A Computer-Aided Approach to Complex Building Layout Problems

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Abstract

This paper discusses the relations between locational objectives for activities and the resultant arrangements of built spaces to satisfy these objectives. In particular it is concerned with objectives which are complex, ill-defined, incomplete, and contradictory It describes the logic, and the uses, of an experimental interactive computer program, CLUMP 3, which enables a designer to test the effects on the spatial structure of a built environment of adopting different locational objectives, and alternative resolutions of conflict amongst objectives.

(1) Locational Objectives and Spatial Order

The notion of ordered, organized spatial relationships is central to architecture. In designing, we attempt to relate each space in the built environment to other spaces, and to the external environment, in accordance with some set of locational objectives which we have explicitly or implicitly adopted.

When the locational objectives are clear and simple, the relationship between objectives and form may be direct and obvious. Consider for instance, the following configuration of dots disposed at randomly selected locations in a plane (figure 1)... that is, their arrangement is not determined in relation to any particular objectives, and there is no discernible order in the form.

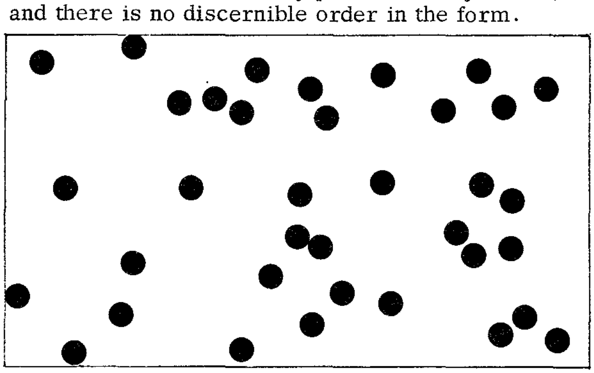

Figure 1

If we now introduce the locational objective "any dot is better adjacent to another dot than to empty space", it is easy to rearrange the dots into a configuration which satisfies this objective, and which as a consequence, displays a clearly evident system of order (figure 2).

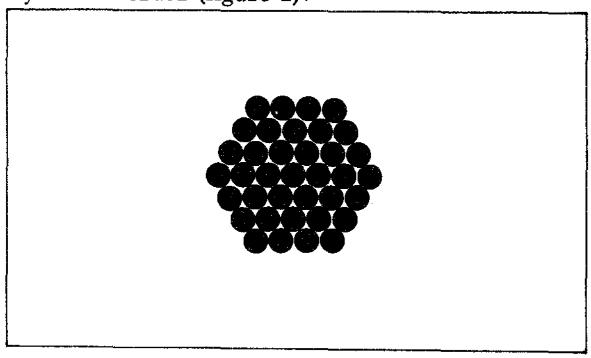

Figure 2

But architecture is rarely so simple. The set of locational objectives which we wish to satisfy will usually be quite large and complex, ill-defined, and riddled with all kinds of conflicts and contradictions. The systems of spatial order which we develop in response need to be much more complicated and subtle than our circle of dots. Furthermore, where incomplete data, ambiguity, conflict, and compromise are involved, there is no clear separation between the processes of definition of objectives and synthesis of form. The information and insights gained as we grope towards synthesis result continually in redefinition and clarification of objectives. We do not always know what we want until we have it.

This paper is concerned with the process of generating spatial configurations in response to such complex objectives. It demonstrates how alternative formulations of locational goals for a set of spaces imply groupings of those spaces together in different ways, and describes an experimental interactive computer program, CLUMP 3, which enables a designer to test the effects on the grouping structure of adopting different locational objectives, and alternative resolutions of conflicts amongst objectives.

(2) Modelling the Spatial System

In order to model problems of spatial grouping in architecture, we must develop some satisfactory definition of the basic spatial components of the built environment, and find a suitable method for describing relevant relationships between these components.

When the Beatles sang "Let's Do It In The Road" they brought into focus the distinction which we draw in our lives between "locational" and "non-locational" activities. Some activities can take place anywhere, whilst some require a specific, definable physical space or facility, with various special properties. Often, an activity will be locational because it requires a more or less immovable piece of hardware (e.g. taking a bath), but as the Beatles knew well, the reasons are often much more subtle, and depend on particular cultural assumptions. We are greatly concerned, in architecture, with identifying those activities which are locational, and building special places for them. Indeed, without the phenomenon of locational activity to consider, architecture would be concerned with little more than the simple provision of shelter.

So, we might consider taking locational activities as the components of our system. It could be objected though, that the properties "locational" and "non-locational" are the extreme points of a scale of possibilities, rather than an either-or choice. This is true of course, but the dichotomy is still useful because it is part of the skill and sensitivity of a good designer to be able to decide, in a given situation, on just which activities will require the making of special places, and which will not. There is never any rigorous set of rules for making these decisions. We must commence building our model, then, at a point where the set of locational activities has already been defined.

The definition of components is still incomplete though, because we have not as yet considered the question of level of aggregation. "Activities" can be endlessly subdivided into component activities, or aggregated into more general activities, so we must select an appropriate scale at which to work. This brings us to the concept of "room". An aggregate of locational activities implies an actual, physical aggregate of built spaces. Thus a "kitchen" is a space and set of facilities to accommodate a set of closely interrelated locational activities. We might accept this object as an indivisible component of our system, considering it to be an aggregate of appropriate size, and identify it equally well either with a description of the locational activities, or the name "kitchen". Acceptance of such an entity obviously implies the acceptance of a whole set of spatial relationships which may or may not be valid. If we have a lot of time, money, information, and patience, we can afford to work with a very fine-grained model. If the economic constraints are more severe, then we must work with larger units, and accept more conventional assumptions.

The components of our system can now be defined as "activity units", arbitrarily sized places made with specific properties to accommodate specific activities, identified either by the name of the place or by a description of the activities. "Activity Units", in a specific situation, either may or may not correspond to "rooms" as they are conventionally defined. (1)

Having defined a set of activity units, the next step in modelling a system of spatially related activities is to make some statements of spatial relationship between them in a way that is rigorous enough to be useful. The simplest and most obvious way of doing this is to set up a square matrix, with activity units ranged along both axes. Each cell can be used to represent a potential spatial relation between a pair of activity units. In each, we can enter some information defining the character of that relation (or non-relation). We could for instance, collect and enter measures or estimates of the cost of flow of people or materials between the various activity units. Such studies have often been carried out (2), but circulation cost data alone is insufficient for our purposes, for we want to simultaneously consider many different reasons for spatial aggregation, not simply minimization of circulation costs.

Another approach would be to enter "measures of relationship" made on some appropriate kind of scale, based on any relevant data or criteria whatsoever. We have a wide variety of different types of scales open to us (3), ranging in strength from simple binary choices of "related" or "not related" to a scale of real numbers. The problem with the weaker scales is that they form very insensitive coding devices, whilst conversely, with the stronger scales, it becomes increasingly difficult to define precisely enough what we mean by "strength of relationship", or to frame exact rules for computing its value, so that we are left with no logical way of making decisions.

A further disadvantage of the square matrix is that there may be a multitude of different reasons for relating spaces, but it does not allow us to record date concerning the particular bases of each decision.

Fortunately we can overcome these difficulties, to a large extent, by use of a rectangular matrix, with the activity units arranged along the vertical axis, and a string of "locational attributes" along the horizontal. Each matrix cell is the intersection of an activity unit with a locational attribute. These locational attributes are imperative statements about the locational properties of activity units, very similar in form to the list of "requirements" found in traditional building programs, for example, "Must be located to be part of activity cycle X", "Must be closely related to facility Y", "Must be on the south wall", "Must have street-level entrance", and so on. "Must have green walls", on the other hand, would not normally be considered a locational attribute. However, the designer may include any consideration at all which he wishes to influence the location of activity units. In each matrix cell, we can enter a decision as to whether that particular activity unit should or should not, in the built environment that we are considering, possess that particular locational attribute. The conjunction of all positive entries in the matrix row now becomes a statement defining all the required locational properties of the corresponding activity unit. From data recorded in this format (through a series of simple binary choices) we are able, as we shall see, to generate useful descriptions of the strength and character of the spatial interrelationships amongst activity units.

Obviously, the selection of our appropriate string of locational attributes is a crucial step in coding data in this fashion. Very precise expression, and a careful thinking through of the implications of each statement are required. A definite coding problem is still with us... there are relations too subtle to be captured in this format, and it is easy to be trapped by ambiguities, but we can do amazingly well, and I have not found a better way. The following working rules have proved to be useful guides for making good locational attribute strings:

1. Each locational attribute should be in some sense elemental. This can be tested by asking, first, whether it can be usefully subdivided into two or more simpler locational attributes, and second, if the making of an interaction decision contributes more than one piece of data.
2. Two locational attributes which will have identical interaction profiles should not

A TYPICAL SET OF DECISIONS FOR A SMALL SUBURBAN HOUSE

ACTIVITY UNITS		LOCATIONAL ATTRIBUTES 1	2	3	4	5	6	7	8	9	10
1	Bathroom 1 (related to bedrooms)			●					●		
2	Bathroom 2 (related to living areas		●	●				●			
3	Breakfast/informal eating	●			●	●		●			
4	Carport	●	●				●	●			
5	Child bedroom				●	●			●		●
6	Child study								●		●
7	Entry area		●				●	●			
8	Family room		●			●		●			
9	Formal dining	●	●					●			
10	Garbage disposal	●		●			●	●			
11	General storage space										
12	Guest bedroom				●				●		
13	Informal entry	●	●		●	●	●	●			
14	Kitchen	●		●	●	●		●			
15	Laundry			●		●		●			
16	Library/study		●					●			
17	Outdoor eating	●	●			●		●			
18	Parent bedroom				●				●	●	
19	Parent private courtyard								●	●	
20	Small child outdoor play				●	●		●			

KEY TO ATTRIBUTES

1 Part of group linked by food preparation/serving/disposal activities
2 Part of group linked by visitor/guest reception/entertainment activities
3 Part of group around main plumbing/sewerage/exhaust vent access point
4 Face east for morning sunlight
5 Part of area supervisable by mother whilst working
6 Oriented towards street
7 Part of activity oriented zone
8 Part of quiet/retire oriented zone
9 Parents' private territory
10 Child's private territory

Figure 3
A Typical Set of Decisions for a Small Suburban House

both be included. One or the other should be selected.
3. Locational attributes which will not serve to distinguish between the locations of different activity units should not be included.

It could be argued that we should make weighted, rather than binary decisions, since some locational attributes will clearly be more important than others. However, the binary nature of the data does not derive from an assumption of equal importance of locational attributes, but from the consideration that if any one locational attribute of an activity unit is unfulfilled, then we must regard the location of that activity unit as unsatisfactory. This in turn derives from the assumption that we do not consider degrees of possession of a locational attribute. A built space either is regarded as having a locational attribute, or not. Some locational attributes can clearly only be of this nature, e.g.,"Must be on the south wall". Others, like "Must be closely related to facility X", can be dealt with by use of the notion of "simple pay-off function"... proximities up to a certain threshold level of distance are considered to be satisfactory, whilst anything beyond is not (4).

Typical activity units, locational attributes, and decisions for a small problem are shown in figure 3.

(3) The Discovery of Groupings

Spatial groups, or clusters are defined by the possession of common locational attributes. If we scan down any column of the matrix in figure 3, we can see that the "yes" decisions in that column define a spatially related group of activity units. From column 4, for instance, we see that breakfast/ informal eating, child's bedroom, guest bedroom, informal entry, kitchen, parents' bedroom, and small children's outdoor play area form together a spatially related group by virtue of possession of the locational attribute "face east for morning sunlight". By taking numbers of columns together, it is possible to form clusters defined by possession of two or more common locational attributes. It is obvious that there are many different ways of grouping activity units together according to common locational attributes. The question is, "Which of the many logically possible grouping strategies will give results that are most useful for design purposes?"

There are two ways of describing the locational attributes of a cluster. We can describe each locational attribute of each activity unit, or we can generalize... describing only those locational attributes common to all members. Unless all members of the cluster have identical locational attributes, we "lose" some data in making this generalized description. Thus the data content of a cluster may be defined as:

$$D = \frac{(n \times q)}{p} \times 100\%$$

n = number of activity units in the cluster
q = number of common locational attributes
p = total number of locational attributes possessed by members of the cluster.

The more "common", and the fewer "exceptional" locational attributes, the higher the data content. It can be seen that clusters having low data content have comparatively little spatial meaning; their members will be more "different" than "alike" in their locational attributes. On the other hand, clusters of high data content imply coherent spatial groupings. We are interested then, in a grouping strategy which yields clusters having the highest possible data content.

Now, in forming clusters, we are transforming our initial representation of our locational objectives, which was useless for design purposes, into another representation... which is considerably more useful because it is simpler. The simplicity of our representation may be defined as:

$$S = \frac{(a - b)}{(a - 1)} \times 100\%$$

a = total number of activity units
b = total number of clusters existing (including one-member clusters)

If no clustering takes place, simplicity is zero, and if all activity units are grouped into one cluster, simplicity is 100%. Other things being equal, the greater the simplicity, the more comprehensible and useful the representation.

But unfortunately, due to the diversity of locational attributes of the various activity units, we can normally only gain in simplicity at the cost of reducing the data content of the clusters. There are two ways of dealing with this. Firstly, we could simply define either the range of sizes or the range of data contents which were of interest to us. The more satisfactory alternative is to generate a hierarchy of clusters in which, as we move up the levels, the clusters are fewer and contain more members, representation is consequently more economical, but more of the richness and complexity in our initial description of the data is lost. At the lowest level, 100% of the initial data is retained, but no simplification is achieved... each cluster consists simply of one activity unit. At the highest level, the simplest possible representation, one big cluster of all the activity units, is achieved at the cost of disregarding most, if not all, of our initial data. If we adopt this approach to forming clusters, the technical problem is to find the best strategy that we can for gradually trading off loss in data against gain in simplicity, so that clusters at any level in the hierarchy are in accord with the principle of maximum possible data content...that is, have as many common, and as few exceptional locational attributes as possible.

The essential operation performed by CLUMP 3 is to generate such a hierarchy of clusters. I have described the details of the algorithm elsewhere (5). The principle of trading off data loss and simplicity gain is illustrated in figure 4. This shows a rather typical pattern for real data.

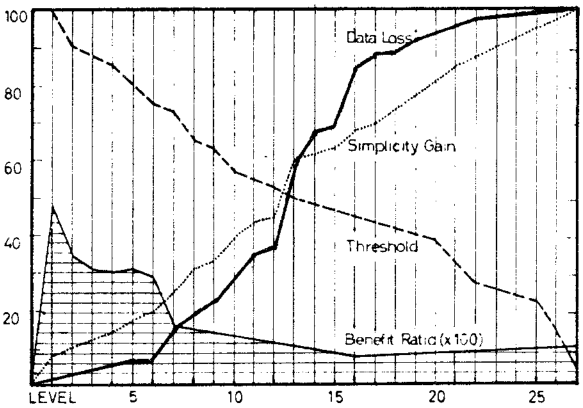

Figure 4
Data Loss and Simplicity Gain

Initially, a number of well-defined, distinctly separate clusters are discovered. Considerable simplification is achieved at the cost of comparatively little data. But it becomes progressively more difficult to achieve further simplification without heavy losses of data. It should be noted though, that even at high levels in the hierarchy, where most clusters are fairly meaningless (and the overall data content is quite low), there may still exist some individual clusters with high data content.

Output from CLUMP 3 is in the form of verbal descriptions of each cluster discovered, in a format designed to be easily comprehensible to a non-specialist user. Figure 5 shows a typical piece of output... a cluster discovered at hierarchy level 2 in the data in figure 3. In addition to the lists of cluster members and common attributes, various numerical measures of the clusters' internal structure and reliability are given. The meaning and importance of these measures is discussed in the following section.

(4) The Structure, Meaning, and Reliability of Clusters Discovered by CLUMP 3

Clusters are generated through a process of "linking together" activity units which have "similar" strings of activity units. The numerical value of similarity between any two activity units is computed as:

$$R_{AB} = \frac{2c}{a + b}$$

c = number of pairs of matched locational attributes
a = number of locational attributes of activity unit A
b = number of locational attributes of activity unit B

At low levels in the hierarchy, the minimum value of R to define a link is high, links are consequently few, and clusters small As we move up the hierarchy, more links form, and clusters grow larger.

Any cluster, at any level, may be drawn as a graph, in which nodes represent activity units, and every activity unit is connected, either directly or indirectly, to every other. Figure 6 shows two such clusters, each containing four activity units, but structured rather differently. We can see intuitively that their meaning may be rather different, as a consequence.

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CLUSTER  NUMBER    2. 1

MEMBERS                                   LINKS              CONNECTED TO
    3 BREAKFAST/INFORMAL EAT                2                  14, 13
   13 INFORMAL ENTRY                        1                   3,
   14 KITCHEN                               1                   3,

ATTRIBUTE LIST  (ATTRIBUTES POSSESSED BY 100.000 PERCENT OF MEMBERS)

PART OF GROUP LINKED BY FOOD PREPARATION/SERVING/DISPOSAL ACTIVITIES
FACE EAST FOR MORNING SUNLIGHT
PART OF AREA SUPERVISABLE BY MOTHER WHILST WORKING
PART OF ACTIVITY-ORIENTED ZONE

PARAMETERS...IAT   15,ASF   3,APR   80.000,LIN   2,PLN   3,ALN   2,
PCN   66.667,PRD    0.0 ,MOA   3
NEXT PAIRS TO JOIN WILL BE...
( 14, 15)  ( 3, 20)  ( 3, 17)  (                          NEW CLUSTER

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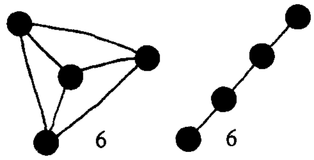
Figure 5
Typical Cluster Description Output by CLUMP 3

Figure 6
Comparison of Cluster Structures



Potential Links	6	6
Actual Links	6	3
Connectivity	100%	50%
Connection Redundancy	100%	0%
Data Content	Probably High	Probably Low
Stability	Probably High	Probably Low

Linearly structured clusters generally have a rather low data content, and tend to be quite sensitive to small alterations in the input data, whereas tightly interconnected clusters have higher data contents, and tend to be much more robust.

In order to assist in the interpretation of clusters, CLUMP 3 prints out a considerable amount of description of the data content and structure of each cluster discovered. It is not always necessary to take account of this, when interpreting output, but it can be of considerable assistance in some situations. The following data is printed out:

IAT ... Number of locational attributes possessed by cluster members.
ASF ... Number of attribute statements sacrificed to form the cluster.
APR ... Data content.
LIN ... Level of hierarchy at which cluster initially formed.
PLN ... Number of potential links in a cluster of this size.
ALN ... Number of links actually formed.
PCN ... Connectivity, $\frac{\text{ALN}}{\text{PLN}} \times 100\%$
PRD ... Connection redundancy $\frac{\text{ALN}-(n-1)}{\text{PLN}-(n-1)} \times 100\%$
MOA ... A measure of the isolation of the cluster from the next most closely related activity unit outside the cluster, $(R_1 - R_2)$, where R_1 is the threshold value of the relationship coefficient at which the cluster formed, and R_2 is the threshold value at which the next new member joins.

A table of all links formed is also given.

As we reach the higher levels in the hierarchy, clusters begin to appear in which the data content, as we have defined it, is zero... that is, there are no locational attributes common to all members. Such clusters are no longer "classes" in the Aristotelean sense (classes defined by sets of characters, the members of which are severally necessary and jointly sufficient, or alternatively severally sufficient and at least one necessary), but they are in the sense that Wittgenstein used when he spoke of classes defined by a kind of "family resemblance". We can still describe the properties of the class quite satisfactorily in statistical terms... x% of members possess attribute A, y% possess attribute B, etc. (6). Where clusters have zero data content, CLUMP 3 prints out a brief statistical description of this type.

(5) Use in the Design Process

The technique which has been described enables a designer to see the spatial implications of adopting a particular set of locational objectives, and test the effects of making alterations in these objectives. Its aim is to facilitate a better understanding of the structure of a spatial planning problem, and the relations between possible alternative solutions, rather than to generate some allegedly optimum configuration. Over the past year, it has been used for this purpose, with considerable success, in case studies carried out at Yale, U.C.L.A., and Rice Universities. It has rarely produced many surprises for competent, experienced building planners, but there is no reason to expect that it should... any more than we would expect the results of structural computations to surprise a good structural engineer.

In its present form, it is not really an economical proposition in most design situations. It is generally far quicker and cheaper to rely on known prototypes and past experience, since input to CLUMP 3 is fairly slow and cumbersome, and output is only in the form of the most rudimentary spatial description... verbal descriptions of clusters. However, it is certainly possible both to make input very much quicker and simpler, and to write heuristic routines to produce output in the form of graphic displays of spatial configurations. Work is now proceeding on both these aspects, and I expect this to result in the development of a very practical working technique.

NOTES

(1) For alternative approaches to this problem, see:
   (a) Alexander, Christopher, and Poyner, Barry, The Atoms of Environmental Structure, Center for Planning and Development Research, Berkeley, 1966.
   (b) Haviland, David S., The Activity Space: A Least Common Denominator for Architectural Programming. Paper presented at the 1967 A.I.A. Architect-Researchers' Conference.

(2) For an early, and excellent, formulation of spatial planning problems in these terms, see: Koopmans, T.C., and Beckmann, M., Assignment Problems and the Location of Economic Activities, in Econometrica, Volume 25, Number 1, January 1957.

(3) Coombs, C. H, Raiffa, H. and Thrall, R.M. Some Views on Mathematical Models and Measurement Theory. Chapter II, Decision Process. Wiley, N.Y. 1954. Edited by Coombs, C.H., Thrall, R.M., and Davis, R.L.

(4) Simon, Herbert, Models of Man, pages 246-248

(5) Mitchell, William J., Computer-Aided Spatial Synthesis, in Proceedings of the Association for Computing Machinery Symposium on the Application of Computers to Urban Problems, New York, August 1970

(6) Hull, David L , The Effect of Essentialism on Taxonomy, Part I, The British Journal for the Philosophy of Science, Volume 15, pages 321-326.