Problem Structuring in Architectural Design

by

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Abstract

The purpose of our research is to describe in operational terms the process of problem structuring while solving spatial problems in architectural design. The designer's behavior is described in terms of *Problem Structuring,* when problem parameters are established or transformed, and *Problem Solving,* when these parameters are satisfied in a design solution. As opposed to problem solving, structuring of problems is a little studied but crucial aspect of complex tasks such as design.

Our work is based on observations derived from verbal protocol studies. To consider various levels of skill, our subjects range from professional architects to novice designers. Subjects are given space planning problems which require them to develop solutions in accordance with individually established constraints and criteria, the majority of which are not explicitly stated in the problem description. Based on the results of the protocol analysis, a framework is developed, which explains how information processing characteristics, problem structure and different levels of expertise interact to influence the designer's behavior.

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1. Background

The design process has been described as a 'problem solving activity within the framework of an information processing model' [Eastman 70]. The process of design is essentially a series of transformations converting an 'ill-structured' problem into 'well-structured' component tasks [Simon 73]. Our research focusses on understanding this process of conversion in terms of two basic functions: Problem Structuring, when problem parameters are established or transformed, and Problem Solving, when these parameters are satisfied leading to a possible design solution. In other words, the process of structuring a design problem corresponds to creating new versions of the initial ill-structured problem which are either well-structured or are made up of well-structured parts.

2. Approach

2.1. The Problem

Our aim is to develop a framework which would be based on the formalization of the design process and would represent the behavior of the designer during the development of the design solution with particular emphasis on problem structuring. The approach comprises of:

1. *Collection of an accurate and detailed protocol.* The protocol shows the verbal and graphic information expressed by a subject during the design process.

2. *Analysis of the protocol.* This leads to the identification of complex operations used in the generation of designs. The organization of this information demonstrates distinct stages of the design process and the gradual transformation of an ill-structured problem into a well-structured form.

3. *Illustration of distinctions between experts and novices.* The ability to retrieve structured information from memory in conjunction with external cues and the selective application of this information to the solution of the problem in a 'goal-directed way' [Akin 79], is the mark of the expert. For the purpose of our research, the novice is defined as not being familiar with any particular design methodology, relying on his limited domain knowledge and his exposure to environments similar to that described in the problem statement. A method of explaining the expert's approach to design is to contrast it against that of the novice.

4. *Development of a paradigm.* This paradigm describes the design process in terms of Problem Structuring and Problem Solving. From our analysis of the protocols, a formal paradigm representing the designer's behavior during the establishment and transformation of parameters^ well as during the actual generation of solutions is developed.

2.2. Subjects

Our subjects include professional architects, students and 'non-architects[1], Arch. ..cts are faculty members of the Department of Architecture at Carnegie-Mellon University. Non-architects are faculty from other departments which include the School of Urban and Public Affairs, Industrial Administration, Electrical and Chemical Engineering. An intermediate level of problem solving is hypothesized to exist among the students, who are seniors or recent graduates of the Department of Architecture. Each test group consists of six randomly selected individuals.

2.3. Experimental Procedure

Subjects were asked to design a layout for a small engineering firm. They were given the office site with clearly marked positions of existing walls, window, doors and radiators. Models of the site and furniture were built from cardboard, with numbers on the furniture pieces matching their description on the instruction sheet (1: Chief Engineer, 2: Staff Engineer, 3: Secretary, 4:Conference).

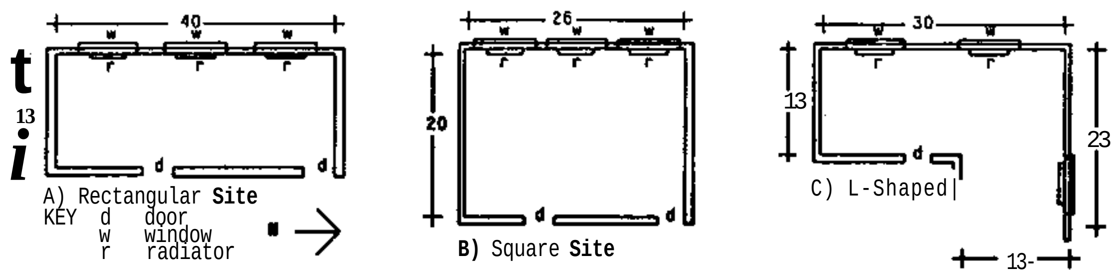

Figure 2-1: Office Sites

To minimize the effects of physical constraints imposed by the site on the design of the final layout, three different office sites (rectangle, square and L-shape) are used (Figure 2-1). To maintain the same level of difficulty in the generation of layouts, the overall area of the sites and the size and number of windows, doors and radiators are the same for all three sites. The entire experiment was video-taped and later transcribed on paper.

3. Representation

A *representation* is a means for organizing information and developing operators suited to that organization [Eastman 79]. Our subjects represented the office furniture as belonging to a definite object hierarchy. There 4lso exists a functional hierarchy which is based on the distribution of furniture to satisfy the functional requirements of the office.

3.1. Object Hierarchy

A hierarchy is established among the pieces of furniture, referred to as the object hierarchy. This hierarchy is derived from the problem specification as well from the prior relationships between objects established through the subjects' knowledge of the problem domain.

Certain objects are recognized as belonging to a particular function as well as dictating the arrangement of surrounding furniture. We refer to these objects as *primary* objects. Other objects necessary for the satisfaction of the functional requirements of a space which depend for their location on the prior allocation of the primary furniture, are referred to as *secondary* objects. In the following example from protocol A5[1], the Secretarial desk which is the primary object dictates the assignment of the typewriter desk and chair which constitute the secondary furniture.

```
A5(primary)   19[2]: That is the Secretarial desk.
(secondary)   20: Secretary would have the typewriter table beside the desk.Typing return.
              21: Swivel chair. (placing chair with Secretary).
```

Figure 3-1: Primary and Secondary Objects

A third category of furniture observed in the object hierarchy is furniture which may be made accessible to multiple functions. Objects which do not belong exclusively to any particular function are referred to as *shared* objects.

3.2. Functional Hierarchy

When furniture is grouped according to the requirements of a particular function, a *design unit* is created. A design unit is at once an area, a volume, as well as a functional concept. It is often represented simply by the primary furniture but may also include the secondary and shared furniture. For example, in the following excerpt A5 is seen to group all the furniture typically used by the Chief Engineer in order to be able to visualize the spatial requirements of the Chief Engineer's unit.

```
A5   8: I think, first I want to get a visual idea of the groups..functional groups.
     9: So I am going to look at the Chief Engineer - has a desk.
    10: He also has, certainly, atleast a chair and probably a bookcase, maybe.
    11: He'd have the bookcase, either on his side or behind his seated position at the desk.
```

Figure 3-2: Formation of a Design Unit

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[1] All examples included in this paper are extracted from protocols of individual subjects from all three test groups. Subjects are identified by A:Architects, N:Non-Architects, S:Students

[2] Index numbers show the sequence in which these sentences appear in the protocol

A *spatial unit* refers to an area created within the main site by the erection of partitions or the grouping of specific pieces of furniture. Like the design unit, the spatial unit may also be conceived as an area, a volume as well as accommodating a function.

3.3. Relationships

We refer to the assignment of attributes to design or spatial units and the establishment of links between units as *relationships.* Relationships seem to be either developed from the problem specifications or from the individual subject's domain knowledge. They represent several different sets of constraints for the design problem and they are defined as follows.

- *Generic* relationships which deal with the fundamental grouping of design elements, may be as simple as the linking of a desk with its chair and as complex as the alignment of internal partition walls with exterior openings.

  A5 123: Dont want to build a wall in front of the windows.

- *Proximity* or *adjacency* relationships usually define adjacency requirements between staff members as well as their need for specific objects of furniture.

  AI 32: (Secretary) is central to all the spaces. She can act as a receptionist. She can act as a resource point.

- *Access* relationships establish means of access between staff members and describe the interaction between members of the office.

  AI 18: Secretary needs to be fairly accessible to everybody.

- *Spatial* relationships determine the spatial requirements of a particular function.

  N5 55: Conference needs to be 10 by 16

- *Functional* relationships deal with requirements related to heating, lighting, privacy and orientation.

  AI 38: Chief Engineer is most remote from the public.

- *Aesthetic* relationships reflect subjects' expression of choices *vis a vis* subjective judgements.

  AI 56: Dont like looking at the wall.
  58: Nicer to face people than to face their backs.

There seems to exist a network of relationships on which the design evolution is based. Whenever specific and externally defined relationships prove inadequate, subjects draw upon personal expertise to infer or generate missing information. Both problem dependent and domain knowledge dependent relationships may be finally viewed in terms of topological and geometric attributes of objects. [Akin 86a]

4. The Paradigm

The analysis of the protocol enables us to develop a framework which is based on the formalization of the design process. It is characterized by three basic operations: (a) problem initialization and the establishment of parameters including constraints and criteria, (b) generation of possible solutions from established constraints and testing them for satisfaction of established criteria, and finally, (c) the restructuring (if necessary) of the problem.

From our analysis of the protocols and our interpretation of the behavior of subjects, a formal paradigm representing the design process in terms of Problem Structuring and Problem Solving is developed, as illustrated in Figure 4-1. The flow of information between these components as the designer attempts to solve the design problem is discussed as the control structure of the model, below.

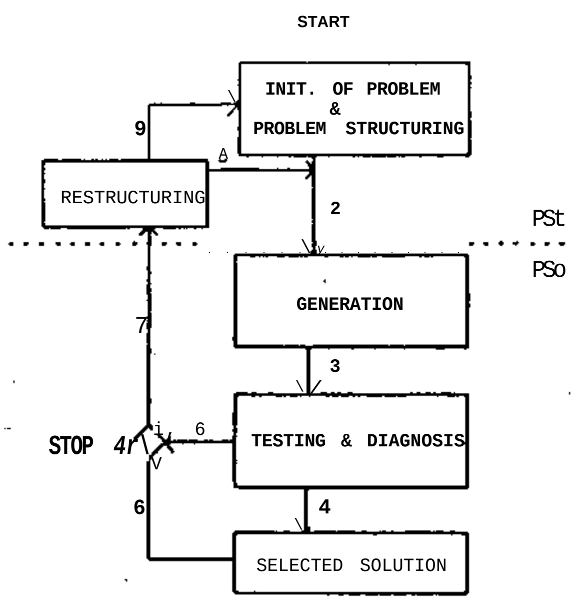


Figure 4-1: The Control Structure

4.1. The Control Structure

The control structure directs the solution generation activity based on the problem parameters established during Problem Structuring. It determines the flow of control between the various components of the design process as the designer seeks a satisfactory solution to the design problem.

At the start of the design process (Figure **4-1, link-1**), the designer must develop an appropriate **formulation of the problem. Since the problem statement provides only limited information, the designer must establish criteria to be met and relationships to be satisfied in order to guide the generation and testing process (Figure 4-1, link-2). The satisfaction of these relationships leads the designer into the next phase when the current layout is evaluated (Figure 4-1, link-3). If the relationships are satisfied, potentially this may bring about the complete solution of the problem (Figure 4-1, links-4&5). Failure to satisfy current relationships leads to the restructuring of the problem (Figure 4-1, link-6&7). This involves the modification of previously established relationships** as well as the relaxation of criteria for testing and the design process is repeated (Figure 4-1, link-8). If the criteria is satisfied and all design units are accommodated, the current layout is included in the set of acceptable layouts from which the final layout is selected (Figure 4-1, link-4). However, available time or a willingness to try out a new scheme in an attempt to improve on the current layout, may prompt the subject to **attempt** to seek yet another solution and thus repeat the design process (Figure **4-1, link-9).**

4.2. Problem Initialization and Structuring

In this phase, problem parameters are established in the form of relationships between design units (Secretary, Chief Engineer, Staff Engineers, Conference) and attributes associated with particular units. We refer to these relationships as *predicates* and will elaborate them in the next section.

From the analysis of the protocols, we find that subjects exhibit two distinct approaches to problem structuring which directly affect the generation of design layouts. Subjects are either guided by the generic, functional or programmatic constraints manifest in the problem solution or they establish specific zonal restrictions to the given site known as structuring according to *Pattern* and structuring according to *Functional Zoning* respectively.

Furthermore, subjects use *behavioral scenarios* in the case of both forms of problem structuring which will be discussed in detail in the next sections.

4.2.1. Predicates

Throughout all of the protocols we studied, subjects stated desired relationships between design units and design elements. We call these relationships, *predicates.* All predicates conform to the general form "if A then B", where two elements (A,B) are bounded by a specific relationship (if-then) either desired or verified in a solution [Akin 86a]. Predicates are derived from the problem specification as well as from the subjects domain knowledge. Predicates can be expressed as either generative, based on which constraints can be used in generating design layouts, or as evaluative, based on which criteria can be applied in evaluating current layouts. They essentially represent the knowledge used to generate and test partial solutions during design.

The following example illustrates how the predicates may be used for both generation and testing of layouts. Subject S1 first establishes a relationship between each Engineer (or worker, as he states) and an exterior window. Furthermore he establishes that the Conference unit does not need a window and allows it to be placed along the inner wall farthest from the window. Since these predicates dictate the assigment of the design units they fall in the category of generative predicates or constraints.

```
SI  (generate)  01: Begin with the classic pattern.  Give the window to the worker.
                09: Place the Conference on this side.  They don't really need the window,
    (test)      20: Windows don't partition the space in proportions to the workers stature.
                21: I give too much space for the Staff Engineers,
    (generate)  22: So, I move (the partition) here___
```

The predicates used for evaluation or criteria, determine the acceptability of the current layout, in this case, the appropriate size of each Engineer's room. The subject feels that the Chief Engineer is entitled to a larger room than the two Staff Engineers and this leads to a natural adjustment of the existing layout. Thus the test criteria is used as the basis for the generation of the next layout by the subject. This requires the translation of the criteria into a constraint which is simply accommodated in the basic predicate representation as: "if A then B => if A then make B".

Subjects used two different ways of organizing the predicates while developing solutions to the problem. Some sought larger constraints, ie, behavioral scenarios to organize the predicates to be satisfied, while others tried to develop solutions by sequentially satisfying individually established predicates. Both approaches to developing solutions are apparent in problem Structuring by Pattern as well as Structuring by Zoning.

4.2.2. Behavioral Scenarios

Behavioral scenarios are constructs which represent behavioral patterns of people in spatial environments. They are derived from our daily experiences and provide useful abstractions for capturing and expressing iarge chunks of functional knowledge [Akin 86a]. The ability to encapsulate and utilize broad features of the design situation in a behavioral scenario, typically distinguishes an expert from a novice. Once a scenario is established, additional relationships are required - both limiting the generation of possible solutions and increasing the number of tests to which the solution must be subjected thus restricting the search. In the protocols, we found three kinds of scenarios: *organizational, functional and formal scenarios.*

Organizational scenarios are developed from the existing staff structure of the office and the manner in which it functions. Factors which influence the organization of layouts include seniority among staff members, the nature of the business and whether the office functions in a participatorial setting or in a strict hierarchial setting. The following example illustrates an organizational scenario visualized by A2, in which all staff members are considered equal and paticipate freely in the office's decision-making process.

```
A2   06: I live in an open space.
     07: No partitions in my office.
     08: With no distinctions between the owner of the practice and the people who work for it.
```

Functional scenarios are developed in accordance with the functional requirements of the office environment. In such scenarios, subjects are primarily concerned with the circulation of individuals within the office. This is demonstrated in the following example in which A3 segregates the circulation of clients within the office from that of trades people.

```
A3   34: This entrance is better for a kind of branching. You are received and you either have
         traffic with the principal or if you are a salesman, you go this way.
```

Formal scenarios exhibit a clear territorial demarcation within the site by individual or groups of staff members. Issues of privacy and lighting dominate and strongly influence the establishment of territorial space. In the following example, A4 conceives the office as comprising of both a private and a public area:

```
A4   10: I'll start from the entrance.
     11: And take a Secretary desk which is #3...
     12: I can obviously put 1t near either of these 2 doors.
     13: If I put it near the middle door, I can then bisect .. private from public space...
         which 1s a good Idea. Just one starting strategy.
```

4.2.3. Structuring according to Pattern

In problem structuring according to pattern, subjects first identify relevant patterns, which **describe the grouping and assignment of furniture in the layout. These patterns arise from three distinct kinds of relationships:** *generic, domain specific and programmatic.*

Generic patterns originate in layouts when generic relationships (Section 3.3) dominate the fundamental grouping of units. The recognition of generic pattern or structure is most apparent in the group of architects or 'experts'. Since domain knowledge is essential to generic-pattern structuring, it is **not as dominant in the layouts generated by the novices who are naturally limited by** their inexperience. Though the architects are seen to be consistent in maintaining generic relationships, there is no case when these relationships solely governed the generation of layouts. However, we did find an example illustrating the domination of generic relationships in the design process among the student subjects (Figure 4-2).

The subject S2 realizes that three offices, each having a window, need to be provided **for the Engineers. In addition to this, a Conference room and Reception area also need to be accommodated. So she proceeds to divide the entire site into five spatial units of acceptable size. We see that such generic relationships as** *partitions not intersecting windows or* ***doors*** **and** ***allowances for door clearances,*** **are strictly maintained.**

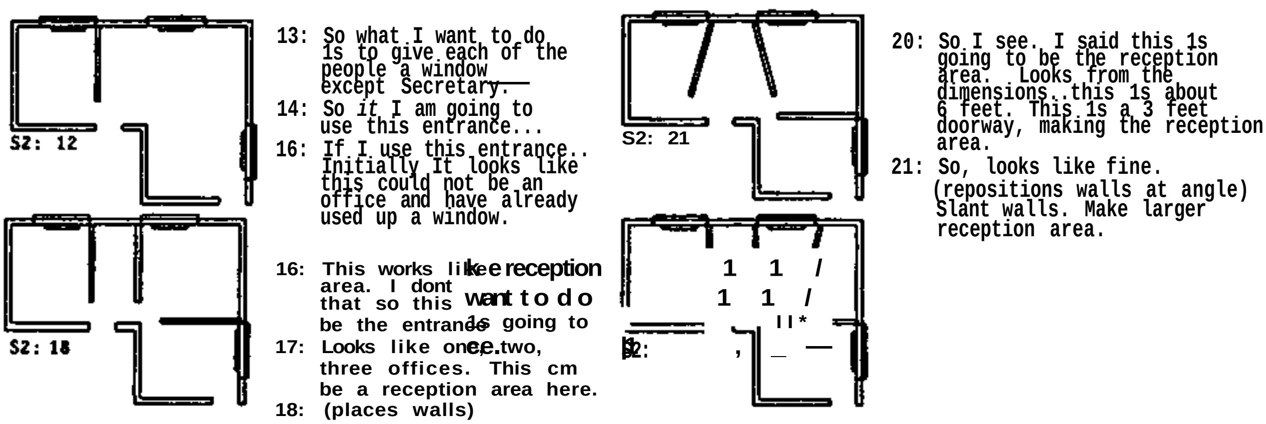
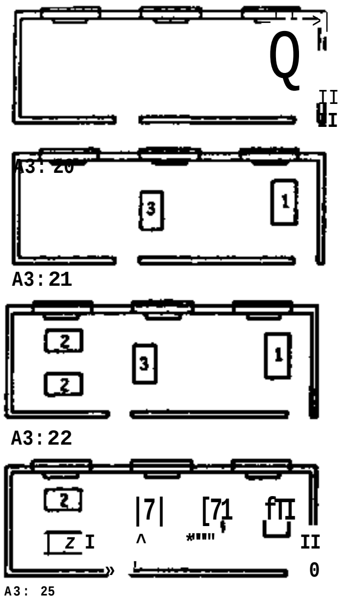


Figure 4-2: Generic Patterns

Domain specific patterns deal with relationships between design elements such as those describing access and functional requirements. Domain specific patterns may be gleaned from the problem description as well as from the subjects' experience. This kind of problem structuring was

apparent in all three test groups. Several non-architects seem to rely mainly on domain-specific patterns to guide their search for a satisfactory solution. This is probably due to the fact that the development of behavioral scenarios is almost entirely absent among non-architects and they rely on the consideration of functional requirements among individual design units rather than the functioning of the office space as a whole. This gives rise to patterns of domain specific relationships governing the layouts.

In the following example (Figure 4-3), we see that the subject A3 considers only the set of relationships which affect the Chief Engineer leading to the assignment of the Chief Engineer's desk. Next, the Secretarial unit is considered, maintaining its link with the central door. Similar reasoning guides the allocation of Staff Engineers and Conference units. This consideration of functional requirements of individual units leading to their subsequent allocation in the site is characteristic of domain specific layouts.



17: Ok. Well.. I will have to say this that because of the arrangement of the entrances, its possible to set the big Chief here. And use this door as a a private access.
18: And then this door would separate the Secretary, who probably should be in the middle..from the 2 horses who do the bidding of the big Chief.
19: So, I will try that arrangement first. See how it works.
20: So, let's see. Is this guy right-handed or left-handed? Ooesn't matter?
21: Secretary Is #3. (places Secretary)
22: (places Staff Engineers). So I use the same...
23: Vhats #8? Oh.. Conference..Oh boy..
24: Well, maybe..maybe.. the conference could happen In the big Chief's office.
25: (places Conference)
26: I gutss..my Idea would be that..a screen..and this Secretary...
27: Conference table could be used by the 2 guys who might meet with the clients when this one 1s away.

Figure 4-3: Domain Specific Patterns

Programmatic or problem-specific patterns are derived from relationships included in the problem statement. The placement of doors and windows, the orientation of the site and the location of radiators all belong to this category. Naturally this influences the problem structuring of every subject and has to be considered at every stage of the design solution.

The generation of the following layout (Figure 4-4), is a result of programmatic structuring because it is clear that the physical constraints of the site play a dominant role in the assignment of the individual design units. The site related constraints are derived from the problem statement and the working material provided to the subject.

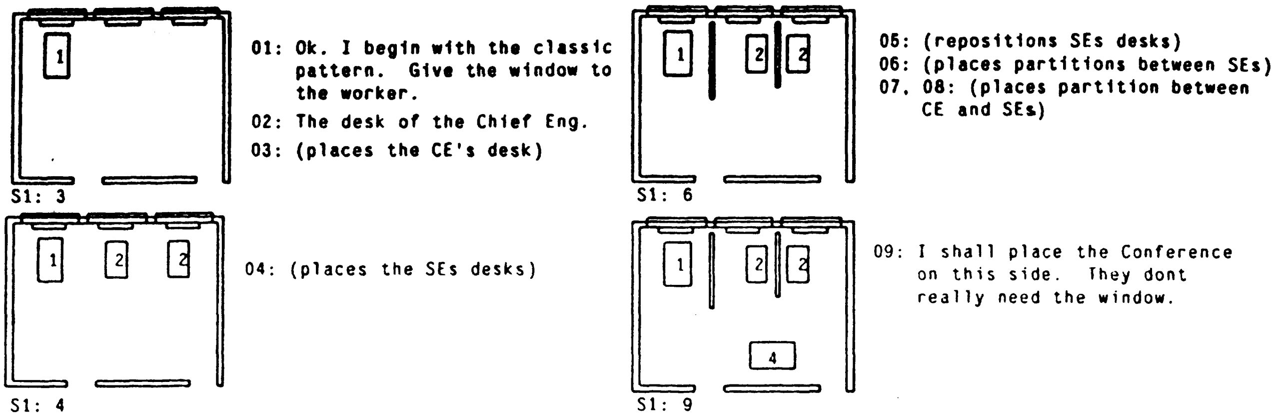


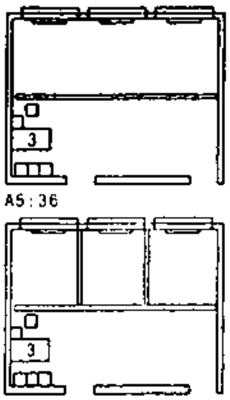
Figure 4-4: Programmatic Patterns

4.2.4. Structuring according to Functional Zoning

In structuring by functional zoning, there is a definite awareness of the size of each design unit and the objects which belong to each unit. In order to determine the size of units, the recognition of the hierarchical relationships between primary and secondary objects is essential (Figure 3-1). Following such an analysis as shown in Figure 3-2, subjects clustered objects according to function - primary objects are linked to their functional unit and secondary objects are placed according to the selected primary objects. This results in the creation of design units of pre-determined size.

Before the design units are assigned to their individual locations, the entire site is divided into zones (Figure 4-5). The number of zones depends on the number of functions to be accomodated and the division of zones is constrained by the position of windows and doors. Design units are accomodated in their respective zones on the basis of requiring adjacency to window or outer door. Adjacency and access requirements between design units, along with other constraints, are tested only after the initial layout is complete.

In Figure 4-5, A5 divides the office site into two principal zones - one along the wall in which the windows are located and the other along the inner wall in which the doors are located. Then he decides that the Engineers are to be placed in the 'window-zone' and the Conference and Reception areas are to placed in the 'inner-zone". Given that five functions (Secretary, Chief Engineer, Staff Engineer 1 and 2, Conference) need to be accommodated, the zones are further divided into five spatial units. The design units of each function are then placed, ignoring for the present the relationships between units. The subject then considers the interrelationships and realizes that the Secretary and Chief Engineer need to be adjacent to each other as well as the Staff Engineers require to work together. The generation of the next layout is based on the satisfaction of these relationships.



A5:36

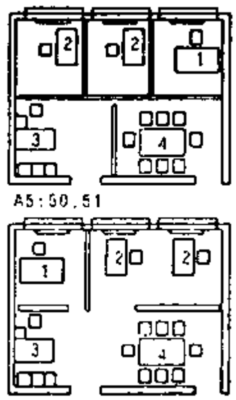
A5:39

35: Just starting out, for assumption, we'll say that the office has 2 zones.

37: There 1s a zone which is to the rear - or to the window side which is most desirable for work space for senior personnel.

38: And a zone on the inboard s ide. will be used for Conference spaces and the reception station from the corridor.

4G: Ignoring for the time being the aspect of doors, would these office spaces make an acceptable size work-stations for the engineers.



A5:50,51

A5:60

50: Ok. Conference space.

52: Of course, this doesn't work too well because we have now the Chief Engineer.. is in essence buried behind the Conference room.

53: That would not be an acceptable arrangement.

54: Of course there is no obligation that the two Staff Engineers would have separate offices.

56: So perhaps, to release that constraint, the Cbief Engineer, is to say logically. riuht behind the Receptionist.

57: So. if someone is coming to tin.- office . . wquld have access to the Chief Engineer after clearing the Receptionist.

Figure 4-5: Functional Zoning

4.3. Generation, Testing and Diagnosis

Once the problem structuring according to pattern or zone is established, the formation of spatial units and the assignment of individual design units is essentially the same for all subjects. Typically, subjects begin design generation with the assignment of the most constrained design element, in this design problem, the Secretarial unit. Assignments are made in sequence, allowing for adequate circulation around elements as well as satisfying established predicates.

Testing involves the satisfaction of established criteria. Failure to satisfy this criteria may lead to problem restructuring which would involve the relaxation of current criteria and may also include the addition of new constraints. Thus, the problem parameters may be modified or elaborated and the generation process is repeated. The successful satisfaction of test criteria results in an acceptable layout which then belongs to a set of possible solutions from which the subject selects the final layout. The generate and test paradigm for design tasks of this kind is discussed in detail in a previous study [Akin 86a].

4.4. Problem Restructuring

The parameters established in the Problem Structuring Phase are subsequently restructured at a later stage in the design process. This is usually a result of a better understanding of the problem statement and the requirements of each function. However, it could also result from the inability of the subject to satisfy all of the initial parameters. We refer to the process of modification and elaboration of criteria as Problem Restructuring.

In the protocols we studied there are 46 instances of problem restucturing (Architects: 25, Students: 7, NonArchitects: 14). During restructuring, subjects decide to either (a) re-prioritize the existing predicates, (b) identify new predicates, (c) eliminate previously established predicates, (d) modify one or more predicates, through elimination, addition or alteration, or (e) identify a new scenario before repeating the design process.

When subjects adjust the priority of existing predicates, they essentially repeat the design process starting with the immediate satisfaction of the relationship(s) which they were previously unable to satisfy. The identification of new predicates constrains the search for an acceptable solution and is a result of a better understanding of the problem. Subjects may be forced to eliminate predicates from an inability to satisfy them in the current layout, or if they violate other predicates of higher priority.

The modification of predicates is carried out in order to conform to a larger pattern, such as a geometric pattern, a circulation network between functions, or an organizational pattern between spatial units. The establishment of a scenario leads to the generation of an entirely new office layout.

Subjects unable to satisfy previously established predicates either modify the existing set of predicates which leads to a *partial restructuring* or they abandon the entire scheme which is described as the *complete restucturing* of the problem.

Partial restructuring is undertaken when the subject is satisfied with the general layout of the current scheme but needs to shift or reorient a few pieces of furniture in order to satisfy the established relationships. An example illustrating partial problem restructuring is illustrated in Fig 4-5 and it occurs as a result of the establishment of a new relationship between design units - namely, the Staff Engineers' need to work together.

Complete restructuring however is carried out when the subject is dissatisfied with interrelationships established between the majority of the design units accommodated in the site. It could also **result** when **subjects** decide to establish a new scenario, or change an important deciding **factor in the layout, like the principal access into the office as shown in Figure 4-6.**

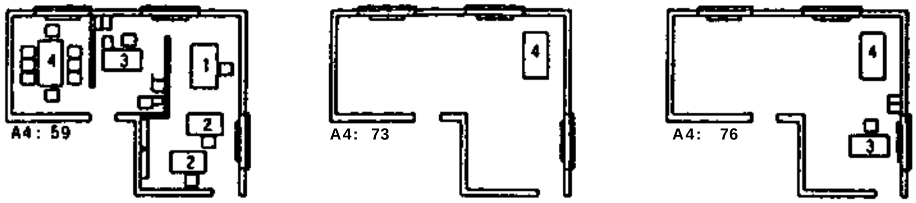


Figure 4-6: Complete Restructuring

5. Conclusion

To date, extensive research has been carried out describing the problem solving process in design. This includes the published works of Akin [Akin 86a, Akin 86b, Akin 86c], Freeman and Newell [Freeman 71], Baer [Baer 68], Henrion [Henrion 74], Flemming [Flemming 86], Foz [Foz 73], and Baykan [Baykan **84]. Many of** the assumptions made in our paper with **regard to problem solving are based on the findings of these prior reports, allowing us to focus our attention on the problem** ***structuring*** **process, which underlies a criticial aspect of finding solutions to ill-defined problems such as design. In a recent paper, John Archea [Archea 86] speaks about "puzzle-making", distinct from problem solving, as the essential task of the architect. We assume that many other design tasks in the field of engineering also have similar properties.**

In our study, we have attempted to operationally define this process of making and remaking structures for a design problem. We conclude that this process involves the pattern of constraints to be satisfied, the "scenarios" which govern the selection of the initial constraint set, and the redefinition of the constraint set (at least so far as space planning problems are concerned). Our descriptions are currently being implemented as a computer program which undertakes problem solving and partial problem (re)structuring. We believe this will permit us to study this paradigm in greater depth, in the near future.

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