GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: September 1, 1977

Project Title: Development of Design Criteria for a Ship Deck Plan Evaluation System

Project No: E-24-659

Project Director: Dr. Robert J. Graves

Sponsor: Naval Regional Procurement Office; Washington Navy Yard

Agreement Period: From 7/22/77 Until 9/30/77

Type Agreement: P. O. No. N00600-77-M-1631, dated 7/22/77

Amount: $8,900 ($7,100 Fixed Price; $1,800 Travel at Actual Cost)

Reports Required: Final Report

Sponsor Contact Person (s):

Technical Matters

Mr. Craig Carlson
Ship Arrangements Branch
Naval Ship Engineering Center
National Center #3
Room 3S 12
Washington, D. C. 20362

Contractual Matters
(thru OCA)

Mr. P. Murphy
Navy Regional Procurement Office
Washington Navy Yard
Washington, D. C. 20374
(202) 433-2909

Defense Priority Rating: DO-S1 under DMS Reg. 1

Assigned to: Industrial and Systems Engineering (School/Laboratory)

COPIES TO:

Project Director
Division Chief (EES)
School/Laboratory Director
Dean/Director—EES
Accounting Office
Procurement Office
Security Coordinator (OCA)
Reports Coordinator (OCA)
Library, Technical Reports Section
Office of Computing Services
Director, Physical Plant
EES Information Office
Project File (OCA)
Project Code (GTRI)
Other

CA-3 (3/76)

Posted
adg
OAH

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 1/25/78

Project Title: Development of Design Criteria for a Ship Deck Plan Evaluation System

Project No: E-24-659

Project Director: Dr. R.J. Graves

Sponsor: Naval Regional Procurement Office
Washington Navy Yard

Effective Termination Date: 10/31/77

Clearance of Accounting Charges: 10/31/77

($7,100 Fixed Price
$1,800 Travel at Actual Cost)

Grant/Contract Closeout Actions Remaining:

P.O. No. N00600-77-M-1631

- X Final Invoice ~~xxxxxxxxxxxxxxx~~
- _ Final Fiscal Report
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ______

Mr. P. Murphy
Navy Regional Procurement Office
Washington Navy Yard
Washington, D.C. 20374

Assigned to Industrial & Systems Engineering (School/Laboratory)

COPIES TO:

Project Director	Library, Technical Reports Section
Division Chief (EES)	Office of Computing Services
School/Laboratory Director	Director, Physical Plant
Dean/Director—EES	EES Information Office
Accounting Office	Project File (OCA)
Procurement Office	Project Code (GTRI)
Security Coordinator (OCA)	Other ______
Reports Coordinator (OCA)	

CA-4 (3/76)

A METHOD FOR SHIP GENERAL ARRANGEMENTS EVALUATION

Robert J. Graves
Leon F. McGinnis

Georgia Institute of Technology
Atlanta, Georgia 30332
October 14, 1977

Prepared for:
Ship Arrangements Branch
Naval Ship Engineering Center

Contract number: N00600-77-M-1631

EXECUTIVE SUMMARY

The ship general arrangements problem is that of locating compartments in a ship in an optimal manner and is an integral component of the ship design process. Two significant difficulties with respect to this problem are those of generating ship general arrangements plans and, secondly, evaluating such plans to determine a good or optimal one as measured against specific criteria. A simplification of these problem statements is known as the compartmentation problem, thus evaluation of compartmentation plans and generation of the compartment plans are the primary and secondary issues discussed in this report.

A procedure for evaluating compartmentation plans is proposed and developed in a conceptual sense. Its major thrust is to develop the various absolute and relative criteria used implicitly in the current system toward more explicit use. Each relative criterion is to be appropriately defined so as to be a function of distance. Importance measures, both for individual compartments interacting under one criterion and for valuing one criteria with respect to another, are used and serve as weights in an explicit scoring model. An example is presented to demonstrate the concepts proposed.

The compartmentation generation problem is developed and integrated with the evaluation problem to show that solution of the mathematical model results in good deck plans automatically where supporting graphics systems can transform the compartmentation solution to a deck plan itself. Discussion of the interactive and systems related nature of the approach is emphasized and points concerning the use of such a system by designers are included. It is noted that these proposed systems are tools to aid designers in making plan comparisons and designing good plans on a more explicit basis.

Finally, a description of the directions of future research is included pointing toward what needs to be done to beneficially implement the proposed concepts.

CONTENTS

CONTENTS (cont'd)

1.0 INTRODUCTION

The objective of ship general arrangement is to locate interacting activities, in the form of compartments, in an optimal manner as detailed plans are developed for ship design and construction. Ship general arrangement is, therefore, an integral component activity of the ship design process. The activities to be located "interact" in a variety of ways and there are numerous criteria by which the final deck plans are evaluated.

At least two interrelated problems can be addressed in ship general arrangement, namely deck plan generation and deck plan evaluation. Clearly the results of the deck plan generation process are the plans themselves and the result of the evaluation system is a "score" or measure indicating the merit of the deck plan design when the criteria are explicitly considered. The interrelationship between the problems is also clear in that once "better" designs can be measured and this information can be used in the design process itself, deck plan generation can be improved. This report concentrates on the deck plan evaluation problem, though some developments on the deck plan design problem are presented and frequent reference is made to the interface between the two.

Special concern for the solutions to these problems rests with the Ship Arrangements Branch of the Naval Ship Engineering Center, United States Navy. In particular, this report was commissioned to develop a conceptual approach toward solution of the deck plan evaluation problem and to suggest study areas requiring special attention when and if the conceptual approach was to lead to implementation. In addition to fulfilling the above objectives, the plan generation problem is defined and presented in the report with demonstration of its relationship to plan evaluation.

1.1 Background

The problem of facility plan evaluation is not uncommon and has received attention from those disciplines involved with building design (architects, industrial engineers and civil engineers) as well as the naval architects interested in ship design. In most cases, the number of interacting activities and the number of decisions about location are so large as to require computer assistance. Thus, the researchers and practitioners in these various disciplines are struggling with a common problem and desiring to develop a practical system for implementing its solution.

Much of the difficulty with the traditional approach to computerized layout is tied to the problem of specifying "closeness preferences" for any pair of activities to be placed. As Francis and White [4] point out, the best that can be done in most situations is to derive interval scale data on closeness preferences (and this with considerable difficulty) when what is needed is ratio scale data. Often as well, the closeness preferences are so aggregated as to obscure the level of detail of plan critique which is needed to aid the plan design process.

1.2 Related Work

Selected references in the literature as well as documents of the Ship Arrangements Branch provide useful insight into the problem and indicate the amount of effort directly in the problem area and in related areas. Several of these references are reviewed in the following paragraphs. None of them address in a detailed fashion either plan evaluation or automatic plan generation.

Frankel [5] discusses in very general terms the problem of modeling the ship design process. GERT networks and risk analysis are proposed as techniques to be used in modeling and analyzing the design process. Superficial discussion of space allocation and arrangement problems is noted. It is suggested that a modified ALDEP-like procedure might be used and that a simple cost model for evaluating plans might suffice. Frankel provides no specifics and gives little in thoughts on implementation.

Alanko [2] deals with internal room arrangements for each space. A direct distance objective is minimized while satisfying constraints on such criteria as room accessibility, room visibility and unobstructed room space. He uses a random coordination generation approach to determine locations.

Marcus [6] considers the problem of the interrelationships between spaces in ship design. His objective involves minimizing path lengths through the system with simplifying assumptions about secondary relationships between rooms. A man-machine system is proposed where the designer interacts with the computer in the design process.

A computer graphics approach is described in Murton [7]. As presented, a cathode ray tube device and a specialized code would aid the designer in the development of deck plans and their alteration.

1.3 Approach

Suppose the problem of deck plan evaluation is considered in two stages. First, the specification of ratio scale measurable criteria which can be computed for any deck plan layout, and second, the transformation of this data by a decision-maker into utility terms, so that preferences between layouts can be established. Current practice includes a board of review whose members essentially maintain the various criteria and associated measurement scales in an implicit fashion and formulate their preference from an implicit aggregation of these criteria scores and measurements.

The approach suggested here is to make the criteria, measurement scales and preference scores more explicit in order to aid the individual designer and the review board members in their collective search for better designs.

The expectation of the use of computer technology in solving the deck plan evaluation problem defines an analogous problem to that already stated. This problem, the compartmentation problem, is a simplification of the deck plan evaluation problem relying upon the assumption that compartment interactions under the criteria can be represented as interactions between compartment centroids and that compartment locations can be specified by means of centroid locations. Thus, a deck plan for the compartmentation problem consists of a list of compartments (hence, centroids) assigned to each zone centroid where a zone generally corresponds to a space between bulkheads. Distances through which the criteria are evaluated become approximated by euclidean or rectilinear metrics using centroid coordinates. The compartmentation problem becomes even more accurate in approximating reality if the compartment areas (or volumes) are augmented by allocations of passageway areas (or volumes) reflecting the actual availability of area or volume for feasible compartment assignments to zones.

Recalling the earlier distinction between deck plan generation and deck plan evaluation, it is seen that compartmentation generation and compartmentation evaluation are similarly related. The compartmentation evaluation problem has feasible solution alternatives as "givens" and attempts to score these alternatives under the criteria to determine the best one. The compartmentation generation problem uses basic data about compartment location, such as space and volume needs and per cent fore-aft considerations, coupled with data about zones, such as area and volume availability, to generate the feasible solution alternatives.

2.0 COMPARTMENTATION EVALUATION

The proposed approach to compartmentation evaluation first involves the specification of criteria used in evaluating plans. These criteria must then be transformed into ratio scale measurable criteria to enable the use of arithmetic operations on the criteria measures; specifically, this transformation must relate each criteria to distance between compartment centroids and is developed in the section titled performance curves. Recognizing that each criterion is not necessarily of equal importance in evaluating the plan and that the interactions of each compartment pair under a given criterion are not necessarily equally important, relative importance weights are defined and a procedure for establishing these weights is discussed. Finally, an example of these proposed techniques is presented and an interactive scoring program used to obtain solutions.

2.1 Criteria

The Ship Arrangements Branch currently uses in an implicit fashion a collection of criteria in both the generation and evaluation problems. This collection consists of two basic classes, namely absolute criteria and relative criteria. Absolute criteria deal with specifications for a given compartment location with respect to hull geometry, such as above or below the waterline, per cent fore or aft of the ship center, and a compartment's location within a certain distance of a fixed object location such as the radar room and the radar antenna. Relative criteria are those concerned with interactions between compartments such as functional interactions and thermal interactions. The ship designer is required to satisfy the absolute criteria and, through location adjustments, works toward improvement against the relative criteria.

A partial list of the relative criteria used by the Ship Arrangements Branch is specified as follows:

Electrical adjacency: compartment pairs may have an electrical adjacency in that both electrical equipment performance and cost of wiring suggest that the compartments should have contiguous or near contiguous locations;

Environmental adjacency: certain environmental considerations such as fumes and vibration can affect the quality of the locations of compartment pairs;

Exterior-interior adjacency: though an absolute criteria with respect to possible compartment locations, this criteria can be viewed as a relative criteria if fictional compartments represented by the longitudinal center plane and the port and starboard hulls interact with other compartments under this criteria;

Functional adjacency: due to the functions performed in each compartment and the consequent activity such as flows of personnel and material between compartment pairs, operational advantages can be obtained through location decisions;

Longitudinal displacement: compartment pairs may have an interaction such as center of gravity concerns with respect to their locations along the longitudinal axis of the hull;

Manpower efficiency: due to the functions performed in each compartment and the likelihood that staffing patterns will not correspond in a one-to-one fashion with compartment functions, manpower savings may be obtained through compartment location decisions;

Noise adjacency: compartment activities may give rise to noise levels which interfere with other compartment activities hence interior noise insulation measures may be reduced through location decisions;

Passage adjacency: due to compartment activities and traffic volumes in passages or a need to move staff quickly as in general quarters alarms, location decisions can result in operational advantages under this criteria;

Plumbing adjacency: compartment pairs may have a plumbing relationship in that compartment function performance and cost of plumbing suggest that the compartments should have contiguous or near contiguous locations;

Safety adjacency: due to the nature of compartment activities general safety levels can be improved through location decisions for both normal operations and combat operations;

Thermal adjacency: different operating temperatures in compartments may create the need for added insulation measures thus location decisions may result in the reduction of insulation requirements;

Transverse displacement: as in longitudinal displacement, compartment pairs may fall under such considerations as center of gravity and ship stability with respect to their locations;

Ventilation adjacency: compartment pairs may have a ventilation adjacency in that their respective function performances and the cost of ventilation installation and operation is affected by location decisions;

Vertical displacement: as in longitudinal and transverse displacement, compartment pairs may fall under considerations such as center of gravity and ship stability with respect to their location.

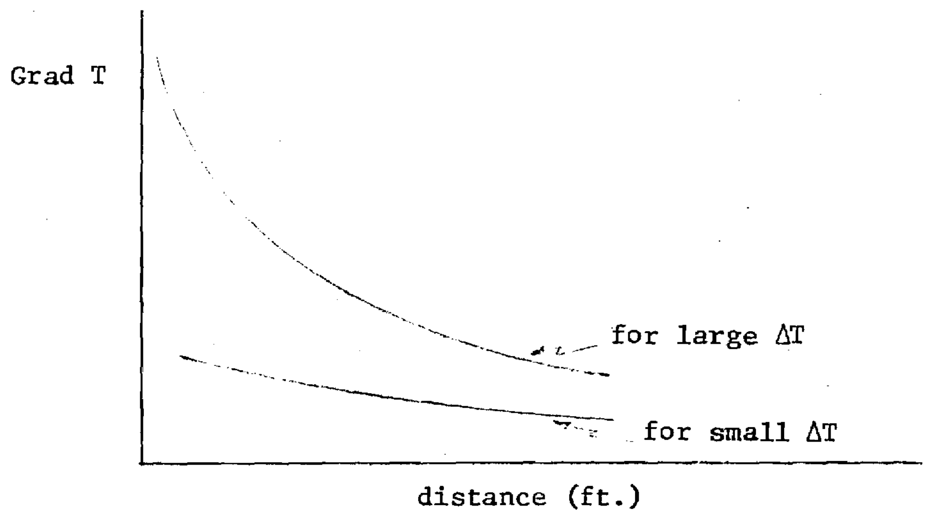
These criteria should not interact with each other, thus each should be carefully defined so as to be independent of the others. Further, they must be translated or transformed into items that are measurable on a ratio scale, i.e. the highest scale level of measurement which allows one to use the three properties of identity, rank order and additivity in performing arithmetic operations on the measurements taken. The need for such careful definition of these criteria and the subsequent transformation is that one can then cast them into a mathematical formulation of the compartmentation evaluation problem and the compartmentation generation problem. The mathematical problem can then be solved in the abstract by mechanical means.

2.2 Performance Curves

The transformation of the relative criteria into ones that are related directly to distance measures (measures of distance constitute ratio-scale measures) is envisioned by means of the development of performance curves. Thus a performance curve is a mathematical function with distance as an independent variable and a criteria measure as a dependent variable. Such a curve can be envisioned in the following example:

Thermal adjacency

Anticipated operating temperatures for compartments are specified during the design process. In locating compartments, it is not desirable to have large temperature differentials between pairs of compartments located adjacent to each other for this might affect the performance of each compartment's function or the insulation needs between them. Viewing the euclidean distance between centroids of pairs of compartments, the <u>rate of decay</u> of this temperature differential with respect to distance is postulated in the performance curve. Curves of different slope and shape may occur for different temperature differentials classes.



Thus, for large ΔT, the rate of decay of ΔT will be relatively high for short distances and will slow significantly as distance increases. For small ΔT, the rate of decay of ΔT will be relatively low throughout the distance.

The determination of such performance curves is of course dependent upon the criterion involved. It is expected that much information toward their development can be gleaned from existing design handbooks, though some performance curves may need to be developed through experimentation.

2.3 Weights and Weight-setting

Each criterion is not necessarily of equal importance in the plan evaluation, nor are the interactions of compartment pairs under the same criterion required to be of equal importance. Thus the concept of importance weights is introduced, providing a means for aggregating these disparate criteria into a composite criterion function. These weights are to be assigned by the decision-maker and bring utility considerations into the explicit criterion function.

Assign a weight, w_{ijm}, to each pair of compartments (i and j) interacting within the framework of criterion m. This weight reflects the relative importance of the interaction of i and j under the m^{th} criterion compared to all other compartment pair interactions under that same criterion. As an example of the use of such w_{ijm}, suppose the captain's quarters (i = 1) and radio room (j = 2) are one pair of compartments with the crew quarters (i = 3) and radio room (j = 2) constituting a second pair of compartments all of which are considered in the context of a thermal adjacency (m = 9) criterion. The designer might make $w_{129} > w_{329}$ reflecting a higher importance on the relative thermal adjacency of compartments 1 and 2 as compared to compartments 3 and 2.

Each w_{ijm} is to be greater than or equal to zero and the sum of the w_{ijm} for a given m should be a consistent quantity, say 1000. Thus,

$$w_{ijm} \geq 0 \qquad \text{for } i, j = 1, 2, \ldots, \# \text{ compartments and } m = 1, 2, \ldots, \# \text{ criteria}$$

$$\text{and} \quad \sum_{\substack{i,j \\ j>i}} w_{ijm} = 1000 \qquad \text{for each } m = 1, 2, \ldots, \# \text{ criteria}$$

In a similar fashion, each of the different criteria can have a different relative importance in the evaluation. Thus, the designer can assign a weight of w_m to each criterion m where $w_m \geq 0$ and $\sum_m w_m = 1000$.

A mathematical model of the compartmentation evaluation problem can now be developed. Consider the following:

C = the compartment set

M = the criterion set

Z = the zone set

$d_{k\ell}$ = the distance between centroids of zone k and zone ℓ

$f_m(d_{k\ell})$ = the m^{th} criterion function (performance curve) for the distance between centroids of zones k and ℓ

$$x_{ik} = \begin{cases} 1 & \text{if compartment i is located in zone k} \\ 0 & \text{otherwise} \end{cases}$$

A given compartmentation plan can then be scored as follows:

$$S = \sum_{i\varepsilon C} \sum_{k\varepsilon Z} \sum_{\substack{j\varepsilon C \\ j>i}} \sum_{\substack{\ell\varepsilon Z \\ \ell>k}} a_{ijk\ell} x_{ik} x_{j\ell} \tag{1}$$

$$\text{where} \quad a_{ijk\ell} = \sum_{m\varepsilon M} w_m w_{ijm} f_m(d_{k\ell}) \tag{2}$$

If a single decision maker assigns all of the weights w_{ijm} and w_m in a manner consistent with his true preferences (utility function) then for two compartmentation plans P and P', S(P) < S(P') implies that the decision maker would prefer P over P' and vice-versa. The scoring model thus is a very powerful tool for the designer, because once the importance weights have been specified, he can use some auxiliary device (e.g. digital computer) to determine preferences rather than making a time consuming manual evaluation.

It is noted that the specific changes from one deck plan design to another deck plan design of the same ship by the same designer are reflected in the $d_{k\ell}$, $x_{ik}x_{j\ell}$ terms in the above. For different designers involved in the same ship design, not only will $d_{k\ell}$, $x_{ik}x_{j\ell}$ likely differ but so might w_{ijm} and perhaps w_m.

The weights reflect an effort to determine an explicit indication of the relative value the decision-maker places on the event under study. Some existing research on such a weight-setting process (von Neumann-Morgenstern utility measures) is based upon the concept of a gamble and requires the decision-maker to establish the probabilities of instances where he is indifferent to certain outcomes. These theoretical concepts are difficult to handle in practice and the procedures cumbersome where large numbers of outcomes are possible. Churchman and Ackoff [1] have developed an approach toward approximate measures of value which appears to be more suited to the weight-setting to be done in the ship compartmentation evaluation problem from the perspectives of understanding the concepts and applying them to a relatively large number of outcomes. The classic tradeoff between theoretical soundness of approach and the degree of accuracy needed for use in the problem context is at work here and the above approaches are included as just examples of techniques for the weight-setting process. Implementation of the compartmentation procedure suggested in this report will require resolution of this problem of weight-setting; a problem whose importance should not be minimized.

2.4 Example of Procedure's Use

A small example to demonstrate the concepts proposed in this report consists of thirty-two compartments with volume requirements as given in Table 1. This example is not intended to realistically represent an actual ship design, but rather to demonstrate the concepts of this proposal. The list of compartments must be complete including those fixed in location by

Compartment	Code	Volume Requirements
Officer Quarters	1	30
Wardroom	2	30
Wardroom Pantry	3	10
CPO Quarters	4	25
CPO Mess	5	25
CPO Pantry	6	10
Crew Messroom	7	50
Scullery	8	15
Galley	9	15
Provisions Storeroom	10	55
Refrigeration Room	11	30
Refrigeration Machinery Room	12	20
Captain's Cabin	13	10
Radio Room	14	25
Chart Room	15	25
Pilot House	16	25
Crew Quarters A	17	30
Crew Quarters B	18	30
Crew Quarters C	19	30
Crew Quarters D	20	30
Crew Quarters E	21	30
Ammunition Stores	22	50
Hospital	23	45
W.C. A	24	5
W.C. B	25	5
W.C. C	26	5
W.C. D	27	5
W.C. E	28	5
Armament Area	29	100
Electrical Equipment Room	30	50
Fuel Storage	31	100
Engine Room	32	75

Table 1: Compartment List and Volume Requirements

other requirements.

The ship zone numbering scheme is shown in Figure 1 with the "weather deck" isolated as zone (1, 2). The zone data is presented in Table 2 including the zone code, length, width, height, volume and the coordinates of the centroid.

Zone	Code	Length	Width	Height	Volume	Centroid Loc. (x, y, z)
(1, 3)	1	10	10	1.00	100	(25, 5, 2.5)
(2, 1)	2	10	10	0.75	75	(45, 5, 1.625)
(2, 2)	3	10	10	1.00	100	(35, 5, 1.5)
(2, 3)	4	10	10	1.00	100	(25, 5, 1.5)
(2, 4)	5	10	10	1.00	100	(15, 5, 1.5)
(2, 5)	6	10	10	1.00	100	(5, 5, 1.5)
(3, 1)	7	10	10	0.25	25	(45, 5, 0.875)
(3, 2)	8	10	10	1.00	100	(35, 5, 0.5)
(3, 3)	9	10	10	1.00	100	(25, 5, 0.5)
(3, 4)	10	10	10	1.00	100	(15, 5, 0.5)
(3, 5)	11	10	10	0.50	50	(5, 5, 0.75)
(1, 2)	12	10	10	1.00	100	(35, 5, 2.5)

Table 2: Ship Zone Data

Two criteria are specified with the first disaggregated to two separate levels. The first involves two different temperature differentials, hence different performance curve shapes. As stated earlier, the entries for these criteria are purely fictitious. The criteria performance curves are displayed in Figure 2 where fairly simplistic curves are used. Weights are assigned to the compartment pairs interacting under each criterion, with this data displayed in matrix form in Tables 3, 4 and 5. It is noted that only compartment eleven's interactions with other compartments have a temperature differential in the range of 26°-50° F thus only these interactions are ranked under criterion 1B (Table 4).

Finally, the example includes several specific or absolute locational criteria. These constraining factors are shown in Table 6.

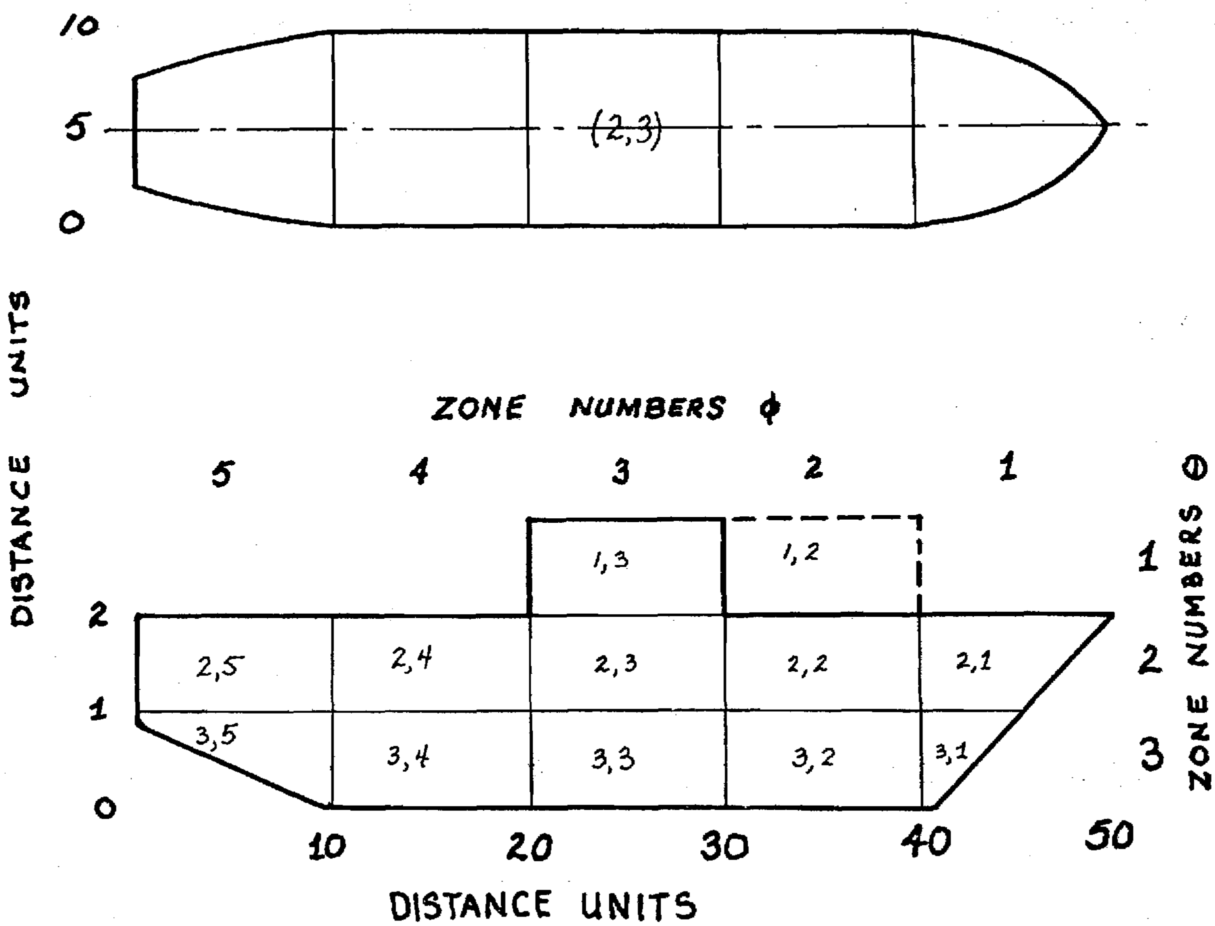


FIGURE 1 : ZONES OF SHIP

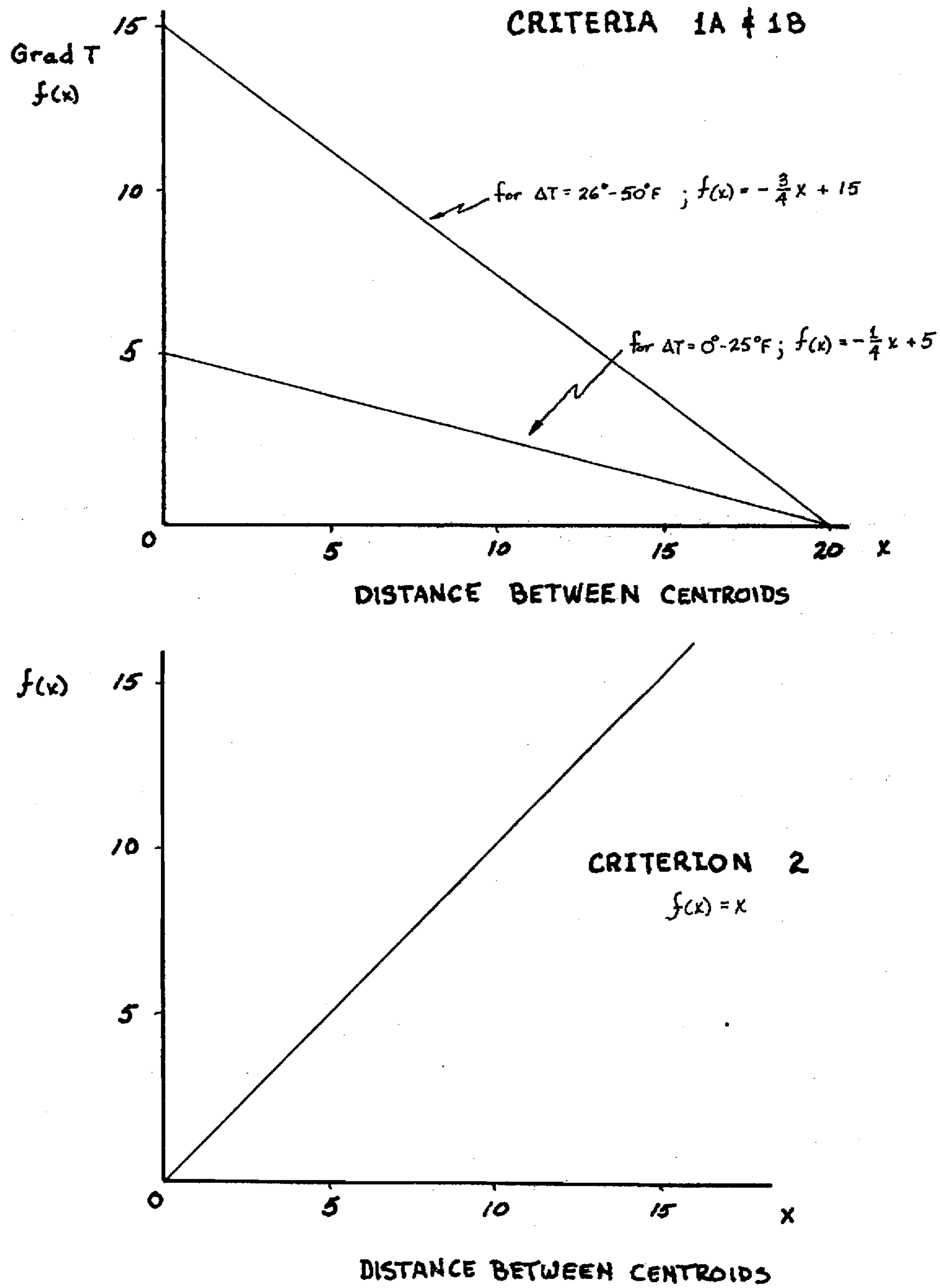


FIGURE 2: CRITERION PERFORMANCE CURVES

CRITERION 1A: $\Delta T = 0°F - 25°F$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1								25	25			25										25								25		25
2								25	25			25										25								25		25
3																																
4								25	25			25										25								25		25
5																																
6																																
7																																
8													25				10	10	10	10	10											
9													25				10	10	10	10	10											
10																																
11																																
12													220				10	10	10	10	10											
13																																
14																							10									
15																																
16																																
17																						8								8		8
18																						8								8		8
19																						8								8		8
20																						8								8		8
21																						8								8		8
22																																
23																																
24																																
25																																
26																																
27																																
28																																
29																																
30																																
31																																
32																																

Table 3

CRITERION 1B: ΔT = 26°F - 50°F

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1											50																					
2											50																					
3																																
4											25																					
5																																
6											50																					
7											25																					
8											50																					
9											50																					
10											50																					
11												50	70	70	50	50	25	25	25	25	25		25						70	70		70
12																																
13																																
14																																
15																																
16																																
17																																
18																																
19																																
20																																
21																																
22																																
23																																
24																																
25																																
26																																
27																																
28																																
29																																
30																																
31																																
32																																

Table 4

CRITERION 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1				10		10		10		10		10		10		10		10		10		10		20		20		20		20		20
2																																
3																																
4									10				10		20		20			20			20		20		20		20		20	
5																																
6																																
7								20			20		20			20			20		20		20			20		20		20		
8																																
9												20				20						20					30					
10																																30
11														20				20						20					30			
12																																
13																																
14																30			30			20				10		30			30	
15																																
16																																
17																																
18																																
19																										50						
20																																
21																																
22																								10								
23																																
24																																
25																																
26																																
27																																
28																																
29																																
30																																
31																																
32																																

Table 5

Compartment	Zone
29	(1, 2)
32	(3, 4)
14	(1, 3)
15	(1, 3)
16	(1, 3)
23	(*, 3)
31	(*, 3)
1	(2, *)
4	(2, *)
17	(2, *)
18	(2, *)
19	(2, *)
20	(2, *)
21	(2, *)

*indicates any value in proper range for θ or ϕ

Table 6: Absolute Assignment Restrictions

An interactive scoring program was used to obtain a score for several compartmentation plans. The computer code is listed in Appendix A and the data set in Appendix B. The output follows showing the compartmentation plan to be evaluated, results of a volume feasibility check (negative entry implies an infeasible condition), the individual criterion scores and their respective weights or w_m, and finally the weighted total score. The user is then asked his desires about changing the compartmentation plan. Changes are entered as (I, K) or (compartment, zone) and the process iterates. The third plan evaluated contained a violation of the absolute criteria specifications and this was noted to the user. A lower score implies a better plan in the scheme used for the example. It should be emphasized that this interactive program is <u>not</u> intended as an illustration of the <u>scoring</u> program, rather it serves to illustrate what <u>can</u> be done.

XNAVY,NAVDAT

P L A N   E V A L U A T I O N   P R O G R A M

COMPARTMENT	VOLUME	ZONE
1	30	2
2	30	3
3	10	6
4	25	2
5	25	1
6	10	3
7	50	11
8	15	10
9	15	3
10	55	5
11	30	4
12	20	2
13	10	5
14	25	1
15	25	1
16	25	1
17	30	6
18	30	6
19	30	6
20	30	5
21	30	4
22	50	9
23	45	9
24	5	7
25	5	7
26	5	9
27	5	5
28	5	4
29	100	12
30	50	4
31	100	8
32	75	10

```
***SLACK VOLUME IN ZONE  1 IS      0
***SLACK VOLUME IN ZONE  2 IS      0
***SLACK VOLUME IN ZONE  3 IS     45
***SLACK VOLUME IN ZONE  4 IS    -15
***SLACK VOLUME IN ZONE  5 IS      0
***SLACK VOLUME IN ZONE  6 IS      0
***SLACK VOLUME IN ZONE  7 IS     15
***SLACK VOLUME IN ZONE  8 IS      0
***SLACK VOLUME IN ZONE  9 IS      0
***SLACK VOLUME IN ZONE 10 IS     10
***SLACK VOLUME IN ZONE 11 IS      0
***SLACK VOLUME IN ZONE 12 IS      0
```

---C U R R E N T   A S S I G N M E N T   S C O R E---

```
CRITERION #   1 :    .09561 POINTS   WEIGHT =  250
CRITERION #   2 :    .98385 POINTS   WEIGHT =  350
CRITERION #   3 :    .96343 POINTS   WEIGHT =  400

        WEIGHTED TOTAL       754.
```

```
DO YOU WANT TO MODIFY THE ASSIGNMENT?(YES OR NO)
? YES
 ENTER THE CHANGED ASSIGNMENTS AS -I,K-
 ENTER -0,0- AF TER THE LAST ONE
? 11,3
? 0,0
```

COMPARTMENT	VOLUME	ZONE
1	30	2
2	30	3
3	10	6
4	25	2
5	25	1
6	10	3
7	50	11
8	15	10
9	15	3
10	55	5
11	30	3
12	20	2
13	10	5
14	25	1
15	25	1
16	25	1
17	30	6
18	30	6
19	30	6
20	30	5
21	30	4
22	50	9
23	45	9
24	5	7
25	5	7
26	5	9
27	5	5
28	5	4
29	100	12
30	50	4
31	100	8
32	75	10

```
***SLACK VOLUME IN ZONE  1 IS        0
***SLACK VOLUME IN ZONE  2 IS        0
***SLACK VOLUME IN ZONE  3 IS       15
***SLACK VOLUME IN ZONE  4 IS       15
***SLACK VOLUME IN ZONE  5 IS        0
***SLACK VOLUME IN ZONE  6 IS        0
***SLACK VOLUME IN ZONE  7 IS       15
***SLACK VOLUME IN ZONE  8 IS        0
***SLACK VOLUME IN ZONE  9 IS        0
***SLACK VOLUME IN ZONE 10 IS       10
***SLACK VOLUME IN ZONE 11 IS        0
***SLACK VOLUME IN ZONE 12 IS        0
+
           ---C U R R E N T   A S S I G N M E N T   S C O R E---

            CRITERION #   1 :    .09561 POINTS  WEIGHT =  250
            CRITERION #   2 :    .93203 POINTS  WEIGHT =  350
            CRITERION #   3 :    .93633 POINTS  WEIGHT =  400

                     WEIGHTED TOTAL       725.
```

```
 DO YOU WANT TO MODIFY THE ASSIGNMENT?(YES OR NO)
? YES
 ENTER THE CHANGED ASSIGNMENTS AS -I,K-
 ENTER -0,0- AF TER THE LAST ONE
? 14,3
? 9,1
? 0,0
```

COMPARTMENT	VOLUME	ZONE
1	30	2
2	30	3
3	10	6
4	25	2
5	25	1
6	10	3
7	50	11
8	15	10
9	15	1
10	55	5
11	30	3
12	20	2
13	10	5
14	25	3
15	25	1
16	25	1
17	30	6
18	30	6
19	30	6
20	30	5
21	30	4
22	50	9
23	45	9
24	5	7
25	5	7
26	5	9
27	5	5
28	5	4
29	100	12
30	50	4
31	100	8
32	75	10

```
 *** COMPARTMENT 14 NOT ASSIGNED TO ONE OF THE REQUIRED ZONES
       1
 ***SLACK VOLUME IN ZONE  1 IS       10
 ***SLACK VOLUME IN ZONE  2 IS        0
 ***SLACK VOLUME IN ZONE  3 IS        5
 ***SLACK VOLUME IN ZONE  4 IS       15
 ***SLACK VOLUME IN ZONE  5 IS        0
 ***SLACK VOLUME IN ZONE  6 IS        0
 ***SLACK VOLUME IN ZONE  7 IS       15
 ***SLACK VOLUME IN ZONE  8 IS        0
 ***SLACK VOLUME IN ZONE  9 IS        0
 ***SLACK VOLUME IN ZONE 10 IS       10
 ***SLACK VOLUME IN ZONE 11 IS        0
 ***SLACK VOLUME IN ZONE 12 IS        0
+        ---C U R R E N T   A S S I G N M E N T   S C O R E---

           CRITERION #   1 :   .11828 POINTS  WEIGHT =  250
           CRITERION #   2 :   .89434 POINTS  WEIGHT =  350
           CRITERION #   3 :   .98391 POINTS  WEIGHT =  400

                  WEIGHTED TOTAL       736.


 DO YOU WANT TO MODIFY THE ASSIGNMENT?(YES OR NO)
```

2.5 Systems Implications

The ultimate purpose of the scoring model being proposed is to provide a tool for the naval architects involved in the compartmentation (and zone layout) decision. This tool should allow them to make plan comparison decisions much more quickly than is currently possible and on a more defensible basis. It is most important that the users of this tool have an accurate perception of what is proposed or finally implemented.

The hardware/software configuration of the final implementation almost surely will have an impact on the users' perceptions (and thus, their acceptance), and this should be taken into account in specifying the implementation. In the example evaluation program illustrated previously, it was clear that the computer program was functioning at the user's command as a "super adding machine" to compute a score for the design specified by the user. The important point is that the human designer is still very much a part of the design process.

In specifying the hardware configuration for the evaluation system, two extreme designs define the limits of what is practicable. At one extreme is an in-shop, stand-alone system incorporating all data management and user interface functions, perhaps in a minicomputer system. The physical proximity of such a system to the users (the naval architects) should emphasize the role of the user and enhance system acceptance. Independent control of the computing facility may also prove desirable. On the other hand, scaling down of computer hardware to what can be justified for a stand-alone system may result in high response times and thus preclude an interactive mode of access. Because interactive design graphics systems are currently being developed, interactive capabilities for the evaluation system also should be given serious consideration.

At the opposite extreme is a remote computing facility with the only in-shop hardware being a communications terminal. Such a system has the potential advantage of providing more powerful computing facilities in terms of hardware, i.e., main memory size, processor speed, direct access storage and other peripheral devices. Remote processing may not be desirable because of control problems and user acceptance.

Decisions regarding hardware configuration for the plan evaluation system depend not only on the subjective issues discussed above, but also on evaluation system requirements. In fact, specification of the hardware configuration and specification of evaluation systems requirements are interrelated decisions. Before making these decisions, several alternatives should be defined and intensely analyzed. Some aspects of the evaluation system's requirements are discussed next.

In implementing the plan evaluation system, there are two related primary considerations: (1) data management and (2) the user/system interface. Data management involves not only the storage and retrieval of data as required to compute a score for a given plan, but also the procedures used to add, delete, or modify data elements. User/system interface refers to all procedures by which the decision maker interacts with the system, either to make changes to the data or call for a score to be computed.

Data management in the plan evaluation system should be relatively straightforward, because all the data can be maintained in indexed lists. Thus, retrieving a data item or modifying an existing item will be fairly easy. Adding or deleting items will be only slightly more difficult. The magnitude of the data management problem can be estimated as follows. Suppose there are 300 zones, 500 compartments, and 10 distinct criteria. If on the average, the activity relationship table for a given criterion is

10% dense, it will contain 12,475 non-zero entries. Thus, it will easily fit into the central memory of a large-scale computer, although in core-out of core processing might be required for a minicomputer system.

For this example, using only crude matricial packing, the total data requirement would be approximately 300,000 elements (or words). Not all this data is required at one time. In fact, the computation of a score can be organized in such a way that only the assignments, the distance matrix, and one activity relationship weight table are needed at any time (for this example, roughly 72,000 elements or words of storage).

The major factors affecting the amount of data are the number of criteria and the average density of the activity relationship weight tables. For example, if the density doubles, then the data requirement goes up to approximately 550,000 elements.

Requirements of the user/system interface depend primarily on whether or not the system is to accommodate an interactive mode of operation and the degree to which it is to be integrated with other existing or planned systems, such as interactive graphics. Above all, the interface should be designed to require a minimum knowledge of computer operations to permit use of the plan evaluation system. For example, the sample program illustrated earlier required only that the user be able to sign on and answer simple questions about the actions to be taken.

The types of functions performed by the user/system interface will include both data management and plan evaluation. A major design criterion should be effective utilization of the user's time.

2.6 Sensitivity

The plan evaluation system has much potential beyond simply scoring various compartmentation plans. First, it can be extended easily to scoring detailed layouts derived from a compartmentation plan. In this case, integration with proposed interactive graphics systems would be a natural consequence.

It would also be relatively simple to develop an option which would have the system create and evaluate many new compartmentation plans, each being only slightly different than a baseline plan specified by the designer. There are a variety of fairly powerful techniques for this type of "neighborhood search," which have proved useful in solving similar problems.

Another potential use for the plan evaluation is the study of the weights themselves. For example, suppose two plans are available, one of which is "known" to be slightly better than the other. The plan evaluation system can be used to study the magnitude and type of changes to the weight data necessary to give reversed scores for the two plans. Such studies are valuable in the process of gaining insight into what the weights "should" be.

3.0 COMPARTMENTATION PLAN GENERATION

The plan evaluation system is conceived as one where compartmentation plans, specified in particular formats, are scored with the score measuring the plan's merit with respect to the criteria. The plan generation problem is that which precedes the evaluation problem and prepares the various alternative plans for scoring. Combining approaches to the two problems should result in better plans in fewer iterations of the entire process. This section of the report discusses the combined problems in terms of their mathematical representation, the systems implications and the sensitivity analyses that are possible.

3.1 Mathematical Model

The mathematical model of the combined problem is simply an enlargement of that specified in section 2.3. The enlargement results from explicitly including feasibility considerations in the form of constraints. Thus, the complete problem is specified as follows:

C = the compartment set

M = the criterion set

Z = the zone set

$d_{k\ell}$ = the distance between centroids of zone k and zone ℓ

$f_m(d_{k\ell})$ = the m^{th} criterion function (performance curve) for the distance between centroids of zones k and ℓ

$$x_{ik} = \begin{cases} 1 & \text{if compartment } i \text{ is located in zone } k \\ 0 & \text{otherwise} \end{cases}$$

V_k = capacity of zone k (volume)

r_i = requirement of compartment i (volume)

$$\text{Minimize} \quad S = \sum_{i\epsilon C} \sum_{k\epsilon Z} \sum_{\substack{j\epsilon C \\ j>i}} \sum_{\substack{\ell\epsilon Z \\ \ell>k}} a_{ijk\ell} x_{ik} x_{j\ell} \qquad (3)$$

$$\text{Subject to} \quad \sum_{i\epsilon C} x_{ik} r_i \le V_k \quad \text{for } k \in Z \qquad (4)$$

$$\sum_{k\epsilon Z} x_{ik} = 1 \quad \text{for } i \in C \qquad (5)$$

$$x_{ik} = 0 \text{ or } 1 \quad \text{for } i \in C,\ k \in Z \qquad (6)$$

$$\text{where} \quad a_{ijk\ell} = \sum_{m\epsilon M} w_m w_{ijm} f_m(d_{k\ell}) \qquad (7)$$

If planar area for each compartment is of concern in the generation of compartment plans, then additional parameters s_i and S_k must be defined as the area of compartment i and the area capacity of zone k respectively, and an additional constraint given by:

$$\sum_{i \in C} x_{ik} s_i \leq S_k \qquad \text{for } k \in Z \tag{8}$$

should be included. Similarly for other constraint sets such as those which might represent the absolute criteria discussed earlier.

The solution to this mathematical problem would be a list of assignments of compartments to zones for each zone. The constraints require that each solution has no more compartments assigned to a zone than there is capacity to handle, (4) and (8), and that each compartment is assigned to one and only one zone, (5) and (6). The best solution, that which minimizes the objective function, will have the minimum weighted distance between related activities.

Hence, through solution of this mathematical problem, it is possible for the designer to automatically generate good compartmentation plans. By control of the w_m and w_{ijm}, the designer can specify the importance of the various relationships to the computer and then ask the computer to devise a good deck plan. Further, if the computer is equipped with graphics capability, the result can come back to the designer in the form of plan layouts.

3.2 Systems Implications

It is considerably more difficult to discuss systems implications for plan generation than for plan evaluation, because it is much less clear exactly how the plan generation problem may be solved. It is clear, however, that plan generation will involve much more computation, implying a need for a large-scale computing facility. It may also be observed that plan generation subsumes plan evaluation.

Figure 3 illustrates one possible mode of iteration between plan evaluation and plan generation. In the small loop the designer interacts with the plan evaluation system to specify or alter the structure of the weights and/or constraints. In the large loop, the designer asks the plan generation system to use the current data base to generate an optimal compartmentation plan. The designer may then go back to the small loop and update the data base to reflect further changes in weights or constraints.

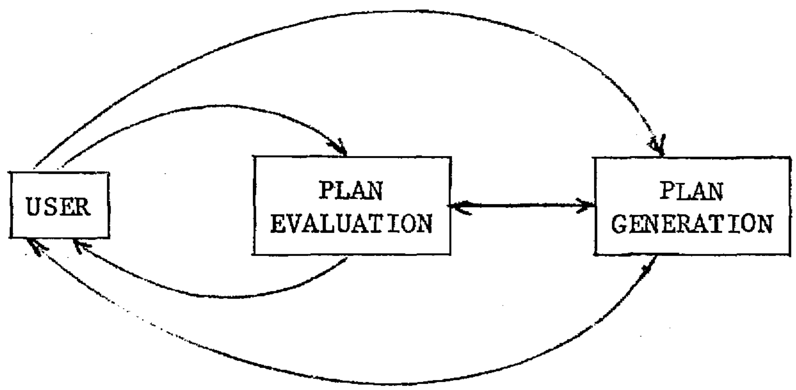


Figure 3: System Interaction

The actual computing and data requirements for the plan evaluation system naturally depend on the method of solution employed. For the example posed earlier of 300 zones, 500 compartments, and 10 criteria, the mathematical model represents a problem several orders of magnitude larger than can currently be optimized using general purpose procedures. Although the special structure of the problem may permit optimization, it is more likely that sophisticated heuristics will be required for practical reasons.

3.3 Sensitivity

Figure 3 presents something of an ideal situation for the user. If the user/systems interface is properly designed, then the user can begin to explore the true ramifications of his assumptions, and the constraints and weights he has specified. For example, he can consider questions such as, "What happens if I optimize only one criterion?" or "How much does this weight have to change to effect a change in the optimal plan?"

The net result, over the long run, of this kind of analysis will be a better intuitive understanding by the users of the real trade-offs being made in ship design. This understanding will lead to more effective use of the plan evaluation and plan generation systems and therefore to better ship design.

4.0 RESEARCH DIRECTIONS

Significant research and development work must be done to properly implement the proposed concept. This work has, by and large, been discussed in earlier report sections but is reviewed in this report segment under sections entitled development of performance curves, design of weight-setting process, data management and evaluation system design, extensions to automatic plan generation and operating pilot model.

4.1 Development of Performance Curves

The development of mathematical functions relating each pertinent criterion to distance is an important work element. Much information toward their development may be gleaned from design handbooks and other sources of existing knowledge. Some, however, may involve experimentation. Careful definition of criteria must precede this task and close coordination with designers would greatly aid the process.

4.2 Design of Weight-setting Process

Implementation of the suggested compartmentation solution procedure requires a resolution of the problem of weight-setting. Both the procedures to be used and the utility of the information must be closely examined. A procedure for setting the w_m may significantly differ from the one used to establish the w_{ijm} for the numbers of w_{ijm} to be specified are very much greater. The utility of the information refers to the degree to which users understand the concepts involved and can translate these concepts into responses. Thus, a collection of processes for obtaining weights may be used where different processes may require different levels of quantitative sophistication on the part of the user.

4.3 Data Management and Evaluation System Design

The form of the data base is fairly well known. The questions remaining to be answered are all conditional. In the first place, the design of the weight-setting process will dictate the form of some of the data management routines. Second, the design of the data management and evaluation systems depends on the mode of use, i.e., batch or interactive.

Once these decisions have been reached, the approach should be to specify several hardware configurations and design around them. Comparison of the alternatives thus generated should include considerations of cost, effectiveness and acceptability.

Because the actual data mangement and score calculation are straightforward, this step in the overall research program should focus on the design of the user/system interface. The system must be accessible to the users, in all senses of the word.

4.4 Extensions to Automatic Plan Generation

This is very much an exploratory phase of the overall research program, because it addresses the issue of a solution algorithm for a problem for which there currently is no useful general purpose procedure. For this reason, the research directions themselves can only be delineated after initial exploratory research.

4.5 Operating Pilot Model

The size of a pilot model design is envisioned as 300 zones and 500 compartments or roughly a large destroyer, but capacity for expansion to 1000 zones and 5000 compartments must be specified. The research, development and testing work addressed in prior sections should culminate in a computer code or collection of codes matching the system design and obtaining solutions to the data of a pilot model. These codes and procedures should be ready for implementation in the Ship Arrangements Branch with appropriate documentation.

5.0 CONCLUSIONS

It is shown that the ship general arrangement problem can be separated into at least two problems known as plan evaluation and plan generation. The analogous abstractions of these problems become the compartmentation plan evaluation and the compartmentation plan generation problems. A procedure is proposed for solving the compartmentation plan evaluation problem. Its basic steps include:

a. Given a feasible compartmentation plan;

b. Given performance curves representing criteria;

c. Given importance weights w_m and w_{ijm};

d. Determine a score for the plan.

The compartmentation plan generation problem is seen as a further extension of the evaluation problem where various feasibility restrictions are explicitly included as constraints in the model. Solution of the mathematical model results in good deck plans automatically and supporting graphics systems could transform this solution from the context of compartmentation to actual deck plans.

Throughout this concept development, an emphasis is placed upon using a systematic approach toward problem resolution. This approach includes a focus on the designer or user such that both the evaluation system and the generation system are activated at his command using a computer as a tool.

At the same time, the systematic approach requires that some elements of the system be made much more explicit than previously. Thus, it is expected that designer time will concentrate on the guidance of the design and the qualitative design aspects with which these other tools cannot deal. In sum, the concept presented should allow designers to make plan comparison decisions much more quickly than is currently possible and provide much more insight into the impacts of alternative design decisions.

REFERENCES

1. Ackoff, Russell L., Scientific Method, New York, John Wiley & Sons, 1962, pp. 83-91.

2. Alanko, James, A Computer Aid to General Arrangements in Ship Design, Master's Thesis, Massachusetts Institute of Technology, 1966.

3. Carlson, Craig, and Cebulski, Donald, "Computer-Aided Ship Arrangement Design," Naval Engineers Journal, October, 1974, pp. 33-40.

4. Francis, R., and White, J., Facility Layout and Location: An Analytical Approach, pp.96-101, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974.

5. Frankel, E., "Ship System Studies. Approaches to Arrangement Design in Naval Ship Concept Development," Office of Naval Research Report NR 276-022, November, 1973.

6. Marcus, Henry, A Computer-Aided Design Method for Optimizing Shipboard Room Arrangements, Master's Thesis, Massachusetts Institute of Technology, 1967.

7. Murton, David, Computer Aided Internal Arrangements of Ships, Master's Thesis, Massachusetts Institute of Technology, 1965.

8. Nehrling, Bruce, Methods for Interactive Ship Compartmentation Based on Pattern Concatenation, Ph.D. Dissertation, University of Michigan, 1974.

Appendix A

Scoring Code Listing

```
      PROGRAM MAIN(DATA,INPUT,OUTPUT,TAPE1=DATA,TAPE5=INPUT,
     1TAPE6=OUTPUT)
      INTEGER LOC(12,3),V(12),VOL(12),W(32,32,3),CW(3),X(32),R(32)
      INTEGER TABL1(100),INDX1(100),TABL2(100),INDX2(32),ITEMP(50)
      REAL D(12,12),F,SCOR(3),SCR,SCORE
      INTEGER OUT,VZ,WIJ,REQ,PTR,DIF
      NC=32
      NZ=12
      NW=3
      IN=1
      OUT=6
      INT=5
      WRITE(OUT,610)
  610 FORMAT(" --------------------------------------------------------
     1---------------"//10X"P L A N   E V A L U A T I O N   P R O G R A
     2M"//" -----------------------------------------------------------
     3------------"//)
 1000 READ(IN,*)I,XZ,YZ,ZZ,VZ
      IF(I.EQ.0)GO TO 1010
      LOC(I,1)=XZ
      LOC(I,2)=YZ
      LOC(I,3)=ZZ
      V(I)=VZ
      GO TO 1000
 1010 DO 1020 I=1,NZ
      I1=I+1
      DO 1020 J=I1,NZ
 1020 D(I,J)=((LOC(I,1)-LOC(J,1))**2+(LOC(I,2)-LOC(J,2))**2+
     *(LOC(I,3)-LOC(J,3))**2)**0.5
 1030 READ(IN,*)I,J,WIJ
      IF(I.EQ.0)GO TO 1050
      IF(J.NE.0)GO TO 1040
      M=I
      GO TO 1030
 1040 W(I,J,M)=WIJ
       GO TO 1030
 1050 READ(IN,*)(CW(I),I=1,NW)
 1060 READ(IN,*)I,J,REQ
      IF(I.EQ.0)GO TO 1070
      X(I)=J
      R(I)=REQ
      GO TO 1060
 1070 PTR=0
 1075 READ(IN,*)I,N
      IF(I.EQ.0)GO TO 1085
      READ(IN,*)(ITEMP(K),K=1,N)
      PTR=PTR+1
      INDX1(I)=PTR
      TABL1(PTR)=N
      DO 1080 K=1,N
      PTR=PTR+1
 1080 TABL1(PTR)=ITEMP(K)
      GO TO 1075
 1085 PTR=0
 1090 READ(IN,*)I,N
      IF(I.EQ.0)GO TO 1100
      READ(IN,*)(ITEMP(K),K=1,N)
      PTR=PTR+1
      INDX2(I)=PTR
      TABL2(PTR)=N
      DO 1095,K=1,N
      PTR=PTR+1
 1095 TABL2(PTR)=ITEMP(K)
```

```
      GO TO 1090
 1100 DO 1105,I=1,NZ
 1105 VOL(I)=0
      WRITE(OUT,100)(I,R(I),X(I),I=1,NC)
  100 FORMAT(1H 24X"COMPARTMENT  VOLUME  ZONE"/32(29X,I2,8X,I4,I6/))
      DO 1200,I=1,NC
      IF(X(I).LT.0)GO TO 9000
      IF(X(I).GT.NZ)GO TO 9000
      VOL(X(I))=VOL(X(I))+R(I)
      PTR=INDX1(I)
      IF(PTR.EQ.0)GO TO 1120
      N=TABL1(PTR)
      DO 1110,K=1,N
      PTR=PTR+1
      IF(X(I).NE.TABL1(PTR))GO TO 1110
      WRITE(OUT,200)I,X(I)
  200 FORMAT(" *** COMPARTMENT "I2" ASSIGNED TO PROHIBITED ZONE "I2)
      GO TO 1120
 1110 CONTINUE
 1120 PTR=INDX2(I)
      IF(PTR.EQ.0)GO TO 1200
      N=TABL2(PTR)
      DO 1130,K=1,N
      PTR=PTR+1
      IF(X(I).EQ.TABL2(PTR))GO TO 1200
 1130 CONTINUE
      N1=INDX2(I)+1
      N2=PTR
      WRITE(OUT,210)I,(TABL2(K),K=N1,N2)
  210 FORMAT(" *** COMPARTMENT "I2" NOT ASSIGNED TO ONE OF THE REQUIRED
     *ZONES "/(5X,20I3/))
 1200 CONTINUE
      DO 1250,I=1,NZ
      DIF=V(I)-VOL(I)
 1250 WRITE(OUT,220)I,DIF
  220 FORMAT(" ***SLACK VOLUME IN ZONE "I2" IS "I8)
      SCORE=0.
      DO 1400,M=1,NW
      SCR=0.
      DO 1350,I=1,NC
      I1=I+1
      DO 1350,J=I1,NC
      IF(W(I,J,M).EQ.0)GO TO 1350
      SCR=SCR+W(I,J,M)*F(M,D(X(I),X(J)))
 1350 CONTINUE
      SCOR(M)=SCR/10000.
 1400 SCORE=SCORE+CW(M)*SCOR(M)
      WRITE(OUT,300)(M,SCOR(M),CW(M),M=1,NW)
  300 FORMAT(1H+,10X"---C U R R E N T   A S S I G N M E N T   S C O R E-
     *--"//3(12X"CRITERION # "I3" : "F9.5" POINTS  WEIGHT = "I4/))
      WRITE(OUT,310)SCORE
  310 FORMAT(1H 19X"WEIGHTED TOTAL "F9.0//)
 1450 WRITE(OUT,400)
  400 FORMAT(" DO YOU WANT TO MODIFY THE ASSIGNMENT?(YES OR NO)")
      READ(INT,410)IANS
  410 FORMAT(A3)
      IF(IANS.NE."YES")GO TO 9500
      WRITE(OUT,420)
  420 FORMAT(" ENTER THE CHANGED ASSIGNMENTS AS -I,K-"/" ENTER -0,0- AF
     *TER THE LAST ONE")
 1500 READ(INT,*)I,J
      IF(I.EQ.0)GO TO 1100
      X(I)=J
      GO TO 1500
 9000 WRITE(OUT,500)I,X(I)
  500 FORMAT(" ****COMPARTMENT "I2" ASSIGNED TO ILLEGAL ZONE "I2)
```

```
      GO TO 1450
 9500 WRITE(OUT,600)
  600 FORMAT(1H ////' ------TERMINATING PLAN EVALUATION------')
      STOP
      END
      FUNCTION F(K,D)
      GO TO (100,200,300,400),K
  100 F=-.25*D+5
      RETURN
  200 F=-.75*D+15
      RETURN
  300 F=D
      RETURN
  400 F=D
      RETURN
      END
 /
```

```
 OLD,NAVDAT
/LNH
```

Appendix B

Data Listing for Example

```
1,25.,5.,2.5,100
2,45.,5.,1.625,75
3,35.,5.,1.5,100
4,25.,5.,1.5,100
5,15.,5.,1.5,100
6,5.,5.,1.5,100
7,45.,5.,.875,25
8,35.,5.,.5,100
9,25.,5.,0.5,100
10,15.,5.,.5,100
11,5.,5.,.75,50
12,35.,5.,2.5,100
0,0,0,0,0
1,0,0
1,8,25
1,9,25
1,12,25
1,22,25
1,30,25
1,32,25
2,8,25
2,9,25
2,12,25
2,22,25
2,30,25
2,32,25
3,8,25
3,9,25
3,12,25
3,22,25
3,30,25
3,32,25
8,13,25
8,17,10
8,18,10
8,19,10
8,20,10
8,21,10
9,13,25
9,17,10
9,18,10
9,19,10
9,20,10
9,21,10
12,13,220
12,17,10
12,18,10
12,19,10
12,20,10
12,21,10
14,23,10
17,22,8
17,30,8
17,32,8
18,22,8
18,30,8
18,32,8
19,22,8
19,30,8
19,32,8
20,22,8
20,30,8
20,32,8
```

21,22,8
21,30,8
21,32,8
2,0,0
1,11,50
2,11,50
4,11,25
6,11,50
7,11,25
8,11,50
9,11,50
10,11,50
11,12,50
11,13,70
11,14,70
11,15,50
11,16,50
11,17,25
11,18,25
11,19,25
11,20,25
11,21,25
11,23,25
11,29,70
11,30,70
11,32,70
3,0,0
1,4,10
1,6,10
1,8,10
1,10,10
1,12,10
1,14,10
1,16,10
1,18,10
1,20,10
1,22,10
1,24,10
1,26,10
1,28,10
1,30,10
1,32,10
4,9,10
4,13,10
4,15,20
4,17,20
4,20,20
4,23,20
4,25,20
4,27,20
4,29,20
4,31,20
7,8,20
7,11,20
7,13,20
7,16,20
7,19,20
7,21,20
7,23,20
7,26,20
7,28,20
7,30,20
9,12,20
9,16,20
9,22,20
9,27,30

```
11,14,20
11,18,20
11,24,20
11,29,30
14,16,30
14,19,30
14,22,20
14,26,10
14,28,30
14,31,30
19,26,50
22,24,10
0,0,0
250,350,400
1,2,30
2,3,30
3,6,10
4,2,25
5,1,25
6,3,10
7,11,50
8,10,15
9,3,15
10,5,55
11,4,30
12,2,20
13,5,10
14,1,25
15,1,25
16,1,25
17,6,30
18,6,30
19,6,30
20,5,30
21,4,30
22,9,50
23,9,45
24,7,5
25,7,5
26,9,5
27,5,5
28,4,5
29,12,100
30,4,50
31,8,100
32,10,75
0,0,0
0,0
1,5
2,3,4,5,6
4,5
2,3,4,5,6
14,1
1
15,1
1
16,1
1
17,5
2,3,4,5,6
18,5
2,3,4,5,6
19,5
2,3,4,5,6
20,5
2,3,4,5,6
```

```
21,5
2,3,4,5,6
23,3
1,4,9
29,1
12
31.5
7,8,9,10,11
32.1
10
0.0
/
```