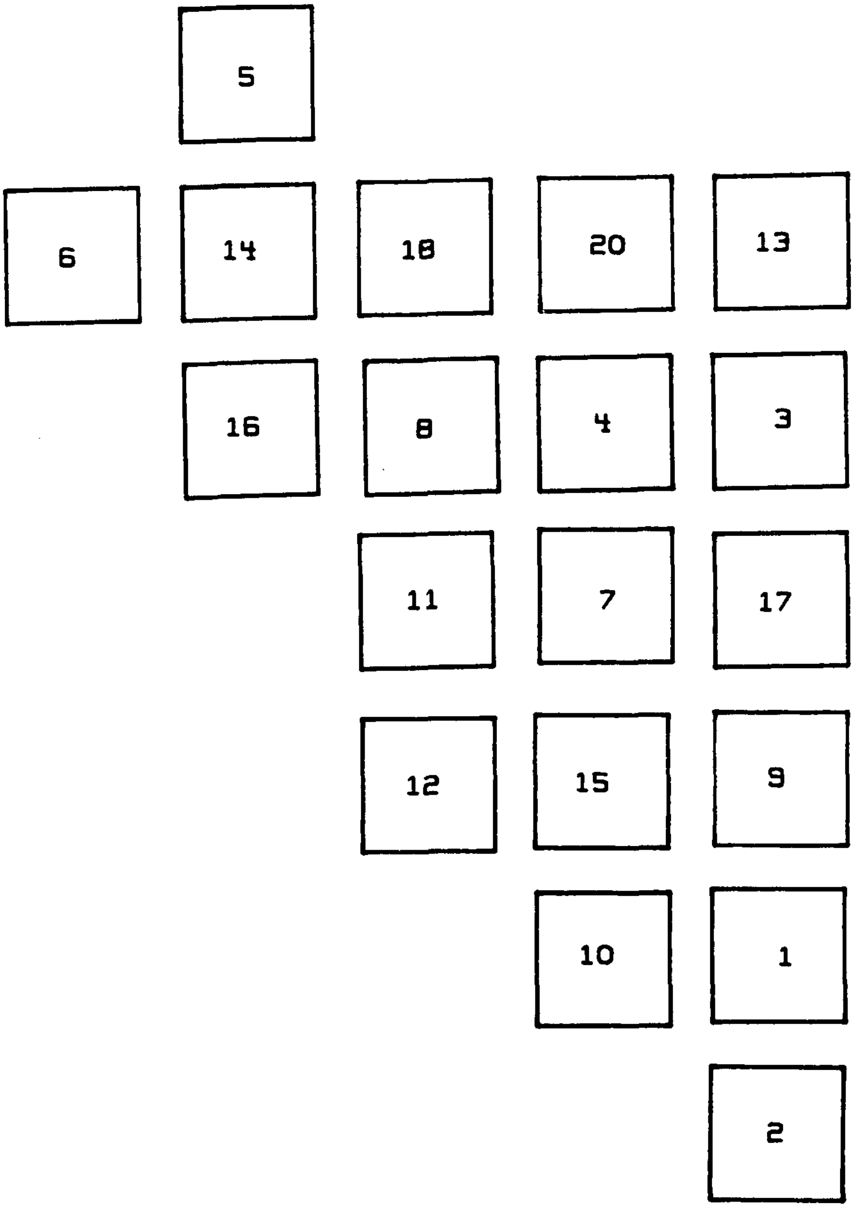


Fig. 3.4e Final Block Plan for Example #2
(REG'D' method)

3.1.2a A Greedy Evaluation. We feel that for completeness an in-depth explanation of one greedy evaluation is appropriate. Consider the state at which the interim Raw Block Plan was at in Figure 3.3;

> Section 8 has been inserted, in the deltahedron, into triangle [4-3-7]. Clearly we can not honor this insertion while maintaining both Regularity and all presently defined adjacencies within the pseudo-dual as we have constructed it.
>
> We carry out Greedy evaluations as follows;

1. Identify alternative Vertex - Edge arrangements,
2. score these arrangements independently, and
3. choose the arrangement with the highest score.

For the current stage there are four arrangements which are candidates for evaluation. These are;

1. E(V8,V4), E(V8,V7), E(V8,V11), E(V8,V11) and E(V3,V4) with CSR score 428.
2. E(V8,V3), E(V8,V4), E(V3,V4), E(V3,V7) and V(3,V11) with CSR score 411.
3. E(V8,V4), E(V8,V7), E(V3,V4), E(V3,V7) and E(V3,V11) with score 420.
4. E(V8,V4), E(V8,V7), E(V8,V11), E(V3,V4) and E(V3,V7) with CSR score 436.

The chosen arrangement is number 4 and the interim Raw Block Plan is redrawn as shown Figure 3.5.

3.1.2b REG Worksheet notation. At this time it is appropriate to explain the notation used on the 'WORKSHEET FIGURES'.

Large Boxes denote initial Sections of the current stage.

Small Boxes denote entering Sections.

Circled Numbers denote adjacency value for the entering sections.

Circled Box denotes an entering Section with a conflict. Underlined numbers indicate section of preference.

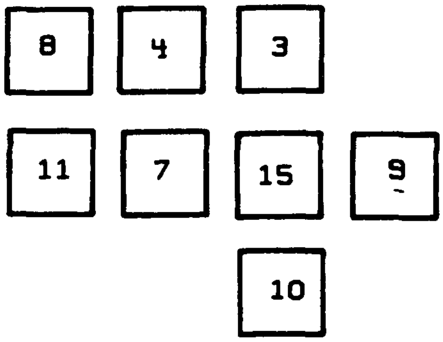


Fig. 3.5 Interim Raw Block Plan for Example #3 After 'Greedy' Rearrangement

3.1.3 The REG'D' Heuristic Phase 2

We have now developed the Raw Block Plan, but this does not meet all of the requirements set, i.e. the general exterior shape does not appear 'REGULAR'. If one was dealing with a modular construction type of operation the Raw Block Plan would probably suffice. However that application is limited. We therefore have a Phase Two of the REG'D' Heuristic. Phase Two is the stage where aesthetic preference, intuitive conception and experience at REGULARIZING block plans all come together.

This is clearly the stage where we must attempt to put reasonable restrictions on the operation to ensure a certain measure of repeatability. The most common restriction one is likely to encounter is the fact that the facility is to be located into an existing area. That area would have fixed exterior and to some extent fixed interior partitions. Without delving into the problems of drawing a Facility Plan we suggest that such a structure be used as a guide while drawing the Raw Block Plan. The process would be the same within the restriction on the fixed area and should produce a Block Plan which could, dependent on relative areas of the sections, be very close to the final Facility Plan. In the cases where we are planning a totally new facility, control panel or whatever, we should let the heuristic be free of external barriers, therefore producing a Block Plan which truly represents the Relative Spatial Locations of the sections making up a facility. That is the application to which we feel the REG'D' and REG'T' heuristics are best suited.

The guidelines for regularizing a Raw Block Plan are straightforward:

1. Representation of a section must be as a square or a rectangle. The rectangle preferably has as its height one half the height of the squares. (This has been found to be a convenient convention with respect to drawing and aesthetics.)
2. The exterior shape should be continuous without alcoves.
3. Forfeiting or sacrificing adjacencies must be done in a Greedy fashion.

We consider these guidelines to be as restrictive as is feasible if aesthetic values are to be input. While they are loose enough that different individuals will produce different Block Plans, which does not meet the repeatability requirement, we do believe that different individuals following the basic rules could agree on a final layout. Once again, Edwards' (1977) Simple Multiattribute Rating Technique could if necessary be applied to resolve the final Block Plan.

As an example of a resultant block plan, consider Figure 3.6. This represents one of several aternatives.

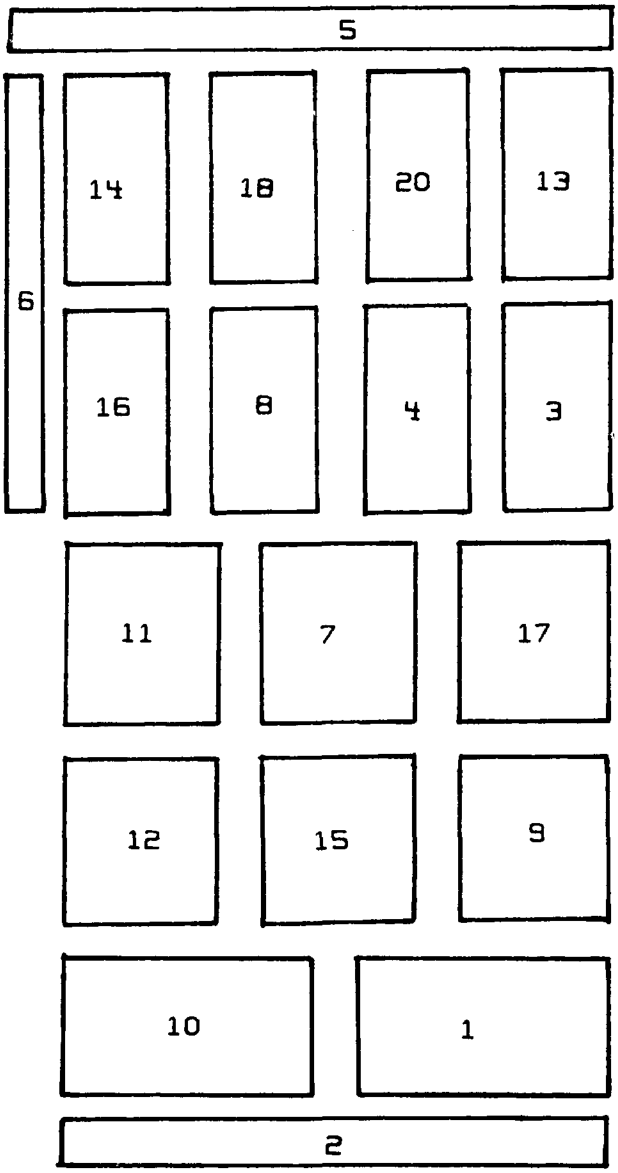


Fig. 3.6 Regularized Block Plan for Example #2
(REG'D' method)

It is evident that one's perspective of the problem and experience will greatly influence the resultant Block Plan. We do feel that if decisions are made greedily, all plans will have similar scores.

The result is nice as far as regularity is concerned. It has a score of NSR - 3964 or a REL-Rd of 95% and a score of CSR -4230 or a REL-Rd of 101%. Recall the deltahedron for this Example #2 scored 4184. As will be seen the REG'T' heuristic produced a slightly higher scoring block plan. Once again the relative merits of various block plans are being compared and again one must decide what 'OPTIMAL' means in terms of specific applications.

3.1.3 REG'D' Shortcomings

The most significant shortcoming of the REG'D' heuristic is related to flow dominance. That is a property of facilities involving a natural trend of sections which have high pairwise adjacency scores so that they tend to form a chain. In fact a property of a deltahedron is that it often copes poorly with either 'HIGH' or 'LOW' flow dominance.

In the case of low flow dominance, most sections have several other sections with which they can be paired. The deltahedron's 'poor' performance in this case is that its structure and construction characteristics are such that it is difficult to identify the best combinations of sections. Low flow dominance is a characteristic of randomly generated problems and as such we consider the problem to be an academic problem which is unlikely to manifest itself in actual applications.

In the cases of high flow dominance the REG'D's problems are once again associated with its relation to the deltahedron. High flow dominance is typically found in assembly line type facilities. Here each section will have a high adjacency score in relation to one or maybe two other sections. The deltahedron tends once again to be indecisive. We have found that in such cases it was necessary to cluster sections for the deltahedron and then apply the heuristic. Example #3 is one which demonstrates this shortcoming and how we effected the clustering to overcome it. (See section 3.3 Examples of REG Heuristic's Applications.)

Another significant shortcoming of the REG'D' heuristic is that of repeatability. Clearly with the considerable aesthetic inputs which are required of the operator there will be differences in the final block plans and to a lesser extent in the raw block plans. As we have eluded to before, it may be possible to develop an expert system which would eliminate this shortcoming, but if one considers the goal of producing ' a spatial block plan consisting of regularly shaped sections arranged in an optimal manner ', we believe that in that sense we have repeatability. Recall that the scores of the different block plans produced following the REG'D' heuristic have been found to be very close, the arrangements are usually similar, they all meet the regularity criterion and finally since we have already conceded that the so called optimal solution is in terms of a HEURISTIC, any one of the block plans which evolve can be called the 'OPTIMAL' one. So then we have repeatability in the sense that the heuristic will lead to the development of a block plan which satisfies our original goal.

The last shortcoming which we will discuss is that the REG'D' heuristic is very much a 'BY HAND' approach. This is a factor which we considered, however we feel that if one wishes to develop an automated system which will accommodate the aesthetic considerations we feel are necessary then that development would represent work outside the scope of this thesis. Such automation would naturally be extremely useful but is considered to be a systems development rather than heuristic development. The other factor is that, although executed 'BY HAND', the heuristic does produce the final block plan in a acceptably short time.

3.2 The REG'T' Heuristic

In this section we will discuss the evolution and application of the REG'T' heuristic.

3.2.1 The Evolution of the REG'T' Heuristic

As we worked with the REG'D' heuristic it was apparent that an investigation into the 'clustering' of sections might be worthwhile. There have been several clustering type approaches developed for solving FLPs. Carter and Whitehead (1975) use clustering techniques for the multi-floor building layout problem, where they cluster in a manner to minimize flow between floors. The problem they are addressing and their criterion for clustering is not the same as ours. Scriabin and Vergin (1985) also use a clustering approach to solve Facility Layout Problems. Their technique addresses only the problem of finding a highly weighted planar graph they do not offer any practical method for producing the regular rectangular geometric dual. Our clustering technique embodies not only the need for a highly weighted resultant adjacency graph but also the need to be able to easily transform that graph into its dual or a highly weighted pseudo-dual.

It was decided to attempt to create a graph which was not maximally planar but was highly weighted and included all the sections of the facility. We did have the requirement to ensure the graph was planar and we did like the concept of clustering. The easiest way to ensure planarity was maintained was to ensure that each face added to the graph be triangular. Triangles are easy to envision and also can represent convenient (small) clusters. Hence the REG'T' ('T' for triangle) heuristic was developed.

The construction of the Triangulated Graph, involving all sections and being highly weighted, was in itself an interesting problem. Clearly there are many approaches available. We developed the 'SEMGRED' function. The SEMGRED function orders the sections, like the WORKDELTA function, by the sum of potential adjacencies. It then evaluates the best three section cluster and attaches the successive sections to the best available pair of adjacent vertices.

3.2.2 The REG'T' Heuristic Phase 1

We initiate Phase 1 of the REG'T' heuristic by applying the SEMGRED function, see Table 3.1, to the REL_chart, which once again must be in the form of a square matrix symmetric about the main diagonal of zeroes.

TABLE 3.1 **SEMGRED Descriptive Flowchart**

1. Select most highly weigthed Section based on the sum of all possible adjacency scores.
2. Select two other Sections to form initial triangle based on highest acheived adjacency score.
3. Evaluate the acheived score of positioning each of the non committed Sections at the available exterior edges. Choose the highest scored arrangement, update the list of available exterior edges and repeat until all Sections have been included in the Graph.

The Phase 1 of the REG'T' heuristic is even simpler than Phase 1 of the REG'D' heuristic. Since the Triangulated Graph is not maximally planar (V≥3) it is much easier to transform it into its pseudo-dual. That is because the valency of the vertices is not maximized hence there are far fewer instances where edges must be sacrificed to maintain regularity. In fact in many cases it was possible to find the pseudo-dual of this form of adjacency graph without sacrificing any adjacencies at all. Once again flow dominance with the REL chart was a major factor in determining whether or not the actual geometric rectangular dual was easily found. In Example #2, with twenty sections to be included, it was only necessary to sacrifice one preferred adjacency, at least for determining the Raw Block Plan.

Figure 3.7 is the SEMGRED output associated with Example #2. Because of the ease of construction associated with this method we have not included an interim Raw Block

Plan since no sacrificing was required for this example. If curtailment is necessary during the development of the Raw Block Plan, for the REG'T' heuristic, it is done Greedily. As one can see because the Triangulated Graph is constructed by adding vertices of degree 2 rather than vertices of degree 3, as does the deltahedron, even as the number of sections gets large the incidents of required curtailment remain low. The reader may wish to recall Figure 3.5-A which demonstrates the large number of curtailments required by the REG'D' heuristic. We acknowledge that the curtailment operation is very easy, but for ease of development preferred the REG'T' heuristic.

The development of the Raw Block Plan follows simple conventions:

1. Form figure as if CSRs are in effect.
2. Place highest weighted adjacencies directly opposite unless a subsequent embedding is related to that pair of vertices.
3. Curtail greedily.

```
THE FIRST TRIANGULATION IS OF  4 7 8

ADD SECTION  3 INCIDENT WITH SECTIONS 4 7   WITH VALUE 182
THE HIGHEST WEIGHTED ADJACENCY IS TO  4
ADD SECTION 17 INCIDENT WITH SECTIONS 3 7   WITH VALUE 172
THE HIGHEST WEIGHTED ADJACENCY IS TO  7

ADD SECTION 15 INCIDENT WITH SECTIONS 17 7  WITH VALUE 176
THE HIGHEST WEIGHTED ADJACENCY IS TO  7
ADD SECTION  9 INCIDENT WITH SECTIONS 3 4   WITH VALUE 166
THE HIGHEST WEIGHTED ADJACENCY IS TO  4

ADD SECTION 19 INCIDENT WITH SECTIONS 9 3   WITH VALUE 153
THE HIGHEST WEIGHTED ADJACENCY IS TO  9
ADD SECTION 11 INCIDENT WITH SECTIONS 4 8   WITH VALUE 157
THE HIGHEST WEIGHTED ADJACENCY IS TO  4

ADD SECTION  1 INCIDENT WITH SECTIONS 15 17 WITH VALUE 164
THE HIGHEST WEIGHTED ADJACENCY IS TO  17
ADD SECTION 10 INCIDENT WITH SECTIONS 1 15  WITH VALUE 171
THE HIGHEST WEIGHTED ADJACENCY IS TO  1

ADD SECTION 16 INCIDENT WITH SECTIONS 11 8  WITH VALUE 161
THE HIGHEST WEIGHTED ADJACENCY IS TO  8
ADD SECTION 13 INCIDENT WITH SECTIONS 19 3  WITH VALUE 189
THE HIGHEST WEIGHTED ADJACENCY IS TO  19

ADD SECTION 12 INCIDENT WITH SECTIONS 10 15 WITH VALUE 165
THE HIGHEST WEIGHTED ADJACENCY IS TO  10
ADD SECTION 20 INCIDENT WITH SECTIONS 16 11 WITH VALUE 150
THE HIGHEST WEIGHTED ADJACENCY IS TO  11

ADD SECTION  2 INCIDENT WITH SECTIONS 10 1  WITH VALUE 183
THE HIGHEST WEIGHTED ADJACENCY IS TO  10
ADD SECTION 18 INCIDENT WITH SECTIONS 9 4   WITH VALUE 141
THE HIGHEST WEIGHTED ADJACENCY IS TO  4

ADD SECTION  5 INCIDENT WITH SECTIONS 2 1   WITH VALUE 140
THE HIGHEST WEIGHTED ADJACENCY IS TO  2
ADD SECTION  6 INCIDENT WITH SECTIONS 12 10 WITH VALUE 146
THE HIGHEST WEIGHTED ADJACENCY IS TO  10

ADD SECTION 14 INCIDENT WITH SECTIONS 18 4  WITH VALUE 179
THE HIGHEST WEIGHTED ADJACENCY IS TO  18
```

Fig. 3.7 SEMGRED Output for Example #2

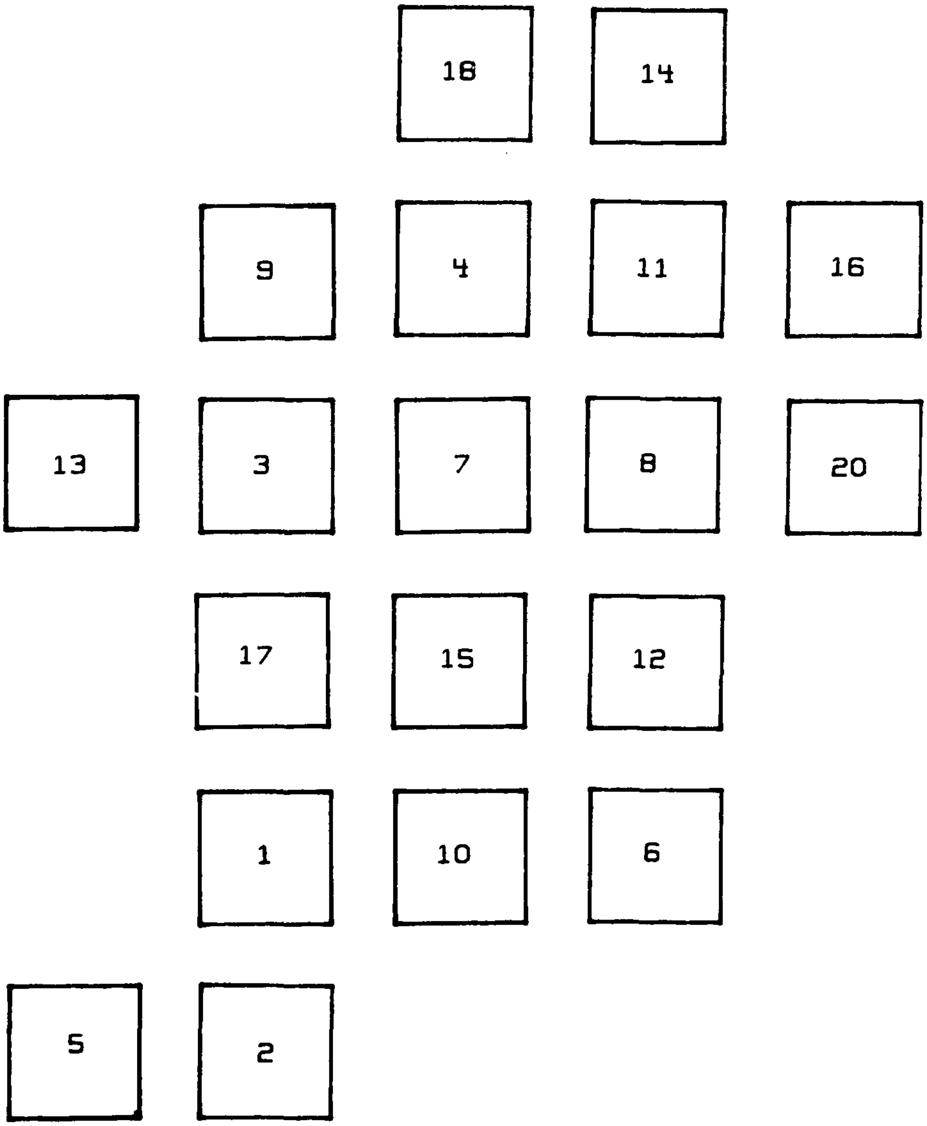


Fig. 3.8 Raw Block Plan for Example #2
(REG'T method)

NOTES FOR FIGURE 3.8: Note that we do not include the REL_chart scores on these graphs as they are being built up. That is simply because curtailment will involve incoming sections and their relation to the potential available adjacencies. Therefore knowing the relative adjacency scores of sections already included is not necessary at this stage.

As before we construct the raw block plans as if four section intersections are allowed. The fact that even for very large problems we can quickly scan all selected adjacencies is used to ensure that the maximum flexibility is maintained with respect to adjacency. We prefer to have the heaviest weighted edges represented as 'wall adjacencies' rather than 'corner adjacencies' (see Figure 3.9). Since we rescore with NSR one out of every pair of corner adjacencies will be lost. Note that in some cases there is only one adjacency credited to a corner, i.e. in the case of a corner involving the exterior when the 'inside section' has another outlet to the exterior. Finally the curtailments are done greedily for Phase 1.

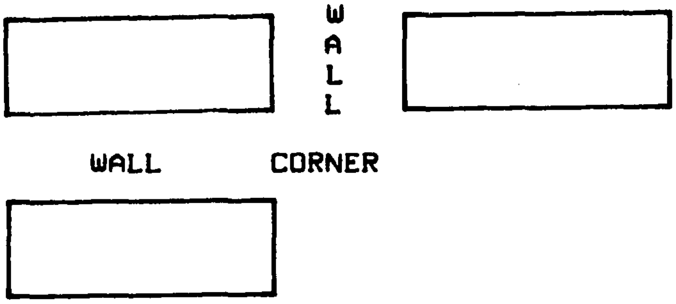


Fig. 3.9 Corner versus Wall Adjacencies

Because there is a significant reduction in the amount of curtailment required during this phase of the application, we have found that the Raw Block Plan produced is essentially repeatable. That is if the simple conventions are followed the resultant Raw Block Plans will be very similar in form and, more importantly, in scoring.

3.2.3 The REG'T' Heuristic Phase 2

Phase 2 of the REG'T' heuristic is virtually the same as Phase 2 of the REG'D' heuristic; they are identical with respect to goals and basic guidelines or conventions. Once again creativity and aesthetic preference has priority over repeatability. We have noticed that the Raw Block Plans produced by the REG'T' heuristic in some cases are easier to REGULARIZE. It is thought that this is due to the maximal planarity of the deltahedron causing so many curtailments that the best clusters of sections are sometimes missed. The Triangulated Graph structure on the other hand is easily transformed into its pseudo-dual and most of the clusters are maintained. It is simply a matter then of reshaping the result into a regularly shaped block plan while maintaining as best possible the integrity and continuity of the clusters. This to a small extent increases the repeatability of the final Block Plans produced via the REG'T' heuristic. That is because there are in general fewer decisions required.

In Figure 3.10 we present one REGULARIZATION of the Raw Block Plan for Example #2. This particular Block Plan scores NSR 3870 or a REL-Rd of 93% and it scores CSR 4265 or a REL-Rd of 102%. We feel this Block Plan may be much more appropriate than the result shown Figure 2.11 for the Block Plan as formed when taking the actual rectangular geometric dual of the deltahedron. This particular example happened to transform easily into a standard rectangular shape. That is not considered a requirement, any reasonable shape for the exterior is acceptable. Restrictions on this would be as a result of influences outside the immediate problem such as available land or perhaps fitting the facility into a specific existing facility.

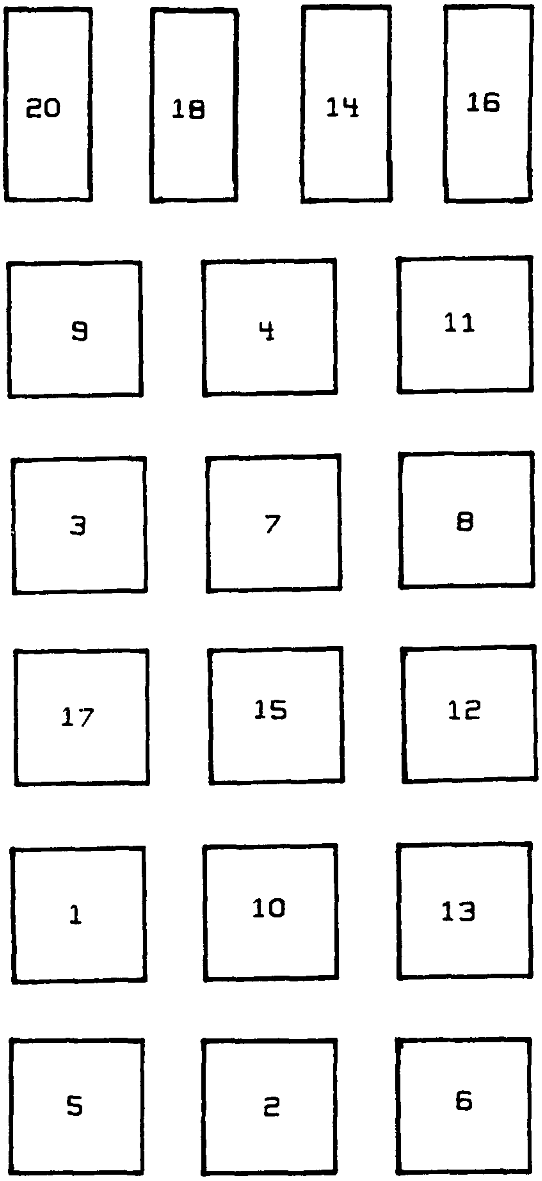


Fig. 3.10 Regularized Block Plan for Example #2
(REG'T method)

3.2.4 REG'T' Shortcomings

REG'T' has the same characteristic shortcomings associated with the REG'D' heuristic with respect to repeatability and application by hand. For the examples thus far completed the REG'T' heuristic has not been affected by the flow dominance of the problem as is the REG'D' heuristic. The REG'T' heuristic does seem faster to apply due to the reduction in the number of decisions required.

3.3 Examples of the REG Heuristics

In this section we will present two more examples of both the REG'D' and REG'T' heuristics. We feel these examples are useful in demonstrating the ease of application, the appropriateness of the final results and hence the appropriateness of these heuristic approaches to solving this class of FLPs.

3.3.1 Example #3

The third example we will present in this thesis is interesting for many reasons:

1. It is the largest example presented.
2. It is an actual application.

3. It has high flow dominance and requires special application for the REG'D' heuristic, and
4. We have included an extension to incorporate areas.

As noted above this is an actual problem. We know the names of each of the sections but do not know the exact function of all of the sections. The biggest assumption we make in applying both of the REG heuristics to this problem is that the REL_chart scores have been determined as a function of direct adjacency. We were given no information with respect to intersection flow or the costs associated, therefore the assumption with respect to adjacency is considered reasonable (since the flows/costs were presumably incorporated in the calculating of the REL_chart scores).

The REL_chart for this example was provided the 'A-E-I-O-U-X' format which some find useful. We transformed it to its' numeric equivalent with A ≡ 64, E ≡ 16, I ≡ 4, O ≡ 1, U ≡ 0, and X ≡ -1. This is a standard interpretation except that normally X is taken to represent some large negative value to ensure dispersion rather than adjacency. We have found that it is often not necessary to score undesirable adjacencies in this manner. Keenan (1986) found similar results via thorough testing.
Parameterization of the REL_chart scores can provide a good

scenario of solutions. It seems to be a function of both REG heuristics that such adjacencies do not manifest themselves. We are careful, however, to check when inserting such sections that these undesirable adjacencies don't happen_ an advantage of the interactive approach. The -1 value then is used more to attract attention to those adjacencies. The REL_chart for Example #3 is shown Table 3.3.

Table 3.2 Section Names for Example #3

SECTION NUMBER	SECTION NAME/FUNCTION
1	Cleaning
2	Deburring
3	Insepection
4	Shipping/Receiving
5	Heat-treat
6	Machine shop
7	Restrooms
8	Maintenance
9	Storage
10	Offices
11	Packaging
12	Resistance Welding
13	Fusion Welding
14	Shear
15	Pressing
16	Lathe
17	Milling
18	ALF 502
19	F100 Room
20	Zyglo
21	Laser
22	Exterior

Table 3.3 REL_chart for Example #3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	EXT
S1	0	64	4	0	16	1	1	0	1	1	1	1	64	4	16	1	1	1	1	1	1	1
S2	64	0	-1	0	1	1	1	0	1	1	1	1	16	4	64	1	1	1	1	1	1	1
S3	4	-1	0	4	1	1	1	0	1	1	16	1	1	1	1	1	1	1	1	1	1	1
S4	0	0	4	0	4	0	1	0	1	1	64	1	1	64	4	1	1	1	1	1	1	64
S5	16	1	1	4	0	0	1	4	1	-1	1	1	1	1	4	1	1	1	1	1	1	1
S6	1	1	1	0	0	0	1	4	1	0	1	1	1	1	1	1	1	1	1	1	1	1
S7	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S8	0	0	0	0	4	4	1	0	4	0	1	1	1	1	1	1	1	1	1	1	1	1
S9	1	1	1	1	1	1	1	4	0	1	4	1	1	1	1	1	1	1	1	1	1	1
S10	1	1	1	1	-1	0	1	0	1	0	0	1	1	-1	-1	1	1	1	1	1	1	64
S11	1	1	16	64	1	1	1	1	4	0	0	1	1	1	0	1	1	1	1	1	1	1
S12	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
S13	64	16	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
S14	4	4	1	64	1	1	1	1	1	-1	1	1	1	0	4	1	1	1	1	1	1	1
S15	16	64	1	4	4	1	1	1	1	-1	0	1	1	4	0	1	1	1	1	1	1	1
S16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	16	1	1	1	1	1
S17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16	0	1	1	1	1	1
S18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
S19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	16	1	1
S20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16	0	1	1
S21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
EXT	1	1	1	64	1	1	1	1	1	64	1	1	1	1	1	1	1	1	1	1	1	0

NOTES FOR TABLE 3.3: This table is again in the form of a matrix symmetric about the diagonal of zeroes. The symmetry of the matrix is important since the adjacency graph created by the WORKDELTA and SEMGRED codes is undirected. Further if the graph is not undirected then the scores associated with pairwise adjacencies must be based on some logic other than that explained earlier.

NOTES FOR TABLE 3.2:The list of section names is provided to aid the reader in interperting the block plans presented.

3.3.1a <u>REG'D'</u> First we will present the REG'D' heuristic's solution to this problem. Because of the low flow dominance we found it difficult to find a useful block plan. It was decided that in cases such as this clustering should be performed before construction of the deltahedron.

It was decided to cluster groups of sections if it could be accomplished in such a way that the clusters would form natural groups, as identified from the REL_chart, where those groups were fairly autonomous. That is to say the members of the cluster had attraction to other sections within the cluster but only attracted to one section outside the cluster. This ensured that when the clustered group was represented as its component sections there would be no conflicts of a section seeking adjacency with more than one section outside the cluster since there is no assurance that such sections would be coincident as would be required if the adjacencies were to be honored. In this example we were able to identify three such clusters involving 17 sections. The clusters identified are:

CLUSTER 1: Sections [12, 16, 17, 18, 19, 20, 21]

CLUSTER 2: Sections [1, 2, 8, 13, 14, 15]

CLUSTER 3: Sections [3, 4, 9, 11]

The newly developed REL_chart for this arrangement of clusters is shown Table 3.3.

TABLE 3.3 Reduced REL_chart for REL'D' Example #3

	C1	C2	C3	S6	S7	S8	S10	EXT
CLUSTER 1	0	1	1	1	1	1	1	1
CLUSTER 2	1	0	64	1	1	4	1	1
CLUSTER 3	1	64	0	1	1	4	1	64
SECTION 6	1	1	1	0	1	4	1	1
SECTION 7	1	1	1	1	0	1	1	1
SECTION 8	1	4	4	4	1	0	0	1
SECTION 10	1	1	1	1	1	1	0	64
EXTERIOR	1	1	64	1	1	1	64	0

One can easily see that the problem has now been reduced to a more manageable size which in this case can be easily handled. That is in fact the case. Consider the Raw Block Plan which was produced using the REG'D' heuristic on this now reduced problem, see Figure 3.11 .

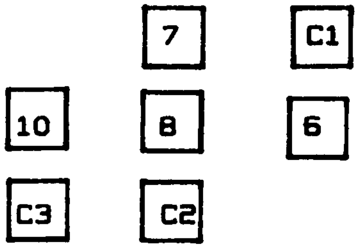


Fig. 3.11 Cluster Block Plan
REG'D' Example #3

We refer to this Raw Block Plan as being the 'CLUSTER' Block Plan. It would normally be simple to develop a spatial representation for the entire problem by arranging the boxes representing the different clusters on the block plan. This would be done by placing the sections in a manner consistent with their preference as indicated on the REL_chart.

For this particular example, however, we want to incorporate areas as well. This changes the problem and we are required to attempt to maintain the relative adjacencies which are represented in the Raw Block Plan while attempting to formulate the Final Block Plan. In the case where areas have been included we may call this a Facility Plan. The problem definition prescribed that we develop the 'Block Plan' and then inflate it to 60,000 square feet to include circulation areas in the appropriate spaces. This direction suited perfectly the applications of both heuristics since they both leave such spaces as they are being developed and will be seen that in most cases the 'circulation areas' appeared to be in correct position as a result of the heuristic's application. Consider the Block Plan presented Figure 3.12.

INSERT FIGURE 3.12 ABOUT HERE

NOTES FOR FIGURE 3.12: This figure is drawn approximately to scale. It suffices to ensure that the layout as shown fits the shape of structure presented when all dimensions on the plans are to scale.

This Block Plan appears to be very regular. We have included the section numbers so that the experienced reader can appreciate that the plant layout as presented is one which 'seems' intuitively correct. Pursuant to earlier discussion we will not discuss the scoring of this layout in detail, because the scores which we assumed to make up the REL_chart are not consistent with the centroid dispersion considerations which must be made when scoring the Facility Plan. However for the readers interest we can report that over 98% of the adjacency scoring accredited to the Raw Block Plan would be valid for this Block Plan/Facility plan and that the plan has a REL-Rd in excess of 100%.

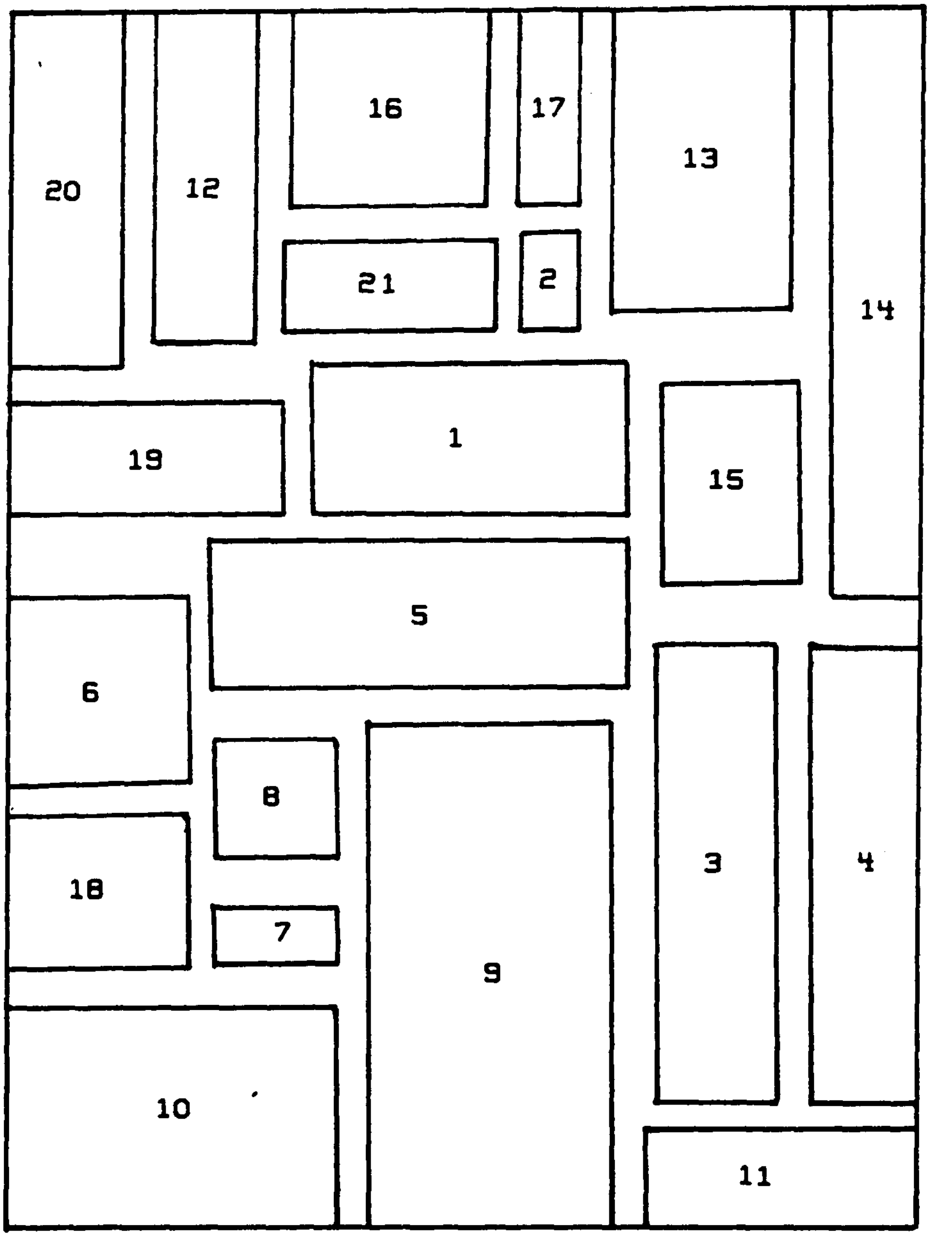


Fig. 3.12 Final Block Plan for Example #3
(REG'D' method)

3.3.1b <u>REG'T'</u> Secondly let us consider the application of the REG'T' heuristic. It is not necessary to do a clustering operation prior to starting the REG'T' heuristic since it is very much a clustering operation itself.

The heuristic was applied to the original REL_chart shown Table 2.2. The resultant Raw Block Plan is shown Figure 3.13. This Raw Block Plan is itself very regular; difficulty was expected in maintaining the adjacencies while including the areas and completely regularizing the Block Plan, but there was none.

The resultant Block/Facility Plan is shown Figure 3.14. This plan is clearly very regular with respect to both the sections and the exterior of the facility. As discussed earlier the REL_chart scores are no longer actually valid but we can report that this plan has a REL-Rd of 98%.

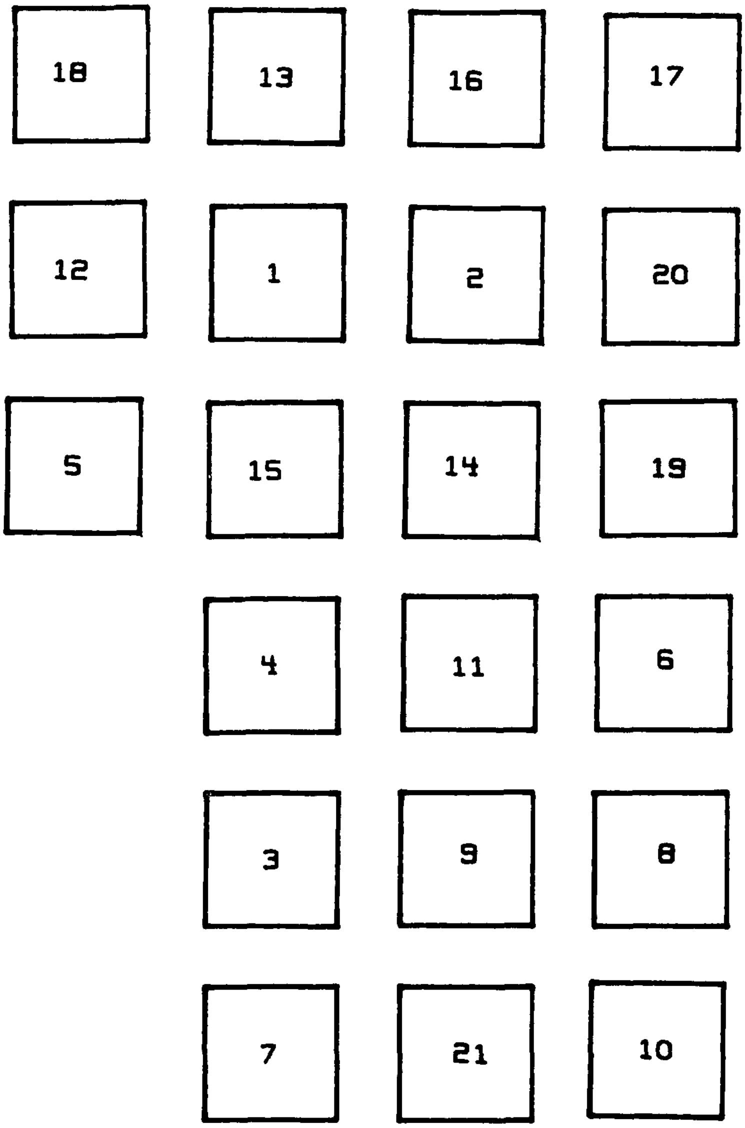


Fig. 3.13 Raw Block Plan for Example #3
(REG'T' method)

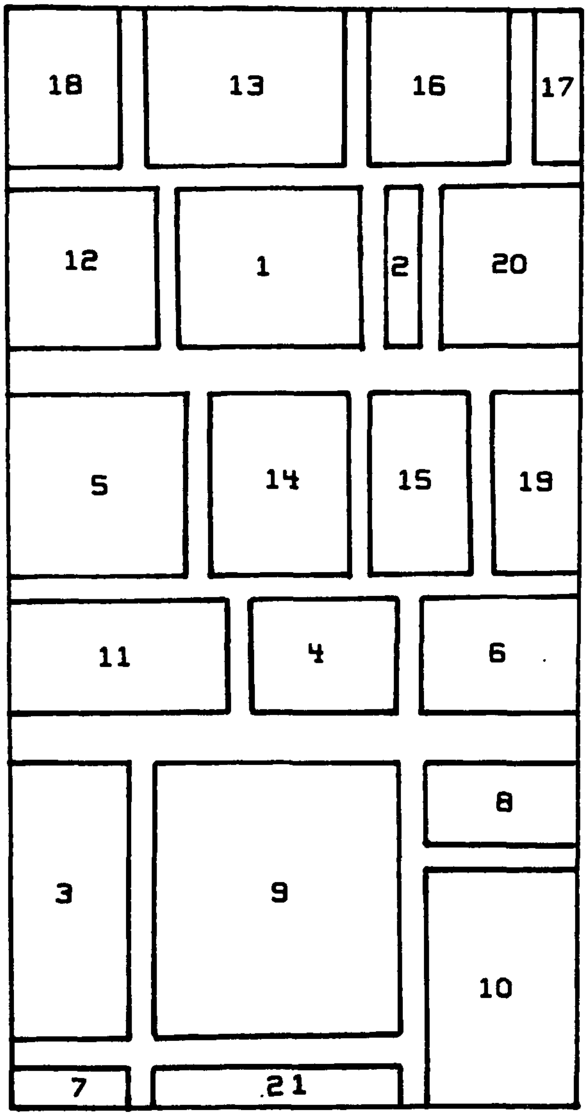


Fig. 3.14 Final Block Plan for Example #3
(REG'I' method)

COMMENTS EXAMPLE #3: Both heuristics have produced, in this case, Block/Facility plans which appear to be very appropriate and at the same time have met a high percentage of the adjacencies proposed by the REL_chart. The REG'D' heuristic seems to score a little better but required transformation of the REL_chart (and therefore the problem before initialization). We say 'seems to score' better since as we have already pointed out we really can't apply the REL_chart scores, in what we consider a conventional fashion, due to inclusion of areas. The REG'T' heuristic while scoring slightly lower, was very easy to apply and required no transformation of the problem.

3.3.2 Example #4

Example #4 was in fact the first problem to which the REG'D' heuristic was applied. We have included it because it is the only problem which we have attempted where we were not able to have a REL-Rd in excess of 100% in the Final Block Plan. We feel the REG heuristics perform better on larger problems. This is intuitively consistent since as the number of sections increases the potential of missed adjacencies to reduce REL-Rd scores is minimized. That is acceptable since in many cases small problems can be 'eyeballed'. However Example #4 is not that trivial a problem, see Table 3.4 for the REL_chart.

Table 3.4 REL_chart for Example #4

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	EXT
Section 1	0	8	5	4	6	7	2	2	2	0	82
Section 2	8	0	25	11	14	9	30	3	3	2	2
Section 3	5	25	0	10	11	12	44	0	75	14	22
Section 4	4	11	10	0	3	4	5	2	2	0	2
Section 5	6	14	11	3	0	4	6	2	2	0	2
Section 6	7	9	12	4	4	0	5	2	2	0	2
Section 7	2	30	44	5	6	5	0	0	39	15	20
Section 8	2	3	0	2	2	2	0	0	2	0	0
Section 9	2	3	75	2	2	2	39	2	0	2	31
Section 10	0	2	14	0	0	0	15	0	2	0	64
Exterior	82	2	22	2	2	2	20	0	31	64	0

3.3.2a <u>REG'D'</u>. We will first present the REG'D' solution to this problem. As can be seen on the REL_chart, Table 3.4, this problem does not display either predominantly high or low flow dominance. The REG'D' heuristic was applied directly and the solution was found at the end of Phase 1 (see Figure 3.15)

The Raw Block Plan for this example is considered to be of adequate regularity to suffice as a Block Plan. The NSR REL-Rd is 95% and the CSR REL-Rd is 101%.

3.3.2b REG'T'. The REG'T' solution to this problem was found very easily. In this case however the Raw Block Plan is not considered adequate as a Final Block Plan, see Figure 3.16. The Raw Block plan scored NSR REL-Rd at 90% and CSR REL-Rd at 98%.

The only reason for not accepting the Raw BLock Plan was greedy. That is to say the Raw Block Plan shown Figure 3.16 was of Regular shape but because of the interactive nature of the heuristic we were aware of an alternate layout with higher scoring. By making the changes, see Figure 3.17, we were able to make slight gains in both NSR and CSR scores of 2% and 1% respectively. The Final Block Plan is also slightly more regular.

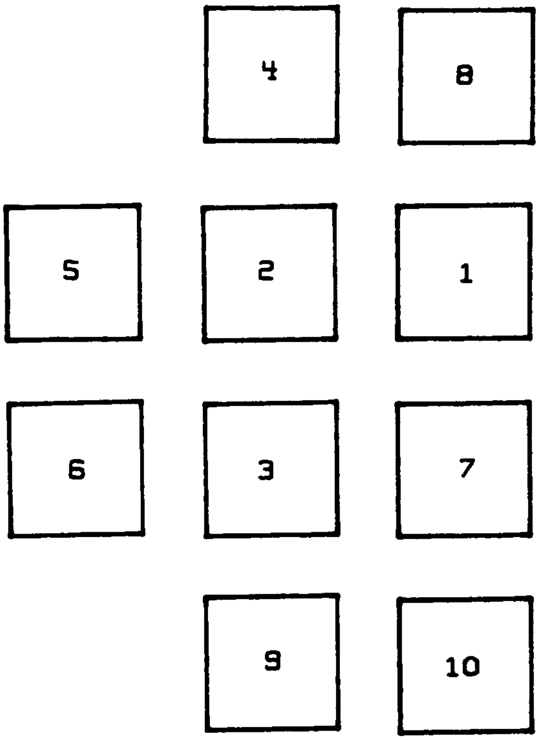


Fig. 3.15 Final Block Plan for Example #4
(REG'D' method)

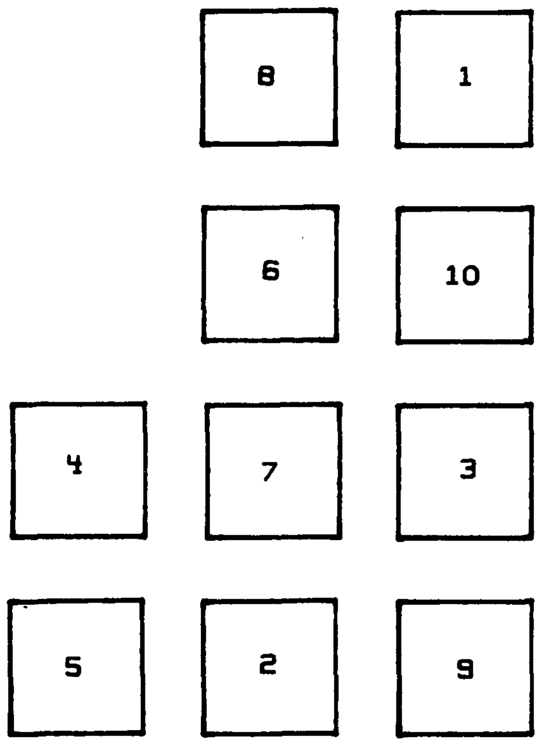


Fig. 3.16 Raw Block Plan for Example #4
(REG'T' method)

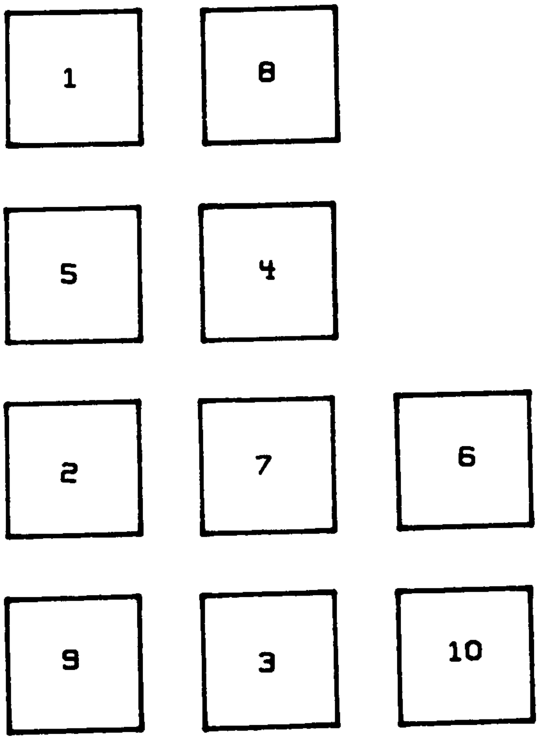


Fig. 3.17 Final Block Plan for Example #4
(REG'T' method)

CHAPTER 4

COMPARISON TO AN ESTABLISHED SOLUTION TECHNIQUE

In this chapter we will compare the results attained using the REG heuristic methods to those of CORELAP. CORELAP has been chosen for comparison by virtue of its acceptance as a workable/useful technique and its similarity in some respects to the REG heuristics. We will first compare and contrast the three approaches, then we will compare the results of their applications to a series of problems which are taken from Nugent, Vollman and Ruml, [1968]. Finally we will discuss the relevance of the comparison.

4.1 Comparison of REG Heuristics to CORELAP

The most prominent variation between the REG Heuristics and CORELAP is the method of evaluation used. As we have discussed earlier for the application of the REG Heuristics the only criterion for scoring is that sections be located adjacent to each other. The heuristics try to MAXIMIZE the accredited score for adjacencies available in the block plan. No penalty for non adjacency is considered. This as discussed is a function of the REL_chart and we have previously assumed that the REL_chart exists in a form consistent with our scoring technique. CORELAP actually considers that non adjacency should cause a penalty to be considered when evaluating a potential layout. CORELAP then is trying to MINIMIZE the sum over the product of distances between sections centroids and the cost associated with moving between the pairs of sections. This approach is more realistic with respect to the form which CORELAP and other conventional procedures consider the REL_chart entries. For the purposes of the following comparison we will use the conventional approach to scoring in an effort to determine whether the REG heuristic output is robust enough to 'compete' with CORELAP. Note that the REG heuristics have the advantage of being interactive while the CORELAP heuristic is not.

Another variation is the method of recognizing adjacency. CORELAP considers sections adjacent only if they have a common wall or boundary. For the REG heuristics we have been considering corner adjacency to be valid. For purposes of comparison we will present the results of both scoring methods.

The mechanics of the three methods are similar. However we feel that the CORELAP approach is slightly myopic as compared to the REG heuristics. Basically the REG'D' heuristic has the advantage of clustering the four most heavily weighted sections in the center of the layout.

By centrally locating these sections we in effect reduce the average distance between them and all other sections of the facility. CORELAP places the most heavily weighted section first but then focuses on that sections relation to others. This is done by selecting subsequent incoming sections in an order based on their relation to previously selected sections in the order of selection. ie. before a section with a '64' relation to the 2nd Section chosen, can enter all sections with a '64' relation to the 1st Section chosen must have been entered. REG'T' is the same as CORELAP with respect to choosing the first section, but chooses the second and third sections based on a combined score and chooses all subsequent incoming sections and their location based on a pair of adjacencies consistent with our corner scoring allowance.

CORELAP can not directly take into consideration sections which have negative REL_chart scores. The problem is that the negative score means that sections should not be adjacent but does not incorporate a distance consideration. Further, since the CORELAP objective is to minimize it would consider negative values as a credit and would attempt to completely isolate the negative pair of sections whereas the negative score really only indicates they should not be adjacent. The negative score must somehow represent a negative cost or profit but the non adjacency criteria usually involves undesireability rather that profit as such. The REG heuristics only consider adjacency and since the goal is to maximize the negative scores are avoided as the block plan is developed. Hence with respect to handling of undesirable adjacencies we feel that the REG heuristics are more realistic.

The REG heuristics by convention allow the exterior to be considered as a section. This ensures that sections requiring adjacency with the exterior have priority to locations on the exterior. CORELAP has a problem with respect to sections requiring exterior locations if those sections are very highly weighted they will tend to be located near the centre of the facility.

4.2 Numerical Comparison of Results

The costs associated with the facility layouts derived using the three methods are tabulated in Table 5.1. It appears from these results that when considering the CORELAP preferred scoring method there is very little difference between the results. When using the REG heuristic preferred scoring method it appears that the REG heuristics layout is slightly less costly. The pictorial representation of the various outcomes are at the end of this Chapter as Figures 4.1 thru 4.7.

Table 4.1 Numerical Comparison of Costs

	CORELAP		REG'D'		REG'T'		
SIZE	C*	R	C	R	C	R	Optimal**
5	25	19	25	19	25	19	25
6	43	38	47	38	44	38	43
7	76	68	74	65	78	66	74
8	110	91	110	88	110	88	107
12	336	273	326	253	318	253	
15	598	483	615	469	623	490	
20	1425	1112	1396	1090	1445	1100	

* C scores are calculated with only wall adjacency
R scores are calculated with wall and corner adjacency

** Optimal scores only calculated for sizes 5, 6, 7 and 8

4.3 Advantages of the REG heuristics

There are several advantages which we feel are apparent in the REG heuristics;

1. they can produce various block plans since they involve some decisions of aesthetic nature and they are interactive approaches. This means the practiced user can see umbrella effect trends and manipulate the developing block plan accordingly.
2. They are easy to apply and the results are as good or better than those achieved via conventional methods.
3. The REG heuristics can realistically handle negative adjacencies, and
4. because of the interactive nature of the REG heuristics we have more confidence in the results.

4.4 Block Plans

Following are the block plans developed using the three methods applied to the sample problems.

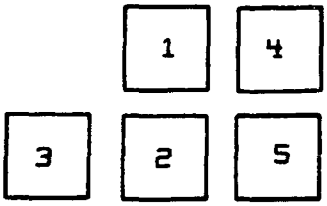


Fig. 4.1a Block Plan CORELAP size 5

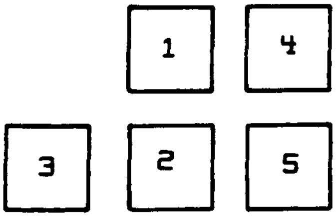


Fig. 4.1b Block Plan REG'D' size 5

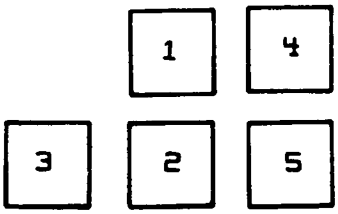


Fig. 4.1c Block Plan REG'T' size 5

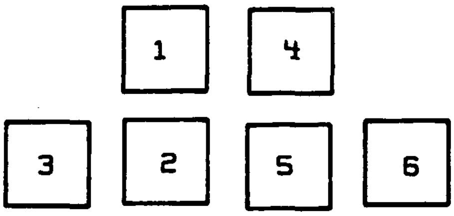


Fig. 4.2a Block Plan CORELAP size 6

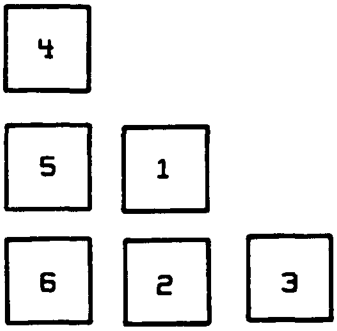


Fig. 4.2b Block Plan REG'D' size 6

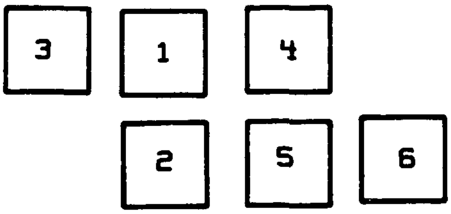


Fig. 4.2c Block Plan REG'T' size 6

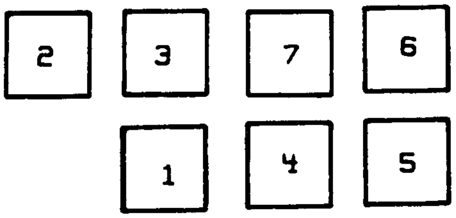


Fig. 4.3a Block Plan CORELAP size 7

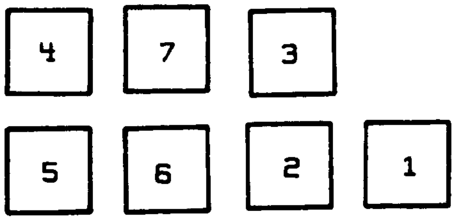


Fig. 4.3b Block Plan REG'D' size 7

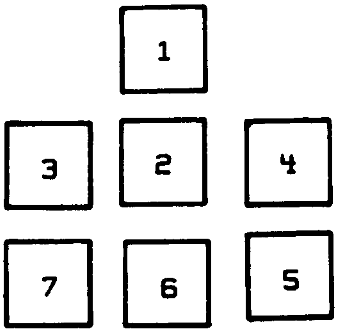


Fig. 4.3c Block Plan REG'I' size 7

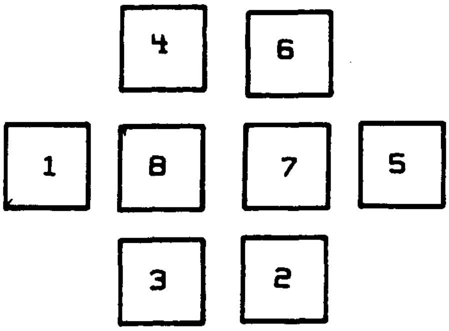


Fig. 4.4a Block Plan CORELAP size 8

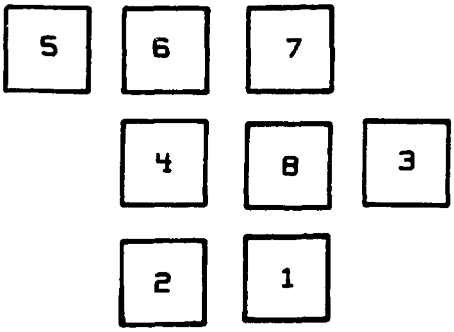


Fig. 4.4b Block Plan REG'D' size 8

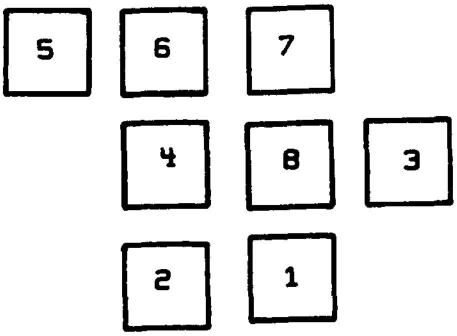


Fig. 4.4c Block Plan REG'T' size 8

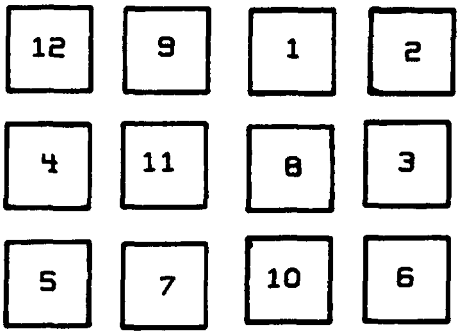


Fig. 4.5a Block Plan CORELAP size 12

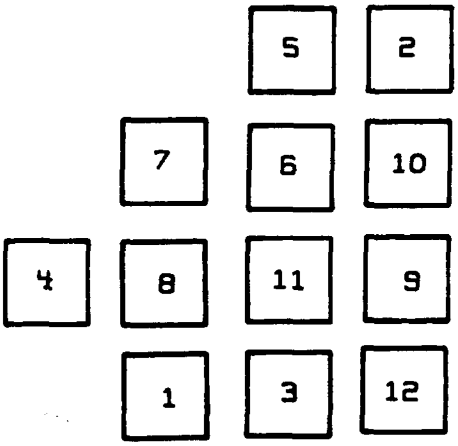


Fig. 4.5b Block Plan REG'D' size 12

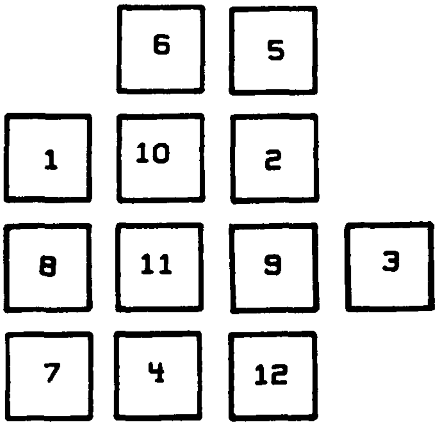


Fig. 4.5c Block Plan REG'T' size 12

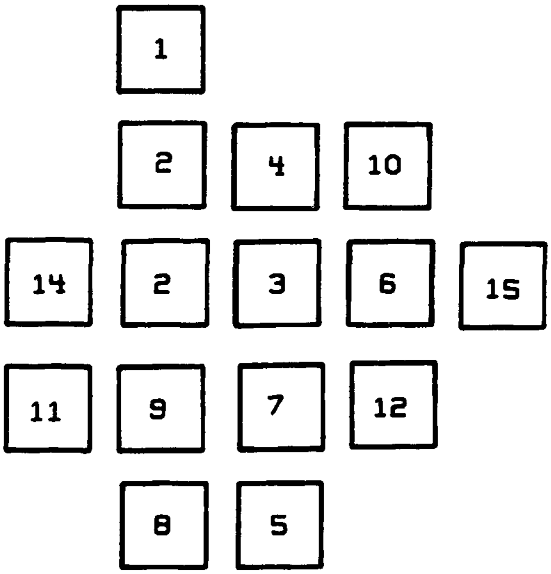


Fig. 4.6a Block Plan CORELAP size 15

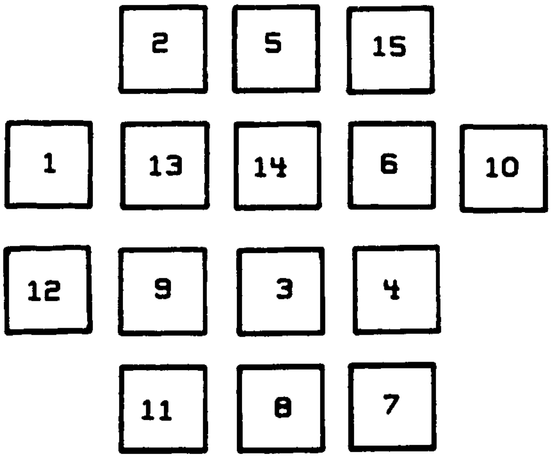


Fig. 4.6b Block Plan REG'D' size 15

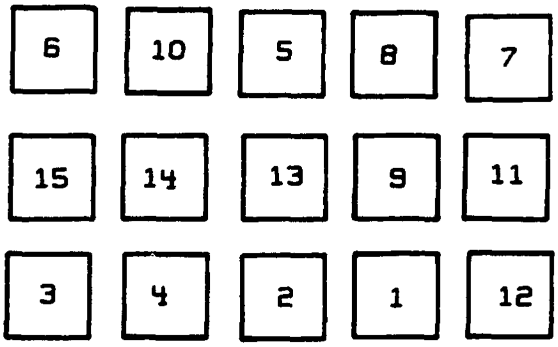


Fig. 4.6c Block Plan REG'T' size 15

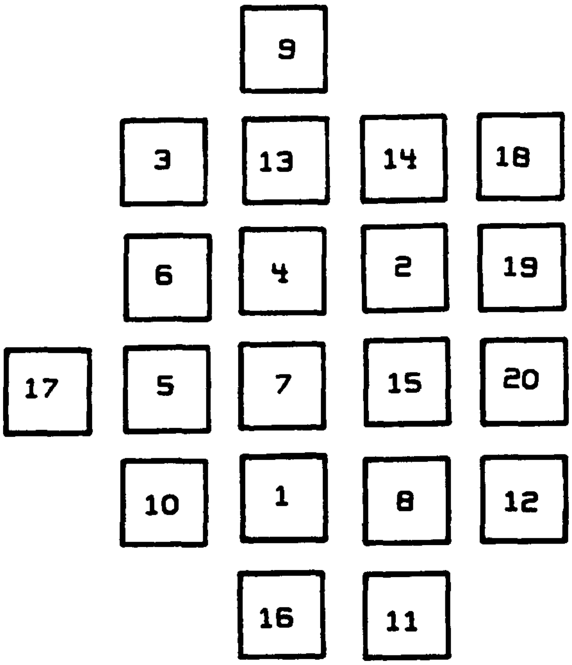


Fig. 4.7a Block Plan CORELAP size 20

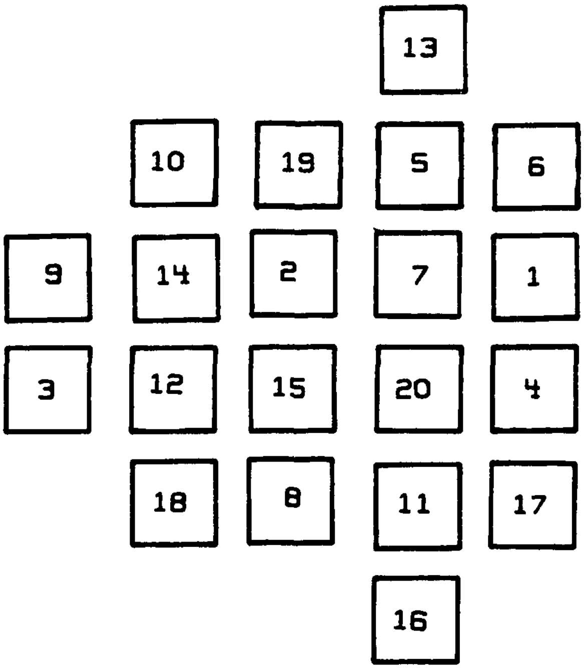


Fig. 4.7b Block Plan REG'D' size 20

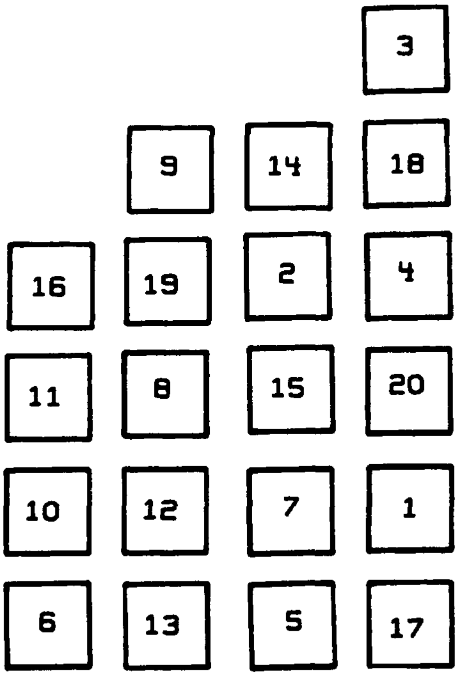


Fig. 4.7c Block Plan REG'T' size 20

CHAPTER 5

CONCLUDING REMARKS

In this chapter we will present a summary of the thesis which highlights the salient features. We will then discuss areas of interest which are related to but beyond the scope of the thesis and finally we will close with some final remarks.

5.1 Summary

In Chapter 1 we have stated the intent of this thesis as being to develop and present two graph theoretic heuristic approaches for solving Facility Layout Problems (FLPs) which require solutions of regular dimensions. We included in Chapter 1 some terms and definitions which in some cases, are specifically oriented to this thesis.

In Chapter 2 we presented the background on FLPs, discussing briefly the various approaches and techniques which have been used historically. The concept of NP - completeness and the requirement for heuristic solutions to that class of problems is introduced. There is significant discussion on the formulation of the FLPs especially with respect to the terms 'Optimize' and 'Relationship Charts'.

The Deltahedron and Triangulated Graph approaches are discussed with respect to their advantages and disadvantages. This chapter is closed by a section dealing with the Block Plan. Specifically we present our interpretation of what a Block Plan is, what form it should be in, what it can and cannot represent and finally we introduce the concept of 'Pseudo-duals' which we use instead of the, more academically oriented 'regular geometric duals'.

In Chapter 3 the heuristics are developed and explained. Included are examples of their application. We have included one example which is an extension to the scope of this thesis in that it incorporates area considerations into the development of what could be used as a Floor Plan.

In Chapter 4 we compared the REG heuristics to CORELAP. We found that the results were similar however we felt the the increased flexibility of the REG heuristics justifies their use.

There are several basic concepts which we feel are underlying themes of this thesis. They are:

1. There is a requirement in real world applications of FLP solution techniques for regularization of the Block Plans. That is 'Optimality' can never be achieved if the optimal solution is not implementable. As academics we

must develop solution techniques which have widespread practical application to get the recognition and support of industry.

2. Heuristic solutions based on graph theoretic techniques have been shown to be 'very good' in all but worst case scenarios. These academically oriented solutions, specifically as developed by Giffin (1984,1986) can be used as a measure of the performance of the heuristics which we have presented.
3. If a solution can be found which is evaluated as being 'very good' based on achieved pairwise adjacencies and which is aesthetically acceptable, then that solution is essentially an optimal one.
4. With regard to the current evolution of Relationship Chart formulation we cannot rationalize the incorporation of areas into the development of a block plan supposedly based on pairwise section adjacency scoring.

5.2 Recommendations

The first recommendation which we make is that the problem of relationship chart development be addressed. It is a difficult problem because of its nature. That is the relationship chart must embody the true costs of operating a facility based on the relative positions of the various sections within that facility. If only one person were to use the facility then the problem is reduced since it is easy to identify the intuitive values associated, but then there is still the problem of quantifying those values and incorporating the real costs of daily operation.

The next recommendation which we make is that an automated system of application for the heuristics presented be developed. While such automation may not be academically interesting with respect to FLPs, it could be very challenging as a system development problem and it could evolve into a commercially useful product. We are not being bourgeois in this recommendation but instead are being consistent with one of our underlying premises that academic endeavors must have useful and practical application if we expect support from industry.

5.3 Conclusions

We have shown, by comparison to solutions known to be 'very good', that the solutions our heuristics produce are 'very good'. The regularity of the Final Block Plan produced by either heuristic has aesthetic as well as practical appeal. We therefore conclude the solutions attained through use of these heuristics can be termed as optimal within the context of heuristic solutions. In general the REG'T' heuristic is easier to apply but in some cases the solution is not as highly scored as its REG'D' counterpart. In actual fact we would use both heuristics and to produce block plans and probably base our final choice on aesthetic preference rather than numeric rating. Through appropriate use of clustering we are confident in using the heuristics presented to attempt any legitimate problem, i.e. one which any of the existing techniques could solve.

While not specifically addressed, we have demonstrated that the solutions which evolve are robust enough to handle the incorporation of area considerations, and produce useful results which are at least as efficient as those found using conventional methods. We have demonstrated this using the CORELAP approach. If one can justify the development of Relationship Charts based on adjacency and incorporating area, and from those develop either a Triangulated Graph or a Deltahedron, then the heuristics presented can be used to obtain a very good and useful solution.

It is felt that this thesis has fulfilled the stated objective.

APPENDIX 1

An Explaination and Listing of Computer Functions used

In this appendix we will present two of the computer programs which were developed for this thesis. Each program will be prefaced with a short description of its use and function. The programs are written in APL (A Programming Language), a language which is by no means 'READER FRIENDLY'. We have included liberal commentary within the function and attempted to use descriptive variables and function names to facilitate readability. It is suggested that readers without experience in APL not attempt to dissect these codes; rather read the introductions and comments to glean the essence of what the codes do rather than how they do it.

A1.1 WORKDELTA

WORKDELTA is so named because it returns the information required to construct a Raw Block Plan without bothering to draw a Deltahedron. We thought of it as giving us what we need to WORK with the concept of a DELTAHEDRON to produce a Raw Block Plan. This function is in essence the same one developed by Atrek and Fifield

(1985) with minor changes involving the presentation of adjacency scores to facilitate block plan development and some changes involving the operators used.

The function accomplishes its task by comparing perspective embeddings. The decision is made greedily. The function is able to pick out appropriate REL_chart scores through use of indices which identify the vertices involved in the various available triangular faces of the deltahedron as it is being constructed. As we have discussed the deltahedron itself need not be physically drawn. The list of triangle and the vertex insertion order are sufficient to uniquely characterize its structure. The Function WORKDELTA is listed at the end of this Appendix.

A1.2 SEMGRED

The name SEMGRED is an abbreviation of SEMI-GREEDY. As we developed the Triangulated Graph approach there were several variations of formulation attempted. We will be listing only SEMGRED. The SEMGRED function was so named because it is only sometimes greedy. We found that the pure greedy approach did not produce a Triangulated Graph with the characteristics we sought. The SEMGRED function does manage to avoid, in most cases, the dreaded 'UMBRELLA EFFECT'. It also creates triangular clusters which for the most part can be left together when regularizing the Raw Block Plan.

Like the WORKDELTA function, the insertion order is fixed based upon relative ranking by popularity, i.e. the sum of the REL_chart scores for each section over the range of the other sections. The first section is thus identified and then it is used to select the best 2 other sections to form with as the initial triangle. These sections are removed from the insertion order and then each section is attached as a vertex of degree 2.

WORKDELTA Listing

```
[0]    WORKDELTA REL;INSERT;MAXPOS;NEWINSERT;SEQ;SEQQ;
       TRIANGL;W;X;Y
[1]    SEQQ←SEQ←⍒+⌿REL
[2]    ⍝
[3]    ⍝ The above line determines the insertion order
[4]    ⍝ by ranking the sections in order of the sum of
[5]    ⍝ their associated REL_chart adjacency scores.
[6]    ⍝
[7]    INSERT← 4 3 ⍴4↑SEQ ⍝ the 1st 4 sections
[8]    ' INITIAL DELTAHEDRON   ',⍕(4↑SEQ)
[9]    ' '
[10]   SEQ←4↓SEQ
[11]   ⍝
[12]   ⍝ The above lines identify to us the first four
[13]   ⍝ sections to be embedded onto the graph and
[14]   ⍝ they drop those sections form the insert list.
[15]   ⍝
[16]   ' THE TRIANGLE INSERTION ORDER IS   ',(⍕SEQQ)
[17]   '  '
[18] ITERATE:
[19] MAXPOS←W⍳⌈/W←+/REL[INSERT;(''⍴1↑SEQ)]
[20] ⍝
[21] ⍝ The line above identifies the best triangle
[22] ⍝ for embedding of the canidate vertex.
[23] ⍝
[24] ' INTO TRIANGLE  ',(⍕TRIANGL←(INSERT[MAXPOS;])),
     ' INSERT SECTION  ',⍕(''⍴1↑SEQ)
[25] X←⍉ 3 2 ⍴TRIANGL,REL[(TRIANGL);(1↑SEQ)]
[26] '       SECTION  ',(⍕Y←(1↑SEQ)),'  HAS REL SCORE
     TO SECTION  ',(⍕(X[1;1])),'    OF  ',(⍕(X[2;1]))
[27] '       SECTION  ',(⍕Y),'  HAS REL SCORE TO SECTION
     ',(⍕(X[1;2])),'    OF  ',(⍕(X[2;2]))
[28] ' SECTION  ',(⍕Y),' HAS REL SCORE TO SECTION '
     ,(⍕(X[1;3])),'    OF  ',(⍕(X[2;3]))
[29] '   '
[30] NEWINSERT← 3 3 ⍴(''⍴1↑SEQ),TRIANGL
[31] INSERT← 1 0 ↓(MAXPOS-1)⊖INSERT
[32] INSERT←INSERT⍪NEWINSERT
[33] ⍝
[34] ⍝ The above series identifies the new triangles
[35] ⍝ which are now available for embedding into and
[36] ⍝ they drop the used triangle which is no longer
[37] ⍝ available from the list which is called INSERT.
[38] ⍝ INSERT a matrix has triangle sets identified for
[39] ⍝ possible embedding as the entering vertices are
[40] ⍝ 3 - connected .
[41] ⍝
[42]  →(0<⍴,SEQ←1↓SEQ)/ITERATE
```

SEMGRED Listing continues

```
[39] ITERATE4:
[40] COUNTER←COUNTER+1 Δ
     NEWGRPSCORES←NEWGRPSCORES,+/C[(AVAILADJ[COUNTER;])]
[41] →(COUNTER=(1+1↑⍴AVAILADJ))/LOOP
[42] →ITERATE4
[43] LOOP:
[44] ⍝
[45] ⍝ Loop ITERATE4; evaluates the vertex in each
[46] ⍝ position available as found on the AVAILADJ list
[47] ⍝
[48] INDEX2←1ΔCOUNTER←⌈/NV×NEWGRPSCORES∘.=⌈/NEWGRPSCORES
     Δ NV←⍳⍴NEWGRPSCORES
[49] ITERATE5:
[50] →(INDEX2=COUNTER)/LOOP1
[51] INTP←INTP,AVAILADJ[INDEX2;]
[52] LOOP1:
[53] INDEX2←INDEX2+1
[54] →(INDEX2≠1+⍴NEWGRPSCORES)/ITERATE5
[55]  AVAILADJ←(RPP)⍴(INTP,(2↑NEWGROUP),((1↑NEWGROUP),
      ¯1↑NEWGROUP))Δ RPP←(1+1↑⍴AVAILADJ),2
       Δ NEWGROUP←ENTER,AVAILADJ[COUNTER;]


[56] 'ADD SECTION',(⍕ENTER),'INCIDENT WITH SECTIONS ',
     (⍕¯2↑NEWGROUP),'  WITH VALUE  ',(⍕⌈/NEWGRPSCORES)
[57] INTP←0 Δ FIRSTGROUP←FIRSTGROUP,ENTER
     ΔNEWGRPSCORES←0 Δ CUMSCORE←CUMSCORE,⌈/NEWGRPSCORES
[58] ⍝
[59] ⍝ After updating the cumulative score and
[60] ⍝ adding the new vertex pairings to and removing
[61] ⍝ the used vertex pair from AVAILADJ, we loop back
[62] ⍝ and continue insertion process until all vertices
[63] ⍝ have been included in the graph.
[64] ⍝
[65] →ITERATE3
[66] END:'THIS ARRANGEMENT WILL HAVE A SCORE OF ',
          (⍕+/CUMSCORE)
```

SEMGRED Listing

```
[0]  SEMGRED RELCHART;RELC1;FIRSTPICK;NEWGRPSCORES;
     SCRLIST;INDEX1;COUNTER;FIRSTGROUP;AVAILADJ;ENTER;
     N;MINIRELCHARTSUM;INTP;INDEX2;NEWGROUP;NV;CUMSCORE;
     RPP;C
[1]  INTP←⍬ ⋄ N←⍳1↑⍴RELCHART ⋄ RELC1←RELCHART ⋄ INDEX1←0
     ⋄ FIRSTPICK←0 ⋄ NEWGRPSCORES←⍬ ⋄ SCRLIST←⍬
[2]  ⍝
[3]  ⍝ Above we have established a variables list and
[4]  ⍝ assigned some variables initial values.
[5]  ⍝
[6]  ITERATE:
[7]  SCRLIST←SCRLIST,+/2↑RELCHART[(INDEX1);
     ⍒RELCHART[(INDEX1);]]⋄ INDEX1←INDEX1+1
[8]  →(INDEX1≠(1↑⍴RELCHART))/ITERATE
[9]  ⍝
[10] ⍝ The loop ITERATE; GREEDILY finds the initial
[11] ⍝ triangulation based best 2 adjacencies.
[12] ⍝
[13] ITERATE2:
[14]  FIRSTPICK←FIRSTPICK+1
[15]  →(FIRSTPICK≠N[1↑⍒SCRLIST])/ITERATE2
[16] ⍝
[17] ⍝ The loop ITERATE2; finds the index of the vertex
[18] ⍝ identified as FIRSTPICK then identifies the
[19] ⍝ index of the 2 vertices which are to be included
[20] ⍝ in the initial triangulation
[21] ⍝
[22] FIRSTGROUP←FIRSTPICK,2↑⍒RELCHART[(FIRSTPICK);]
[23] ' THE FIRST TRIANGULATION IS OF  ',(⍕FIRSTGROUP)
[24] CUMSCORE←(+/+/RELC1[FIRSTGROUP;FIRSTGROUP])÷2
[25] AVAILADJ← 3 2 ⍴(2↑FIRSTGROUP),(¯2↑FIRSTGROUP),
                     ((1↑FIRSTGROUP),¯1↑FIRSTGROUP)
[26] ⍝
[27] ⍝ AVAILADJ is a matrix of incident vertex pairs.
[28] ⍝
[29] ITERATE3:
[30] COUNTER←1↑⍴AVAILADJ
[31] →(COUNTER=INDEX1)/END
[32] MINIRELCHARTSUM←+/[1]RELCHART[FIRSTGROUP;]⋄
     RELCHART←RELC1×(⍴RELCHART)⍴×/N∘.≠FIRSTGROUP
[33] COUNTER←1 ⋄ C←RELC1[ENTER;]⋄
     ENTER←⌈/N×MINIRELCHARTSUM∘.=⌈/MINIRELCHARTSUM
[34] ⍝
[35] ⍝ Non allocated vertexs are evaluated to determine
[36] ⍝ which should be next embedded onto the graph
[37] ⍝ index is identified as the variable ENTER
[38] ⍝
```

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