Systems Analysis For a "New Generation" of Military Hospitals

Volume 6. Appendices: Improvements to Facilities for Patient Care

Final Report

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SYSTEMS ANALYSIS

FOR A "NEW GENERATION" OF MILITARY HOSPITALS

VOLUME 6

APPENDICES: IMPROVEMENTS TO FACILITIES FOR PATIENT CARE

FINAL REPORT
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SYSTEMS ANALYSIS

FOR A "NEW GENERATION" OF MILITARY HOSPITALS

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6.1. INTRODUCTION

This set of appendices deals with studies related to the methods for planning and building military health care facilities and with the actual design of such facilities. An enormous amount of controversy surrounds the design of facilities, and almost any building configuration has its share of enthusiastic supporters. The lesson to be learned from this state of affairs is that, while there are pitfalls to be avoided, and features to be espoused, it is not possible to find designs which are optimal in all respects. For this reason we have sought in this volume and in Volume 3 (Acquisition of Fixed Health Care Facilities) and in Volume 9 (Building Systems in Military Hospitals) to assemble ideas which contribute to good design and to conceive principles and methods by which good designs may be arrived at.

In Section 6.2., we present a brief description of some novel practices in new European hospitals. We have excluded from this section European innovations in building systems, which are dealt with in Volume 9. The practices discussed in this volume have not been evaluated because they are mostly concerned with marginal issues. Nevertheless, they offer some interesting solutions to common problems.

The following section deals with the economic basis for determining the optimum room size. It is a parametric analysis, the detailed results of which are of less interest than the general conclusion that, if one confines his view solely to economic criteria, there is not much justification for building wards with more than six or so beds. There are other noneconomic criteria, such as nurses' preference, patients' preference, interference in ward operations, and convenience in carrying out nursing duties, which are more significant determinants of room size.

In the next section we describe a program called RELATE for computer-assisted layouts of facilities. The use of this program in the design process is discussed at length in Volume 3. The following section compares RELATE and a number of other computerized layout programs.

The remaining two sections are examples of the proposed improvements to the planning process, applied hypothetically to March Air Force Base Hospital. Not only does this example serve to test the practicality of the improvements, but it furnishes a realistic background in which to evaluate the impact of the improvements in terms of costs.

6.2. NOVEL PRACTICES IN EUROPE

6.2.1. INTRODUCTION

During the course of this study we have had the opportunity of visiting a number of hospitals recently built in several European countries. The hospitals visited included only those that were considered to be innovative in concepts that are not normally observed. Full cooperation was obtained through the International Hospital Federation.

The costs of these innovations, especially their impact on operating expenditures, were not available. In every case these hospitals were recently opened and not much operating experience had accrued. When capital costs were available (and some are mentioned in Volume 3 and in Sections 6.6 and 6.7), it was still difficult to make a meaningful comparison because of differences in wage scales and material costs between Europe and the United States.

As a general statement it is interesting to note that in all our contacts with hospitals in many countries the problems and anxieties of the administrators are quite similar: What can be done to reduce hospital costs? What can we do to reduce staff? What can be done to improve efficiency in the kinds of hospitals that become rigid envelopes constricting further developments of the organization?

We are mentioning here only the innovations which could be of possible interest to the Department of Defense.

6.2.2. ENGLAND - THE GREENWICH DISTRICT HOSPITAL

The most innovative prototype experimental hospital of Britain's Department of Health is the Greenwich District Hospital (the structural features of this hospital are discussed at length in Volume 9), which replaces an old existing hospital. The project was started on the basis of the following principles:

- A hospital building is a means of housing an organization to provide medical care facilities for a particular community. Over the life of the building there will inevitably be considerable changes in the nature of the medical care demanded and in the size and character of the community. The building should, therefore, be capable of equivalent change if it is to continue to function efficiently.

- The housing of an organization must take account of its logistics, that is, the best way of moving its people, goods, and information. After some research it became clear to the planners that a horizontal layout (instead of a tower) had advantages because both people and things can move or be moved horizontally more easily and cheaply than they can vertically.

- Construction should be arranged to permit the uninterrupted use of the partially demolished old hospital and partially built new hospital during the period of construction.

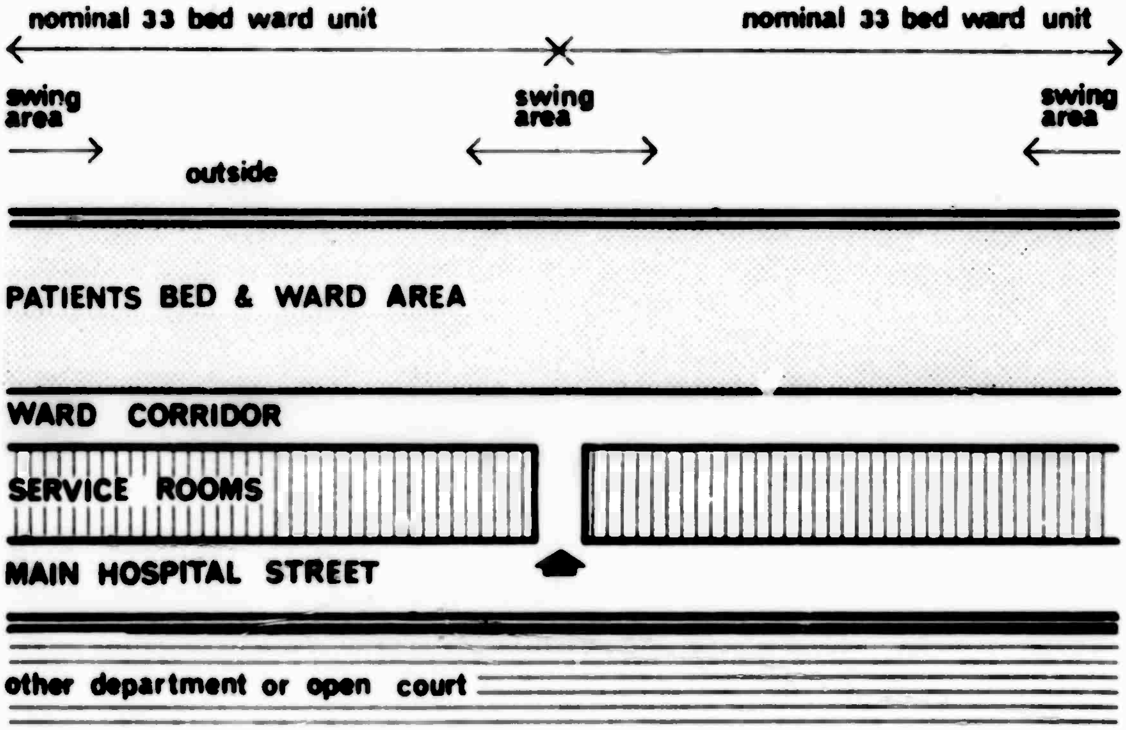
- The building must maintain simplicity of form. The planners of Greenwich Hospital feel that it is easy to confuse people, expensive to move goods around corners and expensive, difficult and inefficient to move services around corners.

6.2.2.1. Building Structure

The Greenwich District Hospital maintains the basic principles in a remarkably elegant design. Although this design was not intended as a system — that is, a kit of parts which can be used elsewhere — but rather as a solution to the particular requirements at Greenwich, the design features obviously have wider applicability. The possibilities are discussed at some length in Volume 9.

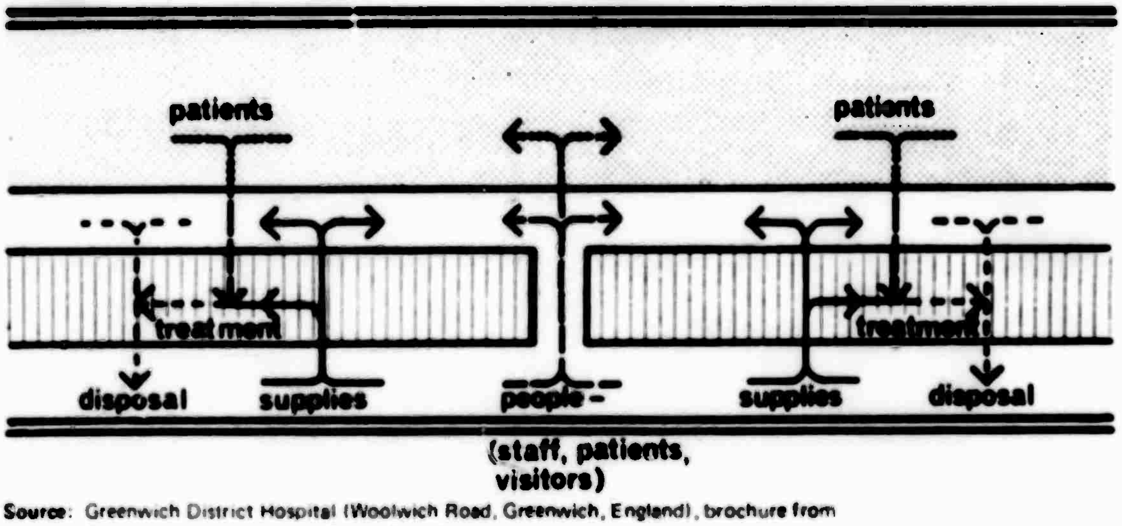
6.2.2.2. Wards and Departments (See Figures 6.2.1 and 6.2.2)

Wards are all on the outside walls, forming a continuous band around the building. On the inner side of the wards a ward corridor separates the patients' rooms from the ancillary service rooms. The glass partitions allow nurses to observe all patients from the corridor without entering the rooms. The ward corridors form an inner barrier between the nursing



Source: Greenwich District Hospital (Woolwich Road, Greenwich, England), brochure from Department of Health and Social Security.

FIGURE 6.2.1 WARD ZONING PLAN



Source: Greenwich District Hospital (Woolwich Road, Greenwich, England), brochure from Department of Health and Social Security.

FIGURE 6.2.2 WARD TRAFFIC CIRCULATION

areas and the busy main hospital corridors on each floor along which supplies, staff, and visitors proceed. Access from the "main hospital corridor" to each ward unit is provided at a number of points, planned to minimize staff walking time. The main hospital corridors are planned to run past three internal courtyards. This allows strangers to orient themselves and helps avoid the monotony of a totally internal environment.

6.2.2.3. Other Services

Below the ground floor is the main vehicular access and car park, with service departments for the whole hospital. The ramp to this basement car park is electrically heated in frosty weather. A special feature of the fire alarm is the installation of heat detectors in the engineering voids between floors.

In every hospital considerable heat is liberated from electrical and mechanical equipment. Using the interfloor service voids much of this heat can be vented directly outside, thus reducing the load on the air conditioning system. These same interfloor spaces are used as the plenum convey exhaust air from the hospital rooms to the outside of the building. This is turn allows 100% fresh air for air conditioning (with no recirculation of air) at low cost.

The greatest demands on a cooling system arise when the room is being heated by the sun. At Greenwich there are pneumatically operated blinds. These are controlled by calibrated solar sensing devices; when the total energy received on a particular area of the building exceeds a predetermined value, the blinds in that area are automatically lowered. These blinds are made of a light-colored woven synthetic material and are comparatively transparent to visible radiation but opaque to the infrared radiation. Automated operation is used because it was found that when shading devices are manually operated, the occupants only lower them when they experience discomfort, i.e., after the area has already absorbed a great deal of heat energy through the windows.

The main pharmacy is in the basement, to gain access to the unloading bay. A special staircase connects it to the pharmacy in the outpatient area on the floor above. The medical records section is also in the basement. An internal staircase and hoist provide a link with the reception desk directly above. Staff changing rooms (male and female), including toilets, showers, changing cubicles, and permanently allocated lockers are in the basement area, immediately adjacent to the entrance from the parking lot.

The outpatient area has a few specific clinics (ophthalmic, dental, prenatal) but it includes 34 general purpose combined consulting/examining rooms, variously allocated according to clinic and specialty demands. The 34 rooms are in rows of 17, but none is far from one of the six waiting areas, each supervised by a clinic receptionist. Adjacent to the outpatient department and the emergency room is a 13-bed day ward with its own operating room. This allows keeping patients for up to 24-hour observation without "entering the system". A playroom area (creche) is provided in the ground floor for small children of patients attending the outpatient department.

A six-section escalator system solves the problem of peak loads, which occur when a shift ends and coincides with visiting hours. This reduces the load on the elevators, leaving them free for non-ambulatory patients.

An innovative procedure for supplying wards allows reducing paper work considerably because no requisitions from wards are required. At regular intervals a supply clerk with a cart comes to the ward area and refills stocks of supplies in cupboards and drawers to predetermined levels, makes his notations of what he left, and continues to the next ward area (topping off method). This includes linen.

Bagged linen and refuse are collected from chutes. In order to avoid the need for interlocking chute doors, each floor has its own pair of chutes, one for bagged linen and one for refuse. Chutes from different floors combine in the void immediately above the disposal room. The laundry is outside the hospital, and overhead rails carry the bagged linen to the vehicle loading bay.

The architecture of the building has a domestic rather than an institutional character, reflecting the concept of residential care rather than custodial care in the old tradition.

6.2.3. SWEDEN - THE LUND HOSPITAL

(The Regional Hospital for Malmöhus County and Southern Sweden, under the Swedish National Social Insurance)

Overlapping design and construction (multitrack scheduling as discussed in Volume 3) allowed the buildings to be completed in three years. This compares with the more usual eight years for investigating requirements; draft proposals; cost estimates; the budget proposal; work projection; approval of drawings; tender documents; collection and testing of firm offers; and final budget presentation to the Central Government (see Figure 6.2.3).

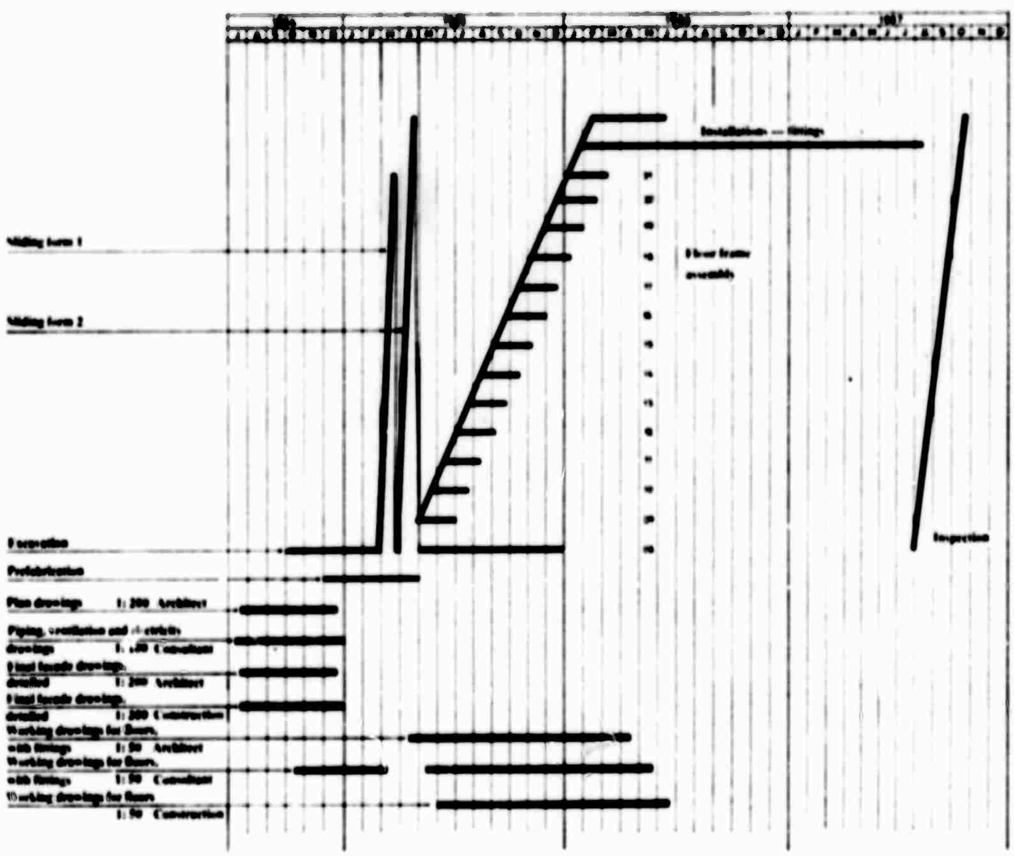


FIGURE 6.2.3
CONSTRUCTION PLAN FOR LUND HOSPITAL*

*Source: Lund Hospital Catalog, p.15

Ward areas are connected to a central EKG unit. Electrocardiograms can be carried out at practically every bed and recorded centrally in the clinical physiological laboratory.

The emergency department in the OPD area is really an independent casualty hospital with its own OPD unit, admission unit, and operating room. Except for admissions to the intensive care units, all night admissions remain in this area until the next morning, when they are transferred to a ward or sent home. This way, the emergency room activity does not disrupt ward operations at night, and admissions are reduced. Separate entrances for stretcher and ambulatory cases to the emergency room allow for separation of patients. The more serious cases are not seen by the ambulatory ones. The emergency room area also has an operating room for night surgery. The recovery room for such cases is next to it.

Preliminary laboratory work is done for all admissions in the OPD area at the "preliminary examination center", using automatic equipment.

6.2.4. OTHER INNOVATIONS OBSERVED

In visits to other hospitals a number of innovations were observed which reveal concepts of patient care of hospital operation different from those usually found in the United States. These are mentioned briefly below.

In some hospitals there was evident an intent to enhance the home-like qualities of the ward. Each ward has a sitting room, a smoking room, and a dining room for patients who are able to use them. Each patient's room has a toilet and a washroom containing a wash basin for the patients and a stainless steel sink and an immediately accessible supply of disposables for staff use. This supply cupboard, containing the more commonly used nursing articles, is replenished from the corridor.

In other hospitals the tops of all operating tables are easily detachable. When placed on a special trolley the top serves as a stretcher on which patients are conveyed to and from the operating room. A patient is transferred to the operating room in the so-called "patient lock." Here, the patient is taken from his bed and placed on the detachable top of the operating table. After the operation, the patient is moved to a clean bed from the "Bed Center," in this same location.

The Bed Center undertakes the work of bed cleaning, thus relieving the wards of these tasks. It has automatic systems for transporting and washing of beds and for disinfecting mattresses and pillows. Sheets, pillowcases, and blankets are removed in the ward and sent via the linen chute to the central laundry. Each bed is taken to the basement area upon discharge of a patient. Upon arrival at the Center, the mattress and pillow are removed and placed in a basket (the size of a bed). These baskets are dimensioned to hold mattresses and pillows for five beds. Thus after five beds have passed, the mattress basket is included as a sixth "bed" in the automatic system. The bedstead is picked up by a fork conveyer in the ceiling of the dirty side of the Center. On reaching the washing and disinfectant zone that divides the dirty from the clean side, the bedstead is automatically transferred to a washing and drying tunnel, in which it is sprayed with water at 90°degrees Centigrade to which disinfectant and wetting agents have been added. Similarly the mattress baskets pass automatically through an autoclave for sterilization. The bedsteads, mattresses, and pillows meet again on the clean side, where the beds are made up by a staff of two. Clean bed linen and any special equipment such as side pieces or drip stands are taken from an adjacent store.

Staff from the Transport Service take the beds from the Center to the admission and bath unit adjacent to the central registration center. Patients arriving by foot, car, or ambulance pass through central registration, directly connected to the admission and bath section. The patient and bed meet in one of the nine rooms of this center, and the patient's clothes are placed in a nearby storage area. Patients are bathed here, dressed in pajamas, placed in the bed, and then transferred to the ward by the transport staff.

There is a control center for the entire ventilation system and heating system, also for fault signals from important equipment such as blood refrigerators, dialysis tanks, etc. The center produces an alarm signal automatically and codifies the location of the fault. (There are 999 contact points.)

In the intensive care unit, all the equipment can be attached to a system of rails on the wall at the head of the bed. This avoids cluttering up the floor around the bed, and saves considerable work by the staff.

An X-ray department as part of the emergency service area allows taking X-rays which have not been arranged by appointment. This avoids interfering with the smooth flow of work in other X-ray examining rooms.

The Cleaning Center takes care of all housekeeping chores. Each cleaner is allotted a section of the hospital to which he returns every day. All equipment is provided at the Cleaning Center (clean side). When the cleaners finish their work they return all the equipment to the Center (dirty side). Cleaners never take trolleys into patient's room. Mops are changed after cleaning each room.

Color codes are used to distinguish different states of contamination - green for dirty, red for contaminated, blue for clean, and yellow for sterilized. This code is used throughout the hospital, with tape affixed to various items and areas depending on their cleanliness.

Dictaphones in emergency rooms, with one belt per patient, attached to his chart, allows prompt transcription of notes with no delays.

The Transport Service relieves the nursing staff from transport work outside their own department. The Transport Center is responsible for conveying patients and supplies, and has a message center. This message center is responsible for mail, messenger rounds, transportation of samples, etc. The external transport is also responsible to this Center.

Locating the intensive care unit on the ground floor, close to the emergency room, is an interesting innovation. Since most of the very sick patients requiring intensive care have been brought to the emergency room from their homes, the proximity of the intensive care unit is an advantage. Furthermore, since both the emergency room and the intensive care unit are staffed on a 24-hour basis, it allows for staffing flexibility at times of breaks, lunch, and so forth.

Conveyor systems for medical records and X-ray films from the storage areas to the OPD receptionist speed up the availability of records needed by examining physicians.

The resident physicians and surgeons have their own apartments within the hospital. They consist of a bedroom, bathroom, sitting room, and kitchenette. This keeps the medical staff available when needed.

6.3. SIZE OF PATIENT ROOMS

6.3.1. INTRODUCTION

Lacking empirical data relating costs of inpatient care in hospitals to the size of the rooms, we postulated a parametric model for economy of scale, which we then used to determine minimum-cost room sizes under a variety of constraints. By using a range of parameter values we tested the sensitivity of the minima to scale factors. Even for a rather extreme rate of economy of scale, it appears that savings associated with multibed rooms become negligible after about ten beds at most. For more conservative rates, the optimum economic size is about half that large or even less, depending on total ward size and the number of classes of nonmixable patients.

The cost per bed is a function of many factors. One is the number of beds per room. At least in civilian hospitals, different rates are charged for private rooms, semiprivate rooms, and multibed wards. It is not easy to determine whether the usual rate differentials are a true reflection of actual cost differences, so our approach has sidestepped the issue of appraising absolute costs. Instead, we have used a parametric model for economy of scale which is flexible enough to encompass a wide range of relative costs.

In order to define the problem for analytical evaluation, it is necessary to make assumptions about the size and distribution of the total bed demand in a ward and the number of classes of nonmixable patients that must be accommodated. These assumptions and their resulting requirements are spelled out in succeeding sections of this chapter. Total cost per ward is obtained by multiplying the cost per room by the requisite number of rooms of any given size. For a sequence of parameter values we have developed cost curves from which minimum-cost room size can be read off directly.

It should be noted that this analysis deals only with the economic aspects of room size; thus it does not try to associate financial value with the social, psychological, and medical benefits of privacy. If such factors dominate the choice and lead to a decision in favor or single rooms, at least this analysis can indicate the relative magnitude of the foregone financial savings.

6.3.2. NUMBER OF ROOMS REQUIRED

For any functionally separate ward in a hospital (for example, an orthopedic ward) there will be some demand pattern for patient beds. Suppose that over a representative period there is an average daily need for m beds, and that the standard deviation about this mean is σ. To provide enough capacity to handle any extreme fluctuation in demand would be wasteful, because usually many of the beds would be empty. Consequently, it is customary to decide on an arbitrary cutoff that will satisfy all but some small fraction of the demand. For instance, we might decide to provide enough beds so that the demand would exceed the number of beds available only 5% of the time. This practice is not unreasonable since generally there are some elective cases for which admission can be delayed without harm until beds are available.

As an example, suppose $m = 85$ and $\sigma = 9.2$. Then a capacity of 100 beds would satisfy the demand approximately 95% of the time. Similarly, if $m = 40$ and $\sigma = 6.3$, a utilizable capacity of 50 beds would satisfy the demand about 95% of the time. These calculations have been based on a Poisson type distribution of demand, but for means of this size, the Poisson distribution is virtually identical with the familiar Gaussian or normal distribution, so there is no great dependence on the special characteristics of the Poisson form of the distribution function. It was used simply for convenience.

To give us a reasonable range over which to evaluate the results, we have adopted 100 beds and 50 beds as cur two benchmarks for patient capacity. These are arbitrary, but not unreasonable for the applications of interest.

If all the beds are in single rooms, there is no problem in accommodating different classes of patients, However, if there are two or more classes of patients that cannot share a room, i.e., men and women, and if there are two or more beds in each room, some excess of total bed capacity is required in order to be certain that a ward can handle 100 patients no matter what mix happens to occur. For example, five rooms of 20 beds each could handle 100 patients only if the number of patients of each type is a multiple of 20. It turns out that six 20-bed rooms are needed to guarantee accommodation for 100 patients of two nonmixable classes occurring in random proportions.

One can run through this type of exercise for any fixed number of beds per room and any number of patient classes, and thereby develop tables of the number of rooms required in order to guarantee that a prescribed total number of patients of any possible mix can be accommodated. We have done this for the two totals, 100 patients and 50 patients, and for constant room sizes (that is, all rooms the same size) with the number of beds per room running from one up to half the total ward size, and for two, three, and four classes of patients. The requirements are displayed in Table 6.3.1.

In this exercise we have not explored combinations of varying room sizes for a given ward because of the great multiplicity of possible combinations. For our purposes, determining an optimum fixed size is believed to be sufficient to indicate what the majority of the room sizes should be for the best economic efficiency, and if one wants to add a few smaller rooms for any reason, the bulk of the saving would still be realized.

TABLE 6.3.1.

NUMBER OF ROOMS, R(N), OF N BEDS EACH REQUIRED FOR ASSURED ACCOMMODATION OF GIVEN LOAD OF MIXED PATIENTS RANDOMLY PROPORTIONED

	r(n) for 100 patients			r(n) for 50 patients		
n	2 classes	3 classes	4 classes	2 classes	3 classes	4 classes
1	100	100	100	50	50	50
2	51	51	52	26	26	27
3	34	35	36	18	18	19
4	26	27	28	14	14	15
5	21	22	23	11	12	13
6	18	19	20	10	10	11
7	16	16	17	8	9	10
8	14	15	16	8	8	9
9	12	13	14	7	8	9
10	11	12	13	6	7	8
11	10	11	12	6	7	8
12	10	11	12	6	6	7
13	9	10	11	5	6	7
14	9	9	10	5	6	7
15	8	9	10	5	6	7
16	8	9	10	5	5	6
17	7	8	9	4	5	6
18	7	8	9	4	5	6
19	7	8	9	4	5	6
20	6	7	8	4	5	6
21	6	7	8	4	5	6
22	6	7	8	4	5	6
23	6	7	8	4	5	6
24	6	7	8	4	4	5
25	5	6	7	3	4	5
26	5	6	7			
27	5	6	7			
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41	4	5	6			
42	4	5	6			
43	4	5	6			
44	4	5	6			
45	4	5	6			
46	4	5	6			
47	4	5	6			
48	4	5	6			
49	4	4	5			
50	3	4	5			

6.3.3. MODEL FOR ECONOMY OF SCALE

Let us take the following formula as a general parametric model for the total cost of providing and servicing a patient bed in a room of n beds:

$$C = a + \frac{c}{n^k}$$

The quantity a represents the minimum cost for which a bed can be operated in an extremely large room; i.e., it is the asymptote which the cost per bed approaches as full advantage is taken of all economies of scale. The quantity c represents the additional cost of operating a bed in a single room. Hence, C = a + c when n = 1.

The factor n^k, depending on the value of k, determines how rapidly C approaches the asymptote, i.e., the rate at which economies of scale can reduce the cost per bed. The general graph of such a function is depicted in Figure 6.3.1 for $k > 0$.

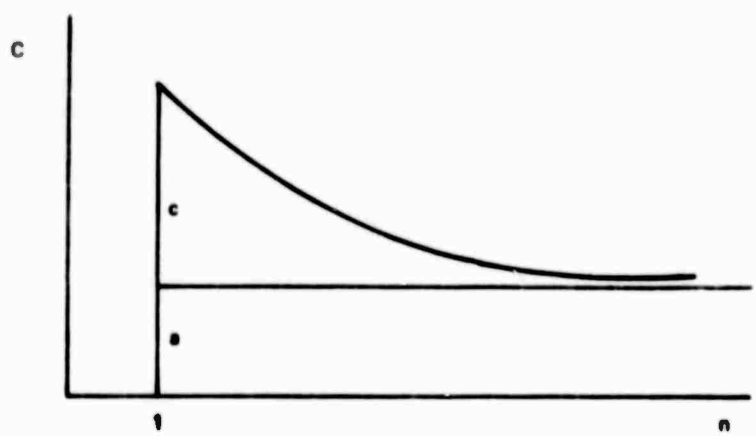

FIGURE 6.3.1 GENERAL MODEL FOR COST PER BED IN ROOM OF n BEDS

Instead of attempting to determine the best numerical values to use for each of the parameters a, c, and k, we felt it would be much more informative to explore a range of values for each. Furthermore, instead of dealing in absolute values, we wanted to examine relative costs, so we have in each instance worked with the ratio of the cost per bed in a room of n beds to the cost per bed in a single room. In effect, we have set C = 1 for a single room and have calculated the fractional cost per bed in a multiple room.

We have used four values for a, namely, $a = 0$, $a = \frac{1}{2}c$, $a = c$, and $a = 2c$, to span the range that appears to be of reasonable interest. These are referred to as Cases 1, 2, 3, and 4, respectively. For each of these cases we have let k take on four values, 0.1, 0.2, 0.3, and 0.5, to represent the range from a slow change of cost with room size to a fairly rapid change. The graphs representing the 16 resultant curves of cost per bed are shown in Figures 6.3.2 - 6.3.5.

If we multiply the cost per bed by the number of beds per room, we obtain the cost per room. This has been done and the results are plotted for all of the cases considered in Figures 6.3.6 - 6.3.9. From these curves one can read off directly the number of single rooms that would cost the same as one room of n beds, for each combination of parameters.

We have not considered it necessary to break out the component costs that contribute to the total cost of providing bed care for a patient, such as floor space, utilities, nursing service, food, linens, cleaning, and maintenance. Some of these will vary with room size and others will not. For analytical simplicty we have merely conceived of all the appropriate costs elements as being subsumed under the three parameters, a, c, and k, and thereby have taken a sufficiently broad range of values to include all reasonable possibilities.

6.3.4. TOTAL COST FOR HANDLING GIVEN NUMBER OF PATIENTS

In Table 6.3.1 we listed for each n the number of rooms of that size that would be required for assured accommodation of 50 or 100 patients of 2, 3, or 4 nonmixable classes. If any entry in that table is multiplied by the cost per room of a size n, as given in Figures 6.3.6 - 6.3.9, we obtain the total cost of the prescribed capacity. In order to continue dealing in costs relative to single rooms, we then divided by 50 or 100, as appropriate, to get the cost relative to the cost of providing the prescribed capacity by all single rooms. If we plot this relative total cost as a function of n we get curves of the sort shown in Figures 6.3.10 - 6.3.13, which are typical examples of the total set.

There is some built-in inaccuracy in this process, because we are costing each room as if it were full, even though there usually is some unutilized excess capacity. Moreover, this inaccuracy is biased, because the larger room sizes generally cause more excess capacity than smaller room sizes. However, there seems to be some evidence* that most of the costs related to hospital bed capacity are fixed and are not responsive to occupancy rate. Once the facilities and staff are provided for a hospital of a given size, the variable costs associated with inpatient bed days become minor. Unfortunately, there is no ready way to estimate their size, but it is reasonable to believe that the differential effect of cost variations with unutilized capacity would exert comparatively little economic leverage on optimum room size.

6.3.5. MINIMUM-COST ROOM SIZE

The first observation to make regarding minimum-cost room size is that if all patients are of one class, and can share accommodations, the most economical arrangement, if there are any economies of scale at all, is simply to have one large room that is big enough to accommodate whatever number of patients is planned for. In other words, only if there are two or more classes of patients that cannot be mixed will a minimum cost occur at other than the upper limit on size.

For convenience we have tabulated the minimum-cost room sizes for all the different cases we have considered and have listed them in Table 6.3.2. This table helps one to see at a glance how the minima shift with changes in the parameter values of our models.

For instance, we can note that the optimum size generally decreases (and never increases) as the number of nonmixable classes of patients increases. Although we have not carried the analysis beyond four classes, it is obvious that this is a monotonic effect, and at the upper limit where no two patients could be mixed, one would be forced to use single rooms exclusively. Extrapolation from Table 6.3.2 suggests that single rooms become optimum well before the number of classes of patients become equal to the number of beds.

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*Ingbar, M. L., and Taylor, L. D., Hospital Costs in Massachusetts, Harvard University Press, 1968, page 62.

TABLE 6.3.2

MINIMUM-COST ROOM SIZES

100 Patients

Case	1(a = 0)			2(a = $\frac{1}{2}$c)			3(a = c)			4(a = 2c)		
Classes	2	3	4	2	3	4	2	3	4	2	3	4
k = 0.1	9	7	3	9	2	2	3	2	1	3	2	1
0.2	33	14	7	11	7	7	9	7	2	3	2	2
0.3	33	20	14	11	7	7	9	7	3	9	3	2
0.5	50	49	33	20	11	7	11	7	7	9	7	4

50 Patients

k = 0.1	7	3	2	7	2	1	1	1	1	1	1	1
0.2	10	6	4	7	3	2	7	2	1	2	2	1
0.3	25	12	6	7	4	4	7	3	2	7	2	1
0.5	25	24	16	10	6	5	7	4	3	7	3	2

Another trend that is apparent is that optimum room size decreases as total ward capacity decreases. That is, for any given model for economy of scale and any given number of classes of patients, Table 6.3.2 shows that the optimum room size for a 50-patient ward is less than or equal to that for a 100-patient ward. Clearly this is also a monotonic type of relationship.

Naturally, the table reflects the expected relationship between optimum room size and economy of scale. Thus, as k runs from 0.1 to 0.5 in any case, the cost per bed decreases more rapidly with room size; consequently, the optimum room size increases. However, at this point it is useful to look at the graphs themselves to see not only where the minima occur but also where the region of diminishing effect sets in. From Table 6.3.2 it can be seen that the cases when a = 0 represent the most extreme cases of economy of scale and lead to the largest values for minimum-cost room size. Yet, as Figure 6.3.10 illustrates, even for the most extreme curves nearly all of the possible economic benefit has been realized by a room size of about ten beds or less; beyond that the curves are comparatively flat or begin to tend upward. This statement is equally true for all of the other cases where the minimum occurred at values of n greater than ten. From a parametric analysis of this sort one gains a sense for the order of magnitude of the room size that is likely to be most economical. By observing where the knees occur in the cost curves, at least an upper limit can be set on room size for economic benefits from economy of scale. This, as we have just observed, appears to be on the order of ten beds, even for the most extreme case considered. For more conservative cases, such as Cases 2 and 3 as described earlier, and for k = 0.2 or 0.3, room sizes on the order of four or five beds are just about optimal.

Thus, there is no indication that extremely large room sizes are really desirable, even from a purely economic standpoint. We believe the cases we have considered and the range of parameter values used are more than sufficient to cover the conceivable variations in economy of scale which are likely to be encountered in practice.

It should be noted that the magnitude of the savings corresponding to a choice of room size for any of the cases considered can be obtained from the ordinate (vertical scale) on the graphs. For example, a particular point on one of the curves, level with 0.80 means that the cost under the selected circumstances would be 80% of the cost of providing accommodation in all single rooms, or the saving would be 20%. Running through the figures, one can see that for some of the cases the potential savings are quite large, while for others they are insignificant. Hence, in addition to considering what the minimum-cost room size should be, it is important to note the size of the accompanying saving. In some cases, though the optimum size is on the order of seven, the amount of the saving is only a few percent and may not be worth striving for, in view of the uncertainty in predicting economy of scale.

6.3.6. CONCLUSIONS

After scanning the cost effects of a wide range of economies of scale, we can conclude that there is no strong financial motivation to move toward extremely large room sizes in a hospital. Something on the order of 10 beds per room should be ample, even under an extreme rate of economy of scale. More reasonable parameter choices indicate that four or five beds per room are likely to be nearly optimal economically. However, the amount of the potential saving can only be estimated within very broad limits without knowing which model best fits a given situation of interest. Something on the order of a 5% to 15% saving seems reasonable for multibed rooms, relative to the cost of providing accommodation in single rooms, but the total variability of parameters is uncomfortably large for making generalized estimates of potential savings.

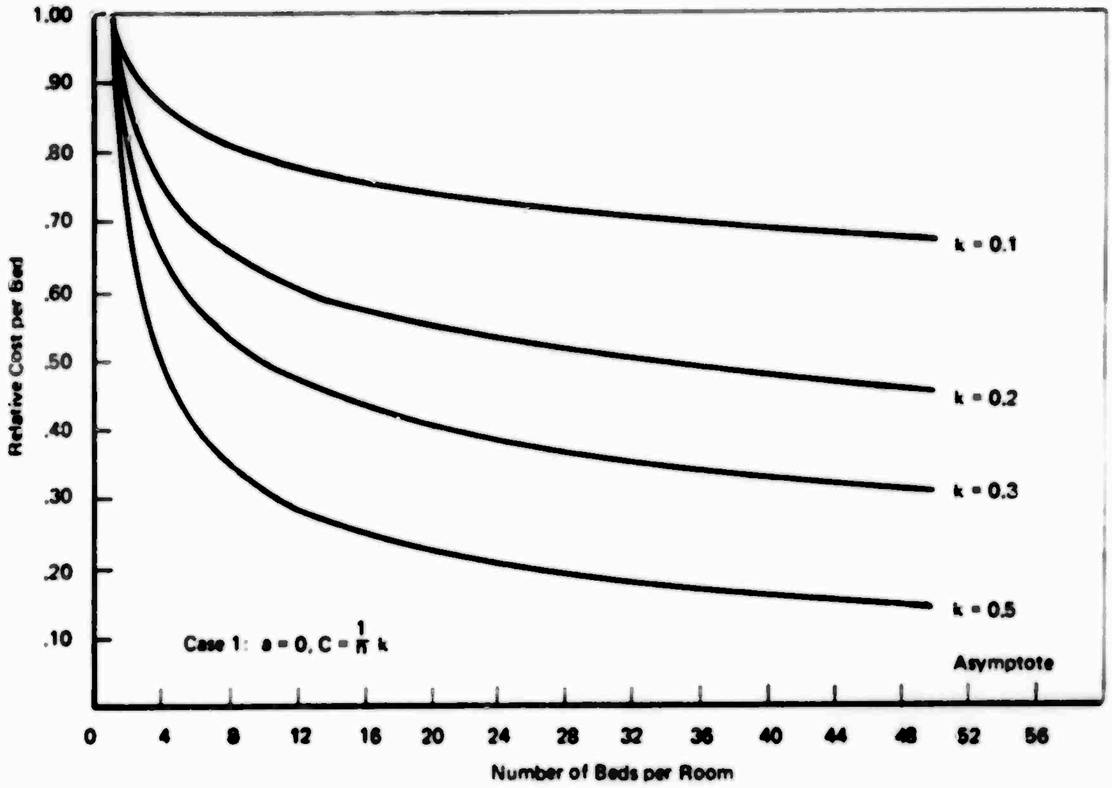

FIGURE 6.3.2 COST PER BED IN ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

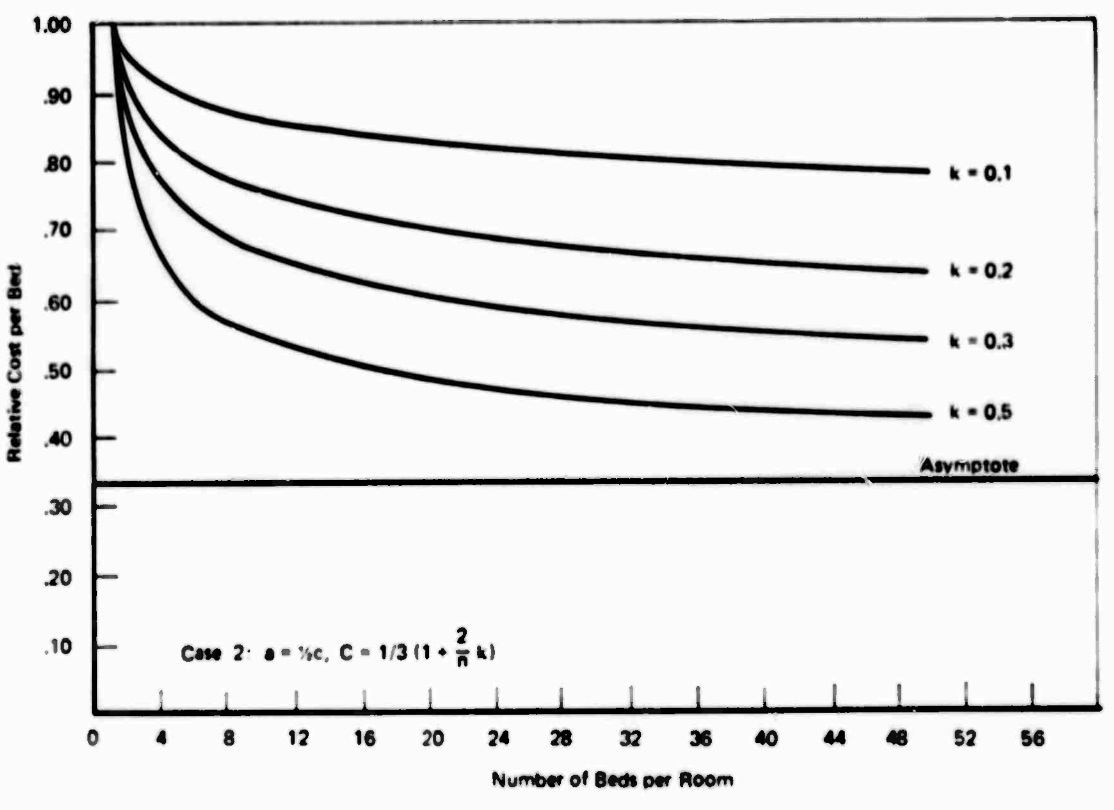

FIGURE 6.3.3 COST PER BED IN ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

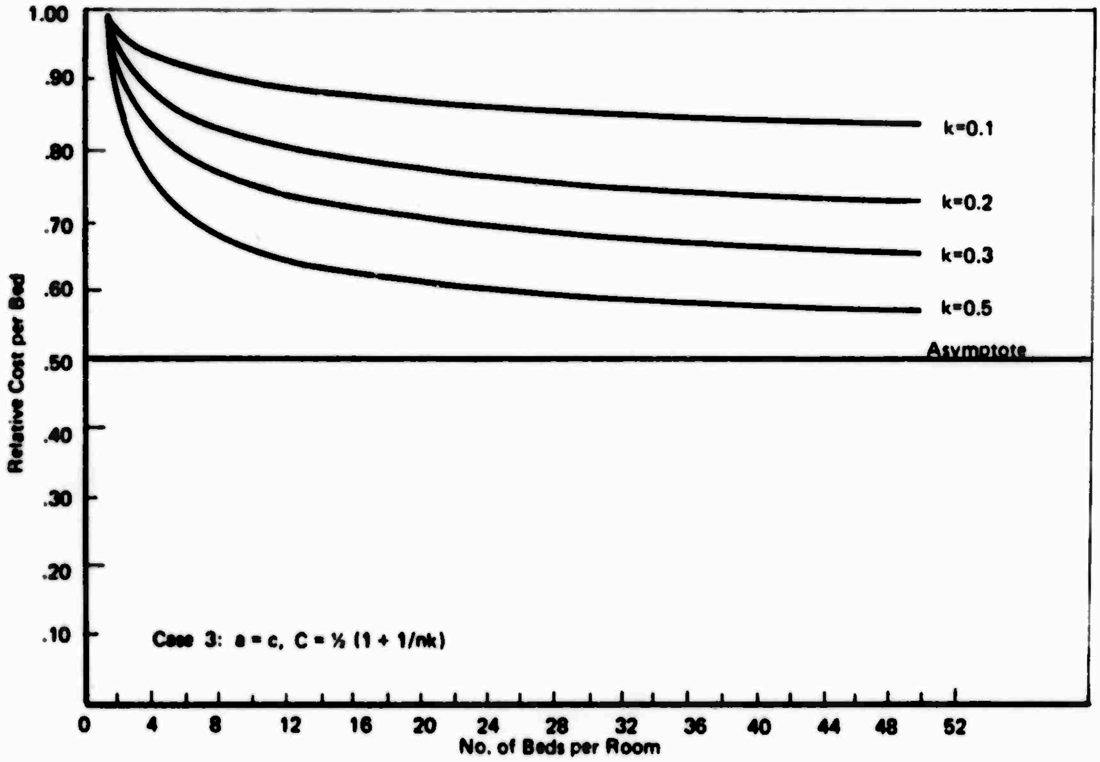

FIGURE 6.3.4 COST PER BED IN ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

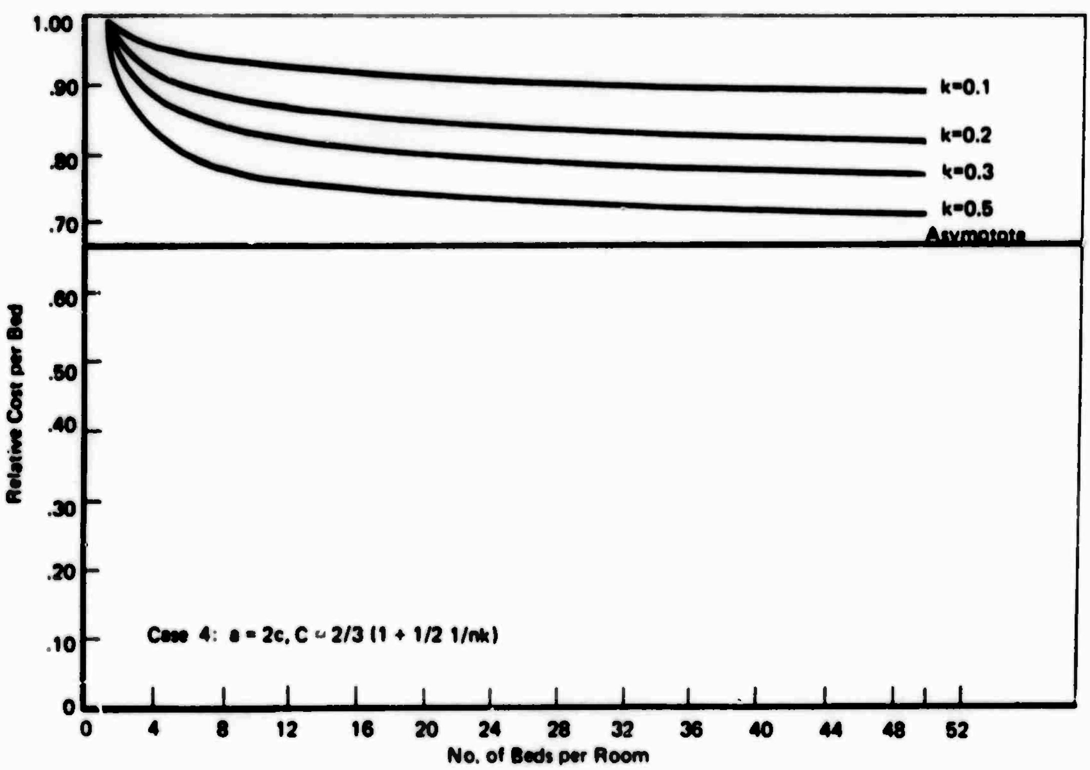

FIGURE 6.3.5 COST PER BED IN ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

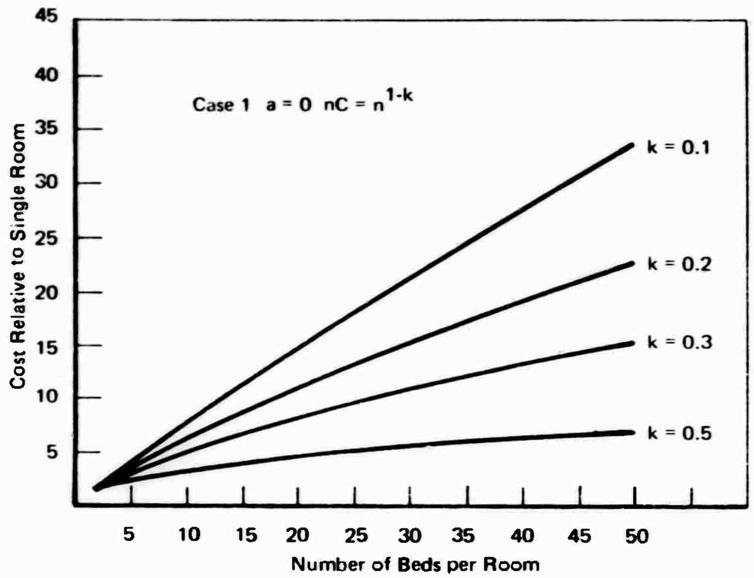

FIGURE 6.3.6 COST PER ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

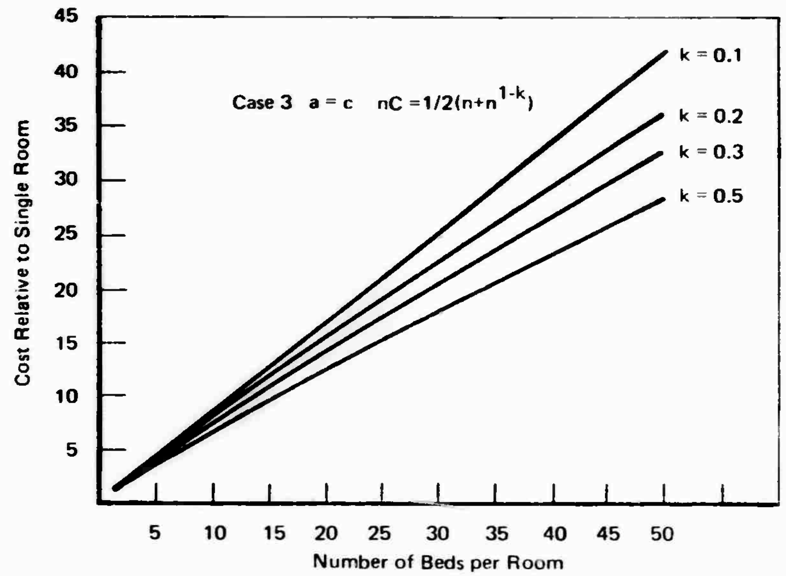

FIGURE 6.3.8 COST PER ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

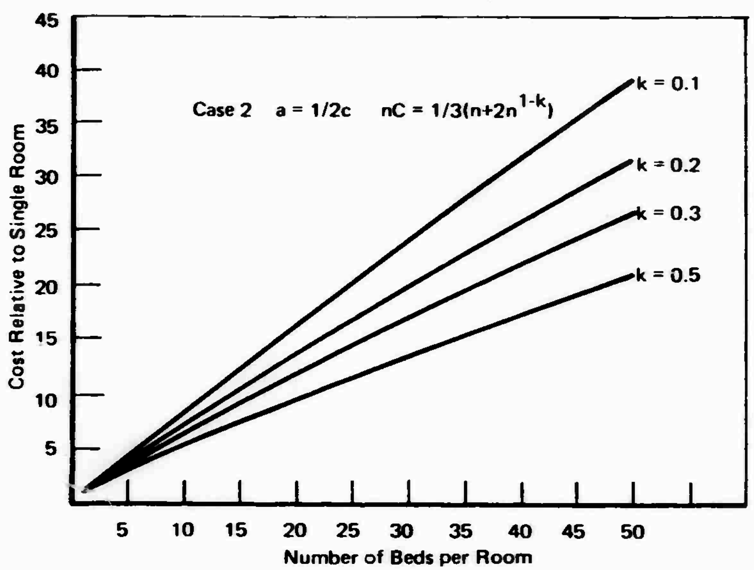

FIGURE 6.3.7 COST PER ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

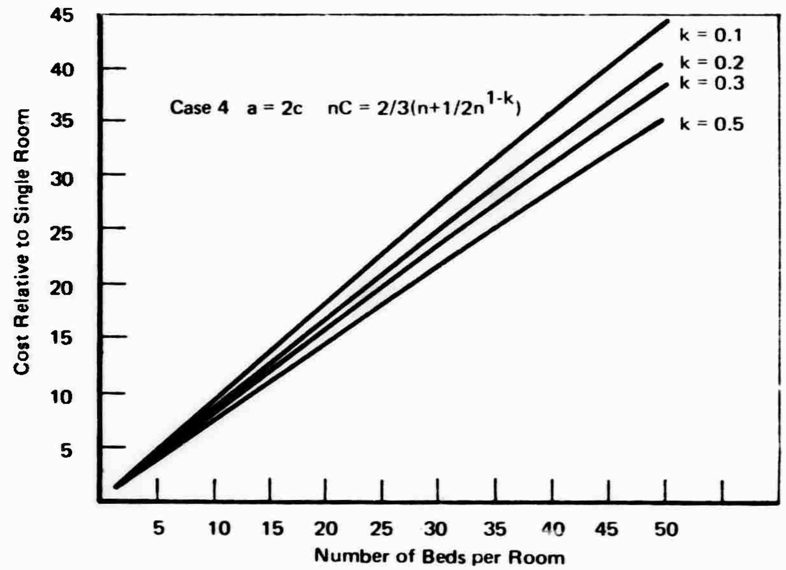

FIGURE 6.3.9 COST PER ROOM OF n BEDS RELATIVE TO COST OF SINGLE ROOM

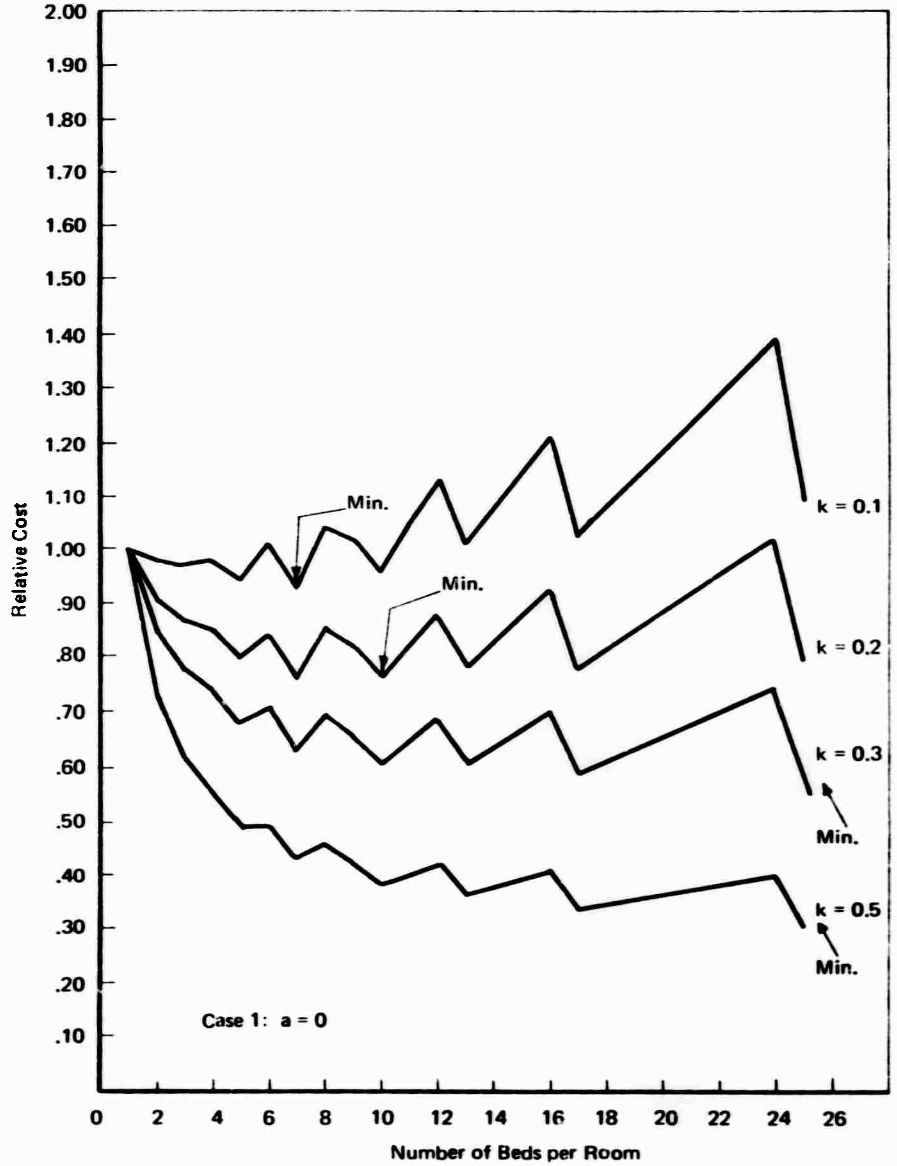

FIGURE 6.3.10 TOTAL COST FOR ASSURED ACCOMMODATION OF 50 PATIENTS OF TWO NONMIXABLE CLASSES IN ROOMS OF n BEDS EACH RELATIVE TO COST OF 50 SINGLE ROOMS

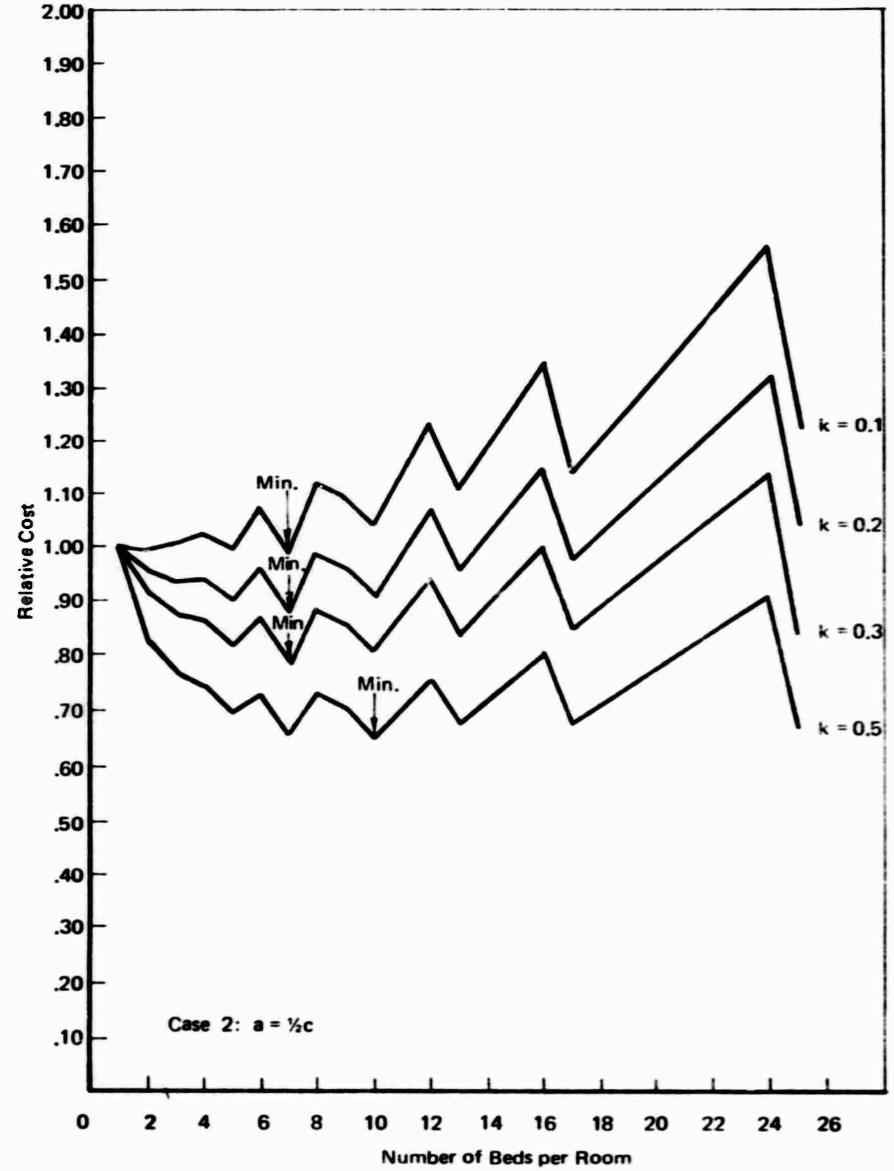

FIGURE 6.3.11 TOTAL COST FOR ASSURED ACCOMMODATION OF 50 PATIENTS OF TWO NONMIXABLE CLASSES IN ROOMS OF n BEDS EACH RELATIVE TO COST OF 50 SINGLE ROOMS

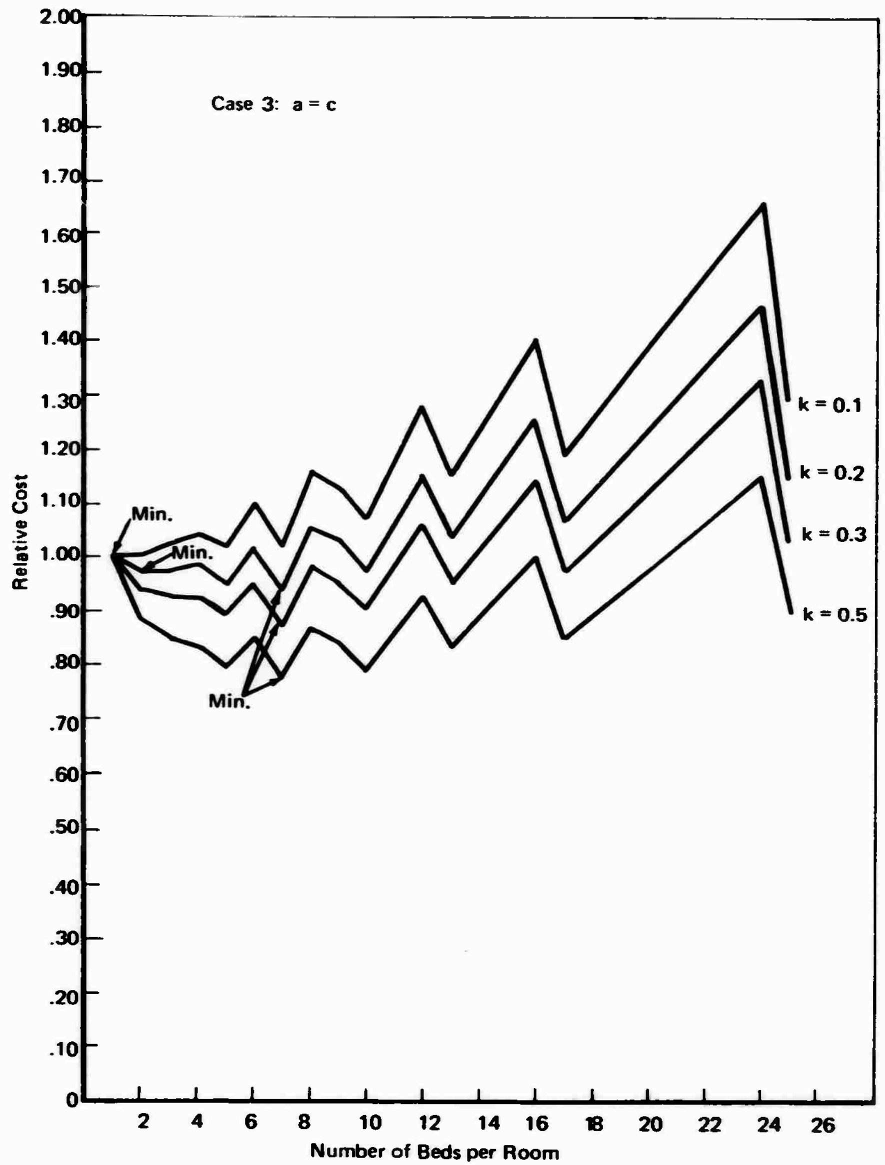

FIGURE 6.3.12 TOTAL COST FOR ASSURED ACCOMMODATION OF 50 PATIENTS OF TWO NONMIXABLE CLASSES IN ROOMS OF n BEDS EACH RELATIVE TO COST OF 50 SINGLE ROOMS

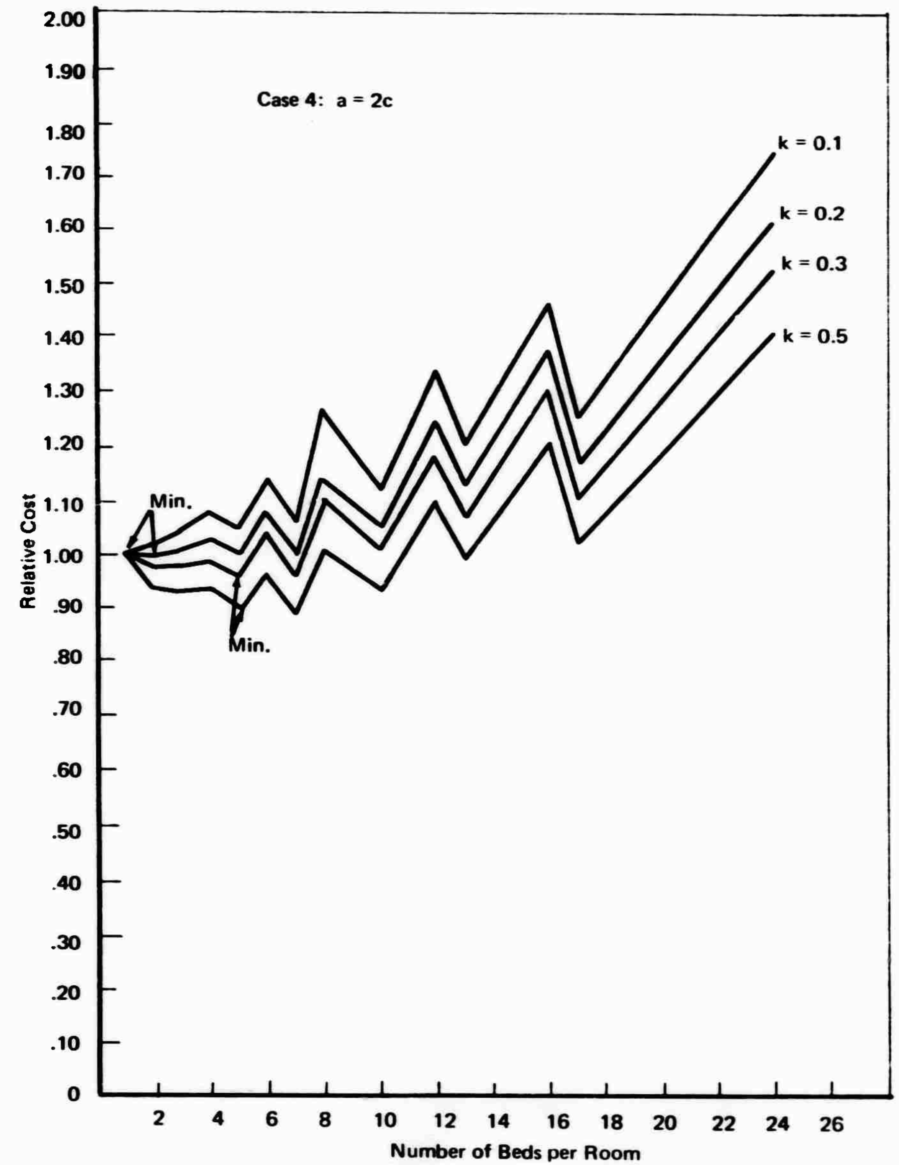

FIGURE 6.3.13 TOTAL COST FOR ASSURED ACCOMMODATION OF 50 PATIENTS OF TWO NONMIXABLE CLASSES IN ROOMS OF n BEDS EACH RELATIVE TO COST OF 50 SINGLE ROOMS

6.4. RELATE

6.4.1. INTRODUCTION

RELATE (RElationship LAyout TEchnique) is a computer program which generates layouts for facilities in three dimensions, based upon the functional interrelationships of the elements* of the facility. It is a tool to aid the planner and the designer in arriving at concept drawings through the form diagrams. RELATE was originally developed by the staff of Lester Gorsline Associates in late 1968 and early 1969 to address the particularly complex layout problems posed by medical facilities. Those involved in the research represented the professions of Planning, Architecture, Engineering and Medical Education. RELATE is, therefore, a truly interdisciplinary product.

RELATE is designed to be used as a tool in the design process. It cannot produce workable, final-form diagrams. The planner or designer works with the computer at a high level of interaction, making and changing the assumptions and data until high quality form diagrams result.

RELATE employs an heuristic (rule of thumb, trial and error) algorithm which attempts to produce good solutions, although the solutions can in no way be construed to be optimal. Input consists of a list of departments with their sizes, shapes (if desired), and interrelationships (affinities). Further, one may input a description of the site which is to contain the resultant layout, whether it is an open construction site with its topographical features, access patterns, existing facilities, and legal codes, or a predefined building shape within which the departments must be arranged. Certain assumptions must be made which define such concepts as adjacency, proximity, and horizontal versus vertical travel. Certain departments will be preassigned to fixed locations and data for evaluating the layouts will be input. The major input qualities are summarized below:

6.4.1.1. Site Matrix

The site matrix describes the features of the site. Using numeric codes, the topography is defined so that the layouts produced will conform

*See Definitions (section 6.4.12).

to the contours of the site. In addition, those areas which must be preserved as open space or are occupied by entities which must be retained are indicated as unavailable for new construction. (see section 6.4.2.)

6.4.1.2. Element Definition

Those departments of the new or expanding facility which are to be included in the computer layout are defined as elements. The conventional departmental breakdowns may give way to more functional definitions and subdivisions. (see section 6.4.3.)

6.4.1.3. Predefined Shapes

Certain elements may, because of function, require a specific layout form. In such cases, it is possible to indicate a definite shape for the floor plan of that element. The computer will observe this as a constraint and the department will have the prescribed shape in the final layout. (see section 6.4.4.)

6.4.1.4. Preassigned Elements

It is often necessary to fix certain elements to specific locations on the site. When expanding existing facilities, those elements which will remain in position are so indicated. Certain elements may be related to other facilities on or near the site and those facilities may be included by preassigning them to their actual locations. They will then affect the new locations of the elements with which they are related. (see section 6.4.5.

6.4.1.5. Affinity Matrix

The Affinity Matrix is the basis for the computer-generated layouts. Once the elements have been determined it is necessary to combine quantitative data and qualitative values into a relationship for each pair of elements. The relationship, or affinity, between two elements indicates a relative need for proximity in the final layout. (see section 6.4.6.)

6.4.1.6. Vector List

The means by which assumptions about space and distance are input, is the Vector List. By the arrangement of spaces around an origin into groups indicating the relative distance of each space from the origin, one can precisely define such values as adjacency, proximity, and the relationship between horizontal and vertical distances. (see section 6.4.7.)

RELATE systematically builds modular layouts based upon the functional interrelationships. Using the preassigned departments as starting points, the computer "grows" the layout, bringing the elements into the layout one by one, using the affinity matrix to determine the order in which each element is added.

Many configurations are generated which differ as a result of random choices among equal alternatives at each step in the process. Each layout is given a rating which is based upon how well the relationships are solved. In addition, other evaluations are performed and the program is capable of screening the layouts according to various criteria selected by the planner or designer using the program. The layouts judged best according to these criteria are printed in a form which is easily interpreted by the user along with a summary of the evaluations for all layouts.

The purpose of this discussion is to present a working description of the concepts involved in the use of RELATE and to describe how the computer program utilizes the concepts and information to produce layouts for facilities. The description is presented in the technical language of neither the architect nor the computer programmer, rather in conceptual translations of the computer process.

6.4.2. SITE INFORMATION

RELATE concerns itself with space and its various features such as location and relative distance. In order to do manipulations with the computer, it is necessary to translate spatial concepts into numbers which can be used by the computer.

When mapping land areas, the cartographer uses a grid system. Such a grid system can easily be converted into a matrix which can be manipulated by a computer. Such a grid will be used to describe the construction site. The grid system is defined in three dimensions.

The module is the basic unit of measurement for the computer system. The dimensions of the module are determined by the planner and will normally be equivalent to the basic planning unit. When referring to spaces and distances, the units of measure will be in modules rather than square feet. The module and the grid must be so sized so that one module will occupy one block of space on the grid.

Figure 6.4.1 shows the concepts of module, grid and matrix in three dimensions. In mathematics, the matrix is an array of numbers or a table. The location of a number in a matrix is conceptually equivalent to the location of a module on the site grid. The coordinates of the site grid correspond to the rows and columns of the matrix. To describe the location of a particular module, the number corresponding to that module is entered into the equivalent space in the matrix.

This device for describing space eliminates the necessity of complicated mathematical conversions and makes maximum use of the planner/designer's own spatial concepts.

A rather complete description of the site is one of the major inputs in order that the form diagrams conform to the actual conditions of the construction site and serve as a convenience to the user as well. This description includes:

- Dimensions of the space in which the configuration must fit,
- Topographical features of the site,
- Boundaries of the site,
- Limitations on height resulting from soil bearing limitations,
- Areas upon which construction is not allowed,
- Actual building shapes (if desired), and
- Areas not a part of the site containing features related to the building.

In order to define the dimensions of the space in which the configuration must fit, a "space envelope" is created by inputting the maximum limitations in each of the three dimensions in numbers of modules. Three numbers are input indicating the limits in the two horizontal dimensions and one vertical dimension. The space envelope is the only **mandatory** site input.

To describe the details of the site a "topography matrix" is generated which contains the information in a form which can be handled by the computer. The contours of the site must be rationalized in terms of a grid. The grid is overlayed on the site drawings. (See Figure 6.4.2) If the module is defined to be 35 feet on a side and the side extremities measure 350 feet by 700 feet, the grid will measure 10 modules by 20 modules overall. The contour lines are defined in intervals which indicate a rise equal to the height of one module. For example, if the module is 10 feet vertically, then the contour lines will indicate a 10 foot rise on the site. These contour lines must then be approximated so that they coincide with the grid lines. The areas defined by these rationalized grid lines are numbered starting at the lowest point with zero in ascending order to measure higher levels in numbers of modules. These numbers measure the levels of the site and the computer assigns construction levels immediately above the site levels, e.g. if a particular point on the site is three levels above ground zero, the construction will begin on level four at that point.

The areas which are unavailable for construction at any level are indicated by a number which is higher than the maximum vertical dimension of the space envelope. The site matrix must be rectangular in shape and must be large enough to enclose the site completely. Areas outside the boundaries of the site are indicated as being unavailable for construction. As in the example, each space in the matrix contains the number assigned to the corresponding location in the site grid.

6.4.3. ELEMENTS

The programmed space of the facility is broken into functional units known as elements. Each element has a unique set of relationships. The conversion of the various functions into elements is based upon many considerations. One element could include a whole department, part of a department or a combination of departments, a clinic, a wing, etc. (See Figure 6.4.3) based on the space requirements and

and interrelationships. The planner/designer defines the elements based on his knowledge of the requirements and his experience.

The element as an entity has certain characteristics such as size, name, type and shape. The size is the square footage of the element and is measured in whole modules. An element must be at least one module in size and will be as many modules as necessary to most nearly approximate the actual square footage. Each element is assigned a name which consists of three characters. This is a convenience to the user and the computer does not use the name in calculations. The final layouts utilize the names of elements to facilitate recognition. The type of an element defines its nature with respect to two qualities. First, an element can be either real or "dummy." A real element is actually a functional element of the facility while a dummy is used for including non-functional spaces in the program. If an element is defined to be real, then it is one of three types with respect to adaptability. The type then defines the nature of element as a result of studies which measure the resistance to change or conversion inherent in the element. This is indicated as hard, medium or soft space. The use of these data is explained later. An element can be assigned a definite shape if desired. This is done by specifying the exact arrangement of modules and this arrangement will be used wherever the element is assigned on the site.

The computer is programmed to recognize an element as one contiguous, inseparable space. Unless the shape of an element is predefined, the computer may assign the element in any configuration observing only the rule that each module of an element must be adjacent to at least one other module of the same element.

Often it is necessary to relate the elements of the facility to other objects which are not part of the facility. These might include open space, access points, trees, or existing facilities. These can be defined as elements for purposes of relating them to actual elements of the facility. These items are categorized as "dummy" elements and are so indicated under element type. Usually these elements are fixed on the site and are not manipulated by the computer, nor are they considered in the evaluation routines.

6.4.4. PREDEFINED SHAPES

In order to predefine the shape of an element (the resulting arrangement of modules within an element), it is necessary to devise a system of describing an arrangement which cannot be changed by the computer but which can be moved around on the site. The shape of an element is described in terms of coordinates which are relative to one of the modules of that element.

A "floating grid" is used to define the arrangement of modules in an element. Figure 6.4.4 is an example of the methodology. It shows:

- The grid and shape of the element containing five modules.
- The floating grid overlaid on the element with the coordinates beginning at zero.
- The method of input to the computer.
- A resulting location of the modules on the site.

The locations are defined by coordinates called vectors. A vector is an ordered group of numbers which defines the location in space relative to an origin. In the example, the origin is the location (0,0). If the module at (0,0) is designated as the anchor module, then the locations of all the other modules are defined by vectors relative to the primary module. If a multi-level shape is desired, a three dimensional grid is used and one more coordinate is necessary--the origin is now (0,0,0).

When the anchor module is assigned a location on the site, it has a set of coordinates defining its location on the site. By adding the vectors* of the other modules to the coordinates of the anchor module,

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*In vector addition, the corresponding coordinates are added separately. For each vector there will be three additions. The order is of prime importance and the vectors must be in the same order as the location coordinates for the three dimensions.

the remaining modules can then be assigned to spaces on the site and the shape will be unchanged. In the example, the anchor module is assigned to the site location (2,4). The coordinates for the remaining modules on the site are derived by adding their vectors to the coordinates of the anchor module and the required shape has resulted.

When predefining the shape of an element, there is no restriction as to contiguity. Parts of the element can be separated as desired by the user as long as the entirety can be contained by the space envelope.

6.4.5. PREASSIGNMENTS

Frequently it is necessary to fix the location of certain elements. As it is necessary to give the computer a starting point, at least one element must be assigned a location on the site by the user. The new facility may have to be related to some existing features on the site. These features are defined as elements and the fixed locations of these elements must be indicated to the computer. Such elements might include access areas, site amenities, existing buildings or certain parts of the new facility for which the locations have been predetermined.

Preassignment is accomplished simply by assigning all modules of the element to particular spaces on the site. The coordinates of these spaces are then input with the element names. These elements will thus remain where preassigned, as the computer will not reassign them.

6.4.6. AFFINITY MATRIX

The difficulty in the layout of large systems is the resolution of many and complex relationships between the elements of the system. In the design of the program, relationships between elements were chosen as the prime rationale for the generation of layouts.

The best layout, with some exceptions, would place every element adjacent to every other element and thereby maximize all relationships. This is physically impossible in most problems. The computer will attempt to find the best solution for relationships while observing the other constraints of the problem.

A method to indicate priorities or strengths of relationships must be devised. The priority of adjacency of one element to another must be analyzed for every pair of elements in the problem. This analysis must take into consideration those factors which contribute to the need for affinity between elements. Some of these are flow of people (patients, staff, visitors), information flow, materials flow, utilities, commonality of construction. Although it is necessary to have as many hard data about these factors as is possible, the determination for the relative need for affinity between each pair of elements must incorporate human judgment.

In order to indicate these priorities, an Affinity Matrix is used, which is a numerical representation of the requirement for proximity of one element with another. A scale of numbers is established beginning at zero which can go as high as desired to designate "Maximum Affinity." The length of the scale depends on the degree of differentiation required. The scale most frequently used is zero to three. The highest number on the scale indicates Maximum Affinity or the elements which have the strongest relationships and, therefore, the greatest need for adjacency. Zero indicates that no relationship exists. The numbers between indicate varying degrees of affinity. These relative values assigned are governed by the relative need for the two elements to be adjacent. An advantage of this method is that each relationship can be considered independently, two elements at a time.

The numbers, determined for every pair of elements, are incorporated into a matrix for input to the computer. The matrix will be triangular in shape (see Figure 6.4.5). The number of affinities to be determined depends on the number of elements and can be calculated as follows:

N = the number of elements

and

A = the number of affinities

then

$$A = \frac{N(N-1)}{2}$$

The set of relationships between elements on the Affinity Matrix must be complete. An element on the matrix which is not related to any other element (its row contains only zeros) will cause an error. Such an element is not really a part of the problem, and it would be better to omit it until the important relationships have been solved. It is also possible to have a group of elements which are related to each other but not related either individually or as a group to the other elements in the problem. This is not easily detected on the matrix but if such an error exists, it will be identified by the computer and information will be printed to assist in finding the isolated group.

The computer program itself can be helpful in defining the Affinity Matrix. After the affinities for the individual pairs have been determined, the total effect of the combination of all relationships can be assessed. By removing all other constraints, the effect of the Affinity Matrix by itself on the configuration can be analyzed. The three dimensional presentation also helps the user to see the effect of the matrix and prompt adjustments to the affinities can be made as problems are discovered in the configurations.

Another utilization of the program to determine relationships between elements is to enter a separate matrix generated solely from one factor, e.g. a configuration based on material flow. This could be compared with other configurations generated from patient flow or information flow in order to rationalize the trade-offs between various criteria.

Flexibility exists in the generation and use of the Affinity Matrix as with most other components of the system. The process is iterative and it is expected that manipulation of the matrix will be required as the output is analyzed. The scale of the affinities can be as short or as long as desired. It will be found, however, that trying to obtain a high degree of differentiation between relationships is not justified by the results, and is time-consuming and difficult.

6.4.7. VECTOR LIST

It is necessary to define spatial concepts to the computer. The user must be able to input the concepts of adjacency, distance, and the relationship between vertical and horizontal distance as they apply to each different problem. Different sites require different relationships between horizontal and vertical distances. A more confined site requires more vertical construction than a large site. The practical definition of adjacency may vary with the overall size of the facility or with different concepts of circulation. By defining these concepts explicitly, the user has the capability of guiding the process toward a better solution.

A "floating grid" is generated which can be superimposed on the site at any location, defining the proximities of all other locations in the vicinity. Figure 6.4.6 illustrates this. Space B on the site represents the location from which it is necessary for the purpose of this process to know the relative distances of all locations nearby. While this is a simple problem for the human mind, the computer must be told precisely how to define the distances. To do this, a grid (a) is created with an origin (space A) which is the location under consideration. The user now analyzes the relative proximity of all surrounding locations. Many of these are equidistant from the origin and thus can be grouped. As the distances become greater, spaces which are "nearly equidistant" can be grouped. The distance is indicated by numbering the locations according to the relative distances beginning with 1 for the most proximate.

If this grid is superimposed over the site plan as in (c), the relative distance of each site location around the original position can be ascertained. The example shows only the horizontal dimensions but locations on the upper and lower levels are defined similarly. It is assumed that all locations which have the same number are equidistant, e.g. all locations numbered 1 are equidistant from the origin. The number of locations to be defined, or the size of the total area, is determined empirically. This determination (clarified in the discussion on generation process) consists of the needs of the computer for space definition and the maximum availability of space to store the vectors in the computer.

The floating grid is input into the computer. The computer uses this grid as an overlay in order to calculate the relative proximities. This information must be organized numerically (Figure 6.4.7). If the origin is designated at the coordinates (0,0,0) the other locations on the grid can be numbered with coordinates relative to that origin. The coordinates of each location are then entered on a list called the Vector List in numerical order by group number. It is then necessary to input into the computer the manner in which the equidistant locations are grouped: (those locations included in each group are considered to be equidistant from the origin), e.g. group one contains four locations all of which are equidistant and these are the first four vectors (coordinates) on the list and are therefore the locations closest to the origin. Group two contains eight vectors and are the second closest, etc.

The user has complete freedom in grouping the spaces and in determining the number of groups. There are no limitations to the number of groups which can be included--however, the arrangement of these groups has an effect on the outcome of the generation process, so that much consideration must be given to the order to the Vector List.

6.4.8. THE PROCESS

Generation of configurations is a growth process. The user makes the first assignment of an element to the site. Using this as a starting point the computer "grows" the rest of the configuration using the Affinity Matrix to govern the order in which the elements are assigned. The Vector List is used to search out available locations.

The computer records the locations of each module of every element on the "Output List." At the beginning of the process, the list contains the locations only of those elements preassigned by the user. As each element is assigned a location on the site, the coordinates of its modules are recorded on the Output List. When the list is complete, the configuration is complete and the process is terminated.

In each step of the process, an element must be selected for assignment and an available location must be found. Both relationships and proximity must be observed. The selection is based upon relationships and the selected element must have affinity for an element that has already been assigned a location (the process of selecting the element to be assigned is further explained in section 6.4.8.2).

6.4.8.1. Assignment of Elements

Elements are assigned module by module. In making assignments, two modules are considered. The first module has a location on the site and is called the "anchor module." The second module does not have a location on the site and it is to be assigned as close as possible to the anchor module. It can either be a part of the same element as the anchor module (where the element has not yet been completely assigned), or a part of a different element when assigning the first module of a new element. Figure 6.4.8 shows the anchor module (*) as part of element 2. The next module to be assigned is the last module of element 2. Then the first module of element 6 is assigned and so on.

When the anchor module has been determined and the module to be assigned is selected, the computer must find an available location as near as possible to the anchor module to which the next module will be assigned. The Vector List is used for this search. Conceptually, the floating grid is overlayed on the site so that the origin of the floating grid coincides with the location of the anchor module. The module will be assigned to the first available space which has the lowest possible number. The search is actually a mathematical process.

The computer records the status of each space within the space envelope. When a location has been selected, this record is checked to see if the location is available. A module may have already been assigned or a location may have been excluded by the topography matrix as being underground or otherwise unavailable. Vector addition is used by the computer to search the record. By adding one of the vectors from the Vector List to the coordinates of the anchor module, the move to another location can be made. Figure 6.4.9 demonstrates this. In the example, the anchor module is located at coordinates (3,6,1). The first vector on the list is added resulting in the coordinates (3,7,1). The record is checked for the location--(1)-- and if it is available, the module is assigned to that location. The computer makes the assignment by entering the element name and the coordinates (3,7,1) on the Output List, and changing the site record to show that the location (3,7,1) is unavailable for future assignment. If the location is not available, the next vector is added and the record is checked. This process is repeated until an available location is found or until the Vector List is exhausted. If the latter occurs, the entire process is begun again and a message will be printed indicating that this has happened. If it occurs too frequently, this indicates that the Vector List needs to be expanded to include more locations.

One of the stated constraints is that elements must be assigned so as to result in one continguous space. This means that each module of an element must be adjacent to at least one other module of the same element. In order to implement this contraint, the search process is restricted to the first group of vectors where the anchor module and the module to be assigned are part of the same element. This then implies that all locations in the first group are adjacent to the origin. This must be considered when ordering the vectors and defining the groups. This constraint does not apply to elements with predefined shapes. The user inputs a special set of vectors for this search process and he may define the shape in any way desired. The Vector List is always used to assign the first module of an element as closely as possible to the preceding element. For the remaining modules of an element, the computer uses only the first group of vectors on the Vector List or when available, the special set of vectors which predefine a specific shape. If there are not enough locations to assign the remainder of the element either in a prescribed shape or so that the modules are adjacent to each other, the first module is then moved to new locations until an area is found which is large enough to accommodate the entire element.

If all locations defined by a group of vectors are found to be unavailable or if the corresponding areas are too small for the new element, the computer changes the anchor module and trys the vector group again before moving to a group with a higher number. For example, if the anchor module is a part of an element containing five modules and if none of the locations defined by vector group one were available when trying to assign a new module, the same vector group would be tried again with another of the five modules as the anchor module until group one vectors had been tried with all five modules as anchor module. If the results still remain negative for available locations, the search will be continued in the same manner using group two vectors until available space has been found for the entire new element.

When assigning elements without predefined shapes it is only necessary to find the proper number of contiguous spaces as long as only group one vectors are used. When a shape has been predefined, however, it is necessary to find the proper number of spaces and these must be in the correct arrangement. After the first module of the element has been assigned, the remaining elements are assigned to the locations defined by the special Vector List. Should a required location be found unavailable, it will be necessary to backtrack to the location of the first module. In this case, the computer will manipulate the vectors so as to translate and rotate the shape in all possible ways with respect to the first module until the proper locations are found. All different orientations are tried before the first module is moved to another location.

As each module is assigned a location on the site, its coordinates are recorded on the Output List. These locations are temporary until the entire element has been assigned as it may be necessary to move to a different location.

Example: Figure 6.4.10 demonstrates the progression of activities and the assignment process. For reasons of clarity, the demonstration is restricted to one level. In actuality, the Vector List contains locations above and below this level and when necessary, elements will be assigned on different levels. Figure 6.4.10-a shows the site plan for level one which contains areas unavailable for assignment because of a hill, because of portions outside the regularly shaped site and because of a lake in the middle of the site. Several elements have already been assigned and several elements remain to be assigned.

The anchor module is designated as a module of element number two (indicated by an asterisk) and a module of element number four has been selected for assignment. The objective now is to assign the module of element number four as close as possible to the anchor module. Using the Vector List, a search is made for available space (Figure 6.4.10-b). The first attempt is made to the right and that location is found to be unavailable. The second trial is to the left and that space is found to be occupied. On the third trial, the space below the anchor module is found to be available so the first module of element number four is assigned to that space. Temporarily, that first module of element number four becomes the anchor module in order to assign the remaining modules of element number four. Only group one of the Vector List is used in an attempt to find space for the two modules which remain in element number four; the spaces are found and assigned as shown in Figure 6.4.10-c.

Assume now that element number five has to be assigned as close as possible to element number two. The anchor module remains the same— the module of element number two indicated by the asterisk (Figure 6.4.10-d). The search pattern is restricted at first to group one vectors but all four positions immediately adjacent to the anchor module are occupied. Before using the next group of vectors, a different anchor module is selected in element number two (Figure 6.4.10-e). Still using group one vectors, the location immediately to the left of the new anchor module is found to be available. The first module of element number five is assigned to the location (4,4,1). With that module of element number five as the anchor module, the second module of element number five is assigned immediately above the first, to location (3,4,1). However, there is no available location to which the third module of element number five can be assigned adjacent to one of the first two modules of element number five. Therefore, the first two modules of element number five are removed and the search pattern is continued. As there are no more available locations defined by group one vectors, a new anchor module is selected (Figure 6.4.10-f). The first module of element number five can be assigned to the location (2,5,1) and there is also room for the remaining two modules to be assigned so that element five is one contiguous space (Figure 6.4.10-g). Element number five has a high affinity for element number two. As this demonstration shows, every attempt is made to assign an element as close as possible to the element for which it has a high affinity. However, the rule concerning the contiguous space within an element must be observed and this, on occasion, will force the element to be assigned some distance away from the anchor module. But, before moving a longer distance away, new anchor modules will be selected from the same element.

Elements that have predefined shapes represent special cases. In Figure 6.4.10-h, element seven has a predefined shape. It is necessary to assign element seven as near as possible to element two. Assume that every module of element number two has been used as the anchor module while searching with group one vectors. Having found that all spaces adjacent to element number two are either unavailable or too small for element number seven, it is now necessary to use group two vectors for the search. The space indicated by the (b) is too small to contain element number seven. When the space below and to the right is found to be unoccupied, the first module of element number seven is assigned to it (Figure 6.4.10-i). Rather than using group one of the Vector List, the predefined shape vectors will be used to search locations for assigning the remaining modules of element number seven. The attempt is made to assign the element exactly in the shape and orientation defined by the input vectors. Before moving a greater distance from the anchor module, the program will attempt to make the assignment of the shape by translation and rotation, i.e. by trying to fit it in any way it can. In this example, element number seven is assigned fitting the orientation indicated (Figure 6.4.10-j). Should the computer not find a space available in order to fit this element, it will move to another module of element number two and move a greater distance from the anchor module until a space is found to accommodate the size and shape of element number seven.

6.4.8.2. Selection of Elements

The Affinity Matrix is used to select elements for assignment into the layout. This assures that the configuration is based on the inter-relationships among the elements.

Each step in the process must include an element already located on the site and one which has not yet been assigned a location. The pair is selected based on a mutual affinity and they are assigned to the site as near to each other as possible. Each element has many relationships and the highest relationships are satisfied first. The selection process is based on the Maximum Affinity between elements (those with the highest number on the scale). Once all of these have been considered, lesser affinities will be used in selecting alternate pairs.

There are two lists of elements to be considered. First, the list of elements in the problem which includes those to be incorporated into the configuration. Second, the list of those elements which have already been assigned (Output List), are maintained in the order of assignment. The element pair consists of the primary element which has been assigned and the secondary element which is to be assigned. The primary element is selected from the Output List. The secondary elements are selected based on Maximum Affinity to the primary element. When all elements with Maximum Affinity to the primary element have been assigned, a new primary element is selected which will be the next element on the Output List.

Occasionally, a point will be reached when none of the elements on the Output List have Maximum Affinity for any unassigned elements. When this occurs, a secondary element must be selected which has a lesser affinity. Having assigned this element (of lesser affinity), new elements are selected based upon Maximum Affinity until it is again necessary to reduce the criterion.

The first elements on the Output List are those preassigned by the user. At least one element must be preassigned as a starting point. If more than one element is preassigned, the order in which they are assigned should be considred carefully as this will determine the initial pattern of the growth of the configuration. The computer will move to the first element and satisfy its Maximum Affinities and will then move in order to the second, third, etc. Widely separated preassignments can tend to disperse the solution and the importance of the relationships must be carefully thought out. This can be a useful device for examining the relationships and does provide the user with a flexibility needed to guide the generation process.

Example: In order to facilitate the process of element selection. the Affinity Matrix is first converted from the triangular form input to a square form. The information remains unchanged but is merely duplicated on the other half (6.4.11). Complete relationships for a particular element can be found, both on one row and on one column.

Figure 6.4.12 shows an Affinity Matrix and an Output List. There are ten elements to be assigned and the Maximum Affinity is three. The first two elements on the list, one and four, have locations preassigned by the user. Note that element number one is one module in size and element four is two modules. At this point, none of the succeeding elements have been assigned.

In step one, a primary and secondary element must be designated. The primary element will be element number one since it is the first on the Output List. The secondary element is selected from the Affinity Matrix. The relationships of element number one (column one) are scanned in order to find an element with the Maximum Affinity which, in this example, is a 3-affinity. The first 3-affinity is with element number three, therefore, the secondary element is element number three. Element three is assigned a location close to element number one (a process described previously). The locations of its modules, with the element name (3), are added to the Output List. Another secondary element is selected from the Affinity Matrix: the next 3-affinity in column one is with element number four which has already been assigned. Element number five is the next and in step two, element number five is assigned as the secondary element. The 3-affinities in column one have been exhausted and a new primary element must be selected. Since element number four follows element number one on the Output List, the new primary element will be element number four. Column four on the Affinity Matrix is scanned and the secondary element in step three is element number ten. Returning to the Output List, element number three, the first assigned with this process is the new primary element. In step four, we find that element three has no 3-affinity with unassigned elements. In step five, element five is the next element on the Output List and thus becomes the new primary element. Element five has a 3-affinity with elements one and two. Since element one has been assigned, element two is the secondary element for step number five. Element ten is the new primary element in step six since the 3-affinities with element five have been exhausted. However, it is found that element ten has a 3-affinity with element four only and element four has been assigned. So element two becomes the primary element in step seven, but element two has no more 3-affinities. At this point, element two is the last one on the Output List. Both a secondary element and a primary element have to be selected and none remain. In fact, none of the elements on the Output List has a 3-affinity with any unassigned element. Thus the criterion is reduced and, using element number one as the primary element once again, an element with a 2-affinity is sought.

In checking the affinities of the primary elements in order, the first primary element having a 2-affinity with an unassigned element is element number three. The secondary element for step eight is element six. Element six is assigned and becomes the primary element for step nine. Again, a 3-affinity is sought. Element number seven is assigned in step nine and element number eight is assigned in step ten. The primary element, six, has no more 3-affinities, so element number seven (next on the Output List) becomes the primary element. Element number seven has no other 3-affinity so element eight is primary for step twelve. Element number eight also has no 3-affinities and again no more elements can be designated as the primary element. Once again, element one is designated as the primary element and 2-affinities are selected. This time, the first one that occurs is a 2-affinity between elements six and nine. When element nine has been assigned, the process is finished. A complete layout has now been generated since all the elements have been assigned.

6.4.8.3. Randomization

It can be seen that the process used by the computer does not insure that the solutions generated will be optimal with respect to the relationships. Differences occur when different decisions are made at each step. For example, if the elements are selected in a different order, the solution will be different, for better or worse. In the search for available space and the selection of each location, the pattern for the whole configuration is determined. Within each group of vectors, the locations are assumed to be equidistant from the origin, but the order in which each location is tested affects the outcome. A different ordering of those equidistant vectors will generate a different solution. These decisions are actually choices among equal alternatives: choosing the next location from the list of equidistant possibilities demands a random decision on the part of the computer. If an element has Maximum Affinity for three other elements, the choice of one for next assignment must be random since the three possibilities are of equal importance. The designer would use a combination of methods at each step. If there was actually no difference he would choose randomly, or he might plan ahead and analyze the effect of each choice. This type of analysis is possible only up to a point. If the designer were capable of a complete analysis, there would be no problem and the layouts he generates would be optimal in every respect. It is more likely that he will lay out a form and then evaluate it and make the changes as necessary. This is time-consuming and the myriad of facts and constraints are overwhelming. This same process is carried out by the computer both to generate the layouts and to form part of the analysis. It is impractical for the computer to go into extensive analysis at each stage of the generation process. Thus, the decisions between equal alternatives are based upon a random process.

Two types of decisions are left to random chance. First, the order in which elements are selected for assignment and second, the order in which equidistant locations are checked for availability. To do this, the Affinity Matrix and the Vector List are "randomized." Thus, while each solution attempts to maximize the affinities and minimize the distances, the solutions will be different because of different decisions made at each step. Each solution represents a different set of decisions and the result will be a range of solutions--some better than others.

A random number is one which is chosen from a group of numbers such that any number in the group has an equal probability of being selected. When facing a decision between equal alternatives, a choice might be made by tossing dice, flipping a coin, or choosing a number from a hat, all of which can be random processes. In a computer, the list of equal choices is placed in random order and then taken in that order. Figure 6.4.13 shows how the Affinity Matrix is randomized. It will be recalled that in picking a new secondary element, the column is scanned and the next element with Maximum Affinity is selected. If the rows of the matrix are randomized each time, the elements with Maximum Affinity will fall into different order, and in the next round of selections, the elements will be selected in different order.

The computer program contains a routine which generates random numbers between specified limits. In order to randomize, two rows are selected at random and interchanged a number of times so that the new order will be very different.

The Vector List is randomized by the same technique as is used on the Affinity Matrix. It is important to keep the groups separate and in the same order since these define ascending orders of distance. The interchange (Figure 6.4.14) is only between vectors <u>within</u> a group. Each time the list is randomized, the equidistant locations within each group will occur in a different order.

6.4.9. EVALUATOR

It is the responsibility of the planner or designer to choose the best of the several configurations generated by the computer. However, many of the criteria he would use in evaluating the configurations can be assessed by the computer. To aid in the comparative analysis of the configurations, the second and perhaps most important section of the system has been developed to perform the evaluations of the solutions generated by the computer. This function should be considered to be open-ended, i.e. those operations now performed represent only a few of the possibilities for computer evaluation. The Evaluator could include any criterion (if it can be programmed) the user might wish applied.

The evaluation function can be used with any configuration. It has been applied to existing structures and to human-generated designs. It is necessary only to define elements, modules and relationships and to input the fixed site locations for the entire entity.

6.4.9.1. Distance Index

Upon the completion of each configuration, the computer generates a "Distance Index." The index is a number which is a relative measure of the efficiency of the layout with respect to affinities and distances. It is used primarily as a device for screening and sorting the configurations and does not, by itself, represent a valid indicator of the quality of a solution.

Each increment of the Distance Index is calculated by measuring the distance between two modules and multiplying that distance by the affinity between the elements of which the modules are a part. The formula for distance measurement is determined by the user and is a mathematical expression which relates vertical distance to horizontal distance. Figure 6.4.15 shows a commonly used method. The user determines the method which best conforms to his assumptions about internal distances.

The distances are measured between every pair of modules in the configuration. Each pair of modules has a mutual affinity which is indicated by a value on the Affinity Matrix. If the modules are a part of the same element, the relationship is always 0 since the affinity of an element for itself is always a 0 on the Affinity Matrix. The distance is multiplied by the affinity to get the Distance Index Increment. If the affinity is 0, the increment will be 0; if the distance is 0 (adjacent modules), the increment will be 0. Greater distances and higher affinities yield higher Distance Index Increments (the Distance Index for a solution is the sum of the increments for every pair of modules). When all requested solutions have been generated, the computer sorts the Distance Indexes in ascending order (from best to worse).

Normally the user will request more solutions to be generated than he wishes to have printed out. Those solutions which are printed represent the best from a large number generated, based on lower Distance Indexes.

6.4.9.2. Adaptability Index

Each element is determined by the user to be hard, medium or soft. This information is input to the computer under element type. These categories describe the quality of construction of the element with respect to the difficulty of changing the space to another use. Hard indicates a high cost of conversion of the space while soft indicates that the space is easily adaptable. Each increment of the Adaptability Index is a relative measure of the difficulty of expanding a module into each of the four adjacent spaces. The index depends on the type of element to be expanded and the type of element which occupies the space into which expansion will take place.

A table is input listing factors for each of the expansion possibilities. (Figure 6.4.16) The factors are determined by the user and are relative values of the difficulty of expanding from one module to another according to the types of spaces involved. Expansion into unoccupied space (outside the building) is included and the factor varies according to the level since expansion to the outside becomes more expensive the higher it is.

Each module is evaluated assuming possible expansion to all four sides and the factors are totaled for all modules to obtain the Adaptability Index. A low Adaptability Index is desirable in order to achieve the minimum cost for future changes.

6.4.9.3. Cost Index

The Cost Index is a relative number which measures certain items of capital cost such as roofing, windows, walls, elevators, stairways and structure. The user assigns factors to each of these items proportional to the relative cost of each. The computer analyzes each configuration and determines the total cost for all factors.

The number of windows (external walls) is determined by counting the number of modules which face the outside. One "window factor" is counted for each module face which has no other module assigned next to it.

The number of modules requiring roofing is determined by those modules with nothing assigned above them. One "roof factor" is counted for each such module.

One "structural factor" is counted for each module in the configuration.

To derive at "costs" for elevators and stairways the entire solution is evaluated and certain rules input by the user are applied. The number of modules on each level is counted. The user must indicate the number of stairways per module on a level, e.g. one stairway for each four modules on a level with a minimum of two per level. The number of stairways are then counted and a factor is added to the Cost Index for each. Elevators are handled in the same way except that the second level only is used to determine the number of elevators required for the entire configuration.

The Cost Index, then, is the sum of all these factors and is an indication of the expense of each configuration and which can be compared to the indexes for other configurations. This routine should be considered open-ended. There are possibly other factors which could be included in such a cost estimate. The factors and the rules for applying them are based upon realistic cost estimates and various legal and safety requirements. However, it must be remembered that the resulting index is only an approximation and its real value lies in the capability of comparing the various configurations generated under similar conditions.

Much development is yet to be done in the area of configuration evaluation. The task of evaluating a large number of solutions is tedious and time-consuming. Many routine questions that might be asked about each configuration can be programmed so that the answers are printed with each solution, or the computer can be instructed to discard solutions failing to meet specified criteria. There are numerous possibilities in this direction.

6.4.9.4. Layouts

The overall listing for each run prints out all the input data for quick reference. The first page is a summary of the data (see sample in Figure 6.4.17). Succeeding pages contain the Vector List, element definitions, Affinity Matrix, dummy elements, predefined shapes and a listing of the preassignments.

As indicated earlier, the computer stores the configurations in the form of a list of element names and coordinates. To assist the user in reading the configurations, a special routine prints the configurations in the form of floor plans of form diagrams. The name of each module of each element is printed in its relative position as in the sample printout. (Figure 6.4.18).

Evaluation results are printed with each solution. A summary of the evalutation results for all configurations generated is printed prior to the listing of the configurations.

6.4.10. CONCLUSION

The planner/designer will analyze and evaluate the printed layouts and make certain adjustments. Since the layouts as generated by the computer are rough, they must be treated as approximations. For example, it is common to find the exterior walls are quite irregular and that frequently modules will be assigned on higher levels with nothing assigned directly below. Such problems are a result of the incremental method of the machine. RELATE is concerned with relationships on a detail level and at present there is no "smoothing" process built in to deal with the overall view.

One layout may be found which is comparatively good in all respects and with some refinement, will be the final form diagram. More likely, however, in the early runs the designer will find errors in his assumptions or will wish to provide further constraints. He may select certain parts of a layout or combination of layouts and preassign those parts for another computer run, leaving the remaining parts to be reassigned by the computer. Such steps in the use of RELATE are important and involve a high level of interaction between man and machine. Of the many layouts generated, some may spark new approaches which might not otherwise have been conceived. Whether or not the designer uses any of the layouts generated by RELATE, the use of the program will force him to clearly state his assumptions and aid him in grasping his own concept and working methods.

In designing RELATE, the attempt was made to maintain as high a degree of flexibility as possible. Many assumptions were left to the user in anticipation that the program would be used by different people under different conditions. Many such assumptions are altered by the simple changing of a data card. Others require reprogramming of the actual procedure. This is particularly true of the evaluation routines. The three indexes described are only the first steps in what will be a much more complete evaluation function. The program which contains the evaluation routines was purposely constructed so that additional routines could be easily added. Such routines would be programmed and entered so that the computer could perform any screening or evaluating to assist the designer.

RELATE has an intrinsic flexibility with respect to scale. Mathematically, the modules used by RELATE are only points in space. Therefore, the square module is only a concept for convenience. In actuality, the computer only manipulates the centroids of the areas on a grid which requires only uniform spacing of these centroids. The module could be any shape as long as it can be represented on a uniform grid. Such practices relate to design concepts, however, as the purpose of RELATE is only to manipulate the functional spaces which are more rationally represented by the conventional square module.

Just as no specific form is represented by the points in space, neither do they represent specific size. Through definition of the scale the planner/designer can work with spaces of any magnitude. The size of a module (the space represented by a centroid), for example, could be defined to be large enough to do regional planning over many square miles, or small enough to plan a single office or laboratory.

RELATE has limitations, many of which have been mentioned. The process of planning and designing is most difficult to program for a computer. Computer programs depend upon comprehensive mathematical formulations of concepts and procedures. Design today is intuitive in large part, but the computer is not intuitive. Until planners and designers can quantify their methods and develop sound mathematical bases for their work, the computer will be unable to participate in all but the most rudimentary tasks. The use of formalized layout approaches requires the acceptance of gross assumptions which are not easily changed. In spite of all attempts at flexibility, this is necessarily true of RELATE.

RELATE is programmed in FORTRAN IV (F) for use on the IBM system 360 model 40. The program requires a minimum configuration of 128,000 bytes of storage. The running time and associated costs vary widely with the size of the problem and the various ways of structuring the input. Layout generation times have varied from 30 seconds for a problem of 30 elements to five minutes for 110 elements. Tests to determine the minimum number of layouts that should be generated have not been made, but the quality of the result should theoretically increase directly with the number of configurations generated.

6.4.11. FUTURE MODIFICATIONS

6.4.11.1. Path-oriented Construction Algorithm

This feature has already been programmed but not completely tested. It is a technique of determining the sequence of assignment of the modules which is not random, but based upon the concept of affinity-value. Recall that the process of selecting the next element for assignment to the layout, the computer scans the column on the affinity matrix of the element already on the site, seeking another element which has the Maximum Affinity rating with it. There might be more than one other element with the highest rating and these are considered as equal alternatives. The order in which they appear on that column will determine the order of their assignment. Therefore, the present method ensures that they will appear in random order and that for each layout they will appear in a different order. By the path-oriented technique the elements will appear in an order which is based on the weight of total affinities of that element. Each row on the matrix (each element) is summed across the affinity ratings. They are then sorted in descending order of the sums. Thus those with the most important relationships will appear first in each column and will be selected first for entry into the layout.

Preliminary tests of this technique indicate that the layouts generated are no better than those generated by the random method. However, due to the logical approach it represents, further testing will be done and it is anticipated that it will be included as an optional feature of RELATE.

6.4.11.2. General Smoothing Routine

Due to the roughness of the output, it has been considered important to develop a routine which will make many of the adjustments unnecessary, thereby making the evaluations output by the computer more valid. Such a routine would fill gaps and tend to make the layouts more workable. No programming has been attempted on this improvement.

6.4.11.3. More Valid Considerations of Light and Air

The present method attempts to make the resulting layouts as compact as possible without regard to necessary windows and open spaces. A method is needed for realistically indicating dynamic inclusion of such features. At present, there are a number of ways for this to be done, Dummy elements for light and air can be included, the site can have a predetermined pattern of open spaces, or buffer space for light and air can be included in the functional elements by expanding their sizes accordingly. These, however, are not entirely satisfactory. The programming has not yet been begun on this step.

6.4.11.4. Zoning of the Site

It is often necessary to indicate ground coverage factors for various parts of the site. The machine would then build over only a certain percentage of the available land in such areas. This could be accomplished by explicitly defining only the necessary percentage of the site to be available, but the selections should be based upon functional needs, rather than such a constraining method.

6.4.11.5. Efficiency

Means for making the operation of the computer method more efficient are being sought. The solution time has been reduced over 60% since the first trials of the program. In addition, input and output techniques are constantly reviewed to detect any potential modifications that might result in easier use.

6.4.12. DEFINITIONS

Affinity — The affinity number, used for a pair of elements, indicates the degree of attraction or relationship between elements requiring proximity. The relative value indicated for each pair is a guide to the relative importance of adjacency based on some scale, e.g. zero to three.

Maximum Affinity — Highest number on the scale of affinities; it describes maximum need for adjacency.

Anchor Module — The module in the layout near which the next module to be assigned will be located.

Configuration — Arrangement of elements in space. Configuration is often called a solution. Each configuration is a candidate for incorporation into the final layout.

Constraints — Definitive characteristics which must be observed within a configuration. Constraints are considered at the time of generation so that each configuration is known to abide by all constraints.

Criteria — Measures by which solutions are evaluated. Criteria may be constraints which are not feasible to program so that the generated solutions are evaluated against criteria and eliminated or adjusted accordingly.

Department — An organizational unit.

Distance Index — An evaluator of configurations. It is a number which represents compactness of the configuration relative to affinities. It is used for sorting and eliminating configurations. It is the sum of the distance index increments.

Distance Index Increment — The distance between a pair of modules multiplied by the affinity between the pair of elements of which the modules are a part.

Element — Smallest individual entity in the system which has its own identity, size and affinities. The size of an element may be one or more modules. An element can include an entire department, a part of a department, or can be a combination of several departments depending on relationships, space and shape requirements or content.

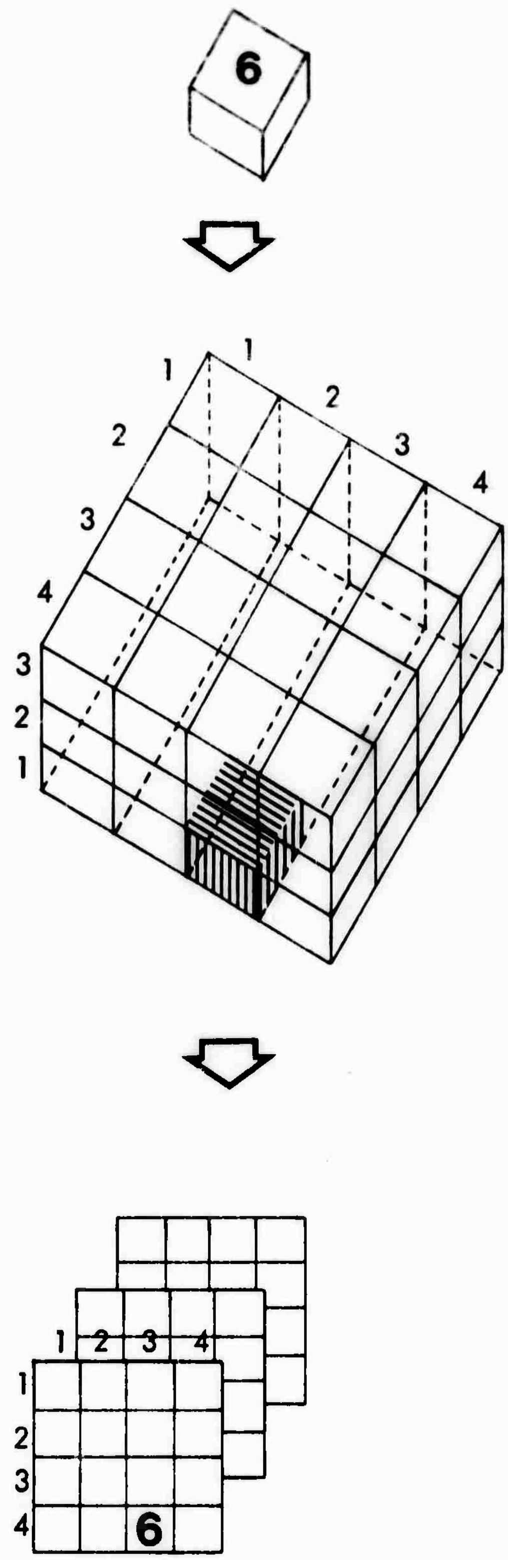
Free Space — Space envelope large enough to allow free growth of a configuration; must be large enough to simulate having no boundaries.

Module — A basic unit of measurement, an enclosed space, the size of which is determined by the planner; it is usually equivalent in size and shape to the planning unit.

Output List — A table which contains a list of the elements and a set of coordinates defining the location of each module of each element.

Space Envelope — Represents the maximum limitations which have been delineated in which the final layout must exist. It is defined in terms of three coordinates which indicate the maximum distance in each of the three dimensions. The distance is measured in modules.

Vector A set of coordinates which defines a point on a graph or a space on a grid or a particular element of a matrix. Vectors can be added and subtracted to transfer one space to another.



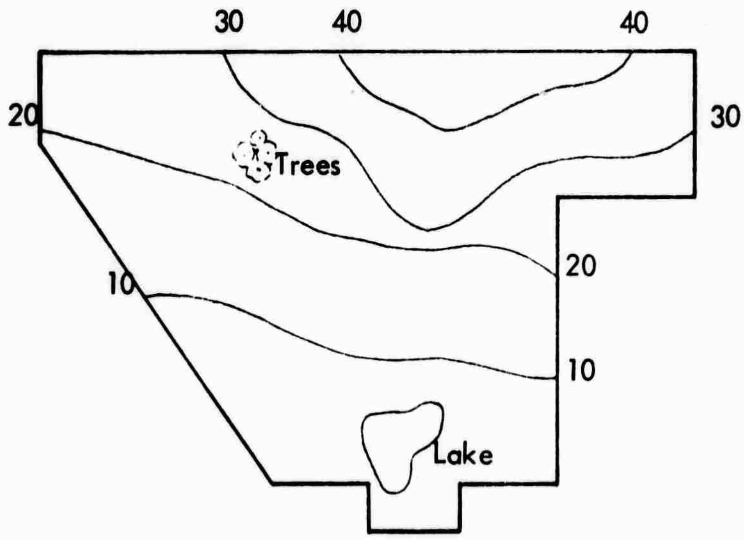
MODULE

SPATIAL GRID

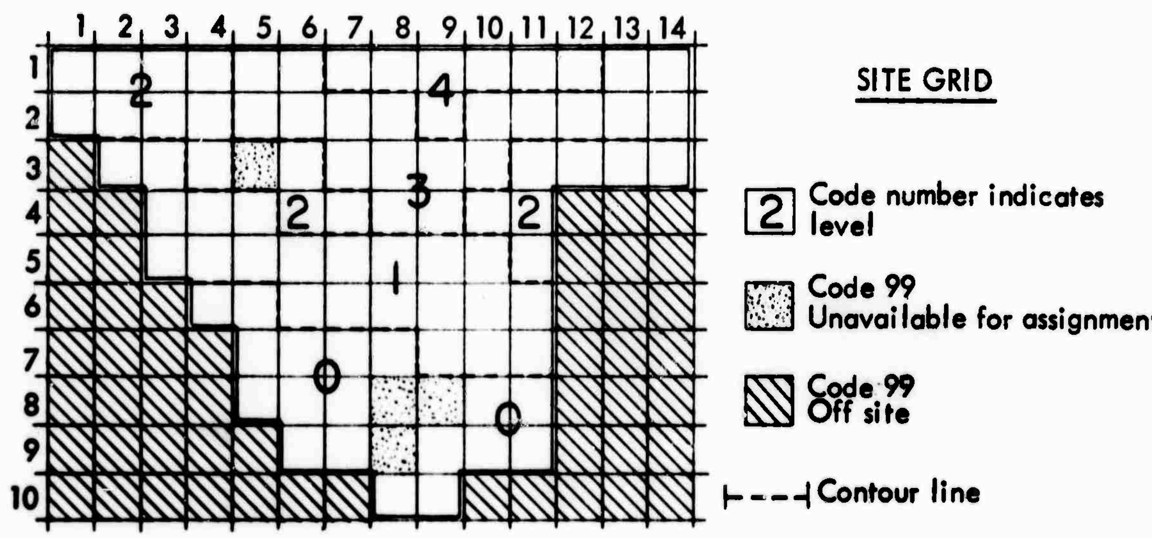
MATRIX

A number in the matrix represents a module. The location of the number on the matrix corresponds to the location of the module on the grid.

FIGURE 6.4.1 SPATIAL AND MATHEMATICAL CONCEPTS



SITE



SITE GRID

MATRIX

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	2	2	2	2	3	3	4	4	4	4	4	4	3	3
2	2	2	2	2	3	3	3	3	4	3	3	3	3	3
3	99	1	1	2	99	2	3	3	3	3	2	2	2	2
4	99	99	1	1	1	2	2	3	3	2	2	99	99	99
5	99	99	1	1	1	1	1	1	1	1	2	99	99	99
6	99	99	99	0	0	1	1	1	1	1	1	99	99	99
7	99	99	99	99	0	0	0	0	1	1	1	99	99	99
8	99	99	99	99	0	0	0	99	99	0	0	99	99	99
9	99	99	99	99	99	0	0	99	0	0	0	99	99	99
10	99	99	99	99	99	99	99	0	0	99	99	99	99	99

COMPUTER

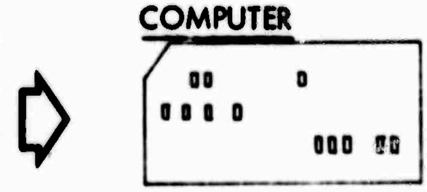
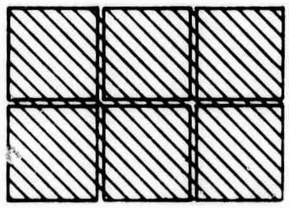


FIGURE 6.4.2 THE SITE MATRIX

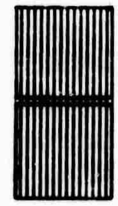
SURGERY

6 Modules



CENTRAL STERILE SUPPLY

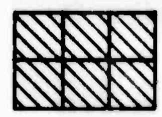
2 Modules



ELEMENT--Smallest individual entity in the system which has its own identity, size and affinities. The size of an element may be one or more modules. An element can include an entire department, a part of a department, or can be a combination of several departments depending on relationships, space and shape requirements, or content.

1.

Element #1 -- 6 modules

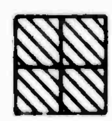


Element #2 -- 2 modules

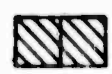
2.

Element #1 -- 2 modules

Element #2 -- 4 modules

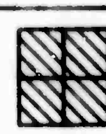


Element #3 -- 2 modules



3.

Element #1 -- 4 modules



Element #2 -- 4 modules

4.

Element #1 -- 8 modules

FIGURE 6.4.3 ELEMENT DEFINITION

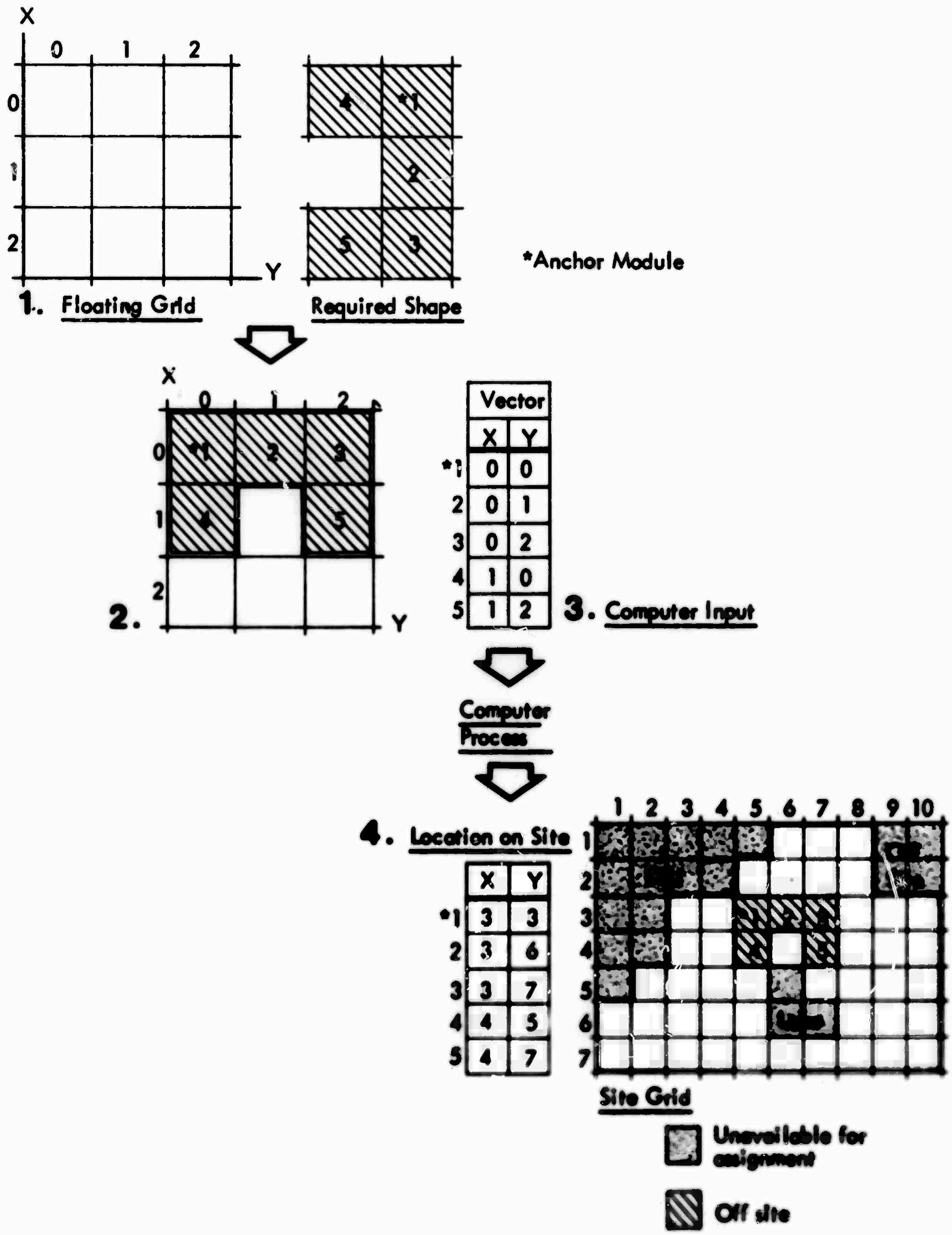


FIGURE 6.4.4 PREDEFINED SHAPES

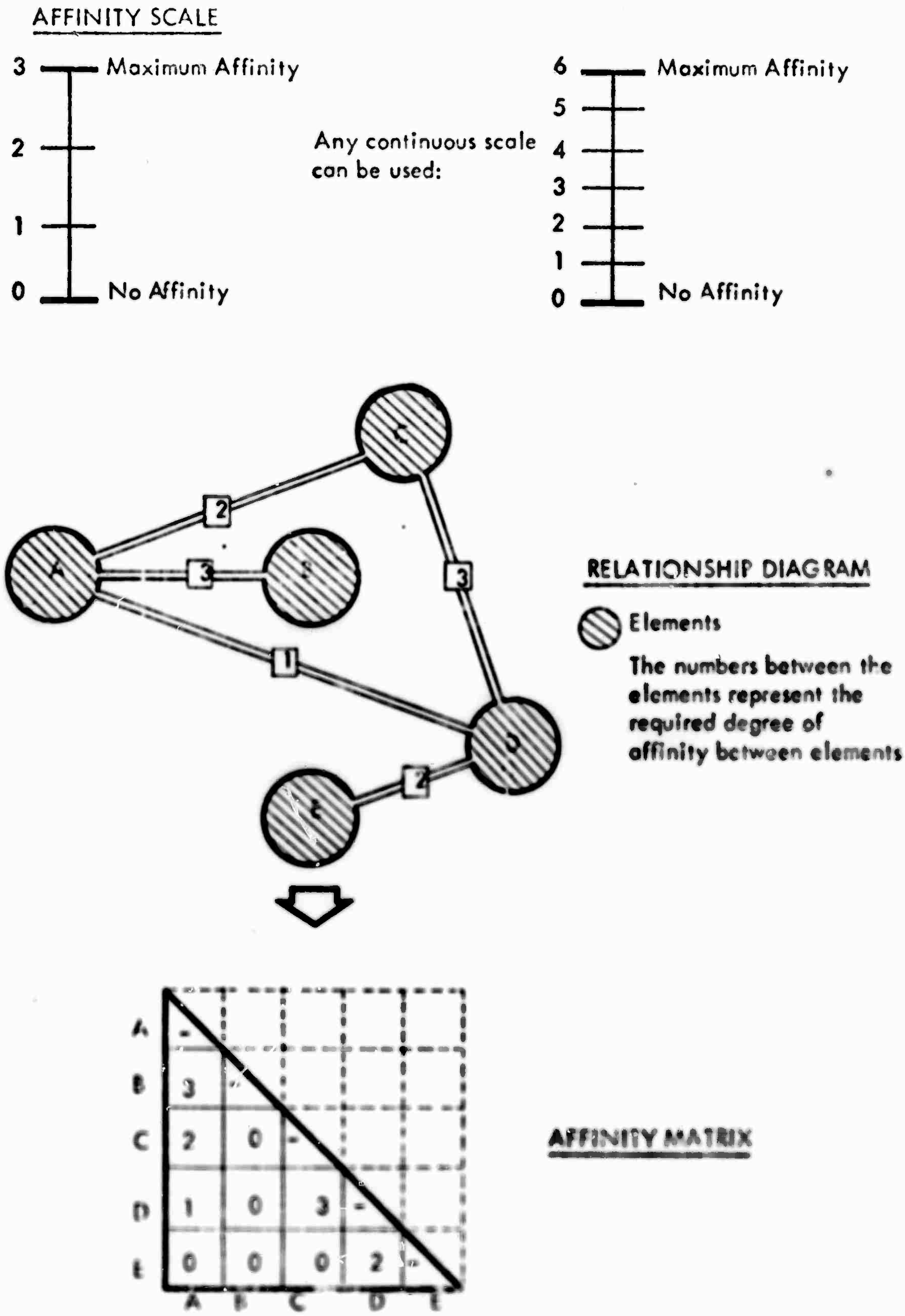
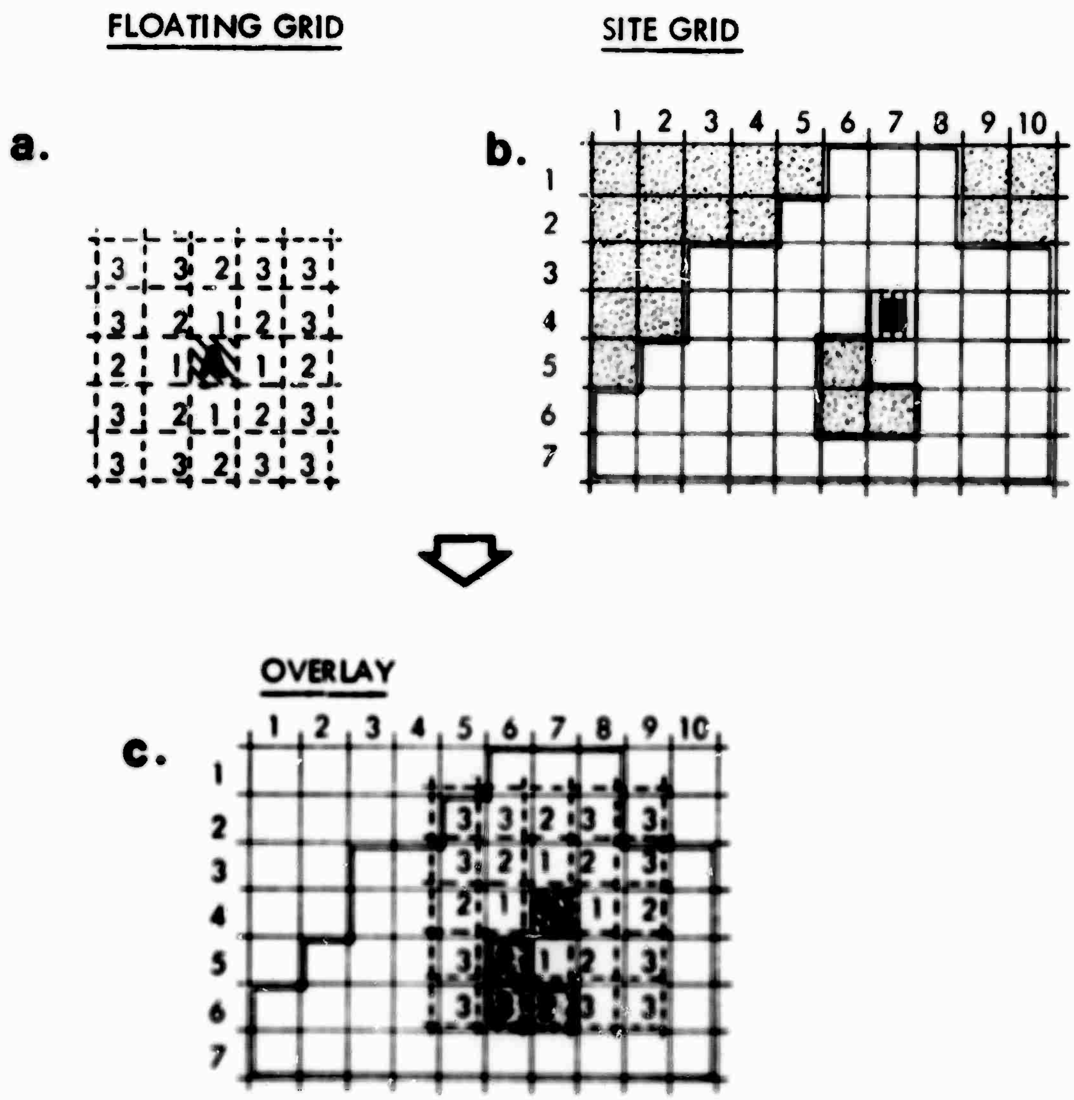


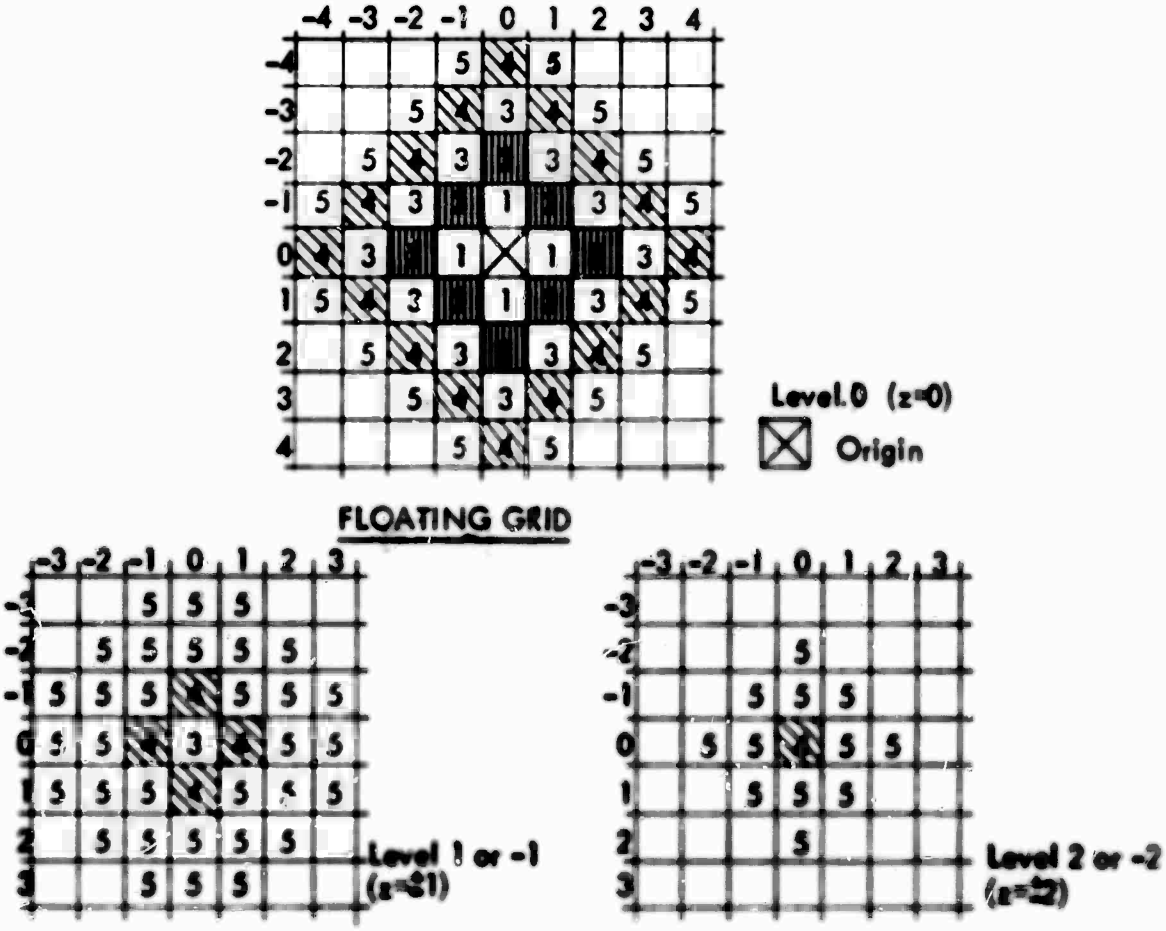
FIGURE 6.4.5 THE AFFINITY MATRIX



The origin of the floating grid (A) coincides in the overlay with the anchor module (B) on the site grid.

FIGURE 6.4.8 DEFINITION OF RELATIVE DISTANCE

The locations around the origin are numbered according to their relative proximity; reflecting the user's assumptions:



Group I contains all elements with a proximity of 1 to the origin, Group II contains all those with a proximity of 2, etc.:

Group I

x	y	z
1	0	0
-1	0	0
0	1	0
0	-1	0

Group II

x	y	z
1	1	0
-1	1	0
-1	-1	0
1	-1	0
0	2	0
0	-2	0
2	0	0
-2	0	0

Group III

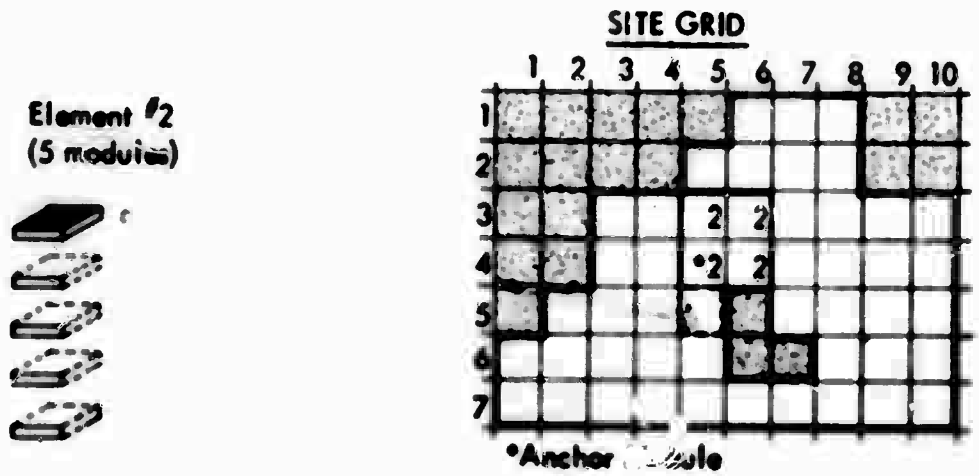
x	y	z
3	0	0
-3	0	0
0	3	0
0	-3	0
0	0	1
0	0	-1
1	2	0
2	1	0
0	-2	0
0	2	0

Group IV

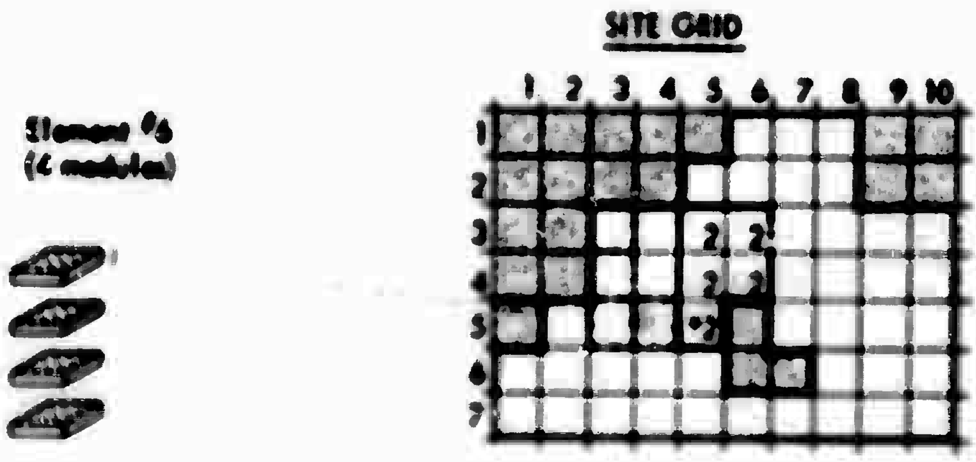
x	y	z
0	0	2
0	0	-2
4	0	0
-4	0	0
0	4	0
0	-4	0
1	0	1
1	0	-1
0	0	2
0	0	-2

FIGURE 6.6.7 GENERATION OF VECTOR LIST

Step 1. Assign another module of same element (2) near anchor module:



Step 2. Assign first module of another element (6) near anchor module:



Step 3. Return to Step 1 and assign remaining modules of element 6.

FIGURE [illegible] ASSIGNMENT

Group I

x	y	z
0	1	0
0	-1	0
1	0	0
-1	0	0

Group II

x	y	z
-1	1	0
1	-1	0
1	1	0
-1	-1	0

etc.

(Coordinates of vectors on the floating grid)

*Anchor module

X	Y	Z
3	6	1

(Coordinates on the site grid)

To move to new locations on the site, vectors are added to the coordinates of the anchor module:

GROUP I

	X	Y	Z
	3	6	1
	0	1	0
(1)	3	7	1

	X	Y	Z
	3	6	1
	0	-1	0
(2)	3	5	1

	X	Y	Z
	3	6	1
	1	0	0
(3)	4	6	1

	X	Y	Z
	3	6	1
	-1	0	0
(4)	2	6	1

(1), (2), (3) and (4) represent the coordinates on the site grid of all possible Group I locations. If none of these locations is available for assignment, the computer will then search Group II locations:

GROUP II

	X	Y	Z
	3	6	1
	-1	1	0
(5)	2	7	1

	X	Y	Z
	3	6	1
	1	-1	0
(6)	4	5	1

etc.

SITE GRID

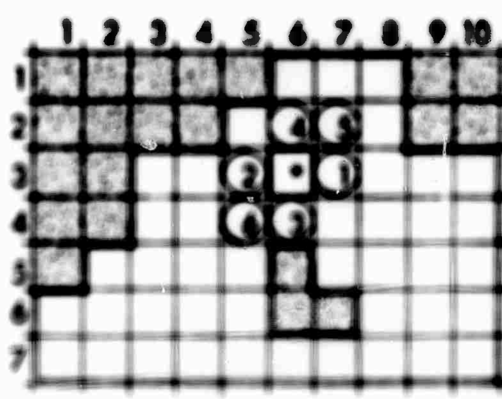


FIGURE 6.4.9 SEARCH PATTERN

SITE GRID

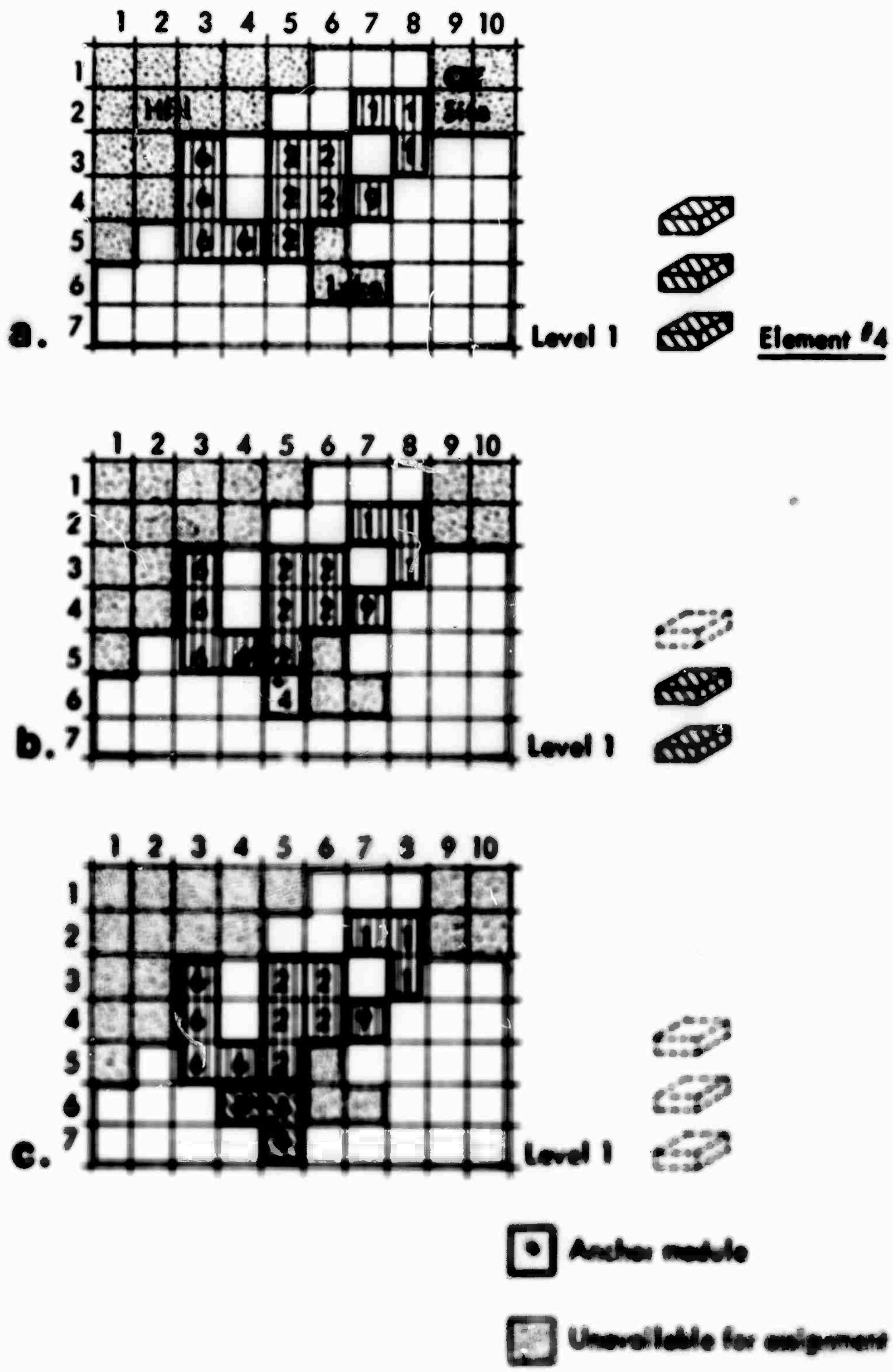


FIGURE 6.4.10 ASSIGNMENT EXAMPLE

g.

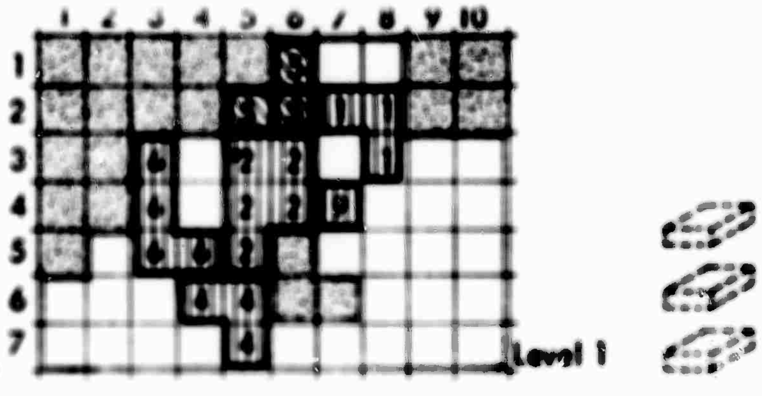


FIGURE 6.4.10 (Continued)

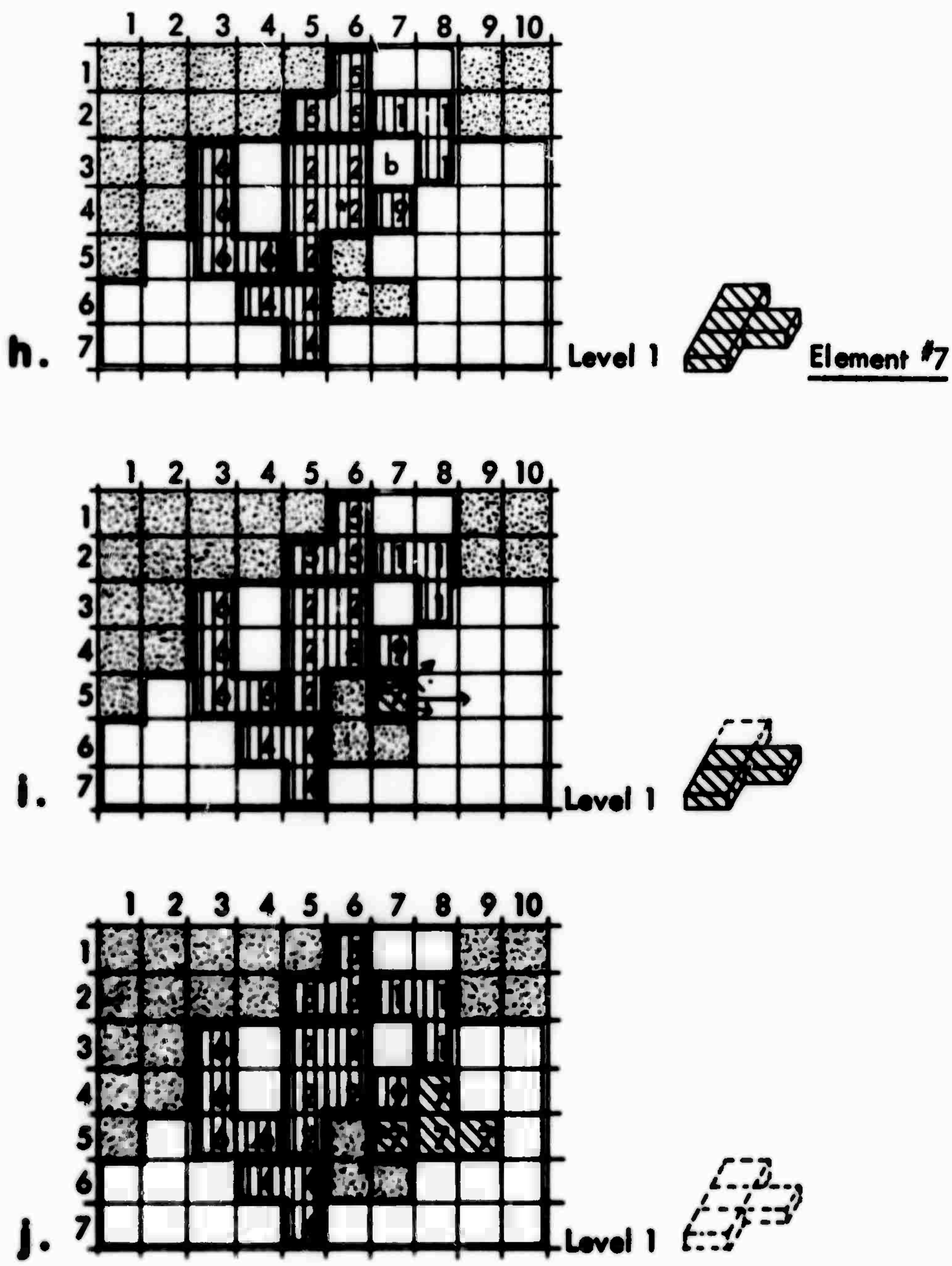


FIGURE 6.4.10 (Continued)

	1	2	3	4	5	6	7	8	9	10
1	-									
2	2	-								
3	3	1	-							
4	3	2	0	-						
5	3	3	1	2	-					
6	0	0	2	1	1	-				
7	0	1	0	1	1	3	-			
8	0	0	0	0	1	3	1	-		
9	0	0	0	0	1	0	1	2	-	
10	2	1	0	3	2	1	1	1	1	-

	1	2	3	4	5	6	7	8	9	10
1	0	2	3	3	3	0	0	0	0	2
2	2	0	1	2	3	0	1	0	0	1
3	3	1	0	0	1	2	0	0	0	0
4	3	2	0	0	2	1	1	0	0	3
5	3	3	1	2	0	1	1	1	1	2
6	0	0	2	1	1	0	3	3	0	1
7	0	1	0	1	1	3	1	0	2	1
8	0	0	0	0	1	3	1	0	2	1
9	0	0	0	0	1	0	1	2	0	1
10	2	1	0	3	2	1	1	1	1	0

The matrix is identical on its opposite halves.

FIGURE 6.4.11 EXPANSION OF THE AFFINITY MATRIX

AFFINITY MATRIX

Elements #	1	2	3	4	5	6	7	8	9	10
1	0	2	3	3	3	0	0	0	0	2
2	2	0	1	2	3	0	1	0	0	1
3	3	1	0	0	1	2	0	0	0	0
4	3	2	0	0	2	1	1	0	0	3
5	3	3	1	2	0	1	1	1	1	2
6	0	0	2	1	1	0	3	3	0	1
7	0	1	0	1	1	3	0	1	1	1
8	0	0	0	0	1	3	1	0	2	1
9	0	0	0	0	1	0	1	2	0	1
10	2	1	0	3	2	1	1	1	1	0

OUTPUT LIST

Step	#	x	y	z
	1	3	5	1
①	4	5	5	1
	4	5	6	1
	3	4	5	1
②	3	4	6	1
	5	3	6	1
③	10	3	7	1
⑤	10	3	8	1
	2	5	2	1
⑧	6	4	4	1
	6	4	3	1
⑨	6	4	2	1
	7	3	3	1
⑩	8	3	2	1
⑬	8	3	1	1
	9	2	2	1

Number of Elements = 10

Maximum Affinity = 3

\# Element Number

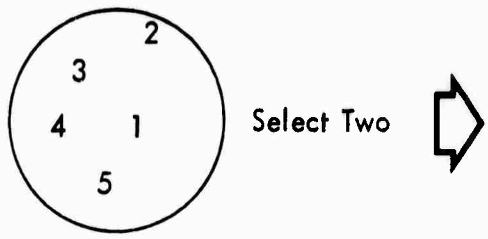
○ "2" Affinity used

Process of selecting next element to be introduced into the layout:

STEP	PRIMARY ELEMENT	AFFINITY	SECONDARY ELEMENT
①	1	3	3
②	1	3	5
③	4	3	10
④	3	3	none
⑤	5	3	2
⑥	10	3	none
⑦	2	3	none
⑧	3	2	6
⑨	6	3	7
⑩	6	3	8
⑪	7	3	none
⑫	8	3	none
⑬	6	2	9

FIGURE 6.4.12 SELECTION OF ELEMENTS

RANDOM NUMBERS



	Row	Interchanges with: Row
①	1	5
②	4	3
③	5	2
④	4	1
⑤	3	2

①

1	2	3	4	5
0	3	2	1	0
3	0	0	0	0
2	0	0	3	0
1	0	3	0	2
0	0	0	2	0

②

1	2	3	4	5
0	0	0	2	0
3	0	0	0	0
2	0	0	3	0
1	0	3	0	2
0	3	2	1	0

③

1	2	3	4	5
0	0	0	2	0
3	0	0	0	0
1	0	3	0	2
2	0	0	3	0
0	3	2	1	0

④

1	2	3	4	5
0	0	0	2	0
0	3	2	1	0
1	0	3	0	2
2	0	0	3	0
3	0	0	0	0

⑤

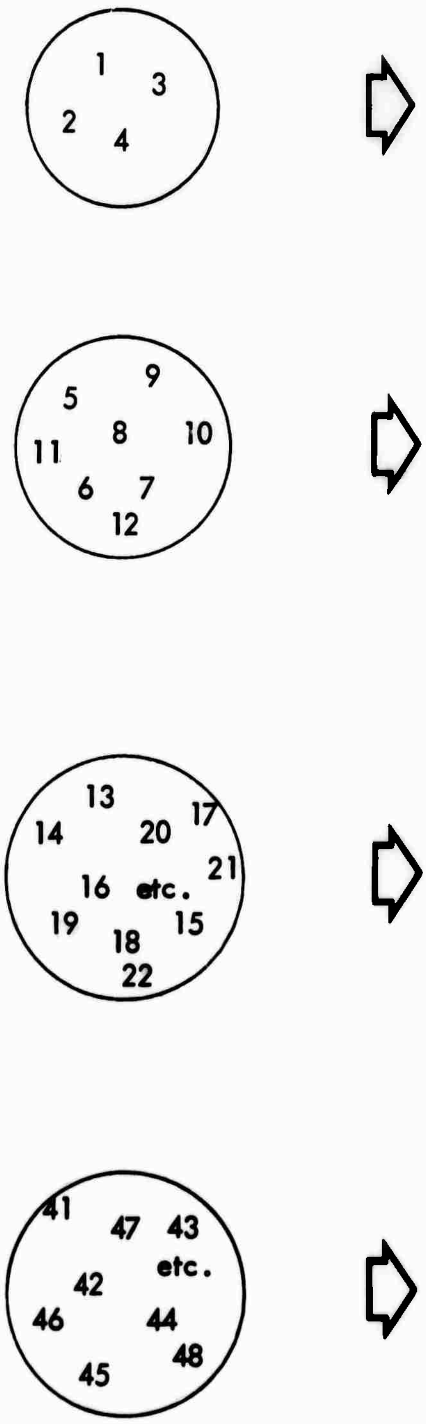
1	2	3	4	5
2	0	0	3	0
0	3	2	1	0
1	0	3	0	2
0	0	0	2	0
3	0	0	0	0

1	2	3	4	5
2	0	0	3	0
1	0	3	0	2
0	3	2	1	0
0	0	0	2	0
3	0	0	0	0

Through continuing the process of interchanging rows, many different random arrangements of the affinity matrix are possible.

FIGURE 6.4.13 RANDOMIZATION OF THE AFFINITY MATRIX

RANDOM NUMBERS
(vectors)



Vector List

x	y	z

Group I

	x	y	z
1	1	0	0
2	-1	0	0
3	0	1	0
4	0	-1	0

Group II

	x	y	z
5	1	1	0
6	-1	1	0
7	-1	-1	0
8	1	-1	0
9	0	2	0
10	0	-2	0
11	2	0	0
12	-2	0	0

Group III

	x	y	z
13	3	0	0
14	-3	0	0
15	0	3	0
16	0	-3	0
17	0	0	1
18	0	0	-1
19	1	2	.0
20	2	1	0
21	0	-2	0
22	0	2	0

etc.

Group IV

	x	y	z
41	0	0	2
42	0	0	-2
43	4	0	0
44	-4	0	0
45	0	4	0
46	0	-4	0
47	1	0	1
48	1	0	-1
49	0	0	2
50	0	0	-2

etc.

As with the affinity matrix, the process of interchange of vectors can be continued so that many possible variations in the vector list occur.

FIGURE 6.4.14 RANDOMIZATION VECTOR LIST

DISTANCE--The distance between any two modules is defined to be equal to the number of modules separating them. An equivalent statement is that the distance is equal to the distance in modules between the centroids, minus one.

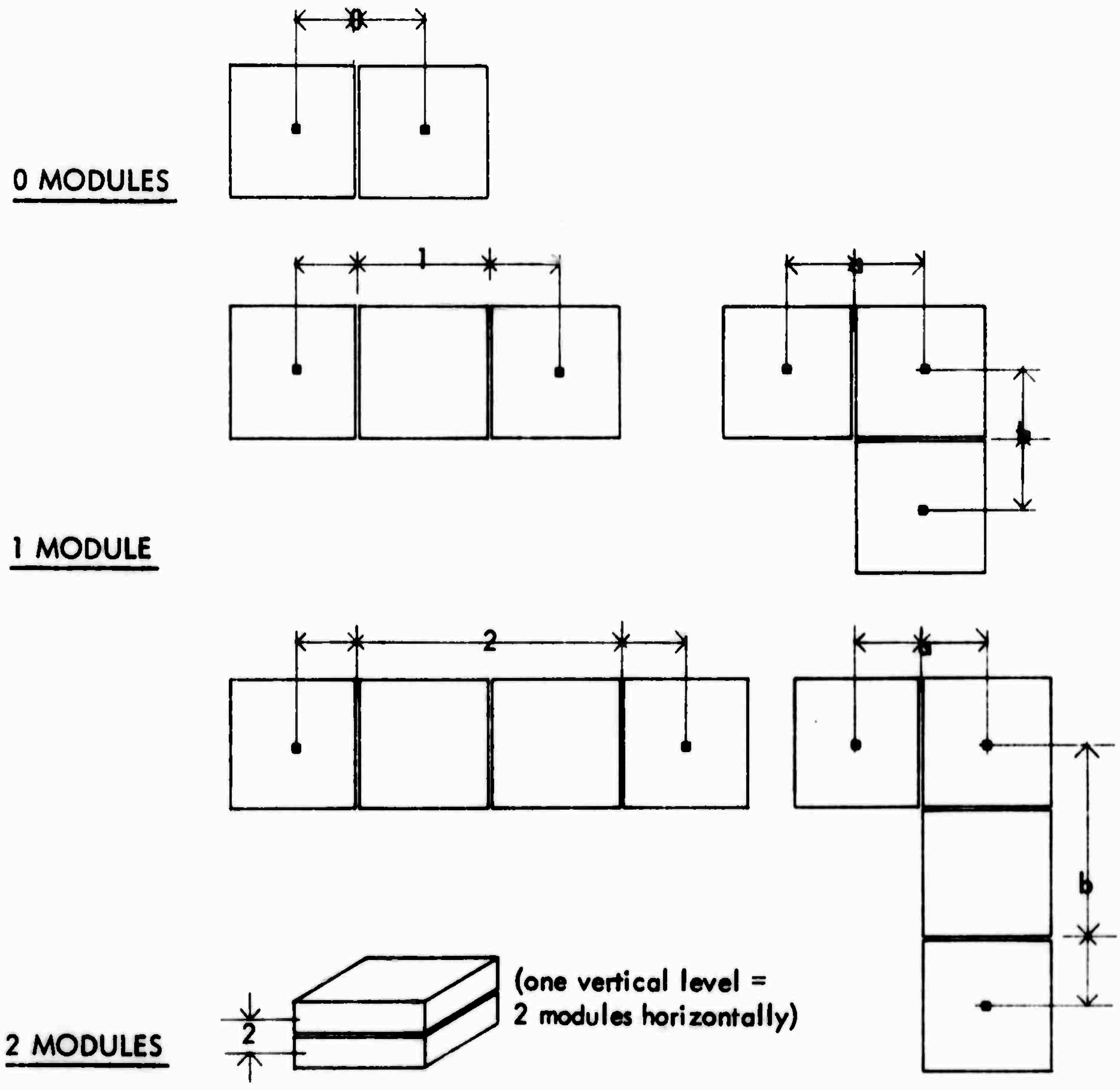


FIGURE 6.4.15 DISTANCE MEASUREMENT

Expansion
From:

Type	to	Type	Factor
Hard	→	Hard	a
Hard	→	Medium	b
Hard	→	Soft	c
Medium	→	Hard	d
Medium	→	Medium	e
Medium	→	Soft	f
Soft	→	Hard	g
Soft	→	Medium	h
Soft	→	Hard	i
Hard	→	Outside	j
Medium	→	Outside	k
Soft	→	Outside	l
Hard	→	Same Element	m
Medium	→	Same Element	n
Soft	→	Same Element	o

The values for a, b, c .... o are based on their relative difficulty of expanding one space into another space according to the types of the two spaces.

FIGURE 6.4.16 ADAPTABILITY INDEX

```
*********  R E L A T E  *********
 (RELATIONSHIP LAYOUT TECHNIQUE)


LESTER GORSLINE ASSOCIATES
BELVEDERE-TIBURON, CALIFORNIA


PROJECT CODE:  MARCH AF


INPUT DATA FOLLOWS:

SPACE ENVELOPE DIMENSIONS:    8   15    6

TOPOGRAPHY IS NOT INCLUDED

                          TOTAL     REAL      DUMMY
NUMBER OF ELEMENTS:        34        32         2
NUMBER OF MODULES:        114       109         5

NUMBER OF PREDEFINED ELEMENTS:     0
```

FIGURE 6.4.17 SUMMARY OF DATA

FLOOR PLAN FOR LEVEL 1 SOLUTION NUMBER 5

	1	2	3	4	5	6	7	8
1			ENT	ENT	ENT	ENT		
2	FD2	FD4	SEM	FO3	FO3	FD3	LPS	
3	FD4	SEM	SEM	FO3	FD3	FO5	FO5	FO5
4	FO1	FO1	CAR	DB6	DB6	DB6	FO5	EHS
5		CAR	CAR	DB2	DB2	DB1	DB1	EHS
6			SER	SER	SER	SER		

FIGURE 6.4.18 SAMPLE PRINTOUT

6.5. SURVEY OF COMPUTER-AIDED DESIGN PROGRAMS

ı.5.1. INTRODUCTION

"Computer-aided design" accelerates the design and decision-making process by rapidly and efficiently performing a number of time-consuming chores that ordinarily are done laboriously by hand. It enables the designer to generate and evaluate a much wider range of alternative problem solutions, space layouts, and site plans in the search for an appropriate design solution.

To put the problem in perspective, one must examine what is and what is not feasible. The term "computerized design" implies a system in which the design is generated by the computer alone. In engineering it is possible to computerize many processes. However, in the realm of architecture, there is not the analytical base required for a total application of the computer. Hence the term "computer-aided design." This implies that while the computer is used (to a greater or lesser degree) in the design process, the responsibility lies with the designer.

The computer must be perceived as an "aid"—a design "assistance" The computer augments, but does not substitute for, human intellect and activity. The emphasis is on interaction between man and machine rather than man or machine action. An interactive design system is one in which designer and computer cooperate in a series of complementary actions and reactions resulting in a process that extends the range of human capacity to deal with complexity and uncertainty within a rational contest.

Computer design systems can be either optimal-producing, or sub-optimal-producing as outlined below. No computationally feasible optimal-producing procedure exists at present, as such a procedure requires a precise definition of optimality. Such a definition must include all constraints, all costs to be minimized, all factors to be maximized, and all other criteria which must be met in an optimal facility. Were such a definition possible for a medical facility, the dynamics of health care would soon render the definition obsolete.

CLASSIFICATION OF COMPUTER DESIGN SYSTEMS
I. COMPUTERIZED DESIGN PROGRAMS
II. COMPUTER-AIDED DESIGN PROGRAMS
A. Optimal-producing
B. Sub-optimal-producing
1. Improvement-type
a. CRAFT
b. FRAP
2. Construction-type
a. ALDEP
b. COMSBUL
c. CORELAP
d. RELATE

Valid, feasible computer-aided design programs will most likely produce sub-optimal solutions. The overall logic used in most computer-aided design programs is heuristic (trial and error, based upon rules of thumb). These programs arrive at logical block-plan layouts, often by mimicking the processes of human designers, but these layouts can in no way be construed to be optimum in the strict mathematical sense.

Computer-aided design programs can be further classified as improvement-type or construction-type. The improvement algorithms accept a layout as input and attempt to improve on it according to some criteria. The construction algorithms arrange spaces into a layout according to some general criteria. Improvement programs can be quite helpful if there is an existing layout and if a proper objective can be defined. Construction algorithms, on the other hand, are less likely to produce layouts of workability, but offer the designer both a basis for beginning his work and, in the case of some programs, a wide range of alternative layouts that can spark new ideas and schemes.

Six computer-aided design programs were surveyed and briefly examined for their applicability to medical facilities. A discussion of each program is given below. Two were designed specifically to handle medical facilities. Two are of the improvement-type, four of the construction-type. All six produce sub-optimal layouts. The programs surveyed are ALDEP[1], CORELAP[2], COMSBUL[3], CRAFT[4], FRAP[5], and RELATE[5]. A brief description of the working method of each program is given. The results of the evaluation are summarized in table-form at the end of this appendix.

There are other programs in existence today. Those included in this survey were selected because of their wide use and are representative of a wide range as significantly different approaches. There are programs such as the HIDEC-RECOMP programs based upon the procedure of Christopher Alexander[6] which address the layout problem but do not produce layouts.

6.5.2. DISCUSSION OF PROGRAMS

6.5.2.1. ALDEP (Automated Layout DEsign Program)

ALDEP is a construction program which utilizes a random technique. The relationship chart is the basis for construction. Up to 63 departments* can be included. The input data include :

- The preference or relationship table indicating the relative importance of having any two departments placed next to each other.
- The departmental areas.
- Width and depth of floor.
- Number of layouts to be tried.
- Any department or departments to be preassigned.

ALDEP will generate as many random layouts as specified by the user.

First an available department is selected at random and located in the center of the layout. The relationship table is then scanned to see if a department has the highest relationship with the preceding department. If one exists, it is placed in the layout; if none exist, then any available department is selected randomly and located. This procedure continues until all departments have been placed in the layout. The layout is then printed.

Each layout is scored on the basis of adjacency of departments. Departments which have common borders with some other departments contribute to the score. The user may specify a minimum acceptable score and only those which meet this criterion are printed. Each layout will be different and will possess a different score.

*The terms "element" and "department" are essentially equivalent although "element" is considered more accurate. The term "department" is used here where it was used by the original author.

6.5.2.2. CRAFT (Computerized Relative Allocation of Facilities Technique)

CRAFT is a computer-aided design tool of the improvement type; it attempts to improve upon a proposed layout. CRAFT utilizes a "transporation" cost criterion and attempts to minimize the materials handling cost by the rearrangement of up to 40 departments.

The input data are:

- An initial layout to scale.
- The volume of traffic between each pair of departments.
- The cost/unit distance/unit volume for transportation between each pair of departments.
- The departments which are to be fixed.
- The parameters which determine the building size, the number of departments and the control scheme for arrangement possibilities, outputs and debugging.

First, the transportation cost is computed for the initial layout using rectangular distances between department centroids. The total transportation cost is computed using the distance between departments, the volume of travel between the departments and the transportation cost/unit distance/unit volume. The program then considers the effect of the interchange of pairs of departments which either are the same size, have a common border, or border on a common third department. The interchange which would produce the largest reduction in total cost is made and the new layout is printed. This procedure is continued until there is no interchange which would improve the total cost.

6.5.2.3. FRAP (Functional Relationships Analysis Program)

FRAP is a layout program of the improvement type. Its purpose is to improve functional relationships in medical facilities through reducing distances traveled by personnel and material between and within buildings.

Moving buildings, moving elements between buildings, moving elements within individual buildings, or any combination of these three types of movements are possible. Elements and buildings may be given fixed locations or may be movable.

Punched-card input includes specific geometric data for each building and the inter-element traffic flow rates. Output includes calculated traffic activities, element arrangements between buildings and vertically within buildings, a map of building positions within rectangular boundaries for the facility grounds, and movements which occur in the program processing.

Program operation involves initial calculations followed by cyclical determinations of building movements, element movements between buildings, and element movements within buildings. Calculations continue as long as any improvement is found for any of the three types of movement within a set of movement cycles, or until a designated limiting number of sets of movement cycles is completed.

FRAP is directed toward minimization of traffic activity, which is defined as the sum of the products of volume flow rate and separation distance for all pairs of elements. The volume flow rate of traffic may be represented by some measure such as number of persons or amounts of materials (with materials and people properly related as to importance or expense) moving between the elements each day or by a relative attraction index. The relative importance of vertical to horizontal movement may be changed by an input conversion factor.

6.5.2.4. CORELAP (COmputerized RElationships LAyout Planning)

CORELAP is a construction program which utilizes path-oriented logic. That is, the layouts are a result of a specific logic rather than a random method, and consequently produce only one solution. The relationship chart is the basis for construction and CORELAP can handle up to 45 departments. The input data include:

- The number of departments.
- The department area.

- The side of the square which is the block size and also determines the scale of the output.

- A relationship chart indicating the relative importance of having any two departments placed next to each other.

- The maximum building length to width ratio to prevent unusually long, narrow buildings.

First, the relationship table is organized and the department which possesses the highest summation of its closeness ratings with all other departments is placed in the center of the blank layout. The relationships of this department are scanned and the department having the highest relationship with it is placed into the layout adjacent to the first department. The remaining departments are similarly selected based upon the highest relationship ratings, or, when none exist, on lower relationship ratings. Each department is placed in the layout adjacent to the department with which it has a high relationship and at the same time near any other department with which it has some relationship. As each department is added, a layout is printed which offers the capability of tracing the progression of the design. These, and the final layout, are printed as a block layout.

6.5.2.5. COMSBUL (COmputerized Multi-Story BUilding Layout)

COMSBUL is a layout program of the construction-type. The relationship chart is the basis for construction of up to 35 elements.

COMSBUL is actually an extension of the CORELAP program which allows buildings of two stories. The main algorithm, input, output, and assumptions are the same as with CORELAP. The modification now allows the layout to begin on a new level once the first has been filled.

6.5.2.6. RELATE (RElationship LAyout TEchnique)

RELATE is a layout program of the contruction-type, utilizing either path-oriented logic, or a random technique. The relationship chart is the basis for construction and a random method of location selection produces random variances upon the layout. The input data include:

- The number and sizes of elements
- An affinity matrix indicating for each pair of elements the relative importance of adjacency in the layout
- The element shapes where desired
- The site, with topographical features and no-build zones
- The locations of any elements to be preassigned
- The number of layouts to be generated by each method (path-oriented or random)
- Evaluation data
- Definition of relative distances (horizontal- horizontal and vertical-horizontal)
- The number of layouts to be printed

Elements are assigned to the layout near elements already in the layout with which a high affinity exists. Using the preassigned elements, the remaining elements are placed into the layout according to their relationships, first with the preassigned element(s), and then with other elements previously placed in the layout. Layouts are generated using a random selection method. These layouts differ as a result of random choices where equal alternatives appear at each step of the process. Beginning with the preassigned elements, the relationshp table is scanned to see if an element has the highest relationship with an element in the layout. If one exists, it is placed in the layout; if none exist, then an element is selected based upon a lower relationship. This continues until all elements have been placed in the layout.

Each layout is given an index which is the sum of all measures of distance between every pair of elements, each weighted by the relationship between each element of the pair. In addition, other indices are generated which measure relative values of capital cost and affinity. The requested number of layouts are then printed with the indices for each.

For a more detailed explanation of this program, see Section 6.4.

6.5.3. EVALUATION OF PROGRAMS

It is felt that none of the programs surveyed can be directly applied to the layout of the military medical facility. ALDEP, CORELAP, and CRAFT are designed specifically for the industrial plant layout although applications have been proposed in more general architectural problems. FRAP and RELATE were designed specifically for the medical facility problem but modifications would be required for implementation by the SGO. Therefore, analysis of the methods centers mainly on the assumptions and techniques employed by each program.

The improvement techniques, CRAFT and FRAP, are not acceptable for the medical layout problem. Generally, they operate on a principle of interchanging elements in order to reduce cost or minimize traffic. Such a single criterion is not sufficient for hospital design. In addition the designer must have a layout to input to the computer. Such a layout would have to be good with respect to all criteria other than materials movement or personnel traffic. The computer is of only minimal use, and may even hinder the process, since it considers only one criterion in a process which requires simultaneous consideration of many criteria.

All programs, with the exception of CORELAP and CRAFT, are capable of layout on more than one level. However, of those programs, only RELATE is truly three-dimensional. While the others move to another level when a lower level is filled, RELATE moves up or down at any point where the relationships would be better solved by doing so. With modern methods of vertical transportation, it is often true that moving up to a higher or lower floor is more efficient than moving a large distance on the same floor.

All the programs use a relationshp matrix as the prime criterion for layout. Only CRAFT employs a quantitative matrix, and that is based on materials handling costs. The others use a matrix which is made up of relative values which can individually be based upon qualitative or quantitative considerations. The method suggested by Muther[7] is the fundamental base for the matrix. Muther suggested that a matrix be devised in which the numbers describe the relative desired physical relationships between elements.

The site or building form is an important consideration. In this area the programs differ considerably. ALDEP, CRAFT, and FRAP require a definite building shape be predefined for input. CORELAP and COMSBUL only require the form to be rectangular and the ratio of width to depth can be changed. RELATE can accept a definite building shape, no shape at all, or a zoning technique to limit ground availability. In effect CRAFT, ALDEP, COMSBUL, and CORELAP are limited to one building while FRAP and RELATE are multi-building techniques.

The construction techniques, CRAFT, COMSBUL, CORELAP, and RELATE all use the relationship matrix to determine the building process. First one element is assigned to the layout, followed by the other elements, one by one. The relationships determine the order in which these elements are assigned, each one being assigned close to another with which it has a high relationship.

The CORELAP and COMSBUL technique sorts the relationship matrix into order according to the sum of all the relationships for each element. This method then results in those elements with the most relationships being brought into the layout earlier, and being more central in the final layout. Only one layout is generated. The programs, then, ignore the possibility of different layouts based on the same relationship patterns. There are no options and no way to preassign element locations.

The ALDEP method brings new elements into the layout based upon higher relationships, but uses a random method which replaces the assumption that those elements with the most relationships should be central. A large number of layouts must be generated to be reasonably certain of achieving one that is near optimal.

RELATE is capable of generating layouts based upon a method similar to that of CORELAP and COMSBUL, at the user's discretion. However, many layouts can be generated which will differ due to a different pattern of element selection. That is, while CORELAP will produce the same layout each time, RELATE utilizes a random process for the assignment of elements to locations under the assumption that where each element is placed as it comes into the layout is as important as the sequence in which elements are brought in.

In every method, it is necessary for the designer to evaluate the layouts and to adjust and refine them to make them workable. He cannot trust that the computer has optimized the layout with respect to even one constraint. Of the construction techniques, only ALDEP and RELATE include an evaluation capability. ALDEP scores each layout according to the number of adjacent elements, weighted by the relationships between elements. RELATE scores each layout according to the distances between each pair of elements in the layout, weighted by the relationships between them. This is used as a preliminary screening device and only the best layouts according to this measure undergo further evaluation. Each layout can also be measured in terms of its capital costs and adaptability. RELATE stands ready to accept any other criteria for evaluation purposes. The designer still must judge and evaluate, but he has some preliminary measures to aid his choice.

The value of FRAP is in the improvement of existing facilities or the improvement of layout proposals. Considerable flexibility is allowed and where the functional-flow criterion is acceptable, may prove quite valuable in secondary analysis for remodeling and expansion.

The Functional Relationships Analysis Program has not been used extensively as it has certain technical limitations. FRAP requires a considerable investment to make it useful and then it would be useful only as an adjunct to more sophisticated methods.

The programs investigated cannot guarantee optimality. CRAFT should produce good sub-optimal layouts, however, with respect to material handling.

Of the computer-aided design programs surveyed, RELATE is most suitable for military medical facilities. It is the only construction program designed specifically for the layout of medical facilities. Only RELATE has a large enough capacity for large facilities. In addition, there are many more options which are, in many cases, necessary for the medical facilities problem, such as predefined shapes, site topography, a large number of preassigned elements, three-dimensional capability, user-defined relative distances, and a sophisticated and quite open-ended evaluation system.

Even RELATE, however, would require modification if applied to the military medical system. The planning methods of the Department of Defense and the assumptions for military hospitals dictate much reworking not only in the methods of the use of RELATE, but in the program itself. In fact, RELATE itself is not static. The methods of use are highly intertwined with the program itself and many of RELATE's capabilities are only special methods of use.

TABLE 6.5.1
COMPARISON STUDY

ITEM	CONSTRUCTION PROGRAMS: RELATE	ALDEP	CORELAP	COMSBUL	IMPROVEMENT PROGRAMS: CRAFT	FRAP
Prime Criterion	Relationship matrix; quantitative and/or qualitative	Relationship matrix; quantitative and/or qualitative	Relationship matrix; quantitative and/or qualitative	Relationship matrix; quantitative and/or qualitative	Materials handling matrix	Interdepartmental flow matrix
Layout Site	No constraints; may input building shape and/or open site with topography, other features	Explicit building shape	Building shape rectangular with the width/depth ratio to be input	Building shape rectangular with width/depth ratio to be input	Explicit building shape	Many buildings with shapes explicitly defined
Major Input Quantities	1-Spatial assumptions 2-Element areas 3-Relationship matrix 4-Site information	1-Relationship matrix 2-Department areas	1-Relationship matrix 2-Department areas 3-Width/depth ratio of building	1-Relationship matrix 2-Department areas 3-Width/depth ratio of building	1-Materials handling volume 2-Materials handling cost 3-Beginning layout	1-Relationship matrix 2-Beginning layout
Output	Many layouts may be requested; each will be different	Many layouts may be requested;each will be different	One layout; block layout printed for each department added	One layout; block layout printed for each department added	One layout; block layout printed for each cost reduction	One layout
Self-evaluation	1-Score based on how well the relationships were solved 2-Adaptability score 3-Capital cost score	Score based on adjacent departments	None	None	Amount layout has been improved	Amount layout has been improved

TABLE 6.5.1 continued
COMPARISON STUDY

	CONSTRUCTION PROGRAMS				IMPROVEMENT PROGRAMS	
ITEM	RELATE	ALDEP	CORELAP	COMSBUL	CRAFT	FRAP
Algorithm Technique (All Heuristic)	Path-oriented and/or constrained random generated layouts	Modified random generated layouts	Path-oriented layouts (logical path from one step to the next)	Path-oriented layouts	Departmental exchanges	Element exchanges
Maximum Number Of Elements	130	63	45	35	40	75
Preassigned Elements	Yes	Yes	No	No	All	All
Predefined Element Shapes	Yes	No	No	No	No	No
Irregular Site (Horizontal & Vertical)	Yes	No	No	No	No	Yes
Variable Assumption About Distances	Yes	No	No	No	No	No
Variable Evaluation Criteria	Yes	Limited	No	No	No	No
Multi-level	Yes	Yes	No	Yes	No	Yes
Accepts Relationships External to the Layout	Yes	No	No	No	No	No
Predetermined Circulation Paths	Yes	Yes	No	No	No	No

6.5.4. REFERENCES

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6.6. APPLICATION OF THE SYSTEM TO MARCH AFB

6.6.1. SUMMARY

March Air Force Base Hospital was selected for testing the use of the computer program, RELATE. The objective of such an exercise is to demonstrate the applicability of such tools in the planning and design of military medical facilities. Studies were made to determine functional relationships between the elements of the program for the March AFB facility. A new design was produced, using RELATE, which can be compared to the existing design as developed under the traditional planning and design process. Extensive cost estimates were developed for the new design for purposes of this comparison.

6.6.2. BACKGROUND

The March AFB Hospital is a United States Air Force Regional Hospital with 200 general/acute beds (175 operating, 25 inactive) and an extended Outpatient Department. It services the March AFB personnel and their dependents and in addition, acts as a consultant and referral center for all Air Force hospitals and selected military installations in Southern California, Southern Nevada, and Arizona. As of late 1969, the time of the investigation, approximately 19 military installations were served primarily through outpatient department consultations. When the March Hospital is unable to handle patient overloads, they are referred to various local civilian health care installations using the CHAMPUS insurance program. Further inpatient referrals, primarily for active duty personnel and beyond March capability, are made to Travis Air Force Base (area) Hospital in Northern California.

The construction of the present March AFB Hospital began on May 18, 1963 and was completed on June 28, 1965. In addition to the two-year construction period from 1963 to 1965, it is estimated that planning for the facility began five years prior to 1963. Therefore, innovations and technological ideas range up to seven years prior to its opening in 1965.

The layout of the hospital is reasonably good. Since it is a relatively new building, its appearance is attractive. In particular, the layout and equipment in physical therapy, urology, and cystology clinics make these areas superior to others. Both the pediatric and obstetric clinics are well-planned, chiefly because they are adjacent to a small enclosed patio where children can play during appointment hours.

The main physical plant is a five-story structure (130,110 square feet) built in 1965 at a cost of $4.7 million. The average cost of the original structure is $36.51 per square foot excluding contractor's overhead and profit. The building as it was constructed in 1965 has a broad base first floor and four additional stories which house nursing units, surgery and operating suite. An extension to the rear was originally planned for light care but is now considered for use as a general orthopedic area having easy access to X-ray, physical therapy and outdoors. The annual maintenance cost for fiscal year 1969 was $1.6 million. Other changes from original planning before 1965 and instituted during the hospital's operational life, include converting the original employee locker rooms into EEG and EKG use. The building form has not changed over the years, but there have been internal moves and expansions of certain functions — i.e., orthopedic, dermatology, and surgical clinics have moved; radiology has expanded; and the Flight Surgeon and his services have never occupied the building, although space had originally been planned for it.

Currently planned alterations include 44,000 square feet of clinic expansion at an estimated cost of $2.5 million. The expansion plan proposes to relocate the Flight Surgeon's facility from its present, separate facility near the flight line into the hospital expansion; also clinics, pharmacy, and radiology are being planned for expansion. The construction start is scheduled for fiscal year 1973.

6.6.3. ANALYSIS

To use RELATE, it is necessary to have a list of the functional elements with their areas. For this test the original program for the March AFB facility, as set forth in the Area Analysis, was used to facilitate comparison of the new design with the old. The areas of the functional elements in the original program were organized into simulated planning units. This "modularization" is required when modular programming methods are not used and the areas are stated as square footage.

In this example, one planning unit equals 750 net square feet. The Area Analysis for the March AFB facility indicated a factor of 1.6 for net to gross conversion to allow for utility shafts, circulation, walls, partitions, and mechanical rooms. Consequently, a planning module of 1200 square feet is used in the Form Diagrams generated by the computer. To facilitate the use of the original space program for March AFB in the RELATE program, several adjustments were made during the process of generating Form Diagrams.

The net areas of the functional elements of the 1965 primary inpatient/outpatient facility as given in the Area Analysis were converted into 109 planning units as shown in Table 6.6.1. For the purpose of this example, the programmed Flight Surgeon medical space was included as one of the functional elements. There has been certain redefinition of the elements:

- Support space is defined as three elements to allow decentralization of the supply function. Each part has its own set of relationships to other elements;

- The nursing function is divided by type of care rather than by elements, with the exception of OB, pediatrics, and nurseries.

The net area of each element is expressed as one or more whole Planning Units, i.e. units of 750 net square feet. Each element expressed in Planning Units is approximately the same net square footage indicated in the Area Analysis. The working drawings were considered when making the approximations since the resulting areas differed somewhat from those stated in the Area Analysis. A major change was surgery. The Area Analysis called for 3,840 square feet, which is about five Planning

TABLE 6.6.1 FUNCTIONAL ELEMENTS/AREAS OF THE MARCH HOSPITAL AND THEIR EQUIVALENT PLANNING UNITS

Element No.	Functional Elements	Sq.Ft.(from Area Analysis)	Computer Abbreviation	Number of Planning Units
1	Administration	7560	ADM	10
2	Clinical	2720	CLS	4
3	Medical Surgical Clinic	1674	MSS	3
4	Urology Clinic	680	URO	1
5	Orthopedic Clinic	760	ORT	1
6	Psychiatric Clinic	360	PSY	1
7	Pediatrics	1270	PED	2
8	Obstetric/Gynecology Cln.	1230	OBG	2
9	ENT Clinic	1350	ENT	2
10	Flight Medicine	1720	FLT	2
11	Laboratories	1800	LAB	2
12	Radiology	2400	RAD	3
13	Physical Therapy	1313	PHT	1
14	Pharmacy	900	FAR	1
15	Dentistry Unit	440	DEN	1
16	Emergency	920	EMR	1
17	Central Sterile Supply	1700	CSS	2
18	Food Service	6180	FOD	6*
19			SUP	8
20	Employees	2070	EMP	3
21	Surgery	3840	SUR	3*
22	Delivery	1863	DEL	3
23	Nursery	1380	NUR	2
24	Recreation and Day Rooms	1840	PAT	3
25	Light Care Nursing		NLI	10
26	Intermediate Nursing		NIT	10
27	Intermediate Nursing & Female Care	31050	NFI	7
28	Pediatrics Nursing		NPE	3
29	Obstetrics Nursing		NOB	5
30	Intensive Care Units		ICU	5
31	Dummy Element (extra)			(Non-functional)
32	Supplies	8065	SP1	1
33			SP2	1

* Adjusted according to working drawings

Units. However, the area in the working drawings was about three Planning Units. The latter figure was used in the generation of Form Diagrams.

The total area was considered when making individual approximations. Rounding to the nearest whole planning unit was proportional. Some elements were rounded up and some down, so that the combined result is as near as possible to the total square footage. Some elements are combined if their relationships are similar. The spaces required for the psychiatric clinic and dermatology clinic are each considerably less than one planning unit. Combining the two into one element of one planning unit solves the problem of area, but examination showed that the psychiatric clinic has unique relationships and should be considered independently. Dermatology, on the other hand, has approximately the same relationships as the other clinics and it was found that the excess space due to the rounding error of the other OPD clinic areas would accommodate the dermatology clinic. It was not included as an element for RELATE, and should be considered in the detailed design.

The Affinity Matrix, as shown in Figure 6.6.1, contains the relationship between functional elements, rating the element pairs by need for proximity. This rating is described numerically as 0, 1, 2, or 3; the digit 0 indicates no affinity, and a higher number indicates a stronger relationship. The methodology for generating this matrix is not fully developed. The data is considered "soft", and further research is recommended. Affinity Matrix criteria includes patient movement, materials handling, utilities and element function.

The Affinity Matrix used in the March AFB hospital example closely follows the relationships established in the original layout. In order to maintain a fair base for comparison, extensive re-evaluation of the interrelationships was not undertaken. Generally, the numbers were derived from experience and analysis of the general data. They were compared with the existing layout, and conflicts were resolved in favor of the existing layout. The computer process itself requires some additional adjustments.

A typical graph used in generating the affinity matrix is shown in Figure 6.6.2. This graph illustrates the relative use of the clinical laboratory by the patients in each of the outpatient clinic services. Numbers are omitted as only qualitative comparison is required. The clinics are divided into groups according to the importance of relationships. The numbers 1, 2, and 3 are the first approximation of the affinity values. This graph represents only one factor contributing to the affinity ratings, as it concerns only patient movement. Other studies evaluated other contributing factors.

Figure 6.6.3 shows the relative importance of the relationships among the clinical laboratories, the clinics, and radiology as affected by the flow of inpatients and outpatients. The chart shows a higher volume of outpatients in all cases. However, when evaluating this factor, the higher mobility of the outpatient must also be considered.

Figure 6.6.4 is an example of the quantitative analysis of patient flow. This information was interpreted, combined with other data, and plotted on a matrix such as that done for staff flow in Figure 6.6.5. In this matrix, the element pairs were evaluated with respect to the volumes and frequencies of intra-element staff movements, on a scale of no travel, some travel, and much travel.

In a complete relationship analysis, which is necessary for the new planning process, such analyses must be carried out for all the contributing relationship factors which are weighted and combined into the final single-value affinity matrix.

Ordinarily, extensive site analysis is performed to quantify site characteristics for computer input. The contours are rationalized for input to the computer, and the site is evaluated to determine the areas for construction. In the March AFB example, the site is flat and presents no constraints. There can be access from any direction, and there are no practical restrictions on size. Consequently, the same site and the orientation of the present facility were used.

Other facilities on the site which are related to some of the functional elements of the new facility should be included in the affinity matrix. In the March AFB example, two "dummy" elements were included to represent access points of the site and "light and air" or open space. Some elements, such as emergency, clinics, and supply, have a definite relationship with access points. Nursing units have a functional requirement for open space. Patient rooms must have windows, and therefore have a high relationship with the "light and air" element. These dummy elements were assigned to the site, using the required number of modules. On the computer-generated floor plans the access modules are indicated by "A." The "light and air" modules are not indicated except by the absence of functional elements. It is not required to preassign "light and air" to a location in the layout. It is possible to leave it unassigned so that the computer will assign it when and where necessary according to the relationship it has with the functional elements.

The output of the RELATE program used in the March AFB example consists of a variety of floor plan solutions. One of these solutions is shown in Figure 6.6.6. The computer printout of the existing layout is shown in Figure 6.6.7. The numbers across the page (1-15) and down the page (1-8) are the coordinates used for identification. Refer to Table 6.6.1 for the key to the abbreviations of element names.

In the RELATE program any number of floor plan arrangements can be requested. The computer generates many but prints only the best results. In the March AFB example, groups of five to ten layout alternatives were used.

Analysis of the layout alternatives is a rather complex and intuitive process. One technique which has been used successfully involves searching a number of layout proposals for similarities. If certain elements are consistently arranged the same way, that arrangement is isolated and preassigned in future runs in which the remaining elements are to be reassigned by the computer. This process is repeated until the layout is complete.

It has been found that design concepts can influence the final building form and that, in fact, design decisions are often required to solve problems. As a designer's tool, the RELATE program can trigger new concepts. It is important to recognize that the most effective use of RELATE involves an iterative process and that the final Form Diagram is based not on one computer layout but on similarities between layouts and a thorough analysis of several alternatives.

In the March AFB example, the Distance Index was used as a basis for preliminary judgments. Those layouts with lower distance indices are the most efficient with respect to the relationships. The Adaptability Index and the Cost Index are most useful for comparing a number of alternative final Form Diagrams.

Form Diagrams assist in rapidly providing alternative design solutions that by conventional design procedures would require many weeks. The best shape building form obtained for the March AFB example, 1969, is shown in the lower section of Figure 6.6.8. The top picture is the shape of the existing hospital. The index indicators for the two designs are as follows:

	old design	new design
DISTANCE INDEX	56578	46427
ADAPTABILITY INDEX	3034	2648
COST INDEX	17372	17038

In this example, the use of the RELATE program improved the relationship efficiency by 22% and increased the adaptability by 15% while maintaining the cost indicator.

At the time this study was being carried out, a design was proposed by the AF Health Facilities Office in San Francisco, which would have relocated Emergency, Radiology and Pharmacy, as shown in Figure 6.6.9. An examination of this layout shows that the affinity requirements for these departments would have been poorly met. Eventually this design was discarded by the Air Force (without use of the RELATE program), but a suitable design might have been found much sooner had a systematic exploration of layouts been possible at the time.

Figure 6.6.10 is the proposed plan for expansion of March AFB facilities, generated by RELATE. Emergency, Radiology, and Pharmacy remain at their present locations, where they can expand directly into a new wing. No rebuilding or new main corridors are required.

Rough schematics were produced to obtain a cost estimate. The actual spaces which were included in the modular estimate are laid out with circulation, utility chases, elevators, stairs, etc. Normally, the SGO would not develop schematics. The plan presented in this example is, like the Form Diagram, only one of several alternatives. Others might yield higher or lower estimates. The schematics and the cost estimator's report are located in Section 6.7.

*************ELEMENT DESCRIPTIONS*************

NO.	NAME	SIZE	TYPE
1	ADM	10	1
2	CLS	4	1
3	MSS	3	1
4	URO	1	1
5	ORT	1	1
6	PSY	1	1
7	PED	2	1
8	OBG	2	1
9	ENT	2	2
10	FL1	2	1
11	LAB	2	3
12	RAD	3	3
13	PHT	1	3
14	FAR	1	2
15	DEN	1	2
16	EMR	1	3
17	CSS	2	3
18	FOD	6	3
19	SUP	8	1
20	EMP	3	1
21	SUR	3	3
22	DEL	3	3
23	NUR	2	2
24	PAT	3	1
25	NL1	10	2
26	NIT	10	2
27	NF1	7	2
28	NPE	3	2
29	NOB	5	2
30	ICU	5	3
31	A	4	0
32	SP1	1	1
33	SP2	1	1
34		1	0

*************AFFINITY MATRIX*************

```
 1 0
 2 20
 3 120
 4 1220
 5 12220
 6 121110
 7 1222210
 8 12121120
 9 122211210
10 1111131130
11 11221122220
12 112231222210
13 1122322112120
14 12222122122110
15 111111211211110
16 1132212212231110
17 11222122222112120
18 221111111111111110
19 1122212112221212220
20 21111111111111111130
21 001121111122111221110
22 0011111210111112211130
23 00111112101111112121230
24 211122111211211112221110
25 1121322122223112222111130
26 11112111111122112221211220
27 111111111111121122212112230
28 1111113111111211222121112330
29 11111112111112112221233223330
30 000011111122121222113221233330
31 3322322223112223123211111111110
32 21111111111121111112111111111130
33 112222222222222222111112111111210
34 3322232222302122131100233333321110

   1234567890123456789012345678901234567890
```

FIGURE 6.6.1 COMPUTER DATA

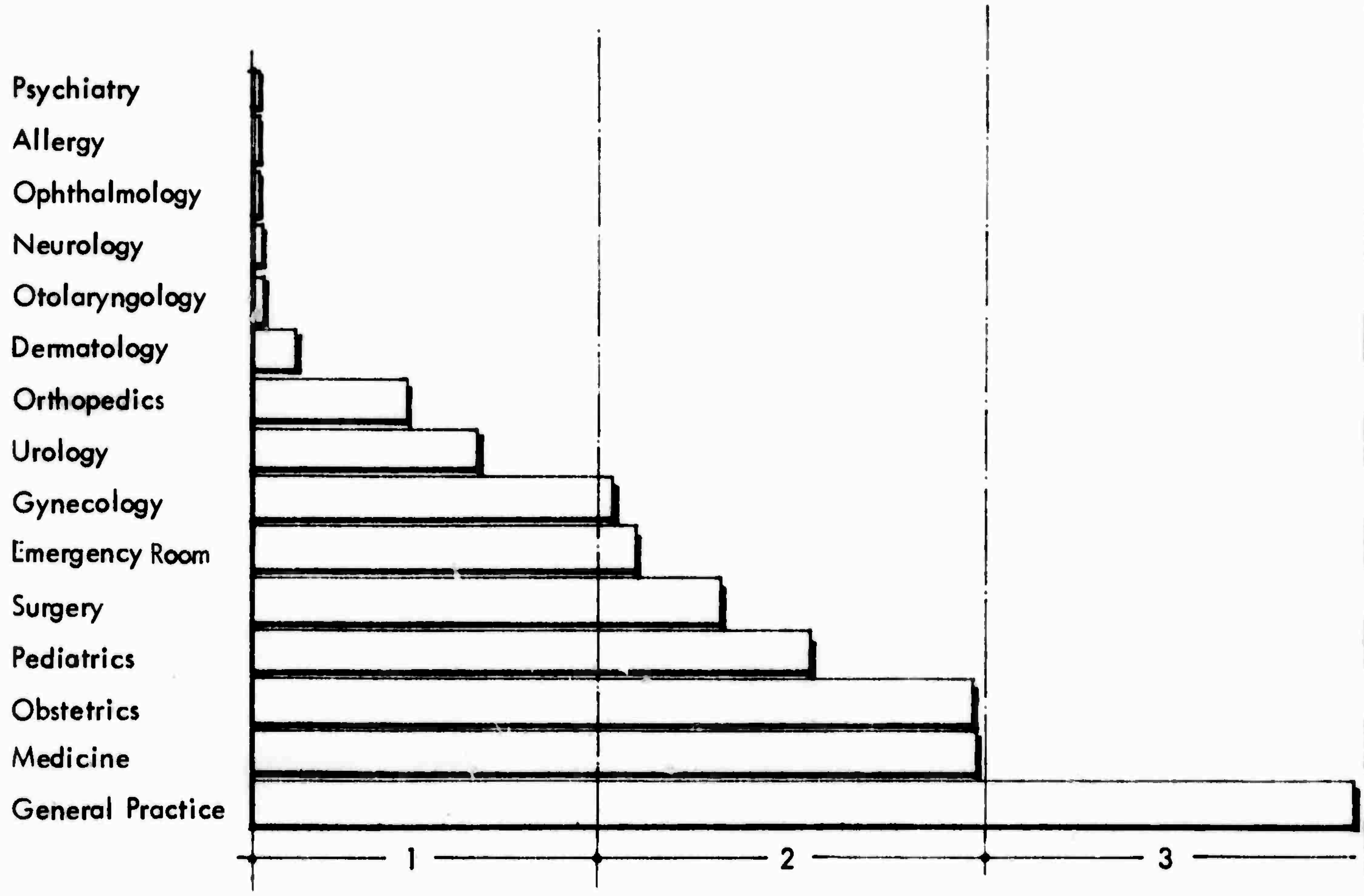


FIGURE 6.6.2 LABORATORY ELEMENT–PATIENT ORIGIN STUDIES

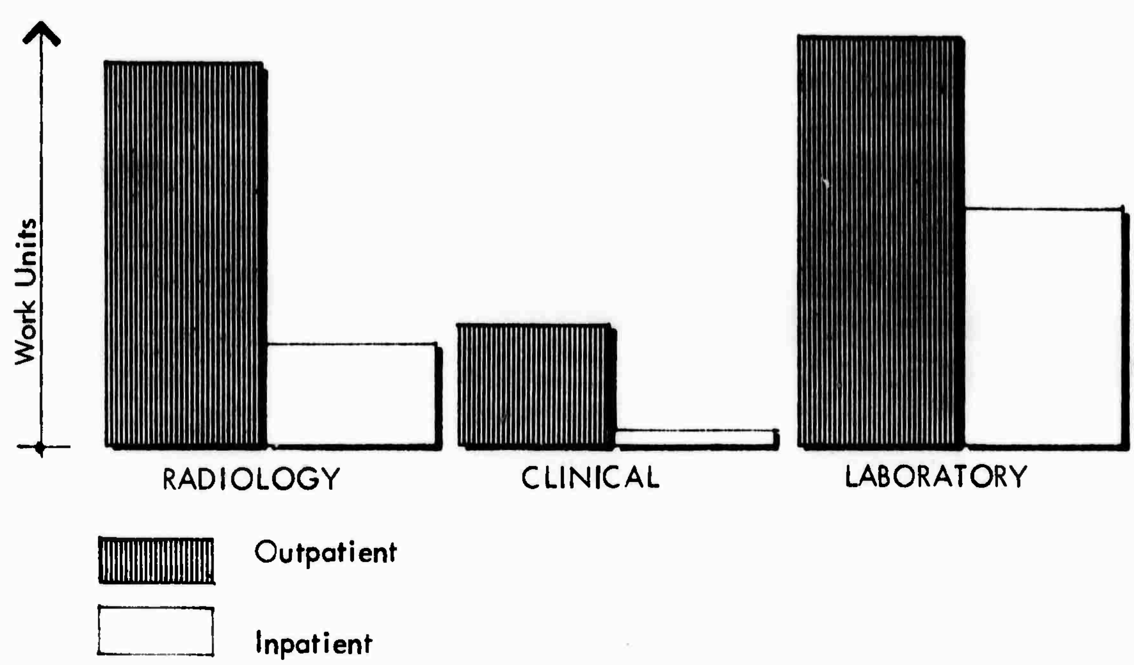
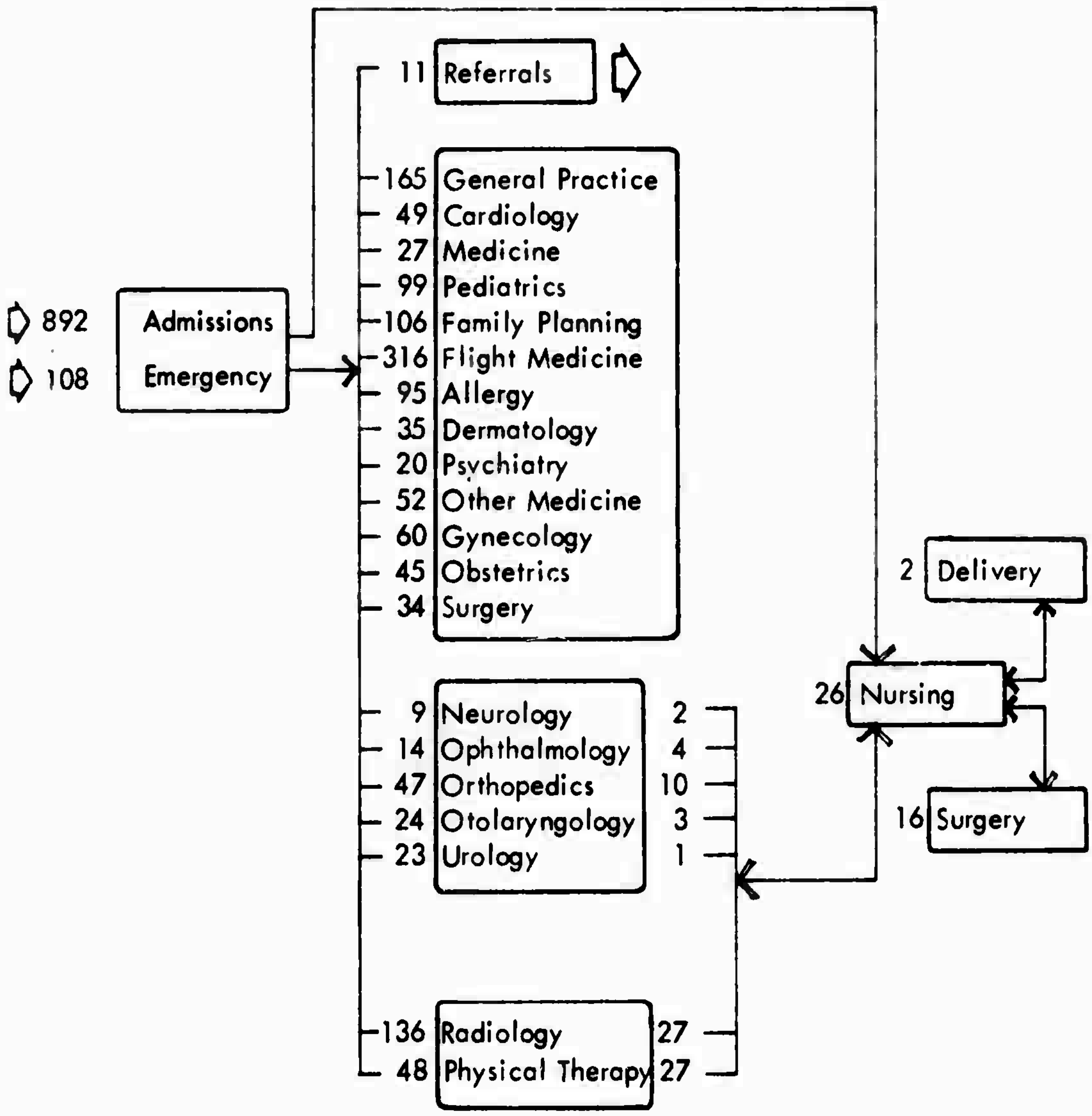


FIGURE 6.6.3 PROPORTIONATE USE OF SERVICE ELEMENTS



Note: Interpolated from March AFB Monthly Base Reports January - December 1969

Number of trips to Services generated by 1000 patients entering a Base Hospital

FIGURE 6.6.4 MAIN PATIENT TRAFFIC FLOW

	Administration	General Clinic	Med./Surg.	Urology	EENT	Psychiatry	Dentistry	Laboratory	EKG-EEG	CSS	Radiology	Phys. Therapy	Pharmacy	Emergency	Food Service	Surgery	Nursing Care	ICU	Maintenance
Administration		x													x				x
General Clinic	x		x					x						x					x
Med./Surg.		x		x				x	x							x		x	
Urology			x					x								x		x	
EENT								x										x	
Psychiatry																			
Dentistry																			
Laboratory		x	x	x	x				x				x			x			
EKG-EEG			x					x						x		x	x		
CSS													x	x		X		x	
Radiology														X		x	x		x
Phys. Therapy																	x		x
Pharmacy								x		x								x	
Emergency		x							x	x	X					x			
Food Service	x																x		
Surgery			x	x				x	x	X	x			x			x	X	
Nursing Care									x		x	x			x	x		x	x
ICU			x	x	x					x			x			X	x		
Maintenance	x	x									x	x					x		

X = major relationship

x = minor relationship

Decisions were based on: type of staff members, frequency of movement and size of group.

FIGURE 6.6.5 TYPICAL GRAPHS USED FOR ARRIVING AT AFFINITY MATRIX DECISIONS ON STAFF FLOW

FLOOR PLAN FOR LEVEL 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1					A		A								
2		ADM	ADM	SUP	SUP	SUP	FOD	FOD	FOD						
3	A	ADM	ADM	SUP	SUP	SUP	FOD	FOD	FOD						
4		CLS	CLS	OBG	CSS	EMP	EMP	FLI	FLI	A					
5		CLS	CLS	OBG	CSS	PED	PED	PHT							
6		MSS	FAR	ENT	LAB	URO	RAD	ORT	PSY						
7		MSS	MSS	ENT	LAB	RAD	RAD	DEN	EMR						
8															

FLOOR PLAN FOR LEVEL 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1															
2		ADM	ADM	ADM	PAT	NIT	NIT	NIT	NIT						
3		ADM	ADM	ADM	EMP	NIT	NIT	NIT	NIT						
4		NOB	NOB					NIT	NIT						
5		NOB	NOB					SUP	SUP						
6		NOB	DEL	DEL	SUR	SUR	SUR	ICU	ICU						
7		NUR	NUR	DEL			ICU	ICU	ICU						
8															

FLOOR PLAN FOR LEVEL 3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1															
2		NFI	NPE	NPE	PAT	PAT	NLI	NLI	NLI						
3		NFI	NFI	NPE	SP1	SP2	NLI	NLI	NLI						
4		NFI	NFI					NLI	NLI						
5		NFI	NFI					NLI	NLI						
6															

FIGURE 6.6.6 COMPUTER PRINTOUT OF PROPOSED LAYOUT

FLOOR PLAN FOR LEVEL 1 SOLUTION NUMBER 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							NLI	NLI	NLI						
2							NLI	NLI	NLI						
3							NLI	NLI	NLI						
4		A						NLI		A					
5	SUP	SUP	SUP	FOD	FOD	FOD	SUP	SUP	SUP	EMR	PHT	LAB	LAB	ORT	DEN
6	SUP	SUP	ADM	FOD	FOD	FOD	PAT	PAT	PAT	RAD	RAD	RAD	URO	SP1	PSY
7	ADM	ADM	ADM	ADM	EMP	EMP	EMP	CLS	CLS	SP2	MSS	PED	OBG	FLI	FLI
8	ADM	ADM	ADM	ADM	ADM	FAR	CLS	A	CLS	MSS	MSS	PED	OBG	ENT	ENT

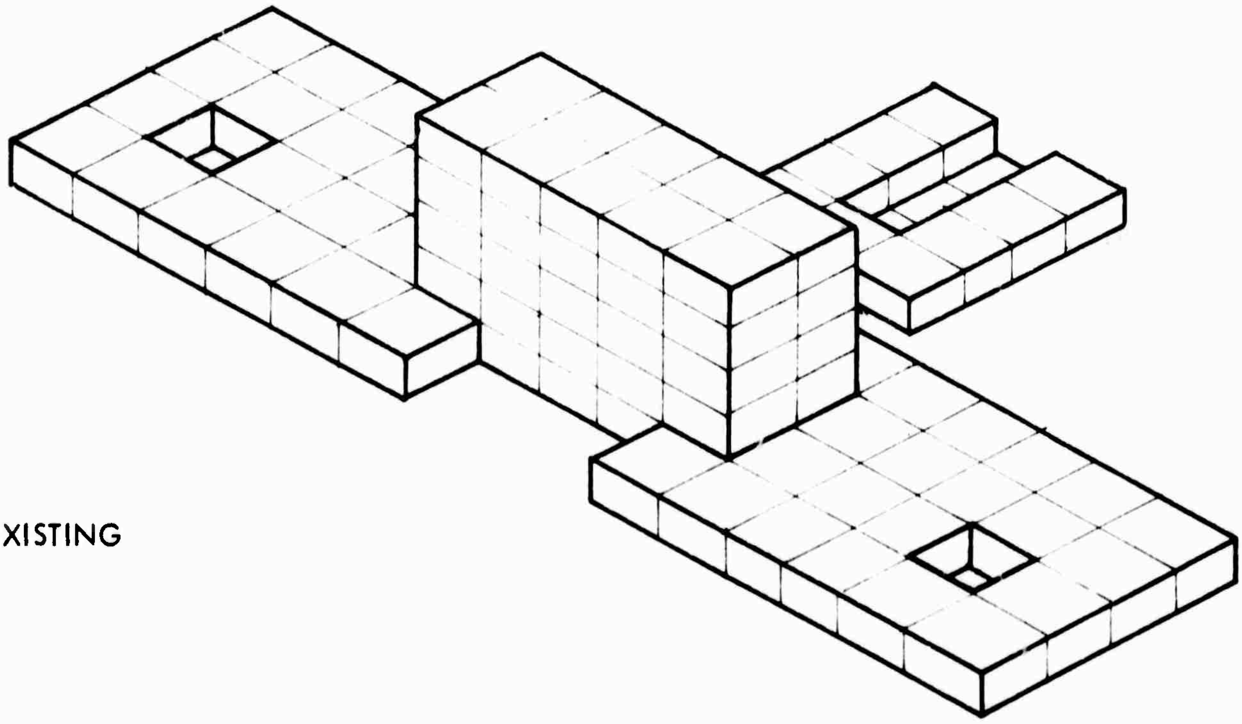
	6	7	8	9	10
5					
6	NIT	NIT	NIT	NIT	NIT
7	NIT	NIT	NIT	NIT	NIT
8					

	6	7	8	9	10
5					
6	NFI	NFI	NFI	NFI	NPE
7	NFI	NFI	NFI	NPE	NPE
8					

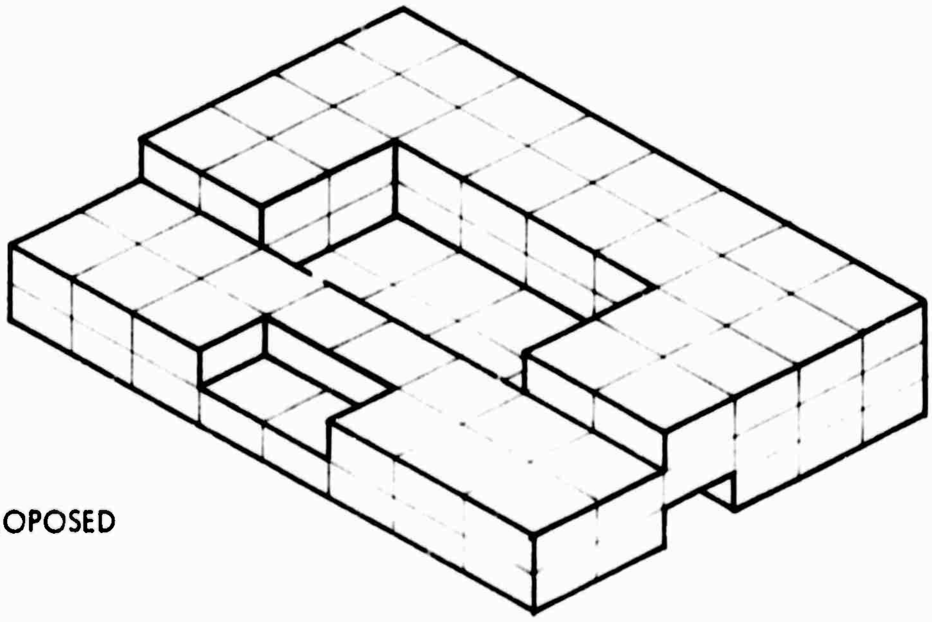
	6	7	8	9	10
5					
6	NUR	NUR	NOB	DEL	DEL
7	NOB	NOB	NOB	NOB	DEL
8					

	6	7	8	9	10
5					
6	SUR	SUR	SUR	CSS	CSS
7	ICU	ICU	ICU	ICU	ICU
8					

FIGURE 6.6.7 COMPUTER PRINTOUT OF EXISTING LAYOUT



EXISTING



PROPOSED

FIGURE 6.6.8 BUILDING CONFIGURATIONS OF MARCH AFB HOSPITAL

FIRST	FLOOR					NLI	NLI	NLI		RAD	RAD	FAR	FAR	EMR	EMR
						NLI	NLI	NLI		RAD	RAD	FAR	FAR	CLI	CLI
						NLI	NLI	NLI		RAD	RAD	CLI	CLI	CLI	CLI
							NLI			RAD	RAD	CLI			CLI
SUP	SUP	SUP	FOD	FOD	FOD	SUP	SUP	SUP	CLI	PHT	LAB	LAB	ORT	DEN	CLI
SUP	SUP	ADM	FOD	FOD	FOD	PAT	PAT	PAT	CLI	LAB	LAB	URO	SPI	PSY	CLI
ADM	ADM	ADM	ADM	EMP	EMP	EMP	CLS	CLS	SP2	MSS	PED	OBG	FLI	FLI	CLI
ADM	ADM	ADM	ADM	ADM	ADM	CLS		CLS	MSS	MSS	PED	OBG	ENT	ENT	CLI

FIGURE 6.6.9 COMPUTER–EVALUATED LAYOUT FOR EXPANSION OF EXISTING FACILITY AT MARCH AFB

FIRST FLOOR

ADM	ADM	SUP	SUP	SUP	FOD	FOD	FOD
ADM	ADM	SUP	SUP	SUP	FOD	FOD	FOD
CLS	CLS	OBG	CSS	EMP	EMP	FLI	FLI
CLS	CLS	OBG	CSS	PED	PED	PHT	
MSS	FAR	ENT	LAB	URO	RAD	ORT	PSY
MSS	MSS	ENT	LAB	RAD	RAD	DEN	EMR
CLI	CLI	CLI	LAB	RAD	RAD	CLI	EMR
CLI	CLI	CLI	LAB	RAD	RAD	CLI	CLI

FIGURE 6.6.10 COMPUTER - EVALUATED LAYOUT FOR EXPANSION OF PROPOSED FACILITY AT MARCH AFB

6.7. COST ESTIMATE OF REDESIGNED MARCH AFB HOSPITAL

6.7.1. INTRODUCTION

This appendix presents the cost benefits derived from using the recommendation and innovation presented in the major body of this report. They include: form diagram, modular (grid) design, systems buildings, and multi-track scheduling. For this example, March AFB Hospital was selected for study. It was found that over a fifty-year life span of the March Hospital facility, the total cost savings are estimated to be $696,000 if the facility were built totally with interstitial space; only $412,000 would be realized if the facility were built with only 47% interstitial space for selected areas such as surgery, laboratory, and outpatient clinics. Calculations, a summary table, and exhibits follow to validate this study.

6.7.2. COST ANALYSIS

Table 6.7.1 presents the findings of this example using the recommendations and innovations stated above. In addition to showing costs for the existing facility over the years, two alternatives are presented. Alternate 1 is built with total interstitial space (and systems buildings) and alternate 2 is built with 47% interstitial space.

Cost savings are not dramatic for total capital investment of either alternate 1 or 2 over a 50-year life span; it approximates 1% or approximately $2,500 to $3,000/year for both alternate 1 with total interstitial space or alternate 2 with 47% interstitial space for selected elements (or departments). Cost savings are somewhat better for plant operations using all interstitial space; they approximate 5% or approximately $11,400 savings per year over a 50-year life. All costs are considered in constant 1970 dollars over the years and inflation is not included, in order to simplify the calculation and comparison.

TABLE 6.7.1 ESTIMATE OF COST COMPARISON FOR MARCH AFB HOSPITAL

UNDER THREE DIFFERENT CONDITIONS*

(Costs in $1000 except in remarks)

ITEM	EXISTING (no interstitial space)	ALTERNATE #1 (total interstitial space)	REMARKS	ALTERNATE #2 (47% interstitial space)	REMARKS
Capital Cost:					
1. Acquisition (130,100 SF)	$5,309	$5,575	uses modular designs, all interstitial space	$5,434	uses modular design, multi-track; only 47% interstitial
2. Alteration initial equipment	1,550 97	1,008 97	same as above	1,295 97	same assumption as above
3. Expansion (120%)	6,371	6,690	same as above	6,521	same assumption as above
4. Use of Form Diagram/ Modular Design	not used	(56)	computer aided design analysis	(54)	computer aided design
5. Use of Multi-track Scheduling	not used	(111)		(109)	
TOTAL CAPITAL INVESTMENT	$13,327	$13,203	saving of $124,000 over existing or 0.93% less	$13,184	savings of $147,000 over existing or 1.10% less.
Operations & Maintenance:					
6. Plant Operations	none	no change		no change	
7. Maintenance	$11,440	10,868	considers interstitial space	$11,171	considers 47% interstitial space for selected elements
TOTAL OPERATIONS & MAINTENANCE	$11,440	10,868	savings of $572,000 over existing or 5% less	11,171	savings of $269,000 over existing or 2.3% less
TOTAL FACILITIES COST	$24,767	$24,071	life span savings is estimated to be $696,000 over existing or 2.8% less	$24,355	life span savings is estimated to be $412,000 over existing or 1.7% less

*See notes on following page.

NOTES TO TABLE 6.7.1

1. All dollars are calculated at base year 1/1970.

2. Life span of hospital is considered to be 50 years.

3. Alteration costs are 25% less over the years for the proposed facility.

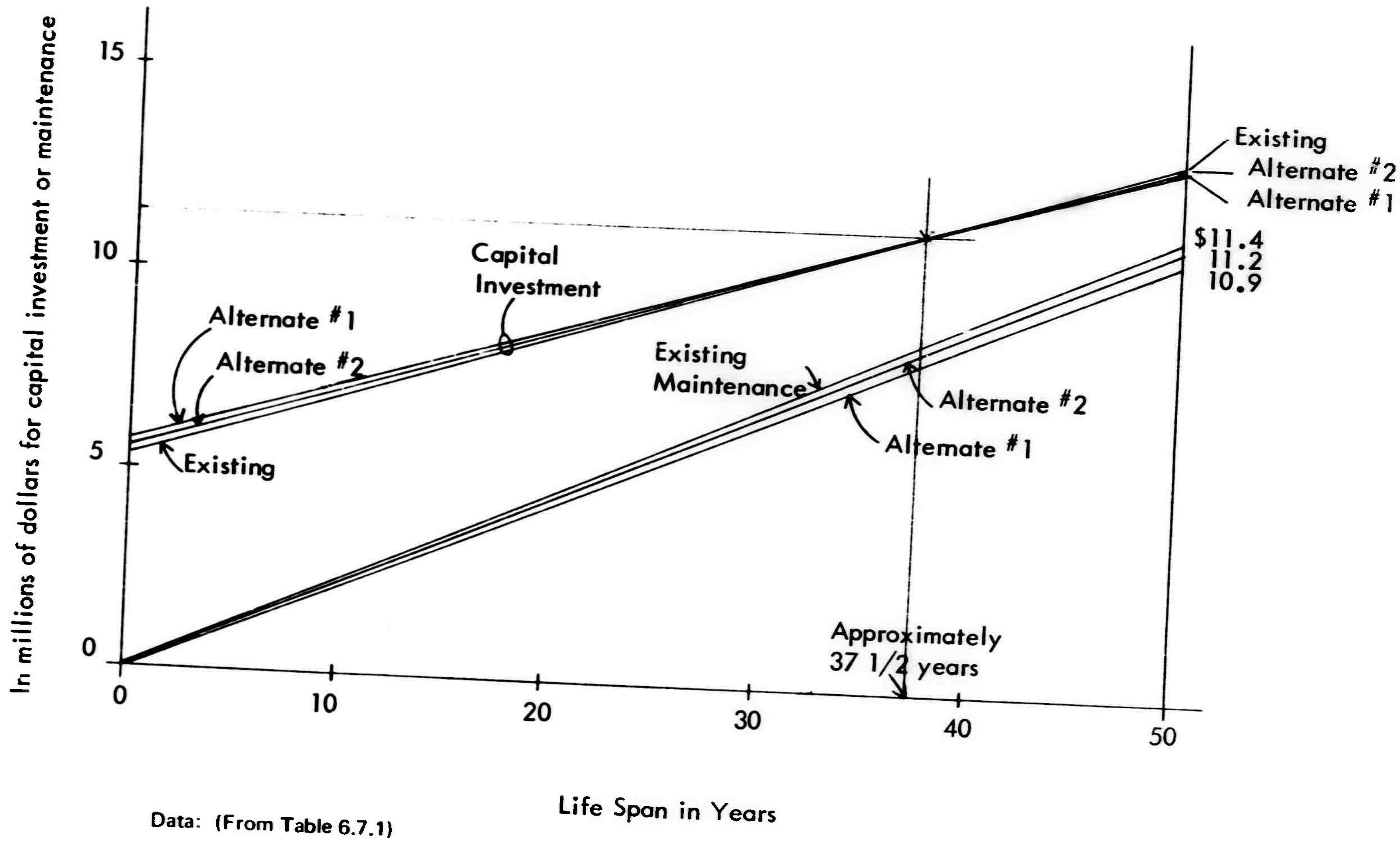
4. Maintenance costs are assumed to be base engineer's costs and exclude utilities and custodial expenses.

5. Capital investment costs for the proposed building for new space are considered to be 5% higher.

6. Number 1, Alteration, includes emergency power generating equipment as an initial addition in 1966. This cost is considered a constant and is adjusted to 1/1970 using the ENR Index ($\frac{802}{647}$ x 78,000) = $97,000.

7. See Figure 6.7.2 for ENR Index.

8. Data are plotted on graph in Figure 6.7.1, for capital investment. only (top linear curve). The payoff for buildings having interstitial space versus non-interstitial space is 37-1/2 years. However, plant maintenance permits a break-even point at approximately 20 years.



Data: (From Table 6.7.1)

FIGURE 6.7.1 LINEAR CURVES FOR CAPITAL INVESTMENT AND PLANT MAINTENANCE

The total cost of the plant—capital investment and plant O&M—for alternate 1 (total interstitial space), appears to be the best buy with a modest 2.8% savings in cost over a 50 year life; on the average, this saving amounts to approximately $15,000 per year. Also, the estimated break-even point for maintenance savings to accrue vs. capital investment payoff would be after 20 years. Facility depreciation is not taken into account.

6.7.3. CALCULATIONS

Calculations supporting Table 6.7.1 follow in Table 6.7.2. In summary, the assumptions are listed below for the categories 1 through 7 on the Table.

(1) Acquisition. Interstitial space is estimated to cost 5% more than a builing without it. See Section 6.7.12 for range of cost from 3-1/2% to 12-1/2%. Modified interstitial spaces are estimated to cost the same.

(2) Alteration. A saving of 35% is estimated and is based on the table presented in Section 3.6.

(3) Expansion. If interstitial space is used, it is expected that it will cost 5% more than a builing without it. See Section 6.7.12.

(4) Use of Form Diagrams and Modular Design. It is proposed in Section 3.3 that the SGO, rather than the engineer, will determine the builing form. In addition it is proposed to use modular grid design. Savings can accrue to 1% or more. See Section 3.6.

TABLE 6.7.2 CALCULATIONS

(All costs adjusted to base 1/170.)

EXISTING	ALTERNATE #1	ALTERNATE #2
1. **Acquisition**		
130,100 SF x $40.81=$5,309,381	A 5% increase in construction costs is assumed. See Section 6.7.12. $5,309,381 + 5%=$5,574,850	A 5% increase in construction cost is assumed for 47% of the 130,100 SF. (See Section 6.7.11). The remaining 53% will be conventional construction.
		130,100 x 47% x $40.81/SF + 5%= $2,620,180
		130,100 x 53% x $40.81/SF= $2,813,972
		Total Cost $5,434,152
2. **Alteration**		
$31,000/year x 50 years = $1,550,000	$1,550,000 - 35% = $1,007,500	$1,550,000 x 53% = $821,500
The cost of alteration is based on the period 1965 to 1969 where alterations totaled $219,000 of which $78,000 was for equipment. The difference is $141,000 or an average of $28,000/year. At 1/1970 costs this is $\frac{802}{725}$ x 28,000= $30,800.	During the same period the alterations costs would be 35% cheaper based on Table 6.7.4.	$1,550,000 x 47% - 35% = $473,525
		Total Alterations $1,295,025
		Only 47% is interstitial space and alteration for this portion only would be reduced by 35%.

TABLE 6.7.2. CALCULATIONS (continued)

EXISTING	ALTERNATE #1	ALTERNATE #2
3. Expansion		
A facility is assumed to grow to 120% of its original size on an S curve. Therefore:	A 5% increase in construction cost is anticipated. See 1. above.	See explanation in 1. above.
		($6,371,357 x 47%) + 5% = $3,144,264
$5,309,381 x 120% = $6,371,257	$6,371,357 + 5% = $6,689,925	($6,371,357 x 53%) = $3,376,819
		Total Expansion $6,521,083
4. Use of Form Diagrams and Modular Grid Design		
Not used.	Assume a 1% savings in A/E fee on initial design only. Use cost in 1. above.	Same assumption as Alternate #1.
		1% x $5,434,151 = $54,342
	1% x $5,574,650 = $55,747	
5. Use of Multi-track Scheduling		
Not used.	Assume four to five separate construction packages on original construction only. An assumption is that there is less risk than one lump sum construction package and LS could be reduced by 2%.	Same assumption as Alternate #1.
		2% x $5,434,151 - $108,683
	2% x $5,574,650 = $111,493	
6. Plant Operation		
An assumption is made that no change will occur over the 50 years relative to savings.	Same assumption as Existing.	Same-assumptions as Existing.

TABLE 6.7.2. CALCULATIONS (continued)

EXISTING	ALTERNATE #1	ALTERNATE #2
7. Plant Maintenance		
The cost of maintenance for calendar year 1969 (to 1/1970) was $143,000 and does not include custodial service. Cost of maintenance of original plant over 50 years:	Estimated reduction of maintenance with interstitial space is 5%. This is considered to be conservative based on a difference of 8-1/2% less at the Dominican Santa Cruz Hospital. Cost comparison:	Same assumptions as Alternate #1. Therefore: ($11,440,000 x 47%) - 5% = $5,107,960
$143,000 x 50 years = $7,150,000		$11,440,000 x 53% = $6,063,200
Cost of maintenance expansion:	March AFB $1.15/SF Dom. SC $ .95/SF	Total Maintenance $11,171,160
($143,000 x 120%) x 1/2 x 50 yrs= $4,290,000	Therefore:	
Total maintenance $11,440,000	$11,440,000 - 5% = $10,868,000	

(5) Multi-track Schedule. It is assumed that on the basis of 4 or 5 separate bid packages, the previous risk assumed by a single contractor will be reduced. Contract(s) duration is expected to be less than 1 year rather than 2 or 3 years. Total contract costs can be reduced by 2%

(6) Plant Operations. No savings anticipated in costs of utility consumption or the number of equipment operators from present practices.

(7) Plant Maintenance. An assumption is that maintenance will be reduced by 5%. Similar conditions at Dominican Hospital at Santa Cruz have reduced plant maintenance costs by 8-1/2%. By separating maintenance personnel from health care spaces and by conveniently exposing utilities in interstitial spaces, ease of maintenance is provided and social communications of the hospital staff personnel is reduced.

6.7.4. CONCLUSION

There is a modest saving in using facilities with distinctively separated utility spaces where maintenance and operating personnel can gain access without interrupting hospital operations. In addition, intersitial spaces permit easier utility alteration. The use of movable partitions and long spans permit functional changes with in-house personnel rather than by contract.* In both instances, maintenance and alterations are less costly and easier to perform. However, there is a 5% premium to permit this for which a cost pay-off does not occur for twenty years after the facility is erected regardless of whether it expands or not. A facility having distinctly separated utility spaces would permit easier expansion.

*Interviews were conducted with Texas Instruments, Salk Laboratories, and Rex W. Allen, Architect.

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*Interviews were conducted with Texas Instruments, Salk Laboratories, and Rex W. Allen, Architect.

6.7.5. CONSTRUCTION COST INDICES

Over the past nine years, construction labor rates have risen between six and seven percent per annum. Until the last two years material prices were fairly stable, making an average annual increase of only two or three percent. Improved construction methods, prefabrication or shop manufacture, and increased use of mechanical equipment have modified the effect of the labor increases; the combined effect has been an annual cost increase of three to four percent. In the last two years there has been a marked fluctuation and increase in material prices, resulting in annual cost increases twice as severe as in the previous five or six years.

Engineering News-Record maintains two distinct construction cost indices, one for "buildings" and the other for "general construction." Each is based on a hypothetical block of construction requiring the same quantity of steel, lumber, and cement combined with two hundred manhours of labor (all skilled for "buildings", all unskilled for "general construction"). The indices were reevaluated in 1938 and 1921 respectively but are based on 1913. If the mixes of materials and labor were reasonable at the conception, they are not necessarily so now. In any case the indices take no consideration of other materials, the use of equipment, advances in construction methods, or changing styles of buildings over the last half century. In fact, the material component of both indices is unduly influenced by the price of lumber (as demonstrated by the figures below) and the labor represents over 80% of the building index. Yet E.N.R. indices are widely quoted in the industry.

Marshall & Stevens publish a building cost index based on actual building contracts and sales. Imperfect as this may be, it does take into consideration changes in methods and actual buildings costs. Generally the M&S index indicates a much less dramatic fluctuation in cost than E.N.R.; however, it does tend to lag behind actual costs.

Below are cost indices from these two sources over the past five years.

Date		ENR* San Francisco Bldg.		G.C.		M&S Western	
3/1965		657		1059		3709	
	Increase		5.32%		1.08%		2.15%
3/1966		692				3789	
	Increase		5.20%		6.38%		4.61%
3/1967		728		1217		3964	
	Increase		5.49%		8.13%		3.70%
3/1968		768		1316		4111	
	Increase		11.15%		11.70%		6.56%
3/1969		856		1470		4381	

Our records show approximately 3% increase in 1965 and 1966, 4% in 1967, 8% in 1968 and 6% in 1969.

It seems reasonable to anticipate labor rates to continue to rise at about 8% per annum and material prices to stabilize as military spending decreases, to an annual increase of about 3%. The resultant annual increase in construction cost may be expected to be approximately 6%. ENR forecast a continued increase of 9-10% per annum, and M&S suggest from 3-7% per annum.

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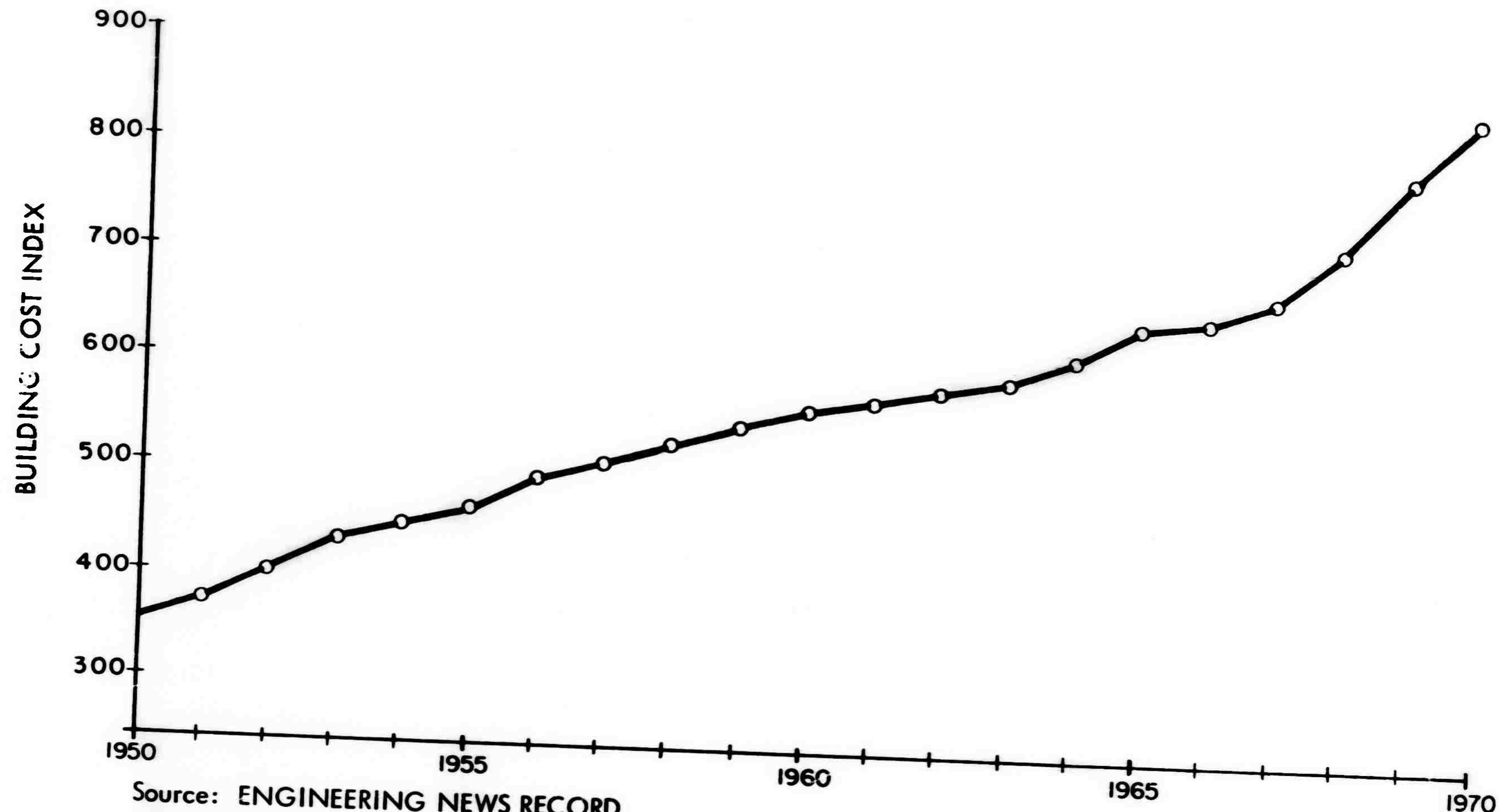
* Also see Figure 6.7.2.



Source: ENGINEERING NEWS RECORD
*1913 = 100

FIGURE 6.7.2 ANNUAL AVERAGES OF BUILDING COSTS OVER 20 U.S. CITIES

6.7.6. FACTORS INFLUENCING CONSTRUCTION COSTS

There are four basic categories of factors influencing costs:

1. Location

2. Building configuration

3. Proportion of departmental usage

4. Flexibility and quality of construction and finish

These may be subdivided:

1. a. Economic area
   b. Proximity to sources of labor and materials
   c. Climate
   d. Site conditions

2. a. Total overall size of construction project
   b. Floor area to exterior wall ratio
   c. Story height
   d. Number of stories

3. a. Various departmental areas
   b. Circulation
   c. Auxiliary buildings or equipment space

4. a. Structural design spans
   b. Type of floor systems
   c. Quality of finish

The components relating to location and building configuration account for more than half the cost of the project, and the factors affecting these have a greater effect on the total cost than the proportion of departments within the building. The costs of components affected by departmental usage vary more with quality and design for flexibility than with the proportion of area occupied by the various departments.

Examples:

1. Interior partitions, finishes, and equipment in different types of hospitals, assuming a variety of likely mixtures of departmental areas, may vary $3.00 per square foot.

2. The exterior wall to floor ratio may vary by more than 100%, affecting construction cost by more than $3.00.

3. Special foundations and long-span structural systems may add $3.00 per square foot to the total cost.

4. A larger narrow building is more economical than a small square building but less than a large square building. Large square buildings are impractical without interior courts.

Project		Floor to Wall Ratio
Oak Knoll		.347
Letterman		.276
March		.400
RELATE	2-story	.281
	4-story	.374
	8-story	.562
MofH	A	.535
	B	.511
	C	.365
	D	.152

Unless greater study is given to the design problems, it is impossible to obtain a meaningful comparison of mechanical and electrical costs in different configurations of structure or arrangements of services.

6.7.7. COMPARABLE ANALYSES OF OAKLAND NAVAL HOSPITAL, LETTERMAN HOSPITAL, AND MARCH AFB HOSPITAL

Principally the component costs of three military hospitals, Oak Knoll, Letterman, and March AFB have been analyzed. This analysis of March AFB has been prepared from actual cost information and estimates furnished by Colonel Herr, MCLO, Air Force, San Francisco. It varies slightly from the national breakdown. In addition, the following has been considered:

- The theoretical substitution of separate facilities for ambulatory patients;
- The costs of planning modules of six hospital departments; and
- The costs of three configurations of typical structural modules.

After studying the various influences on costs of hospital construction, it was found that site conditions, climate, and building configuration--floor to wall ratio, total gross area, and height--have a much greater influence on costs than the proportionate mix of departmental areas. For this reason we think that departmental costs should only be added to separately considered building and site costs and should not be considered part of modular costs.

Oakland and Letterman analyses were produced from the attached analyses dated 2 February 1970. March AFB analyses were produced from working drawings issued by USAF Corps of Engineers, Base Schedule & Construction Cost Estimate dated 29 April 1963, and Real Property Accountable Record Buildings dated 8 September 1965. The March analysis is of the Main Hospital Building only. All costs have been adjusted to base 1/1970 San Francisco.

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*Prepared by MDA Construction Cost Consultants, San Francisco, California

TABLE 6.7.3 ANALYSIS AND COMPARISON
(dollars per square foot)

		Oakland	Letterman	March
1.	Foundations (excluding siteworks)	$0.60	$0.63	$0.45
2. & 3.	Structure—vertical and horizontal elements	7.20	7.30	7.59
4.	Exterior walls	2.52	2.31	2.40
5.	Roofing and waterproofing	0.31	0.31	0.66
6.	Interior partitions	3.26	3.18	3.52
7.	Floor, wall and ceiling finishes	2.52	2.44	3.75
8.	Building function equipment	3.44	2.50	2.79
9.	Vertical transportation	1.85	1.94	1.79
10. and 11.	Plumbing and HVAC	9.84	10.67	8.97
12.	Electrical	2.95	3.13	4.54
13.	Fire Protection	—	--	0.05
		$34.49	$34.41	$36.51
	Contractor's Job & Office Overhead & Profit	2.56	2.69	4.30
	Gross Construction Cost	$37.05	$37.10	$40.81

6.7.8. CONSIDERATION OF A MODULAR REDESIGN OF MARCH AFB HOSPITAL

This study is extremely theoretical, based on known costs of existing facilities, general layouts of isolated hospital departments, and a general structural design for a modular frame. The figures in this Exhibit indicate a pattern achieved by this one study. Further studies may rearrange the pattern of figures to give conflicting results. If this line of research is to be pursued, it is recommended that further in-depth studies with more advanced design criteria be made.

This study of modular design and planning module costs are expressed in factors which may be used as input to the RELATE program. This is also considered to be a report on the theoretical modular redesign of March Air Force Base Hospital including a consideration of the effects of "plug-in" sub-modules.

6.7.9.1. Object

To estimate the cost feasibility of a modular concept for the new hospitals and to assess the effect on cost of the concept of dynamic environment by the use of plug-in sub-modules.

6.7.9.2. Method

To prepare a cost analysis of the modular redesign of the March AFB Hospital and compare it with the analysis of the March AFB Hospital as actually built. (See costs of original March in Section 6.7.8.)

6.7.9.3. Assumptions

Comparison of the March analyses will show the increased cost of redesigning the hospital on a modular basis. The following notes on the individual components of the analyses may assist in a better understanding of the comparison; those components upon which the modular redesign has had a major effect (numbers 2, 6, and 10) are marked with an asterisk.

---

*Study by MDA Construction Cost Consultants, San Francisco, California.

(1) Foundations:

The figure for the Modular Redesign has been based on assumptions of suitable requirements and will obviously vary from site to site. No great emphasis should be placed on the difference between the two figures.

(2* & 3) Structure:

The increased cost of this element in the Modular Redesign is due to two factors: a) the increase in the floor spans, and b) the increase in the floor-to-floor height due to the introduction of the interstitial space.

(4) Exterior Walls:

March exterior walls cost an average of $6.25 per square foot of surface. For the purposes of the modular design we have allowed an average of $10.31 per square foot, which we consider reasonable for this type of construction. Both plans have a floor to wall ratio of about 0.4.

(5) Roofing and Waterproofing:

No comment.

(6*) Interior Partitions:

The increased cost of this element in the Modular Redesign is due more to the requirements of dynamic environment and the consequent considerable use of demountable partitions. The two factors of redesign and environment are, however, interrelated, and for this reason this element has been marked as one upon which modular redesign has had a major effect. The use of demountable self-finished partitions is reflected by a slight reduction in the cost of wall finishing (see Component 7).

(7) Floor, Wall & Ceiling Finishes:

The reduction of this element due to the use of demountable partitions has been mentioned above; however, the reduction is not as great as might be supposed, due to the use of a modular ceiling-lighting sub-system.

(8) Building Function Equipment:

It has been assumed that the equipment requirements would be the same in both designs.

(9) Vertical Transportation:

The cost of this element in the Modular Redesign is based upon two staircases and four elevators.

(10* & 11) Plumbing and HVAC:

The increased cost of this element in the Modular Redesign is due to the modular layout of the pipe and ductwork. Although it is possible that mass production techniques could reduce this element, the actual cost effect cannot be assessed at this point in time, and the element has been priced on the basis of current methods of construction.

(12) Electrical:

It has been assumed that the requirements for this element would be the same in both designs.

(13) Fire Protection:

March appears to have had only a limited fire sprinkler system in one area. It is assumed that the Modular Redesign will require full sprinkling on both occupied and interstitial floors.

This Exhibit is concerned solely with the effect of a modular redesign on the capital cost of the building. No attempt has been made to assess the possibility of lower operating and alterations costs due to the modular redesign.

Plug-in Sub-modules: an attempt has been made to assess the cost of using "plug-in" sub-modules for the North & South half modules of the First Level of the Modular Redesign. A copy of this assessment follows. It must be understood that these figures are theoretical; a great deal more information would have to be provided before the cost of this scheme can be assessed accurately.

It has been assumed that the "plug-in" units could be built and installed at a cost of $12.50 per square foot. This assumes a high degree of standardization and sufficient demand to warrant mass production methods of manufacture.

Drawings providing a modular concept to support these studies are included in Figures 6.7.3 through 6.7.6.

TABLE 6.7.4. ANALYSIS OF MODULAR REDESIGN OF MARCH AFB HOSPITAL

Note: All costs have been adjusted to base 1/1970 San Francisco

	March AFB Modular Redesign	Reduction for Use of Plug-in Modules	Revised Analysis Where Plug-in Modules Used
1. Foundations (excluding siteworks)	$ 0.38	$ --	$ 0.38
2.&3. Structure--vertical & horizontal elements	9.53	--	9.53
4. Exterior walls	4.05	0.34	3.71
5. Roofing & waterproofing	0.64	--	0.64
6. Interior partitions	4.00	0.43	3.57
7. Floor, wall & ceiling finishes	3.70	0.40	3.30
8. Building function equipment	2.79	--	2.79
9. Vertical transportation	1.73	--	1.73
10.&11. Plumbing & HVAC	9.50	0.32	9.18
12. Electrical	4.54	0.21	4.33
13. Fire Protection	0.85	--	0.85
	$41.71	$1.70	$40.01
Contractor's Job & Office Overhead & Profit	4.17	0.10	4.00
Gross Construction Cost	$45.86	$1.80	$44.01
14. Plug-in Modules			1.34
Gross Construction Cost			$45.35

TABLE 6.7.5

FACTOR TABLE USED IN DETERMINING COST PER SQUARE FOOT

Analysis of effect on cost of different configurations of a group of 16 structural modules as LGA sketches dated March 10, 1970.

1.	Two-story building with eight modules per floor	Wall/floor ratio .281
2.	Four-story building with four modules per floor	Wall/floor ratio .374
3.	Eight-story building with two modules per floor	Wall/floor ratio .562

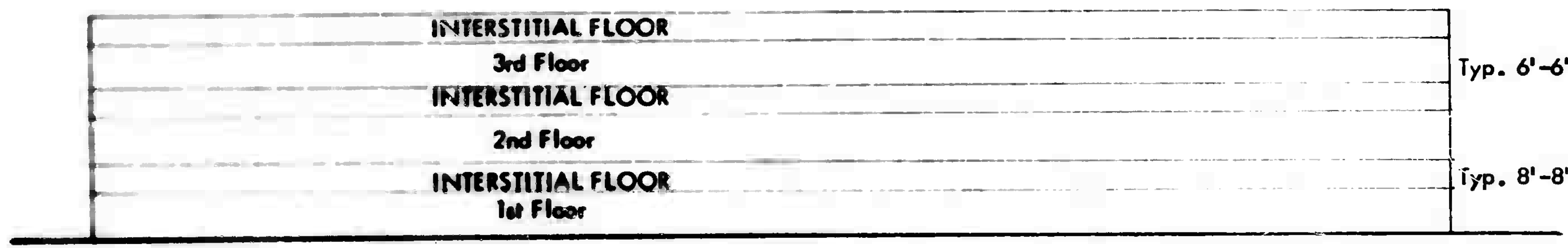
	Factors Per Square Foot								
	Structure & Shell			Interior Finish & Services Department					
Components	2	4	8	Lab & Del.	Nurs.	Surg.	Phys. Ther.	Clin. Ped.	Rad.
1. Foundations	40	25	27						
2. Vertical structural members	40	44	73						
3. Floors & roof systems	875	870	865						
4. Exterior cladding 100% Fenestration (Select one or	305	405	620						
Nil Fenestration take mixture)	205	275	425						
5. Roofing & waterproofing	80	40	20						
6. Interior partitions				165	295	325	210	450	310
7. Floor wall & ceiling finishes				355	260	590	400	270	355
8. Equipment & fittings				225	190	530	220	155	250
9. Vertical transportation	85	165	215						
10. Plumbing	25	30	55	375	325	275	200	250	200
11. Heating, ventilating & air conditioning	490	410	425	75		100	75	75	75
12. Electrical	235	210	215	200	160	250	160	200	275
13. Fire protection systems	85	75	80						
				1395	1230	2070	1265	1400	1465

The above factors are based on three very different configurations of 77440 SF of building comprising 64 planning units in 16 structural modules. Planning units studied are as shown on Lester Gorsline Associates departmental plans dated April 9, 1970. <u>Site preparations and utilities are not considered</u>.

To find factor for total building: take total of structure and shell factors according to shape and height and according to percentage fenestration, add an average of the departmental factors according to the proportionate minimum of departmental areas.

	Lab & Del.	Nurs.	Surg.	Phys. Ther.	Clin. Ped.	Rad.
Assuming a four-story 16-module building containing 64 planning units as follows:	8	30	8	4	8	6

with 50% fenestration, the building factor would be 3610--this multiplied by a San Francisco June, 1970 factor of .0115 equals a reasonable cost per square foot of building excluding site development and utilities.



SECTION

NOTES:

- STRUCTURAL & MECHANICAL AS SHOWN ON ENGINEER'S CALCULATIONS
- SYSTEMS CEILING
- PART REMOVABLE PARTITIONS, REST CONVENTIONAL (O.R. SUITES, RADIOLOGY, LABS)
- RE: 1st FLOOR; ONE STUDY AS SHOWN ON PLANS
  ONE STUDY WITH N. & S. HALF MODULES AS PLUG-IN UNITS
  (SEE DRAWINGS) AND REMAINDER MOVABLE.

FIGURE 6.7.3 MODULAR LAYOUTS FOR ESTIMATING

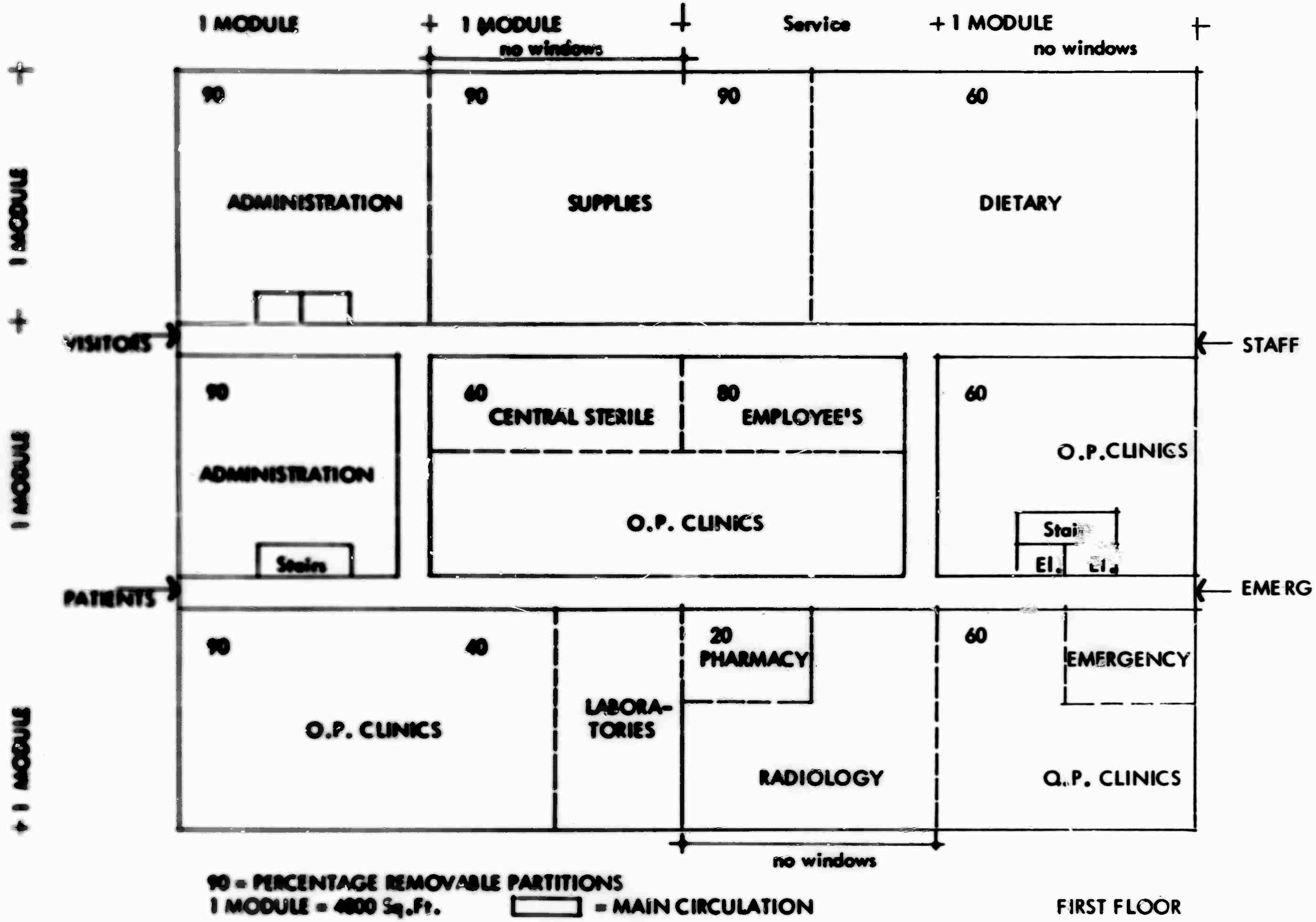


FIGURE 6.7.4 MODULAR LAYOUTS FOR ESTIMATING–FIRST FLOOR

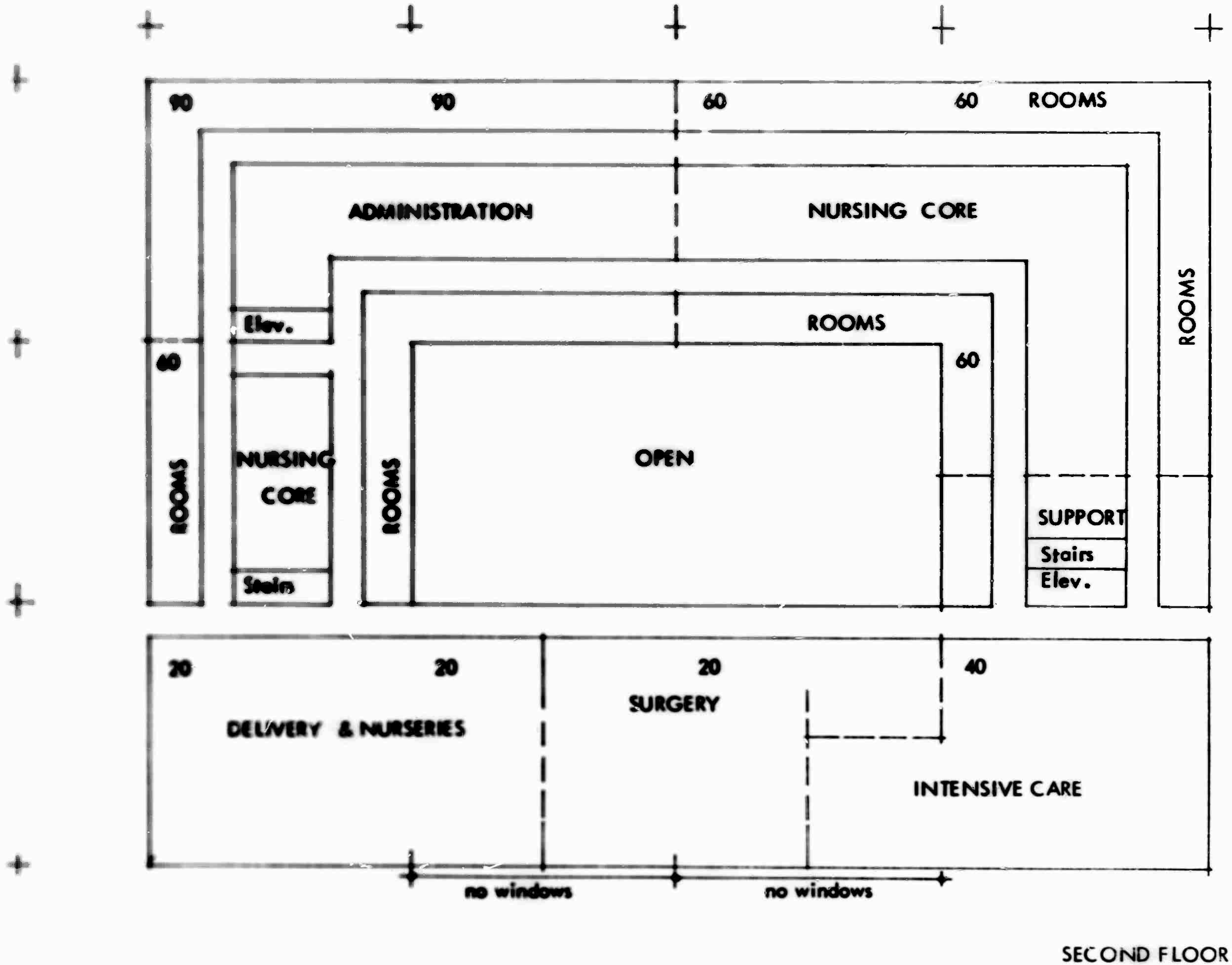


FIGURE 6.7.5 MODULAR LAYOUTS FOR ESTIMATING–SECOND FLOOR

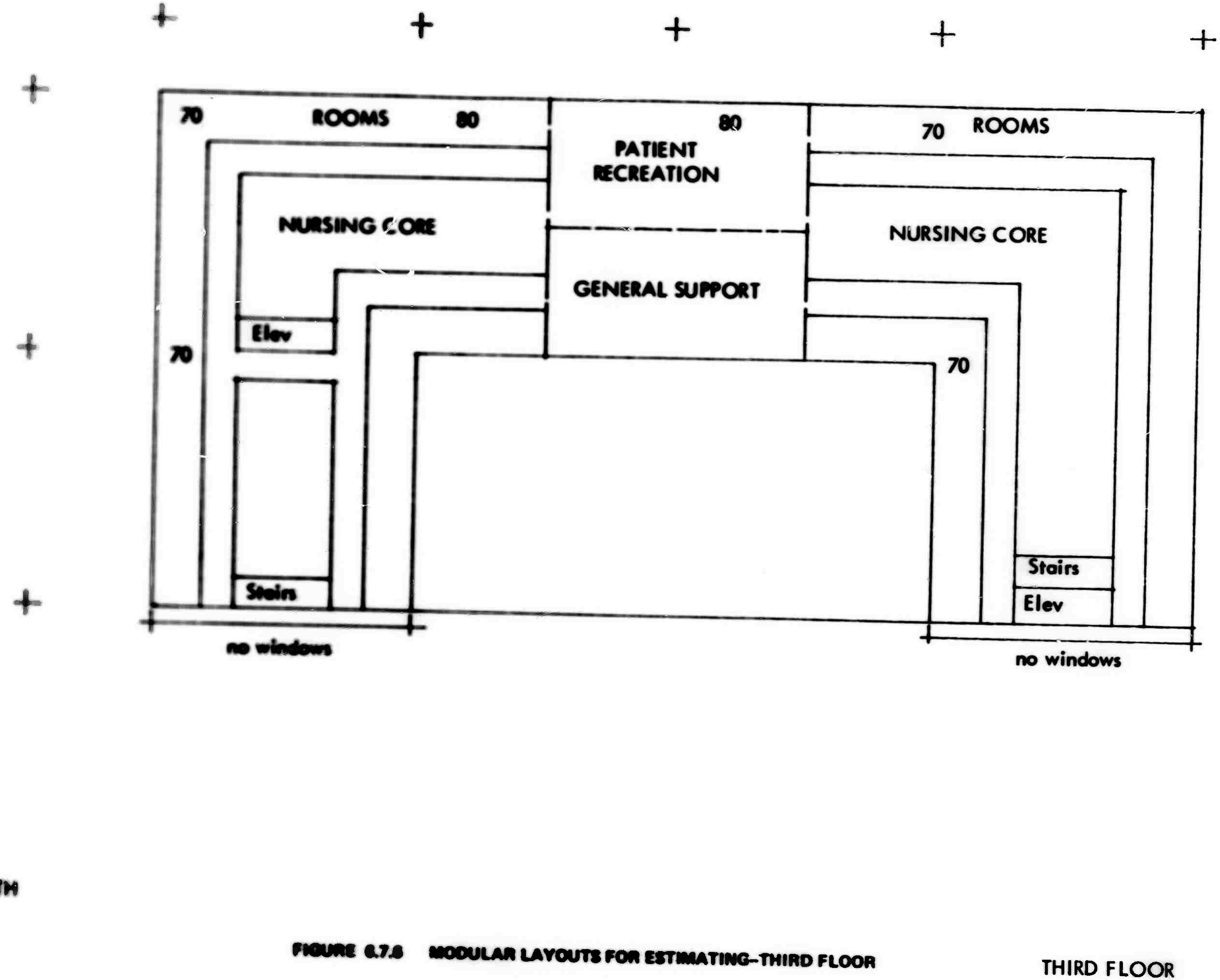


FIGURE 6.7.6 MODULAR LAYOUTS FOR ESTIMATING–THIRD FLOOR

6.7.9. MODULAR REDESIGN OF MARCH AFB HOSPITAL

One of the most extensive investigations carried out on hospitals is that of the British Department of Health and Social Security (DHSS). The large amount of hospital building completed in recent years in Britain has enabled DHSS to compile and tabulate a considerable volume of data and use it to predict the probable cost of future hospitals. The accuracy of their predictions has been such that their tables of Departmental Cost and Area Guides are now used to establish the cost limits of all hospitals planned and built in the British Isles.

The modified tables attached to this Exhibit were used to assess the cost of March AFB Hospital and gave a figure of $40.25 per SF, which is within 1 1/2% of the cost of that hospital as actually built ($40.81 per SF—see Section 6.7.8.) and sufficiently close to consider it worthwhile pursuing this line of investigation further.

TABLE 6.7.6

COST ANALYSIS

Department	Area (SF)		Cost ($M)
1. Administration	11,400		$ 320
2. Supplies	7,200		363
3. Dietary	7,200		263
4. Central Sterile	1,800		115
5. Employees	1,575		44
6. OP Clinics			
Consulting Suites	11,460		327
Operating Theater	4,100		139
Dental Surgery	1,200		43
Orthopedic Clinic	1,090		32
7. Laboratories	2,100		82
8. Pharmacy	900		30
9. Radiology	3,300		106
10. Emergency	900		30
11. Delivery & Nurseries	6,300		187
12. Surgery	5,100		257
13. Intensive Care	5,400		186
14. Support Store and General	3,750		189
15. Wards, Patient Recreation, Nursing Core and Ward Circulation	44,344		1,541
	119,119		4,251
16. Communications	15,281	(12.83%)	545
17. Other On-Costs			
Elevators (4 No)			200
Auxiliary Buildings		(0.75%)	32
Abnormals—Building		(6.50%)	276
—Engineering		(2.50%)	106
	134,400*		$5,410 = $40.25/SF**

*Under modular take-off, actual space exceeded the original area of 130,100 SF. The modular space was used as it was easier to work with but the design conditions are conventional.

**Gross construction cost. Represents cost of conventional construction including contractor's job and office overhead and profit. For cost of modular redesign, add 12-1/2% or $5.03/SF, giving a gross construction cost of $45.28/SF.

TABLE 6.7.7 HOSPITAL DEPARTMENTAL COST AREA GUIDE
(Modified British DHSS Tables)

Service and Department (1)	Functional Units (2)	Departmental Areas (to nearest 100 SF) (3)	Cost Guide $M (4)	Optional Extras (5)
Administration Services				
General	9 points/300 beds	11,300	317	Additional for Non-Resident Staff Changing (excluding medical staff)
	12 points/450 beds	13,200	355	250 N-R Staff $ 10,000
	16 points/600 beds	15,100	403	300 N-R Staff 24,000
	20 points/800 beds	17,000	451	400 N-R Staff 53,000
Main entrance accommodation	9 points/300 beds	2,200	62	500 N-R Staff 86,000
	12 points/450 beds	2,300	67	600 N-R Staff 115,000
	16 points/600 beds	2,600	72	
	20 points/800 beds	2,800	77	
Medical records	9 points/300 beds	3,100	77	Additional for Telephone Equipment
	12 points/450 beds	3,900	96	180 Extensions $ 58,000
	16 points/600 beds	4,600	120	200 Extensions 67,000
	20 points/800 beds	5,400	144	300 Extensions 96,000
Group accommodation	19 points	5,200	134	400 Extensions 130,000
	30 points	7,200	182	500 Extensions 163,000
	40 points	9,100	226	600 Extensions 197,000
Inpatient Services				
General acute wards	30 beds	8,500	307	
	60 beds	16,900	586	
	120 beds	33,800	1,171	
	180 beds	50,700	1,762	
	240 beds	67,700	2,347	
	300 beds	84,600	2,938	
	360 beds	101,500	3,523	

TABLE 6.7.7 (cont'd.)

Service and Department (1)	Functional Units (2)	Departmental Areas (to nearest 100 SF) (3)	Cost Guide $M (4)	Optional Extras (5)
Inpatient Services, contd.				
General acute wards	420 beds	118,400	4,109	
	480 beds	135,300	4,694	
	540 beds	152,200	5,280	
	600 beds	169,100	5,866	
	660 beds	186,100	6,456	
	720 beds	203,000	7,042	
Children's wards	20 beds	9,500	283	
	40 beds	18,900	557	
	60 beds	28,400	835	
	80 beds	37,800	1,109	
Geriatric wards	28 beds	8,800	302	
	56 beds	17,600	533	
	112 beds	35,200	984	
Maternity department (Pre-natal clinic)	50 attendances	5,200	144	
	100 attendances	7,600	206	
	150 attendances	10,000	269	
Maternity department (Reception and admin., admission, ward units and labor room)	50 beds	28,800	854	
	100 beds	53,100	1,541	
	150 beds	78,500	2,227	
Maternity department (Delivery room)	Single in conjunction with labor room	1,900	96	
	Single	2,700	115	
Nursery—intensive care	15 cribs	4,000	149	
	20 cribs	4,400	168	
	25 cribs	5,100	192	

TABLE 6.7.7 (cont'd.)

Service and Department (1)	Functional Units (2)	Departmental Areas (to nearest 100 SF) (3)	Cost Guide $M (4)	Optional Extras (5)
Main operating facilities				**Additional for cooling plant**
Operating rooms and related rooms	1 room	5,900	283	1 room $29,000
	2 rooms	8,500	408	2 rooms 34,000
	3 rooms	11,100	528	3 rooms 38,000
	4 rooms	13,700	648	4 rooms 43,000
	5 rooms	16,400	782	5 rooms 43,000
	6 rooms	19,300	912	6 rooms 48,000
	7 rooms	22,100	1,046	7 rooms 53,000
	8 rooms	24,800	1,181	8 rooms 58,000
Surgical Sterile Supply for Depts. with no nearby sterile supply	Serving 4 rooms	1,800	115	**Additional for cooling plant**
	Serving 5 rooms	2,000	125	Irrespective of number of rooms
	Serving 6 rooms	2,200	134	$5000
	Serving 7 rooms	2,400	144	**Emergency Sterilizer**
	Serving 8 rooms	2,600	149	$5000
Sterile store (where no SSS provided)	Serving 4 rooms	550	24	
	Serving 5 rooms	600	29	
	Serving 6 rooms	700	34	
	Serving 7 rooms	800	36	
	Serving 8 rooms	900	38	
Diagnostic & Treatment Facilities				
X-ray department	1 R/D room	4,600	149	
	2 R/D rooms	5,400	173	
	3 R/D rooms	6,300	202	
	4 R/D rooms	7,500	240	
	5 R/D rooms	9,000	283	
	6 R/D rooms	10,000	336	
	7 R/D rooms	12,600	389	
	8 R/D rooms	13,500	418	

TABLE 6.7.7 (cont'd.)

Service and Department (1)	Functional Units (2)	Departmental Areas (to nearest 100 SF) (3)	Cost Guide $M (4)	Optional Extras (5)
Diagnostic & Treatment Facilities, contd.				
Pathology department	Area laboratory	20,000	782	
Mortuary and post-mortem room	300-bed hospital	2,500	91	
	500-bed hospital	2,800	110	
	800-bed hospital	3,500	134	
Physiotherapy department	16,000 I.T.U.'s	4,700	120	Additional for:
	24,000 I.T.U.'s	5,500	139	Hydrotherapy pool and ancillary rooms $72,000
	32,000 I.T.U.'s	6,200	154	Large gymnasium (i.e. extra over cost of small gymnasium included in Column 4) $24,000
Occupational therapy department	30 places	4,700	115	
	40 places	5,800	144	
	50 places	6,900	168	
	60 places	7,900	192	
Medical photography	Department	1,500	43	
Outpatient services				
Examination rooms	36 Doctor sessions	7,000	206	
	72 Doctor sessions	12,100	346	
	108 Doctor sessions	17,200	480	
	144 Doctor sessions	22,200	614	
Recovery rooms	8 beds	2,900	86	
	12 beds	3,400	106	
	16 beds	4,400	130	
	20 beds	5,200	154	

TABLE 6.7.7 (cont'd.)

Service and Department (1)	Functional Units (2)	Departmental Areas (to nearest 100 SF) (3)	Cost Guide $M (4)	Optional Extras (5)
Dental rooms	1 room	800	29	
	2 rooms	1,200	43	
	3 rooms	1,600	53	
	4 rooms	2,000	67	
Emergency	Patients in a 3-hour peak period			
	60 patients	7,100	216	
	110 patients	8,100	245	
	160 patients	9,100	274	
Emergency operating rooms	60 patients	4,500	216	Additional for Cooling Plant
	110 patients	4,600	221	Irrespective of size $24,000
	160 patients	4,700	226	
Emergency recovery rooms	8 beds	2,900	86	
	10 beds	3,300	96	
	12 beds	3,600	106	
Emergency orthopedic and fracture clinic	18 Doctor sessions	2,900	86	
	27 Doctor sessions	3,900	115	
	36 Doctor sessions	4,800	144	
	45 Doctor sessions	5,800	173	
Service facilities				
Pharmacy department	400-bed hospital	6,000	202	
	800-bed hospital	8,500	269	
Central Sterile Supply	Department	4,000	202	

TABLE 6.7.7 (cont'd.)

Service and Department (1)	Functional Units (2)	Departmental Areas (to nearest 100 SF) (3)	Cost Guide $M (4)	Optional Extras (5)	
Service facilities, contd.					
Central kitchens	300 meals	3,200	125	Additional for Bulk Food Storage	
	400 meals	3,800	144	300 meals	$14,000
	500 meals	4,500	158	400 meals	19,000
	750 meals	5,600	202	500 meals	24,000
	1,000 meals	6,700	240	750 meals	38,000
	1,250 meals	7,700	283	1,000 meals	53,000
	1,500 meals	8,300	326	1,250 meals	62,000
				1,500 meals	77,000
Laundries	Articles per week				
	45,000	9,300	504		
	60,000	12,000	629		
	75,000	13,800	754		
	90,000	16,300	878		
	110,000	19,700	1,046		
Teaching facilities					
Nurses'training school	100 students	5,400	134		
	200 students	7,400	182		
	300 students	9,700	235		
	400 students	12,200	288		
	20 students	2,000	58		
	40 students	2,600	67		
	60 students	3,300	82		
	80 students	3,500	91		

TABLE 6.7.7 (cont'd.)

Service and Department (1)	Functional Units (2)	Departmental Areas (to nearest 100 SF) (3)	Cost Guide $M (4)	Optional Extras (5)
Staff facilities				
Dining rooms	125 meals	1,700	48	
	250 meals	2,700	72	
	500 meals	5,000	125	
	750 meals	7,400	178	
Residential accommodation for staff	100 points	4,300	72	
	150 points	6,400	106	
	200 points	8,600	139	
	250 points	10,700	173	
	500 points	21,500	341	
	750 points	32,200	504	
	1,000 points	42,900	667	
Hospital engineering and works services				
Boiler room and fuel storage	Solid fuel or oil fuel			
	6,000 lbs steam/hour	2,300	173	
	15,000 lbs steam/hour	3,800	264	
	21,000 lbs steam/hour	4,400	326	
	30,000 lbs steam/hour	5,500	418	
	40,000 lbs steam/hour	7,300	523	
	70,000 lbs steam/hour	11,600	754	
Maintenance shops	300-600 beds	4,400	91	
	600-800 beds	5,700	115	

6.7.10. SELECTED AREAS FOR INTERSTITIAL SPACE TO SUPPORT ALTERNATE 1

The table below is from a study conducted by the American Hospital Association in 1965 and shows which departments fall above and below the average construction cost. This table is used for the purpose of separating out selected departments (or elements) which are the minimum recommended for interstitial space; all elements above the average construction cost are listed below except laundry and housekeeping*. In the case of March Hospital 36% of the space exceeded the average construction cost. For the purpose of this report the outpatient area is considered to exceed the average construction cost. Outpatient area is considered to be over 1.0. In addition, 33% more space (33% x 46,800 S.F.) will be included in the initial construction to take care of the first expansion and variance, to bring the total to 47%. This percentage is used in the calculations.

TABLE 6.7.8

SELECTED ELEMENTS FOR MARCH AFB HOSPITAL

Element	# of Modules	Space in Square Feet (according to modules)	Percentage	Adjusted Percentage
Laboratory	2	46,800**	36	47
Radiology	3			
Pharmacy	1			
Surgical	3			
Obstetrics	3			
Emergency	1			
Dietary	6			
Central Supply	2			
Outpatient Service	18			
All other space	70	84,000	64	53
TOTALS	109	130,800***	100%	100%

*Laundry and housekeeping in the AHA Study were shown to exceed the average construction cost but are not considered as candidates for interstitial space.

**This amount of space is increased by 33% on 15,400 S.F. making a total of 62,200 S.F. planned as interstitial space.

***Under modular redesign, actual space exceeds the original area of 130,100 for March AFB Hospital.

6.7.11. STATEMENTS CONCERNING COSTS OF USING INTERSTITIAL SPACE

1. Robert H. Chapman Associates, Health Planning Consultants of New York City, state in their letter of July 27, 1970 to Lester Gorsline Associates, as follows:

   "We were consultants to McMaster University and worked with Zeidler in the development of the project."(firm of Craig, Zeidler & Strong Architects)

   "We have made studies for a 575,000 square foot 'Medical Loft' for Harlem Hospital, New York City. This building will contain clinics, labs, support services, diagnostic services and a Community Mental Health Center. We estimated that the additional cost of a long span (64' vs 24') building would be $2.00/square foot and the cost of additional exterior wall would be $0.30/square foot. This was offset by estimated savings in the installation of sheet metal, piping and electrical work at the interfloors which we estimated at $1.00/square foot. The estimated penalty then came to $1.30/foot or a little more than 2% increase in construction cost. I think it was an optimistic estimate." (assumes $75/square foot for construction costs)

   "We are considering interfloor systems for a number of current projects and are investigating two further options: One, the use of larger numbers of smaller size air handling units to make possible their placement in the interfloor space rather than in penthouses. Two, use of the perimeter of the building at the interfloor levels for offices, or other habitable spaces."

2. The cost of constructing the Dominican Hospital in Santa Cruz was $3,325,000 for 94,060 square feet, or $35.20 per square foot. in 1968. Adjusting this figure to 1970 by the ENR index, shows a cost of $(\frac{802}{651} \times \$35.20) = \$43.20$ per square foot. This is $(\frac{\$2.39}{\$40.81}) =$ 5.8% higher. This hospital carries an interstitial floor throughout. Future costs of similar structures would be lower by approximately 10% of all mechanical costs. (See Engineering News Record February 5, 1970, page 36, for statement by mechanical/electrical subcontractor to this effect.)

3. Quincy Jones Associates, Architects, of Los Angeles, California quotes $2/square foot more than conventional. Using a base price of $65/square foot for conventional construction makes interstitial space 3% higher. Information obtained by telephone in July, 1970.

4. Kaiser Engineers calculates a cost of 5¢/square foot per inch of depth for interstitial space. If interstitial space were 8'0" but costs, figured on 6'0" depth (assuming 2'0" deducted for being ceiling for conventional construction) would be $3.60/square foot additional, this is approximately 5-1/2% additional cost to the base of $65/square foot.

5. Russo & Sanders A/E Consultants of New York City, estimates an increase of 5-1/2% for the Greenpoint Hospital.

6. The Veterans Administration construction manager estimates the increased cost is 10% due to interstitial space. This hospital was designed by Charles Luckman and Associates.

7. Generally there is an absence of plant operating and maintenance costs for hospitals having interstitial spaces.

8. The conclusion of Hellmuth, Obata & Kassabaum, Inc., in their report "University of Wisconsin Medical Center, Service Systems Analysis" on page 25, concludes that there is:

   a. some savings in design. time and money
   b. little or no extra construction cost
   c. some savings in operational cost
   d. large savings in change of use.

Conclusion:

It is estimated that the range of cost for interstitial space is between 0 and 12-1/2 percent. The lower number is for modified interstitial. For the purposes of estimating, a figure of 5% will be assumed. The table below summarizes the findings:

TABLE 6.7.9

SUMMARY OF FINDINGS

Architect	Amount of Increase
Robert H. Chapman Associates	2.0%
Rex W. Allen Associates	5.8%
Quincy Jones Associates	3.0%
Kaiser Engineers	5.5%
MDA - Cost Consultants	12.5%
Russo & Sanders, A/E Consultants	5.5%
Other inquires, combined	4.0% (approximately)
Veterans Administration Hospital San Diego	10.0%

CAMBRIDGE,
MASSACHUSETTS

CHICAGO
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