J. ENVIRONMENTAL SYSTEMS, Vol. 6(1), 1976-77

BEHAVIORAL DESIGN USING SPACE ALLOCATION*

W. R. SPILLERS
Professor of Civil Engineering and Engineering Mechanics
Columbia University

G. GREENWALD-KATZ
Architect and Research Associate
Columbia University

BRADLEY SOULE, M.D.
Nat. Institute Child Health and Human Development
Bethesda, Maryland

KAY STANDLEY, PH.D.
Nat. Institute Child Health and Human Development
Bethesda, Maryland

ABSTRACT

A procedure is described whereby behavioral studies can be used quantitatively in determining architectural layouts through a space allocation algorithm. In this case the space allocation algorithm becomes something of a communications device between the behavioral sciences and the technical areas of building design.

Introduction

The need for behavioral input in building design has been well documented [1]. Historically, the architect has accepted this type of input in an ad hoc manner, as he could find it, but there is now a tendency to attempt to formalize this aspect of design and to develop design teams which include behavioral scientists. A basic

* This work has been supported in part by the Sloan Foundation and the National Science Foundation.

doi: 10.2190/CXPY-NL96-LAHH-XRCU
http://baywood.com

problem in so doing is how, precisely, are behavioral studies to be manifest in building layout.

In this paper a method is presented for the inclusion of behavioral studies in building layout using a simple generalization of a space allocation algorithm. The idea is roughly that behavioral data is frequently spatial in nature and similar in form to the data required for space allocation. The necessary transformations of data and modifications of a space allocation algorithm are described below in conjunction with a simple behavioral study. For those who are not familiar with the space allocation problem, its basic structure is also described below.

Space Allocation

In simple situations, the designer has no peer in terms of layout; there is no question that he can produce by hand the best designs at the least cost. But as the magnitude of a project increases, the amount of available information becomes enormous and the designer at some point may look to the computer for assistance. One form of assistance available to him lies in the space allocation algorithms [2].

Early in the design of a project, the designer has information which includes a list of departments (project elements), department areas, an adjacency matrix which indicates the relationships between the departments, a building envelop (which can be varied parametrically), and some information concerning departments whose location is "fixed" by design requirements. (The adjacency matrix is simply a means for expressing formally relationships like "department A should be near department B.") From this information there are various space allocation algorithms which can be used to generate preliminary layouts automatically.

Figures 1-2 indicate in a very simple case what the input to a space allocation algorithm looks like and some typical output [3]. These figures are part of the example which is developed later, but it is convenient to introduce them at this time in order to aid the discussion of the space allocation problem. There are, first of all, nine departments and their areas listed. Each department may be related to every other department qualitatively on a scale from one to nine (see the adjacencies). These qualitative relationships are then converted to quantitative relationships through the "cost categories" listed. Roughly, the available space is divided into grid points which are to be occupied by modules of the various departments. (In this case the grid size is 9×9.) As the cost

SPACE ALLOCATION
TEST RUN
NIH DATA

PARAMETERS:

MODULE GRID SIZE (HORIZONTAL X VERTICAL):	9 X 9
NUMBER OF DEPARTMENTS:	9
NUMBER OF COST CATEGORIES:	9
NUMBER OF FLOORS:	1
LENGTH:	9.000
WIDTH:	9.000
FLOOR HEIGHT:	1.000
NUMBER OF LAYOUTS:	1

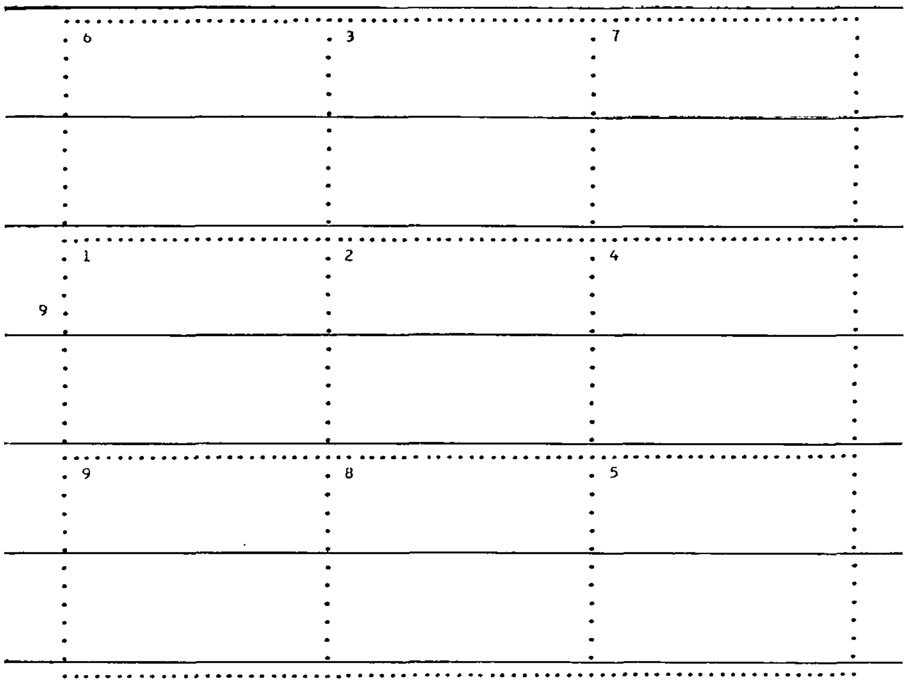
	DEPARTMENT	AREA	ADJACENCIES (DEPARTMENT-CATEGORY)									
1	CHIEF PSYCH	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	1	2	3	7	6	4	5	6	5
2	PSYCH 1	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	2	1	4	4	8	6	5	8	8
3	PSYCH 2	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	3	4	1	8	7	5	3	6	6
4	PHYSICIAN 1	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	7	4	8	1	7	6	7	5	5
5	PHYSICIAN 2	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	6	8	7	7	1	6	6	3	4
6	SECRETARY	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	4	6	5	6	6	1	4	6	6
7	RES ASST	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	5	5	3	7	6	4	1	7	7
8	PHYSICIAN 3	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	6	8	6	5	3	6	7	1	2
9	PSYCH 3	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	5	8	6	5	4	6	7	2	1

Figure 1.

categories indicate, moving up in the affinity scale implies moving toward less urgent relationships; the higher numbers which are negative in this case actually imply rejection.

In any case, the designer enters with qualitative relationships between departments, these relationships are given a quantitative interpretation by the cost categories, the space is divided into

FLOOR NO. 1 FOR LAYOUT NO. 1 9



COST CATEGORIES FOR LAYOUT NUMBER 1

1	500.000
2	85.000
3	70.000
4	50.000
5	30.000
6	10.000
7	-10.000
8	-30.000
9	-40.000

Figure 2.

modules, and the algorithm attempts to place the available department modules in a manner which minimizes

$$\Phi = \sum_{i,j} A_i \; A_j \, | \, r_{ij} \, | \, w_{ij}$$

in which

A_i - area of department i
r_{ij} - relative position vector of the centroid of department i with respect to department j.
w_{ij} - weighting factor reflecting the affinity of department i for department j.

In this case, e.g., department 1 is related to department 5 by an affinity of 6; since the "cost" of category 6 is 10, it follows that w_{ij} is 10. The algorithm simply attempts to minimize weighted walking distances between centroids as they are specified by the adjacency relationships (matrix).

In general there are some interesting open questions concerning requirements which must be made on the data in order to produce unique layouts. In this case it is clear that the above data will not produce a unique layout (e.g., a 90° rotation of any given layout will not affect the value of Φ); in order to be able to proceed, one module of department 6 was "fixed" in the upper left hand corner of the layout. The algorithm then generated the layout shown in Figure 2 without further intervention.

It should be noted that these space allocation algorithms in general produce layouts in three dimensions rather than two.

Computer Graphics

As described above, the space allocation algorithm is passive; i.e., layouts are made on the basis of given data and there is no opportunity for the designer to intervene in the layout process (although he may, of course, subsequently rerun his job with modified data). Figures 3-4 show an alternative, interactive computer graphics mode of design which has considerable potential. In this mode the designer is able to communicate directly with the computer using the light pen and the typewriter keyboard [4].

The most obvious reasons for the designer to turn to interactive computer graphics are the possibility of graphical communication with the computer and the immediacy of the results. Beyond these reasons lie the fact that design is an extremely sophisticated and complex process which cannot exist in a medium which does not support a high rate of information transfer. And characteristic of graphical communication is a high rate of information transfer.

Beyond the characteristics of graphical communication, computer graphics tends to remove much of the drudgery of computer usage and opens the door to users who have little interest and/or training in computer sciences. With computer graphics, the behavioral

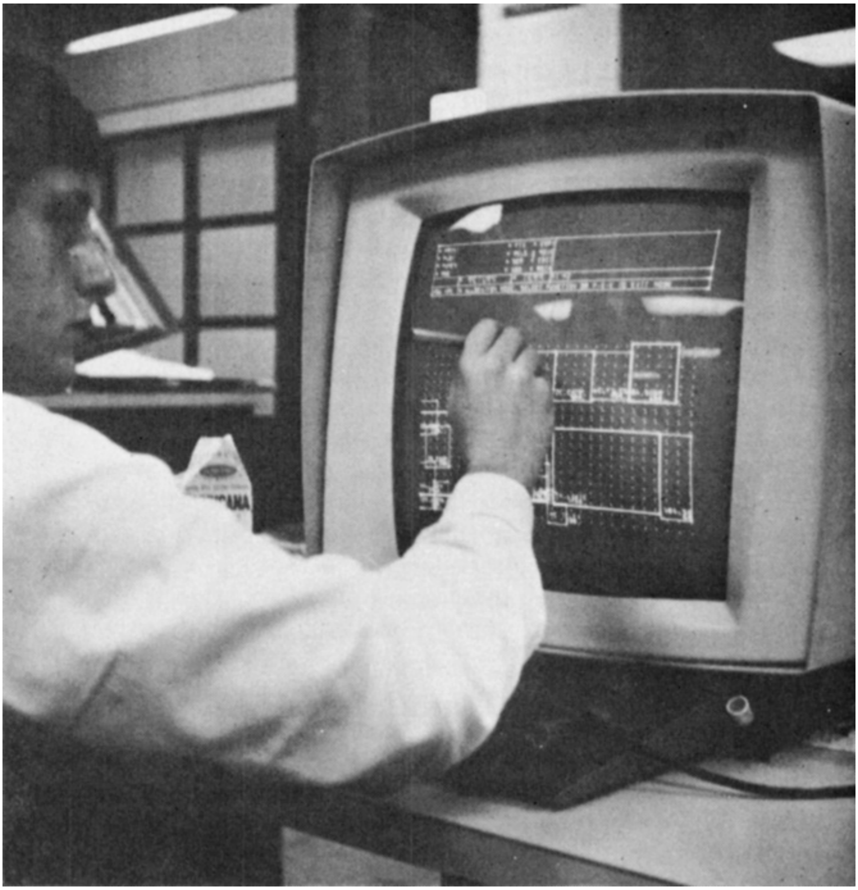


Figure 3. Designer using an interactive graphics terminal.

scientist, e.g., can assume an immediate role on the design team without investing time in the technical aspects of building layout and design since it affords him the possibility of receiving the information he requires in graphics form, precisely as he needs it.

In terms of space allocation there are additional reasons for going to computer graphics. Space allocation is one of those cases in which it is necessary to resort to heuristics since there is no available algorithm capable of solving the associated optimization problem. The result is that the layouts generated are less than perfect and must be edited (which can be done most conveniently by hand at a graphics terminal). Beyond this, in going from a poorly structured design problem to space allocation, many

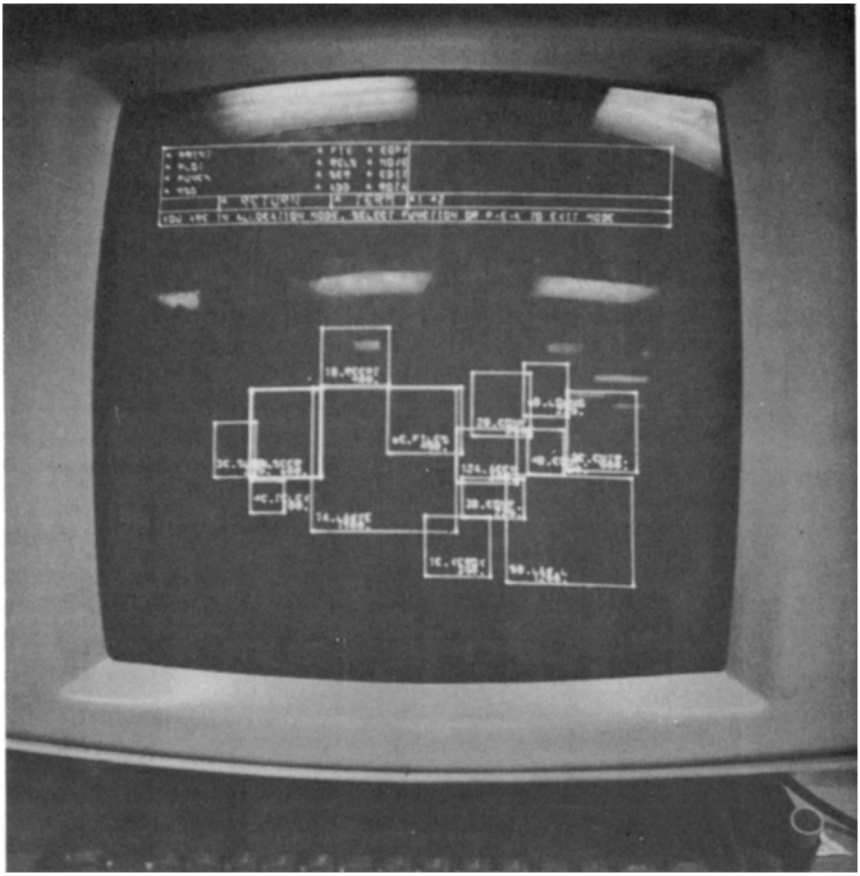


Figure 4. Designer using an interactive graphics terminal.

parameters are introduced in a rather arbitrary manner. Using interactive computer graphics it is possible to investigate conveniently the effect of varying these parameters. The designer can, in effect, sit at the terminal and "play" with the layout. It is not now possible, without human intervention, to make these kinds of studies.

An Example of Behavioral Design

Given a space allocation algorithm it will be shown in this section how a rather trivial behavioral study can be used to generate layouts (see Figure 5). Actually, neither the study nor the

Occupational classification
A—chief psychologist
B—psychologist
C—psychologist
D—physician
E—physician
F—secretary
G—research assistant
H—physician
I—psychologist

Status Hierarchy (highest to lowest)
A, B, C, I, H, D, E, G, F

Seniority (most to least)
A, G, B, C, I, F, H, D, E

Question 1—"Who do you want to work with, most to least?"

		Individual choosing								
		A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
	1	B	A	G	B	H	A	B	I	H
	2	C	D	A	A	I	E	A	E	E
	3	I	G	B	H	A	B	C	C	A
	4	G	C	H	I	C	C	F	D	C
choice	5	H	E	I	E	D	G	E	A	G
	6	E	H	E	C	G	H	D	G	D
	7	D	I	D	G	B	I	H	B	F
	8	F	F	F	F	F	D	I	F	B

Question 2—"Who would you like to have an office next to, most to least?"

		Individual choosing								
		A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
	1	F	A	G	H	H	G	F	I	H
	2	B	D	A	I	I	D	E	D	D
	3	C	C	F	F	F	E	C	E	E
	4	G	G	B	E	A	I	A	F	G
choice	5	I	F	I	G	G	H	D	C	F
	6	H	I	H	A	G	A	I	G	C
	7	E	E	E	C	D	C	H	A	A
	8	D	H	D	B	B	B	B	B	B

Question 3—"Who do you get information from, most to least?"

		Individual choosing								
		A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
	1	F	A	G	B	H	A	C	I	H
	2	C	C	F	F	I	B	F	F	F
	3	B	D	A	A	A	C	A	C	A
	4	I	F	B	I	C	G	B	A	E
choice	5	G	G	I	G	F	I	I	E	C
	6	H	I	H	H	G	H	E	G	G
	7	E	E	E	E	B	E	H	D	B
	8	D	H	D	C	D	D	D	B	D

Figure 5. A behavioral study.

layouts produced are important. What we believe to have potential here is ability for behavioral studies to affect building layouts in a quantitative manner.

Figure 5 shows a behavioral study which involves nine people in an office and their response to three questions. The problem is to produce a layout which satisfies as nearly as possible, the requirements of these people.

The first problem encountered in using data of this type with a space allocation algorithm is that the relationships are symmetric in space allocation (if A loves B then B loves A) while they are not in this study. This problem was solved by using a symmetric weighted combination of the responses to the questionnaire. Roughly, more weight was given to the choice of the individual with the higher status in order to produce a symmetric combination: If A_{ij} is the ranking which department i gives to department j, a symmetric combination

$$A^*_{ij} = (s_i A_{ij} + s_j A_{ji})/(s_i + s_j)$$

is formed. Here s_i is the status weighting factor of member i. (These were assumed to vary linearly from eighteen down to ten.)

The other problem to be overcome was that ordinarily the space allocation algorithm is given a single adjacency matrix, while in this case there are three such arrays. This problem was also solved by taking weighted combinations. That is, if A^*_{ij}, B^*_{ij}, and C^*_{ij} represent the three symmetric arrays generated as described above, single linear combinations, D_{ij}, of these arrays were formed as

$$D_{ij} = \alpha_1 A^*_{ij} + \alpha_2 B^*_{ij} + \alpha_3 C^*_{ij}$$

At this point the data has been transformed into a form acceptable to the space allocation algorithm and two layouts have been generated using different values of the parameters α_1, α_2, and α_3. In the layout shown in Figures (1-2) $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$. Figures (6-7) show an addition layout in which $\alpha_1 = .166$, $\alpha_2 = .333$, $\alpha_3 = .5$. In this case the algorithm has torn department 4. While it did not seem important to do so in this example, had the interactive space allocation system been used, it would have been a simple matter to edit this layout to produce something more realistic.

Concluding Remarks

The addition of behavioral parameters to a space allocation algorithm poses problems which were solved here by introducing

SPACE ALLOCATION
TEST RUN
NIH DATA

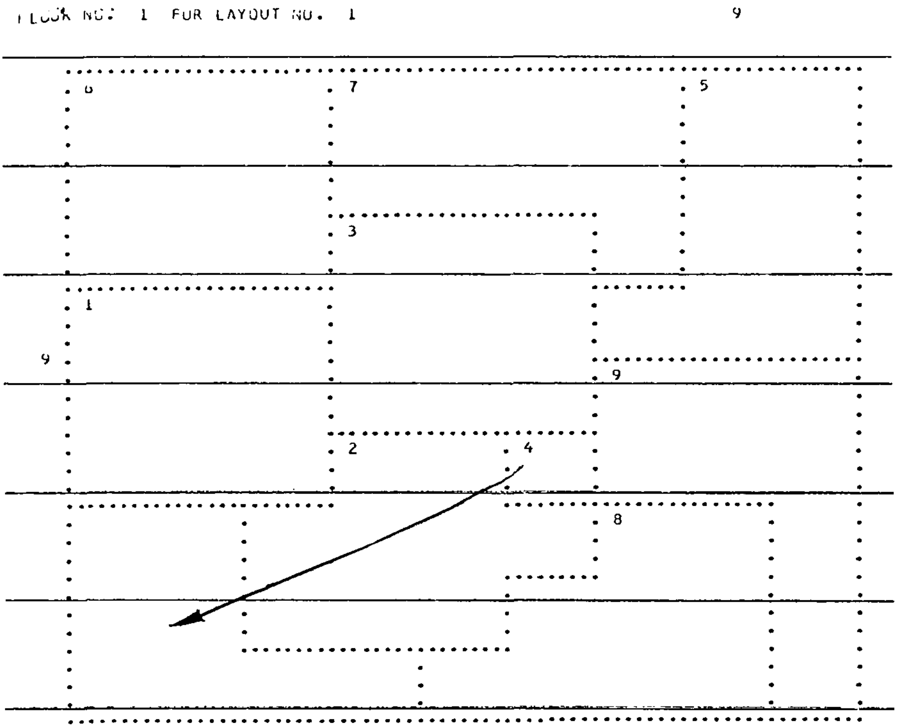
PARAMETERS:

MODULE GRID SIZE (HORIZONTAL X VERTICAL):	9 X 9
NUMBER OF DEPARTMENTS:	9
NUMBER OF COST CATEGORIES:	9
NUMBER OF FLOORS:	1
LENGTH:	9.000
WIDTH:	9.000
FLOOR HEIGHT:	1.000
NUMBER OF LAYOUTS:	1

	DEPARTMENT	AREA	ADJACENCIES (DEPARTMENT-CATEGORY)									
1	CHIEF PSYCH	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	1	3	3	7	6	3	5	7	5
2	PSYCH 1	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	3	1	4	4	8	6	6	9	8
3	PSYCH 2	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	3	4	1	9	7	5	2	6	6
4	PHYSICIAN 1	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	7	4	9	1	7	5	7	5	6
5	PHYSICIAN 2	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	6	8	7	7	1	6	6	4	4
6	SECRETARY	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	3	6	5	5	6	1	4	5	5
7	RES ASST	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	5	6	2	7	6	4	1	7	6
8	PHYSICIAN 3	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	7	9	6	5	4	5	7	1	2
9	PSYCH 3	9.	DEPT/	1	2	3	4	5	6	7	8	9
			AFFIN/	5	8	6	6	4	5	6	2	1

Figure 6.

some new parameters: the responses were weighted according to status in order to make them symmetric and the arrays themselves were weighted in order to obtain a single input array for the space allocation algorithm. Each of these weighting factors is an additional parameter which must be determined. These parameters are in addition to the existing parameters in the space allocation



COST CATEGORIES FOR LAYOUT NUMBER 1

1	500.000
2	85.000
3	70.000
4	50.000
5	30.000
6	10.000
7	-10.000
8	-30.000
9	-40.000

Figure 7.

problem which were introduced to transform the unstructured design problem into a well posed optimization problem.

In many cases it is not at all clear how to select these parameters. For space allocation it is sometimes possible to vary parameters systematically and observe the effect of these variations on the resulting layout; the layout may not even be sensitive to these variations in which case matters simplify. But in general, adding behavioral parameters to a space allocation algorithm is a question of combining dissimilar quantities and will require considerable study to be done properly. It is, in fact, the problem faced by ecologists today as they attempt to include questions such as environmental impact in the traditional studies of design alternatives which are based on cost. In these terms it is not then surprising to see this problem reemerge when behavioral scientists are added to the team of building designers.

The work described here represents only a beginning but in some sense it tends to throw the ball back to the behavioral scientists. In the past, since it has been difficult to incorporate behavioral studies in building layout, it was, in some sense, less critical what these studies were about. As it becomes feasible to use behavioral studies directly in problems of layout, it becomes paramount to know precisely the manner in which they relate to a given project.

REFERENCES

1. R. Gurman, (ed.), *People and Buildings*, Basic Books, Inc., New York, 1972.
2. W. R. Miller, "Bibliography: Computer-Aided Space Planning," Eighth Annual Design Automation Workshop, Atlantic City, June 1971.
3. W. R. Spillers and P. Weidlinger, "An Algorithm for Space Allocation," Proc. 5th Annual ACM Urban Symposium, pp. 142-157, August 1970.
4. W. R. Spillers and S. Al-Banna, "An Interactive Computer Graphics Space Allocation System," Proc. 9th ACM-IEEE Design Automation Workshop, pp. 229-237, June 1972.

Direct reprint requests to:

W. R. Spillers
Department of Civil Engineering and
Engineering Mechanics
Columbia University
New York, New York 10027