A Design Methodology for Ships and other Complex Systems

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A design methodology for ships and other complex systems

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A methodology for designing large multiunit, multipurpose ocean based systems is proposed. The methodology is in fact a disciplined procedure for selecting the system and its characteristics that will best satisfy the overall problem objective. The methodology addresses all stages of design of large systems from the design of a particular subsystem to the design of an overall system. Emphasis in this paper is on the exploratory phase of the proposed methodology.

1. INTRODUCTION

> ‘Since the fabric of the world is the most perfect and was established by the wisest Creator, nothing happens in this world in which some reason of maximum, or minimum would not come to light.’
> EULER

The purpose of this study is to attempt to improve the methodology for designing large multiunit, multipurpose systems. Systematic research on design methodology for large systems, such as that underlying this study, has been neglected in spite of the marked growth of interest in such systems during the last quarter century. This is understandable, because before the advent of computers, it was not feasible to design a large system by any but very simple methods because of the time limitation imposed in all real life problems.

Within the last decade or so, many analysis techniques that could not be solved realistically without the aid of the computer, have been programmed for the computer. This has had the net effect of extending considerably the ability of the designer because it has relieved one of the major constraints on his activity, namely time.

Unfortunately, the direct contribution of the computer to design methodology is small because the capabilities provided by the computer do not augment the user’s abilities as a designer but rather as an ‘analyst’. For this reason, it is felt that research leading to documentation of an improved large system design methodology that also best takes advantage of today’s tools is both timely and worthwile. In this study the authors propose such a methodology as a first step in providing a framework for such research. The methodology is divided in this paper into two phases, the exploration phase and the synthesis phase.

2. EXPLORATION PHASE

The steps involved in the exploration phase of the proposed methodology are shown diagrammatically in figure 1. Note that the case where no feasible system can be identified is not shown in figure 1 but is discussed later on in the paper.

The input to the exploration phase comprises the objective of the overall problem that the user wishes to investigate. The output of this phase is the macro level description of the system that will best accomplish the objective the user selected. The procedure for converting the input to the exploration phase to the output is iterative, with the detail of description increasing in each iteration until the system that will best fulfill the overall problem objective and the

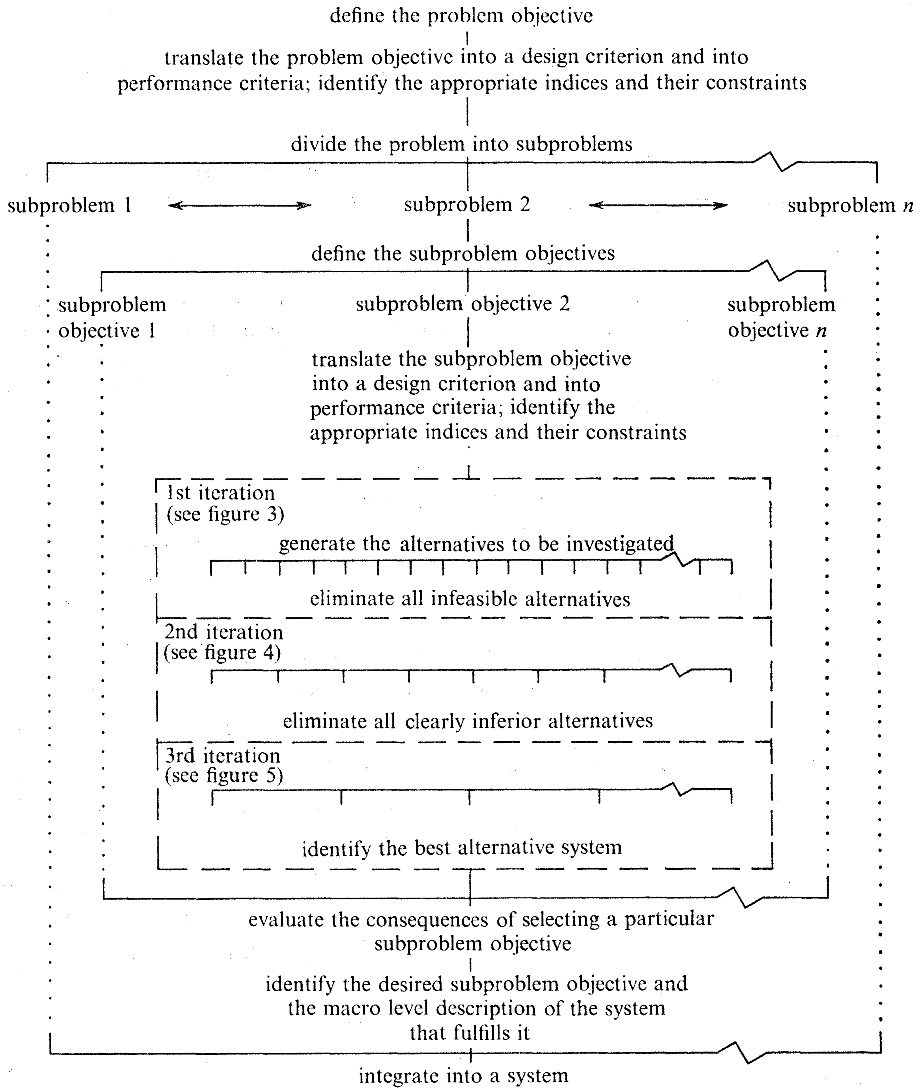

FIGURE 1. Exploration phase flow diagram.

major characteristics of this system are identified. A general discussion of the steps shown on figure 1 and of the iteration scheme involved in carrying out the exploration phase follows.

(*a*) *Definition of the problem objective*

The objective of most problems that man is capable of conceiving or is interested in solving is that of choosing the course of action which, subject to the prevailing constraints, optimizes (maximizes) the 'well being' of all concerned. What is meant by all concerned depends on the level to which the problem addresses itself; for example an individual, a group, a city, a nation, etc. The methodology proposed in this paper addresses itself to such large scale problems which, aside from the difficulties of measuring and defining what is meant by the well-being of all concerned (even if 'all' is an individual), are also not possible of solution as an entity. This inability forces the introduction of a major approximation in the proposed methodology.

This approximation involves the division of a given problem into subproblems. These are in turn further subdivided into even lower level problems, until such a level is found where each of the subproblems involved can be solved by a single person using whatever resources he can bring to bear in a finite (usually prescribed) amount of time. The notion of subdividing a given problem into lower level problems is central to the methodology of this study and it appears in both the exploratory and synthesis phases. Therefore it is imperative to examine it closely and to understand its limitations and its requirements if acceptable results are to be obtained.

First, it is easy to see why subdivision of a given problem into lower level problems imposes limitations on accuracy and is therefore an approximation. Even if all of the lower level problems were correctly identified and each were correctly solved to yield an optimum solution, the aggregate of these lower level problem solutions do not necessarily optimize the total problem under investigation. This is because in real life, a given problem is not an aggregate of independent subproblems but rather an aggregate of interacting subproblems.

The undesirable effects of the approximations introduced by the subdivision into subproblems can be minimized by:

(*a*) providing channels of communication among the investigators of the different subproblems,

(*b*) defining the different subproblems so that the degree of interaction with the other subproblems is kept to a minimum, and

(*c*) reducing the number of subproblems to a minimum.

With regard to the third step, the number of subproblems should not be reduced by increasing the size of the remaining ones without considering the fact that each subproblem must be of such a size as to allow its investigator to correctly solve it in a finite amount of time, to the extent and degree of accuracy deemed necessary. It is in this area that the availability of computers can increase the quality of large systems design. This is so because the analytical powers of the designers are increased, with the result that the computer not only allows them to investigate problems which were previously beyond their capabilities, but also makes it possible to solve larger subproblems than were feasible before the advent of computers.

Next, we observe that the person working on a subproblem is likely to have incomplete knowledge of the overall problem. Therefore he needs firm guidance to insure that his considerations reflect the fact that his problem is really only a subproblem of a larger problem. This can be done only by defining the objective of the subproblem correctly. This requires that the subproblem objective be:

(*a*) consistent with the objective of the underlying higher level problem(s),

(*b*) exhaustive and all inclusive in its nature,

(*c*) written in such clear language that it can be understood by its investigator whoever he may be (for example politician, social scientist, lawyer, economist, scientist or engineer), and

(*d*) flexible enough to allow the investigator to exercise his imagination when creating the alternative candidates for the objective under investigation (see § 2*c*).

The burden of defining the correct objective for a given subproblem rests with the individual concerned with the (sub)problem which is at least one level higher than ours. However in complex cases even this individual may not be in a position initially to supply us with the objective for our subproblem. He may need more information to formulate this objective and for this purpose, it may be desirable to define and investigate a number of alternative objectives before selecting the desired objective for our subproblem. The procedure to be carried out for each alternative subproblem objective before selecting the desired objective is shown in figure 1 where a number of objectives are to be examined for the subproblem under consideration.

It is evident from the foregoing that if the methodology is to perform as desired, the action described in the following four steps needs to be completed at the outset of the solution process. These four steps are:

(*a*) Define the overall objective of the problem to be investigated.

(*b*) Identify correctly all the subproblems that make up the problem under investigation.

(*c*) Identify the correct size of each subproblem such that:

- (i) effective communication among the different subproblems can be established,
- (ii) the number of subproblems involved introduces the minimum degree of approximation, and
- (iii) each subproblem can be solved to the degree of accuracy and extent deemed necessary in the finite time alloted to it.

(*d*) Define the subproblem objectives to be investigated.

(*b*) *Translation of the problem objective into a design criterion and into a set of performance criteria*

In § 2*a* we noted that the meaning of 'well being' of all concerned needed further definition. This is accomplished by translating the overall problem objective into a design criterion which clearly identifies our overall goal. This design criterion is in the form of a mathematical expression interrelating the different indices used to measure the degree of 'well being' provided by each proposal. In addition we need to identify the constraints that define the permissible range of variation of these indices.

We also need to define a set of performance criteria. These criteria are in the form of mathematical expressions interrelating the different indices used to verify that a proposal will have the desired performance. As before we also need to identify the constraints that define the permissible range of variation of these indices.

Similarly for each subproblem objective, the design criterion and the performance criteria, i.e. the mathematical expressions interrelating the appropriate indices, and the appropriate constraints must also be defined.

The distinction between the terms 'design criterion' and 'performance criteria' as used in the previous discussion needs clarification. In general we would like in any problem to seek to optimize (if that is possible) the design criterion but we do not necessarily seek to optimize performance criteria; rather we seek simply to insure that values of the indices used to measure performance fall within the ranges of values defined by the constraints. If in a particular case, we do desire to try to optimize a performance criterion then it must be incorporated into the mathematical expression forming the design criterion.

Summarizing, the following three steps must be taken before proceeding further with the solution process:

(*a*) (i) Translate the overall problem objective into a design criterion by developing the mathematical expression that interrelates the appropriate problem indices in a manner that is amenable to analysis and is compatible and consistent with the goal of the project.

(ii) Repeat the above step for each subproblem objective.

(*b*) (i) Write out the mathematical expressions forming the performance criteria by interrelating the appropriate problem indices.

(ii) Repeat the above step for each subproblem.

(*c*) Associate constraints with each index defining the acceptable range of variation of each index.

Further research in all facets identified in these steps is needed to advance the state of the art of this methodology particularly as it relates to ship design. For example, a new index for measuring a ship's ability to survive a collision at sea is needed because a number of deficiencies have been associated with the survivability index currently in use.

(*c*) *Transformation of a design criterion and a set of performance criteria into a system design*

Upon completion of the three steps of the previous section, one would like to formulate the problem in such a way as to be able to use an indirect optimization method. This would locate the desired optimum system in a mathematically rigorous manner. Unfortunately, this is impossible for the design of large systems such as ships with the present technical and scientific state of knowledge. For this reason it is necessary to introduce an approximate but workable solution technique. This is the iterative approach mentioned earlier which involves:

(*a*) the generation of a number of alternative systems to be examined, and

(*b*) identification of the 'best' alternative from among the ones examined. ('Best' as measured with respect to the design criterion.)

The technique used to accomplish the second step is called the direct search method. In contrast to the indirect method it is not mathematically rigorous and it requires more work on the part of the designer. An example of the application of this method is given by Murphy, Sabat & Taylor (1965).

Step (*a*) of the preceding calling for the generation of a number of alternative systems raise the following questions:

(*a*) How do we generate the alternative systems to examine?

(*b*) How many, and what alternatives do we generate for examination?

(*c*) How do we describe these alternatives?

(*d*) How do we select from among these alternatives in each iteration of the solution process?

iteration	input	first step	output
1st	problem objective	crude description of large number of possible alternative systems	feasible alternative systems
2nd	output of first iteration	more detailed description of all feasible alternative systems	feasible *and attractive* alternative systems
3rd	output of second iteration	still more detailed description which permits the identification of the most desirable configuration of each feasible and attractive alternative system	best system for the particular objective under investigation

Figure 2. Outline of the iterative procedure.

In the discussion that follows the authors attempt to answer these questions. This discussion is in the same order as the steps of the flow diagrams of the three iterations shown in figures 3, 4 and 5. The reader should therefore refer to these figures while reading the text. The input, output and first step of each of the three iterations are outlined in figure 2. The justification as to why an iterative procedure was selected is postponed until the end of this section.

In the first step of the first iteration (figure 3) the designer should attempt to generate the largest possible number of alternatives that appear to satisfy the demands of the objective under investigation. The only tools he has available for doing this are his imagination, his past experience, and the experience of his fellow men as reported in the open literature. Although

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past experience is an enormous asset in design, the investigator should be careful not to let it interfere with his imagination because this will reduce his creative ability, which in itself is the very essence of design. The number of alternatives to be examined must be as large as time and other resources permit. This is desirable because the larger the number of alternatives he tries, the more chances he has of coming closer to the true optimum than he otherwise would. This follows from the fact that if he tries all possible alternatives without in any way sacrificing the quality and quantity of the effort devoted to each alternative (an obvious impossibility), the solution found by a direct search technique is identically equal to the true optimum.

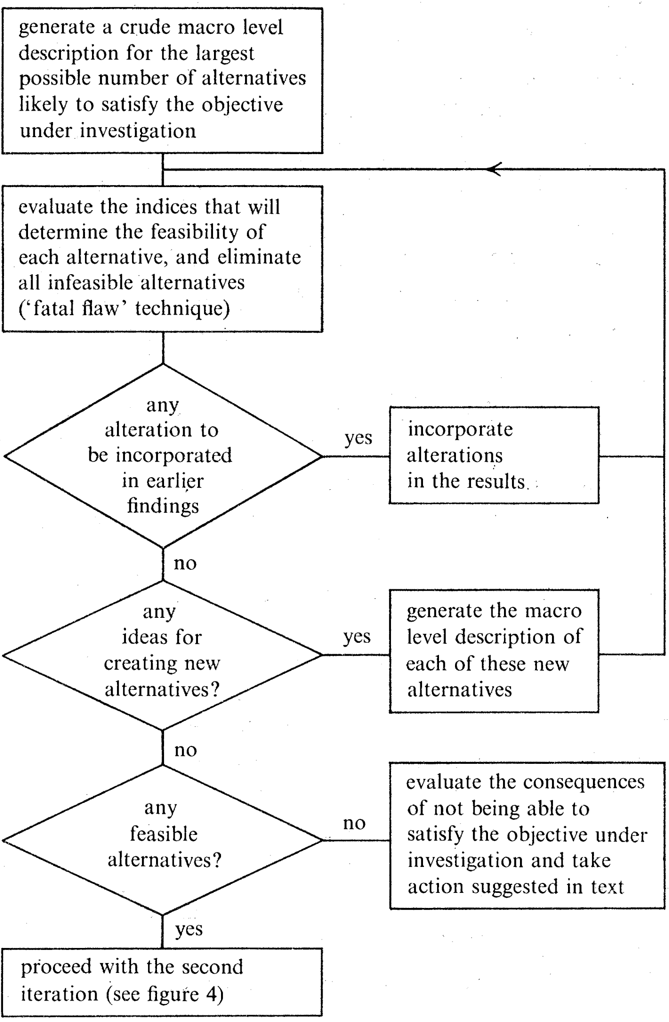

FIGURE 3. Exploration phase. First iteration of solution process.

Once the alternatives to be investigated have been identified, the next step is to generate a relatively crude macro level description of each of these alternatives. This description will in turn permit, among other things, a rough calculation of the values of the various indices. A comparison of these indices to their constraints will determine which alternatives are not feasible. This is known as the 'fatal flaw' technique and by this technique infeasible alternatives can be quickly identified and disposed of, which in turn allows the designer to direct all his efforts to the feasible alternatives.

There is always the possibility as the design methodology proceeds that errors in previous findings will be discovered. Alterations arising from such a cause should be introduced at this point and treated as shown on figure 3.

It is also possible that ideas for additional alternatives will be generated from the results of the first iteration. If this is the case, and if conditions permit it, these new propositions should also be examined as indicated in figure 3. The usual outcome of this first iteration is a number of feasible alternatives that are worth considering in greater detail. In the event that no feasible alternatives can be generated at the conclusion of the first iteration, then the consequences of not being able to satisfy the objective under investigation are evaluated. This will suggest which of the following possible courses of action should be taken:

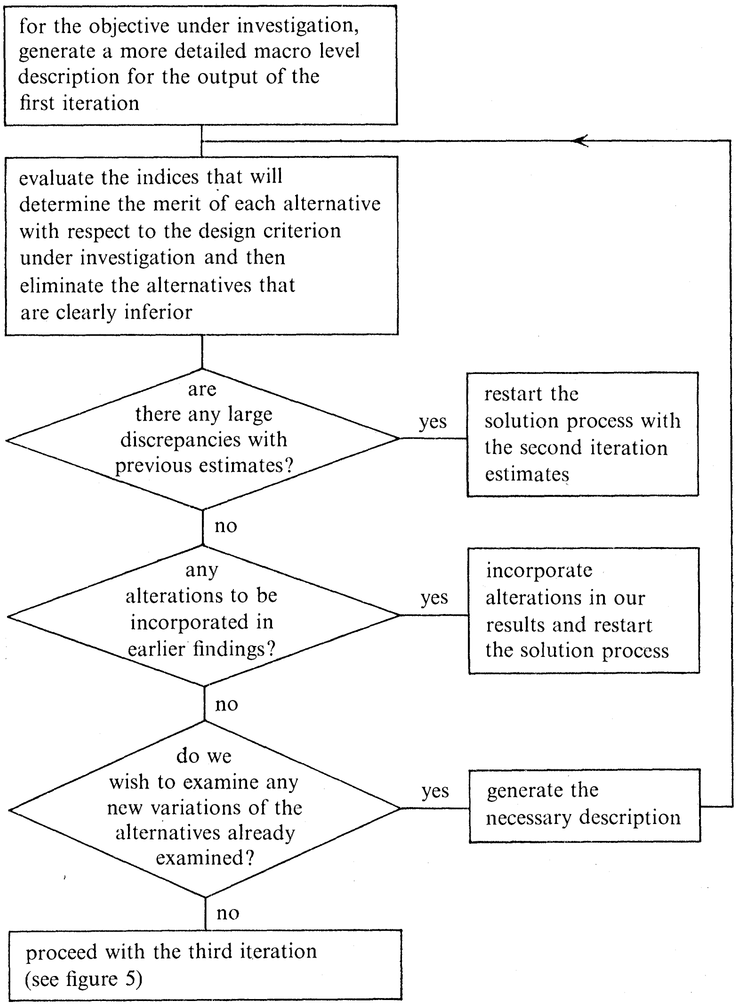

Figure 4. Exploration phase. Second iteration of solution process.

(i) Redefine the problem objective.
(ii) Initiate research that might permit a feasible system to be developed in the future.
(iii) Abandon the project.

If feasible solution(s) are found in the first iteration of the analysis, the designer is then in a position to continue with the second iteration of the solution process (figure 4).

In this iteration, the designer further examines the alternative systems that survived the fatal flaw elimination of the first iteration. In order to be able to do so, it becomes necessary to provide a more complete and more accurate (but still macro level) description of each alternative than was necessary for the first iteration. The selection mechanism in this step is simply one that eliminates all alternatives that are clearly inferior with respect to the design criterion under investigation.

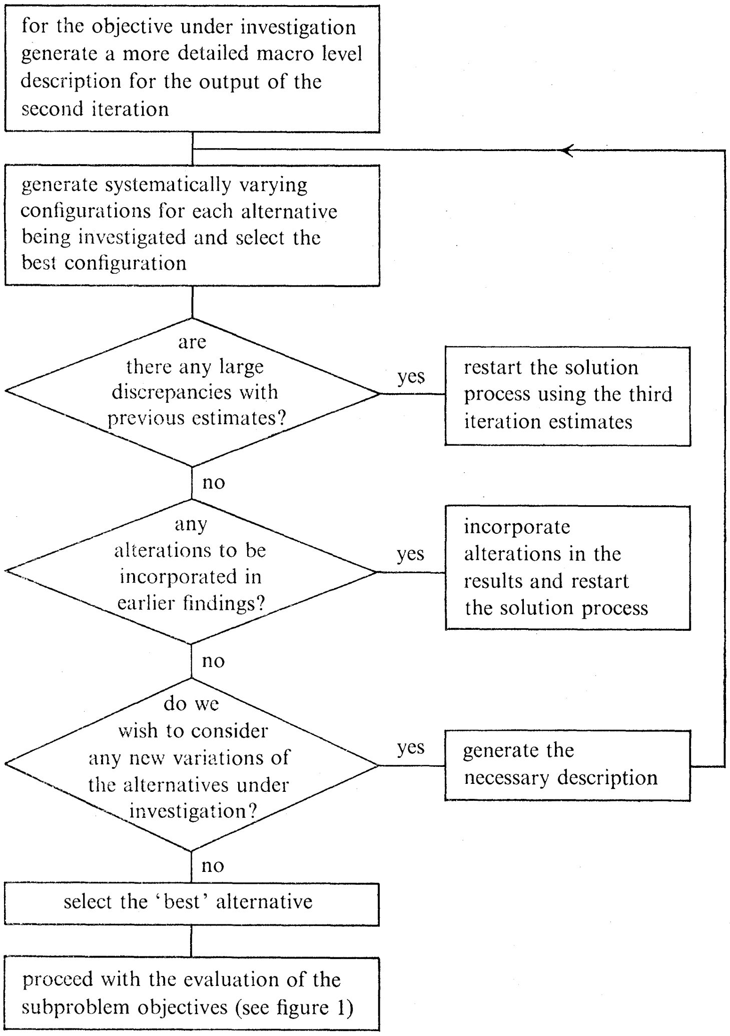

FIGURE 5. Exploration phase. Third iteration of solution process.

The designer should now compare his first iteration estimates with the more accurate estimates obtained in the second iteration. If there are large discrepancies between them, it is necessary to reexamine the first iteration for the possibility of a wrong decision. In addition it is conceivable as in the previous iteration that an alteration needs to be incorporated in our findings in which case the necessary action is indicated in figure 4.

It is possible that from the results of the second iteration, ideas for variations on the alternative systems examined may be generated. If this is the case, and conditions permit it, these new propositions should also be examined as indicated in figure 4.

The usual output of the second iteration is a small number of alternatives that merit further examination. Each of these alternatives are feasible and the numerical value of their criterion is likely to be similar. For this reason, a small change in the configuration of an alternative might sway the decision one way or the other. In order to eliminate this undesirable possibility, it is necessary at the start of the third iteration (figure 5) to generate an even more detailed description of the alternative systems that survived the second iteration and to transform the configurations of these alternatives to that configuration which gives the maximum chance of survival to each alternative. This is achieved by examining systematically varying configuration for each alternative and selecting the most desirable one.

The authors recommend that this selection be made using a direct search technique in which different configurations for each alternative are systematically generated. The selection of the 'most desirable' configuration can then be made either by inspection or by the computer where 'most desirable' is defined with respect to the design criterion under investigation. In generating these systematically varying configurations for each alternative the designer is guided by available results, his own experience, the decision maker's attitudes towards the different elements of the design criterion and the results of the sensitivity analysis that he is able to perform on the design variables. The authors recognize that the recommended technique requires more time and effort on the part of the designer than if a completely automated selection technique such as that described by Mandel & Leopold (1966) were used. But the additional problem understanding gained by the recommended procedure may more than compensate for the added work it causes to the designer.

As before, it is important for the designer to compare previous estimates with the more accurate estimates obtained in this iteration. If there are large discrepancies between them, it is necessary to reexamine previous actions for the possibility of a wrong decision. If an error is discovered at this point in the iteration necessitating alterations in previous findings, then the solution process must be restarted as indicated in figure 5.

It is possible that while working within the third iteration, ideas for variations on the alternatives under investigation will be generated. If this is the case, and conditions permit it, these new propositions should also be examined as indicated in figure 5.

The final outcome of the third iteration is the single subsystem that has the best value of the design criterion under investigation. The results of this iteration for each subproblem objective must be presented clearly and non ambiguously, and provide all the necessary information:

(*a*) to the decision maker concerned with the higher level problem than the one currently investigated, in order to permit him to select the 'best' subproblem objective, and

(*b*) to the investigators who will be concerned with the synthesis design phase of the subsystem associated with the subproblem objective finally selected.

While it is implied in the foregoing that the comparison between objectives (see also figure 1) is to follow the third iteration of the solution process, the designer might find it preferable to present his results for a preliminary comparison at the conclusion of each iteration. This is particularly preferable if by so doing it is possible to eliminate an undesirable objective at an early stage of the analysis. Whether this should be done will depend upon the nature of the problem under investigation.

In general it is not intended that the steps outlined in this methodology should be blindly followed in all applications. Rather it is intended that this methodology should provide the basis for disciplined thought to help guide the designer through the steps of the design of a complex system.

When large system problems are defined, a limitation is always imposed upon the resources (time, money, manpower, and equipment) than can be used to obtain their solution. This limitation severely restricts the quality of our analysis for each subproblem by reducing the number of alternatives we can investigate or reducing the amount of effort we devote to a particular alternative. The proposed iterative procedure is intended to provide a compromise between these two conflicting effects by allowing us to investigate a large number of alternatives in some detail and thus maximizing the chance of identifying the alternatives that merit an indepth analysis.

The question of resource allocation is also very important, because by increasing the resources allocated to a subproblem it may be possible to obtain vastly improved results. Fortunately, there exists a point of diminishing return, where the return on investing additional resources is insignificant. For this reason, the objective of the overall planner is that of estimating this point for each subproblem and thus allocating the available resources most effectively. The iterative scheme described in this section is designed to give the best possible answers for a given amount of resources.

(*d*) *Evaluation of the problem objectives*

For some of the problems encountered in practice it is conceivable that when the design criterion is identified, all the indices that measure success with respect to this criterion have a common denominator (usually monetary). In this case, the choice from among the different proposals is very simple; we would choose that course of action which maximizes beneficial effects (usually revenues) minus detrimental effects (usually costs). In order to be able to do so, two conditions are necessary:

(*a*) all beneficial and detrimental effects must be quantifiable, and

(*b*) all beneficial and detrimental effects must be measurable in the same units.

If both these conditions are satisfied, then the problem is said to be unidimensional.

Unfortunately, most of the problems in the real world are anything but unidimensional. For large systems, many of the indices associated with the design criterion are quantifiable (hard ware cost, for example) but there are usually some attributes of the criterion which are intangible, i.e. they are not quantifiable (aesthetic considerations for example). In addition, even if the indices are quantifiable, they may be non-commensurable, i.e. they do not have a common index of comparison. For example, in the design of a motor car, some of the indices that will be involved will be the ones associated with passenger safety, passenger comfort, and cost, each of which employs different units in evaluating the overall merit of a proposal.

For such a non uni-dimensional problem, the course of action is by no means clear. A large choice of objectives is open to the person who defines a subproblem objective from among the variety of combinations of non-commensurate decision elements. However in order to proceed it is essential to identify the single 'correct' subproblem objective with its associated single design criterion. This can be achieved in the following manner:

(*a*) A number of alternative subproblem objectives and the design criterion associated with each objective are defined.

(*b*) For each objective and its criterion,

(i) design indices are evaluated in their own units, and

(ii) visual aids are prepared to describe the intangible attributes of the design criterion.

(*c*) Objective judgement is used to evaluate the consequences of selecting one objective over another.

This analysis and the selection of the final objective should be performed by the person concerned with the problem that is at least one level higher than the subproblem for which the analysis is being performed because these persons are in a better position to assess the consequences of such a selection.

Since man has not been able to quantify the thinking process of the human brain, it is preferable that this analysis and selection be made manually and not in an automatic fashion. However the human mind is limited in the number of non-commensurate indices that it can simultaneously trade off one against the other. Therefore it is essential to limit to the minimum possible, the number of non-commensurate indices that are associated with each subproblem design criterion. Another disadvantage of the proposed procedure is the fact that there are no hard rules for selecting from among alternatives, so it is possible for the decision maker to select an objective using non objective judgement. Fortunately, this danger can be easily alleviated by requiring that the decision maker justify his decision in front of a small but interested audience. Incidentally, this is the approach used, with great success, in the consumers' research publications.

The foregoing approach represents a major departure from existing practice where a subproblem objective is often treated as rigid input. The approach of this methodology calls for the evaluation of the consequences of selecting different subproblem objectives and thus permits an informed final selection of the 'correct' subproblem objective. Since the selection of the 'correct' subproblem objective is a necessary condition for the correct solution of the overall problem, the quality of designs accomplished in accordance with this methodology should improve.

(*e*) *Tools needed for the exploration phase of the proposed methodology*

The basic tools needed in this phase are the ones necessary to provide the estimates required at the different iterations of the solution process. These are:

(*a*) statistical and historical data
(*b*) analytical models, and
(*c*) simulation models.

Those who have not used such tools in the past may have reservations about the utility of the proposed method because:

(*a*) the required data is not available at this time or the problems of organizing existing data in the forms needed are immense,

(*b*) not all analytical models needed are available, and

(*c*) not all the simulation models and the decision techniques necessary are available in the forms needed.

However, the authors believe that the investment in the development of such tools is extremely worthwhile because the proposed methodology is likely to improve the end result. In the interim period, while all the tools are not yet available, the authors recommend the use of the proposed methodology with whatever tools are available, and with whatever can be developed during an investigation. However such development should not be undertaken if it threatens to degrade the quality of the primary outcome of the investigation, namely the system itself.

An additional benefit will result from implementation of the proposed methodology. This will be the identification of the voids that exist in present technology. Such knowledge can serve to direct future research in a more organized and cost effective manner than has been the case in the past.

The preceding concludes the discussion of the exploration phase. A brief discussion on the synthesis phase of the proposed methodology follows.

3. SYNTHESIS PHASE

In order to provide the reader with the complete description of both phases of the proposed design methodology for large multiunit, multipurpose systems a brief description of the synthesis phase is included in this section.

The output of the exploration phase is the quantitative description of the problem objective and the macro level description of the system that would 'best' accomplish this objective. In the synthesis phase this output is converted into the micro level description of the system under investigation from which the actual system will be built.

The synthesis phase involves three essentially sequential stages; preliminary, contract and final design.

The procedure involved in the preliminary design stage is essentially the same as for the exploration phase. The difference is that in this stage, the interest is to identify the best configuration of a particular system rather than to identify the best system. The beginning of the investigation leading to the identification of the best configuration of the system under investigation already commenced at the beginning of the third iteration of the exploration phase.

Early in the preliminary design stage it is necessary, for the same reasons as before, to divide the problem into subproblems, for example, into hull, machinery, propulsion, etc. subproblems or subsystems as they are commonly known. However before such a subdivision is made, the first step of the preliminary design stage should be to amplify on the outcome of the exploration phase in order to provide a sufficiently detailed description of the system under investigation that will permit the correct subproblem definition. As in the exploration phase, it is necessary in this stage that certain subproblems that would have been best worked sequentially have to be worked in parallel because of the time constraint. Under these circumstances, it is particularly important again to define carefully the subproblem objectives to be investigated and to provide effective means of communication among the investigators of the different subproblems.

Once the subproblem objectives are identified, each objective is translated into a design criterion and into a set of performance criteria together with all pertinent constraints. At this point the iterative procedure for the determination of the best configuration for each subsystem can commence, and upon completion, the evaluation of the subproblem objectives can be performed. Upon completion of this evaluation the preliminary design is synthesized by integrating the results of the different subsystems.

The tools used in this stage are detailed analytical methods, usually computer aided. If these tools are to be effective, they must be designed to be versatile, and they must be fully documented. It should be pointed out that in this stage it is almost impossible to develop such tools when they are needed so that long range planning is essential. Fortunately, many of the basic tools are available and once the problem indices are defined, the larger part of the preliminary design can be carried out using the method outlined in §2.

Although the principles involved in the exploration phase and in the preliminary design stage of the synthesis phase are the same, the level of detailed information needed in the latter phase is much greater than in the former. Therefore it follows that research conducted to develop the concepts and tools necessary to implement the exploratory phase will not necessarily suffice for the preliminary design stage. For any given system independent research is needed for both phases.

In the contract design stage, the output of the preliminary design is transformed into a detailed micro level description of the system. The detail of description is such that an experienced shipbuilder can make an estimate of the time and cost of construction.

In the final stage of the synthesis phase, which is final design, the output of the contract design is transformed into actual working plans from which the ship is to be built.

4. Conclusion

The effort in recent years to produce design tools and computer aids for the total design procedure has not been large. However by far the larger part of this effort has been devoted to developing tools and computer aids for the final design stage and for the construction of conventional ships. This is understandable because with conventional ships where the system and subsystems are well known at the outset and the system's final configuration can be readily predicted, application of the methodology proposed in this paper will yield small payoff compared to the payoff that might accrue through the development and application of aids applicable to the final design and construction of ships. This however is not the case with unconventional ocean based systems. With unconventional systems, the configuration of the system and its subsystems that will best fulfill a given objective is not known and cannot be predicted from previous experience because no such experience has been gained.

In this case, application of a methodology such as the one proposed in this paper can yield substantial economic payoff. If we carry out an exploratory phase with a disciplined procedure this forces us to examine carefully the overall system at the outset, and subsequently to examine sets of alternative subsystems. Thus the chances of our detecting the crucial subsystems early on is greatly improved. Once these crucial subsystems have been identified, resources can be allocated to examine them in detail long before they are built and before they jeopardize the operation of the whole system.

Considering the rapidity with which new unconventional ocean based systems have come into being in the past decade, it is likely that the next decade will see even more demand for such unconventional systems. It behoves the profession in the 1970s to begin work on a methodology that will help insure the success of the ships of the 1980s.

The methodology proposed in this paper should be viewed as the start of such an effort. The authors do not suggest that it be followed blindly but rather they suggest that it should be adapted to the particular problem in hand. One of its advantages compared to older manual design procedures is the fact that it was developed from inception to capitalize on the availability of computers whereas computer aids have had to be forcibly introduced into the older procedures. This advantage combined with the fact that older manual procedures are inadequate for the design of complex, unconventional systems renders the proposed methodology worthy of consideration by the profession.

5. Recommendations

The following recommendations apply to further research within the framework of the proposed methodology pertinent to the design of ships, other ocean based system, and their subsystems:

1. Further develop both the exploratory and synthesis phase of the proposed methodology and employ it in the actual design of a complex ship or other ocean based systems.

2. Develop new performance indices in those performance areas where the indices are currently ill-defined or not defined at all.

3. Further develop a decision making procedure that will enable the decision maker to define the correct problem objective and to identify the system that will best fulfill this objective.

4. Define those problem areas involved in the ship design process where no or inadequate design aids and tools exist and develop new tools in these areas.

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