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# The Design of Aircraft Using the Decision Support Problem Technique

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# ABSTRACT

The Decision Support Problem Technique for unified design, manufacturing and maintenance is being developed at the Systems Design Laboratory at the University of Houston. This involves the development of a *domain-independent method* (and the associated software) that can be used to process *domain-dependent information* and thereby provide support for human judgment. In a computer-assisted environment this support is provided in the form of solutions to Decision Support Problems.

We define design as the process of converting information that characterizes the needs and requirements for a product into knowledge about the product itself. The knowledge about the process of converting information into knowledge is embodied in the DSP Technique and the software, called DSIDES, is being developed to support its implementation. The development of DSIDES is linked inextricably to the development of the Decision Support Problem Technique. The DSP Technique is based on a particular view of the world and a set of paradigms. It includes four phases, namely, planning, structuring, solution and post-solution analysis. Four major types of DSPs have been identified, namely, selection, compromise, hierarchical and conditional. The current DSIDES package can only be used to solve selection, compromise and hierarchical DSPs. At this time there is no computer-based support available for the planning and structuring phases of the DSP Technique. Therefore, the principal goal of our project is to establish the efficacy of using the selection and compromise Decision Support Problems in aircraft design.

An idealized perspective of the conceptual design stage involves three phases, namely,

Phase 1 - the generation of many concepts and the identification of potentially superior ones based primarily on qualitative rather than quantitative information. A preliminary selection DSP is offered as a means to achieve the desired outcome.

Phase 2 - the identification, using insight-based 'soft' and science-based 'hard' information, of a very limited number of superior alternatives that should be developed further. A selection DSP is recommended for this phase.

Phase 3. - the development of the concepts using engineering analysis into feasible alternatives and the improvement through modification of one or at most two alternatives. This is achieved via a compromise DSP.

Decisions in all three phases require the modeling and optimal trade-off between technical and economic efficiencies that are inherent in the domain of application. In our case the domain of application is the conceptual design of a subsonic jet transport.

We chose the Boeing 727-200 as the focus of our study. It was our intention to use this airplane for illustrating both selection and compromise. Unfortunately, we lacked experience and were unable to find the right type of information to support the creation of selection templates for the Boeing 727-200 airplane. Hence, for selection, we relied on a paper study that was the outcome of a student competition. We found sufficient information to create a general compromise template for the design of subsonic jet transports and to particularize it for the Boeing 727-200 aircraft. Hence, in our case, the solution of the preliminary selection DSP feeds into the selection DSP but the solution of the selection DSP does not feed into the compromise DSP. Conceptually we see no problem in demonstrating the link between selection and compromise, that is, between phase 2 and phase 3. We recognize, in practice, the problem of selection in the conceptual phase of aircraft design is far more complex than is depicted in the examples described herein; we have used these examples to explain the process of selection. We therefore suggest that at the time of reading the focus remain on the process of selection rather than the technical details of the examples.

A **general** template for the conceptual design of subsonic jet transports has been created. The template is first particularized for a Boeing 727-200 subsonic jet transport, exercised and to the extent possible - validated. As part of the validation process three questions are posed and answered, namely:

> Can the template be used to design subsonic jet transport?
> In what ways should the template and the associated software be improved?
> How can the template be used in the conceptual design of aircraft in general?

In April 1985, we were in the process of confirming the soundness of the compromise DSP template - and were extremely excited by this prospect. The student team in the excitement of the moment got carried away and posed a very intriguing question:

> Can the compromise DSP template be used to design a Boeing 747 airplane?

An answer to the question was developed over a period of three weeks in the last month of the academic year. Hence, only qualitative conclusions can be drawn.

We are confident in recommending the use of the preliminary selection and selection DSPs in the conceptual design phase. In selection, however, the proposed method of normalizing and using both ratio and interval scales in calculating the merit function can be criticized. Our current approach is suitable when hard information dominates the selection. In the intermediate case, that is, when there is a fair amount of both hard and soft information available there are currently two options available, namely, convert all ratio scales to interval scales or the approach presented in our report. We are reluctant to recommend converting ratio scales to interval scales and then solving the selection DSP because in doing so some very important technical knowledge is inevitably lost. We believe that our current approach is suitable, in the intermediate case, if used by knowledgeable engineers with caution.

The two selection templates, developed for this project, do provide a basis for developing and incorporating rigorous measures for modeling and trading off economic and technical efficiencies that are inherent in the aircraft designs at this early stage in design. The templates are not sufficiently complete, however, to be useful in the real-life design of subsonic transports. A real-life template for this activity, in our opinion, can only be developed with active participation from industry. Support for this is strongly urged.

We believe that the compromise DSP template is sufficiently complex, comprehensive, and realistic for it to be used for validation purposes. We feel comfortable with results to conclude that the efficacy of using the method and the template in the conceptual design of aircraft has been demonstrated and warrants further support for development. Recommendations for improving the general template are presented. None of these improvements are likely to reverse the principal conclusion arrived at in this report; they will only reinforce the principal conclusion. There is a vast amount of technical information available in the public domain that can be used to refine the formulation of the compromise DSP template and to create new ones. We recommend that this work be undertaken at a university with a program in aeronautical engineering and also where there is work already underway on developing a design assistant for aircraft design.

The principal benefit of implementing the recommendations regarding the templates is that this action will facilitate a better understanding of the issues involved and hence make it easier to use these templates in practice. In selection this will result in an understanding of the criteria and attributes and an identification of the type and quality of information needed to arrive at decisions. In compromise, the implementation of the recommendations will foster a better understanding of the interactions between the variables, constraints and goals. Both are essential for facilitating the use of these templates by industry.

An experienced aircraft designer might well ask: "What is to be gained from redesigning the good old Boeing 727-200 or redoing a paper study (that was done by students) involving aircraft selection? After all aircraft have been successfully designed and built for many years without the use of Decision Support Problems - so what's new?" Yes, we have used existing information, but now organized in a manner that supports human judgment and hence has the potential to contribute to an increase in the efficiency and effectiveness of the designer. This is particularly important at the dawn of, what some futurists call, the Information Age. Intelligent design assistants are under development at various centers around the world. It is generally accepted that "intelligent" computer-based design assistants will become available - albeit, initially, for very limited and specific design tasks. The development of knowledge representation schemes, inference algorithms and machine learning is based on the notion that knowledge can be obtained from experts; a time consuming and difficult process. Another way is to provide this knowledge through machine learning from simulation; a nearly impossible task with the current status of machine learning.

Central to the development of the DSP Technique and the DSIDES System is the development of a scheme to represent design information in a knowledge base. This requires the conceptual categorization of knowledge in terms of representation as well as the role it plays in capturing the DSP process and domain specific information about the artefact. The knowledge base includes two types of knowledge: knowledge about the process of design and knowledge about the artefact being designed. The knowledge about the process (procedural knowledge), in our case, is embodied in the Decision Support Problem Technique for design. On the other hand, declarative knowledge is a set of facts represented (usually) according to the protocol defined by procedural knowledge. This knowledge is embodied in a DSP template.

In our scheme, the information and knowledge associated with an entire class of DSPs is stored as a template on the computer. A template, is the representation of the mathematical form of a class of DSPs on the computer. Once a general template, within a domain, for a class of problems is developed it can be used to formulate specific DSPs in this domain by using a subset of information from the template or through the addition of information to it. These templates, we believe, provide a basis for providing knowledge for intelligent design assistants. The knowledge that is sought can be obtained through "intelligent" simulation involving a designer and a tool like DSIDES. Our scheme lies in between the two schemes, for acquiring knowledge, listed earlier. The DSP templates are meant to evolve with time and we have provided some proof of this by extending the Boeing 727 template to design a Boeing 747-like aircraft. We therefore believe that our work is important in the context of being able to (on a continuing basis) use/structure existing information to help in the process of creating knowledge for intelligent design assistants or expert systems. Specifically, this includes, creating and modifying heuristics and/or rules of thumb. At the other end of the spectrum a tool like DSIDES could be used to do away with rules of thumb and replace them with analysis that is more rigorous.

A solution to a DSP does not guarantee a superior solution. The adage, garbage in garbage out, still applies. It is extremely easy to get a false sense of security because one is using a computer-based system to support decision making. The quality of the information on which a recommendation may be based is dependent on the effectiveness of the engineer in posing the right questions and using the proposed decision aids with caution. The recommendation, however, for a course of action (as in the past) is still the responsibility of the engineer

# ACKNOWLEDGEMENTS

This project would not have come about without the encouragement and patience of Dr. J. S. Sobieski of the NASA Langley Research Center. For this we are extremely grateful. A significant amount of the work described in this report was supported through funds provided by the NASA Langley Research Center (NAS 1-18117) for the period October 1985 through September 1986. This support is gratefully acknowledged. We received a no-cost extension from NASA Langley, until June 1987, to complete this work. The cost of computer time was borne totally by the University of Houston. Paul Erb, Mark Miller and Steven Bultema of Conoco Inc., Houston worked with us on two consulting jobs. This involved using our prototype MacDSIDES System and their contribution to its development is acknowledged. The experience gained by working on two real-life engineering problems was invaluable in the development of the software and the work reported in Chapter 3.

# NOMENCLATURE

| | |
|---|---|
| $a$ | Speed of sound |
| $A$ | Aspect ratio |
| $b$ | Wing span |
| $c$ | Specific fuel consumption |
| $C_{Db}$ | Base pressure coefficient |
| $(C_{Df})_B$ | Body skin friction coefficient |
| $C_{Dmin}$ | Minimum drag coefficient |
| $C_{Do}$ | The zero lift drag coefficient |
| $C_f$ | Turbulent flat plate skin friction coefficient |
| $C_{Lmin}$ | Lift coefficient for the minimum drag coefficient |
| $C_{Lmax}$ | Maximum lift coefficient (assumed value) |
| $d$ | Fuselage diameter |
| $D$ | Drag |
| $e$ | Planform efficiency factor |
| $e'$ | A constant: assumed average value = 0.96 |
| $E$ | Endurance or loiter |
| $K$ | Wing drag-due-to-lift factor |
| $K'$ | Induced drag, i.e., inviscid drag due to lift |
| $K''$ | Viscous drag due to lift due to flow separation and increasing skin friction |
| $l$ | Fuselage length |
| $l/d$ | Body finess ratio |
| $L/D$ | Lift to drag ratio |
| $M$ | Cruise Mach number |
| $M_c$ | Landing and take-off Mach number |
| $N$ | Number of engines (for this study N =3) |
| $q$ | Dynamic pressure |
| $R$ | Range |
| $R''$ | Lifting surface correlation factor |
| $S$ | Wing planform surface area |
| $S_L$ | Required landing field length |
| $S_s$ | Wetted area of the body surface |
| $S_{TO}$ | Required take-off field length |
| $S_{wet}$ | The wetted area of the wing ($2S_e$) |

| | |
|---|---|
| $T_i$ | Installed thrust |
| $T_R$ | Required thrust for cruise |
| t/c | The maximum thickness ratio of the airfoil |
| U | Useful load fraction |
| V | Cruise velocity [use 0.8 Mach = 458.88mph] |
| W | Maximum landing weight |
| $W_{TO}$ | Aircraft take-off weight |
| W2/W1 | Phase 1 weight change ratio, taxi and take-off |
| W3/W2 | Phase 2 weight change ratio, climb and accelerate to cruise conditions |
| W4/W3 | Phase 3 weight change ratio, fuel for cruise |
| $\gamma_L$ | Required climb flight path angle for missed approach |
| $\gamma_{TO}$ | Required climb flight path angle for take-off |
| Subscript TV | Target value |

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# CHAPTER 1
# THE DECISION SUPPORT PROBLEM TECHNIQUE AND PROJECT GOALS

The Decision Support Problem Technique for unified design, manufacturing and maintenance is being developed at the Systems Design Laboratory at the University of Houston. This involves the development of a domain independent method (and the associated software) that can be used to process domain dependent information and thereby provide support for human judgment. In a computer-assisted environment this support is provided in the form of solutions to Decision Support Problems. The principal goal of the project is to establish the efficacy of using Decision Support Problems in aircraft design. In this chapter an overview of the Decision Support Problem Technique, Decision Support Problems, the project goals and mode of execution are presented.

## 1.1 AN OVERVIEW OF THE DECISION SUPPORT PROBLEM TECHNIQUE

Independent of the approaches or methods they use, designers are involved in two primary activities: ***processing symbols*** and ***making decisions***. The symbols processed by engineers are words (verbally, in natural language), numbers (mathematically, using the symbolic language of, say, algebra or geometry), and graphs (visually, using diagrams, flow-charts or three-dimensional models). The principal utility of processing symbols, in any design method, is to provide a means for a designer to identify and formulate a problem so that it can be modeled as realistically as possible and the formulation translated to a structured form amenable to solution. In design processes, decision making has been and is the principal function of human designers. In our opinion, the common characteristics in all design methods and approaches are stages, iteration, symbol processing and decision making.

We believe that design productivity can be improved through the application of a systematic and structured decision making process to the design of most real-life engineering systems. Decisions made in designing such systems are based on information from different disciplines. The computer-based tools that are presently used to support decisions are discipline-based and analysis-oriented. Decisions are improved by repeated analysis; an inefficient though effective approach. Since analysis is discipline-based the interaction between disciplines cannot be taken into account without the use of synthesis.

A comprehensive approach called the Decision Support Problem Technique [38,39] is being developed and implemented, at the University of Houston, to provide support for human judgment in design synthesis. The DSP Technique consists of three principal components: a design philosophy expressed at present in terms of paradigms, an approach for identifying and formulating DSPs and the software necessary for solution. Each is briefly discussed in the following sections.

### 1.1.1 The Decision Support Problem Technique - Some Paradigms

The technique is based on the following assertions:

- Design involves a series of decisions some of which may be made sequentially and others that must be made concurrently.
- Design involves hierarchical decision making and the interaction between these decisions must be taken into account.
- Design productivity can be increased through the use of analysis, visualization and synthesis in complementary roles, and by augmenting the recognized capability of computers in analysis to include the use of expert systems with limited (at present) capability in synthesis.
- The technique that supports human decision making, ideally, must be
  - process-based and discipline-independent,
  - suitable for solving open problems, and
  - must facilitate self-learning.

The design of most real-life engineering systems is characterized by the following descriptive sentences:

- The problems are ***multi-leveled***, ***multi-dimensional*** and ***multi-disciplinary*** in nature.
- Most of the problems are loosely defined and open-ended; virtually none of which has a singular, unique solution, but all of which must be solved. The solutions are less than optimal and are called ***satisficing*** solutions.
- There are ***multiple measures of merit*** for judging the "goodness" of the design, all of which may not be equally important.
- All the information required may not be available.
- Some information may be ***hard,*** that is, based on scientific principles and some information may be ***soft***, being based on the designer's judgment and experience.
- Design is the process of converting information that characterizes the needs and requirements of a system into knowledge about the system itself.

The design of a complex engineering system involves partitioning of the system into smaller manageable parts which in turn require the formulation and solution of a series of problems involving decisions to be made by the designer. This type of design has been termed Hierarchical Decision Making and the difficulties inherent in accomplishing system design, we believe, can be dealt with using the Decision Support Problem Technique.

Decision Support Problems provide a basis upon which a designer can make the decisions encountered in design. Solution of the Decision Support Problems is expected to result in superior (or possibly optimal) designs. The Decision Support Problems are capable of handling multiple objectives that model both analysis-based "hard" and insight-based "soft" information.

The ultimate design scheme must be based on life-cycle considerations, namely, design, manufacture and maintenance. There are two types of hierarchy evident: a discipline-based hierarchy and a process-based hierarchy. In our opinion, the inclusion of life-cycle considerations for engineering systems will increase productivity and hence industrial competitiveness. Further, we assert that this increase in productivity can be achieved by developing and using design schemes that are process-based and discipline-independent.

For real-world, practical systems, all of the information for modeling systems comprehensively and correctly, will not be available. Therefore, the solution to the problem, even if it is obtained using optimization techniques, cannot be the optimum one with respect to the real-world. However, this solution can be used to support a designer's quest for a superior solution. The function, therefore, of the Decision Support Problem Technique is to provide support for human judgment. In a computer-assisted environment this support is provided in the form of optimal solutions for **D**ecision **S**upport **P**roblems (**DSPs**). Formulation and solution of DSPs provide a means for making the following types of decisions:

- **Selection** - the indication of a preference, based on multiple attributes, for one amongst several feasible alternatives.
- **Compromise** - the improvement of a feasible alternative through modification.
- **Hierarchical** - Decisions in which both selection **and** compromise occur.

- **Conditional** - Decisions in which the risk and uncertainty of the outcome are taken into account.

The application of selection and compromise DSPs in aircraft design is the principal topic covered in this report and hence a brief overview of only these two DSPs follows.

### 1.1.2 The Selection and Compromise Decision Support Problems

Selection in design and management involves making a choice between a number of possibilities taking into account a number of measures of merit. These measures of merit may not all be of equal importance with respect to the decision. Some of the measures of merit may be quantified using 'hard' science-based information and others may be quantified using 'soft' information that is empirical in nature or derived from experience-based insight. The key issues are: there are a number of possibilities, there are a number of measures of merit and these are quantified using hard and soft information.

The selection Decision Support Problem can be used in engineering in all stages of design. It can also be used in engineering management as a tool to resolve conflicting opinions. In engineering design there are two distinct types of selection: one that is based on the use of soft information (information derived from insight-based judgment) only and the other that makes use of both hard (information that can be quantified using some theory) and soft information. The process associated with the use of soft information only we call ***preliminary selection*** and the other we have named ***selection.***

In ***preliminary selection*** we start with **concepts**; the end product of ideation. We evaluate the concepts based on **criteria.** The criteria are quantified using experience-based judgment (or soft information) only. Hence, preliminary selection should only be used to identify the top-of-the-heap concepts. The solution to the preliminary selection DSP involves the **rank ordering** of concepts. Therefore one cannot automatically infer, from the rankings, by how much one concept is preferred to another. Engineering analysis is then 'performed' on the top-of-the-heap concepts (as many as one can afford) and the **concepts** become **feasible alternatives.**

In ***selection*** we start with **feasible alternatives**. We evaluate the feasible alternatives based on **attributes** (using both hard and soft information). We solve the selection DSP to identify the best alternative. The solution to the selection DSP involves the ordering of alternatives. One can infer from the ranking by how much one alternative is preferred to another and therefore the best alternative is known.

The Decision Support Problem for selection is stated as follows:

| | |
|---|---|
| **Given** | A set of ***alternatives.*** |
| **Identify** | The principal ***attributes*** influencing selection.<br>The ***relative importance*** of attributes.<br>The ***feasible*** alternatives. |
| **Rate** | The alternatives with respect to their attributes |
| **Rank** | The feasible alternatives in order of preference based on the computed ***merit function values.*** |

The highlighted words are the descriptors of the selection DSP.

In the **compromise** DSP the multiple objectives are formulated as goal constraints. The set of system constraints and bounds defines the design space and the set of syatem goals defines the aspiration space. A compromise Decision Support Problem has the following structure:

**Given** A feasible alternative.
**Find** The values of the independent ***system*** variables (they describe the physical attributes of an artifact)
The values of the ***deviation*** variables (they indicate the extent to which the goals are achieved).
**Satisfy** ***System constraints:*** These must be satisfied for the solution to be feasible.
***System goals:*** These need achieve a specified ***target value*** as far as possible.
***Bounds:*** Lower and upper limits on the system variables and the deviation variables.
**Minimize** An ***objective*** that quantifies the deviation of the system performance from that implied by the set of goals and their associated ***priority levels*** or ***relative weights.***
**Test** The validity of the solution.
The sensitivity of the solution to the assumptions made and the information utilized.

The highlighted words are the descriptors for a compromise DSP.

This formulation of a compromise DSP represents a **hybrid** formulation of an optimization problem. It incorporates concepts both from traditional mathematical programming and goal programming. It is similar to goal programming in that the multiple objectives or goals are formulated as goal constraints and the objective is solely a function of the goal deviation variables. The concept of having system constraints is retained from traditional mathematical programming. Special emphasis is placed on the bounds, unlike traditional mathematical and goal programming. Further details are presented in [26,31,36]

### 1.1.3 A Decision Support Problem Template

The word "template" is used extensively in this report and it is therefore defined in this section. Central to the development of the DSP Technique and the DSIDES system is the the development of a scheme to represent design information. This requires the conceptual categorization of knowledge in terms of representation as well as the roles it plays in capturing the DSP process and domain specific information about the product.

Two types of knowledge can be identified: knowledge about the process of design and knowledge about the product being designed. As defined by Rich [49, Ch. 7] procedural knowledge is a set of well-defined procedures that represent information about doing things. The knowledge about the process (procedural knowledge), in our case, is embodied in the Decision Support Problem Technique for design. On the other hand, declarative knowledge [49, Ch. 7] is a set of facts represented (usually) according to the protocol defined by procedural knowledge. This knowledge is embodied in a DSP template.

The information and knowledge associated with an entire class of DSPs is stored as a **template** on the computer. A template therefore, is the representation of the mathematical forms of a class of DSPs on the computer. The mathematical form of a DSP is formulated using the descriptors mentioned in Section 1.1.2. Once a template within a domain for a class of problems is developed it can be used to formulate specific DSPs in this domain by using a subset of information from the template or through the addition of information in the template. A schematic for templates, in design, manufacturing and maintenance, in terms of the type of information it stores are presented in [19].

### 1.1.4 The Decision Support Problem Process

The principal role of any design process is to ***convert information*** that characterizes the needs and requirements for a product ***into knowledge*** about the product itself. The DSP Technique facilitates the conversion of information for the product into knowledge about the product that can be used for its manufacture. As indicated earlier its principal role, in the design of real life engineering systems, is to facilitate the support of human judgment in the process of design. In the DSP Technique identification, decomposition, organization and synthesis are used:

- to **identify** the ***information*** that characterizes the needs and requirements for the design and is necessary for the ***process*** of design,
- to **decompose** a system design problem into appropriate decision support problems,
- to **organize** the domain dependent information in a form suitable for solution, and
- to **synthesize** the component solutions into one "system" solution and thereby gain ***knowledge*** about the ***product*** being designed.

In the DSP Technique the process, for converting information into knowledge, consists of four phases and six steps. The four phases are shown in Figure 1.1. The phases require:

1 **Planning**: Identifying and stating the DSPs in words.

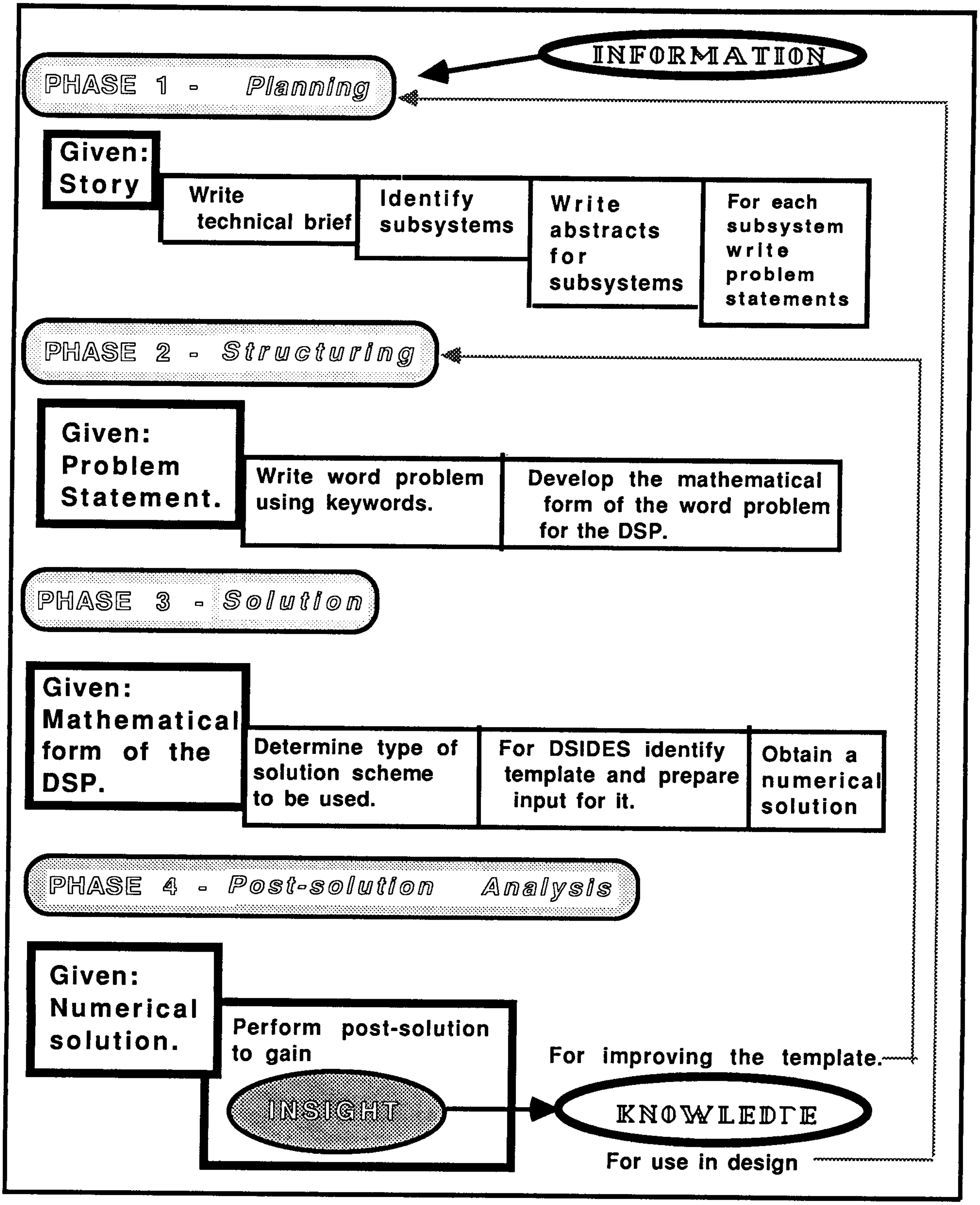



FIGURE 1.1 -- PHASES OF THE DSP TECHNIQUE

2 **Structuring:** Formulating the DSPs in words and then in mathematics.
3 **Solution:** Finding the numerical solution.
4 **Post-solution analysis:** Validating the solution and performing a sensitivity analysis.

These phases are valid for any stage in the design process. The DSP Technique can be used for designing systems and components.

## 1.2 PREVIOUS APPLICATIONS AND IMPLEMENTATION OF SOFTWARE

The software for the Decision Support Problem Technique continues to be developed by the Systems Design Laboratory at the University of Houston. The software is called DSIDES (Decision Support In the Design of Engineering Systems). It has been implemented in FORTRAN for main-frame and super-mini computers and is currently operational on VAX 11/780, CYBER 850, AS9000N (an IBM look-alike) and Honeywell computers. A simpler version of the software has been implemented in BASIC for use on micro-computers. At the University of Houston, the micro-computer version of the software has been developed for the Macintosh and is called MacDSIDES.

The current DSIDES package can can only be used to solve selection, compromise and hierarchical DSPs. At this time there is no computer-based support available for the planning planning and structuring phases of the DSP Technique. A very limited capability for post-solution analysis has been included in the DSIDES System. The DSIDES software consists of

- a processor that facilitates the sculpting and loading of program libraries,
- an interactive processor (to create and maintain data sets),
- two programs to solve decision support problems, namely,
  SELECT (a program to solve selection decision support problems), and
  ALP (a program to solve compromise decision support problems),
- and a post-processor.

The implementation of SELECT is summarized in [25,32,34,35] and of ALP in [31,32,36].

Preliminary selection DSPs cannot be solved using the DSIDES software. Both the preliminary selection and the selection DSPs can be solved using MacDSIDES. Both these programs are highly interactive, user friendly and extensively tested. The capability for solving compromise DSPs on a micro-computer is being developed.

To date, ship design has been the largest single application of the DSPs [28,58,59]. Applications involving the design of damage tolerant structural systems [54] and mechanical systems [17,40,44] have been successful. DSPs for hierarchical design [8,24,55,58] have been developed. At present, at the University of Houston, the DSIDES software is being used to the design of aircraft, mechanical linkages [40], a solar powered agricultural water-pumping system [7,8] and composite material structures [22]. Other projects that make use of the DSPs include, the development of a method for data compression and a template for condition-based, predictive maintenance for turbomachinery. These projects are undertaken with Boyce Engineering International, a local company, that has developed an excellent product called DATM4 for on-line monitoring of rotating machinery. We are using a grant from Shell Development Company of Houston, to develop the capability to integrate the design of a mechanical component, the design of the composite material from which it is made and the manufacture of the component. Efforts are underway for the incorporation of intelligence into the DSIDES software [18,19,20]. The incorporation of the DSP Technique in a teaching curriculum is described in [37,41,42].

What is the current status of development? An investigation into hierarchical design has been made by Sobieski [60]. Solution of structural hierarchical design problems by means of a Decision Support Problem was first proposed by Kuppuraju, et al. [24]. An application of a DSP in structural design was demonstrated in [26] and subsequently Shupe et al. [55] have shown how it could be used in the hierarchical design of structural systems.

We now believe that we were successful to the extent reported in [55] - only because the engineering system that we dealt with (in that case structures) involved information from a single discipline. From the subsequent work involving the design of thermal system [8], ships [58], an idealized drill casing subjected to a pseudo shock load [18] and composite materials we have come to recognize that we know very little about the behavior of hierarchical DSPs involving the design of systems that are governed by technical factors whose roots are in different disciplines[1]. This represents the focus of our current developmental efforts (see Chapter 7, Section 7.3.2).

## 1.3 PROJECT GOALS AND EXECUTION, AND ORGANIZATION OF REPORT

### 1.3.1 Project Goals and Execution

As indicated earlier the Decision Support Problem Technique includes four phases, namely, planning, structuring, solution and post-solution analysis. Software exists only for the solution phase of the DSP Technique. Therefore, our focus in this report is on explaining the use of Decision Support Problems (as opposed to the Decision Support Problem Technique) in aircraft design. The DSPs represent fundamental building blocks and can therefore be uncoupled from the DSP Technique and used with any other design method.

We started work on this project in October 1985. At that time we had developed and successfully implemented a compromise DSP template for ships, Lyon and Mistree [28]. We had some idea of the structure and had developed a method of solution of the selection DSPs. Our principal goal was to demonstrate the efficacy of using selection and compromise Decision Support Problems in aircraft design. This includes showing how DSPs can be used in the conceptual stage of design to

[1] As a point of clarification: the problems we face are not because of the different domains of application (e.g., thermal systems, composite materials, etc.) but because of the fact that within each domain the design is governed by different disciplines (e.g., heat transfer, fluid mechanics, vibrations and strength - in thermal system design).

create knowledge about the aircraft and the trade-offs between technical and economic considerations. We therefore started work on two fronts, namely,

- developing the selection DSP methodology and associated computer software, and
- creating and validating selection and compromise DSP templates.

At the start of the project we had no knowledge of how aircraft were designed nor any knowledge of the sources of information. Steps to overcome this were undertaken by Stergios Marinopoulos and Jon Shupe in October 1985. Early in the project it became clear that that our efforts should be directed to the conceptual stage of aircraft design. This is what we have endeavored to accomplish. As the study progressed we decided that there was sufficient information in the public domain to create a template for the conceptual design of a subsonic, jet-propelled transport aircraft, namely, the Boeing 727-200. This is the template that has been developed and used to demonstrate the efficacy of using the compromise DSP in aircraft design. In creating this template we used many of the analytical methods and quantitative relationships presented by Loftin and Nicolai in their books [27,43].

In December 1985 Marinopoulos proposed a compromise DSP template for the Boeing 727-200. David Jackson joined our team in January 1986. Jackson together with Joe Entrekin and Micheal Bradberry implemented, validated and extended Marinopoulos' proposed template in May 1986 [9]. This formed the basis of our interim report [33] to our sponsors. David Jackson continued the development of the compromise DSP template and extended it to include aircraft economics. This is the template that is described in this report. Improvements to the DSIDES system were made throughout the duration of the project by Saiyid Kamal and this culminated in a thesis [18] in May 1987. Both Marinopoulos and Jackson submitted an Honor's thesis [29,16] documenting their work on this project and both graduated with "Honors in their Major" in August 1986 and December 1986, respectively.

Stergios Marinopoulos and Jon Shupe started the development of a case study involving aircraft selection and writing the code for solving selection DSPs on the Macintosh. In December 1986 a case study involving preliminary selection and selection was proposed and solved on the Macintosh. This is the case study that has been included in this report. In January 1986 Micheal Harrison, Dae Lee and James Vick significantly improved the prototype code written by Marinopoulos and Shupe and gave us MacDSIDES in May 1986. In August 1986, Judson Hall, Eduardo Bascaran and Jon Shupe wrote the manual for the MacDSIDES software [33, Unit 3 and 34]. The MacDSIDES system continues to be developed by Eduardo Bascaran and Jon Shupe. PC-DSIDES (for use on IBM PC's) is being developed by J.K. Allen. This will provide the capability for solving preliminary selection, selection and compromise DSPs.

### 1.3.2 The Organization of the Report

In the remainder of this report we present material to establish the efficacy of using the selection and compromise Decision Support Problems in the conceptual design of aircraft. In Chapter 2 the relationship between selection and compromise in the conceptual design stage of aircraft design is described. The problem statement involving selection in aircraft design is presented and this is followed by a description of the mathematical constructs of the compromise DSP, a problem statement, and the word formulation of a compromise DSP template for the design of subsonic jet aircraft. In Chapter 3, the method for preliminary selection and selection is explained using a simple example that involves V/STOL aircraft. Emphasis, in this chapter, is on the constructs associated with selection and how it may be useful in the conceptual phase of aircraft design - and - not on the results of the example. The mathematical form for the compromise DSP template presented in Chapter 2 is derived in Chapter 4. The template is particularized for a Boeing 727-200 and validated in Chapter 5. In Chapter 6, the use of the template in designing subsonic jet transports in general is described. A critical evaluation of the templates and suggestions for further work are included in Chapter 8. An overview of the steps involved in formulating DSPs is presented in Appendix. In Appendix B the subject of creating scales and weights based on experience-based judgment is addressed. The computer implementation of the compromise DSP template is covered in Appendix C and a annotated output is included in Appendix D by way of example.

# CHAPTER 2
## SELECTION AND COMPROMISE IN THE CONCEPTUAL DESIGN OF AIRCRAFT

In this chapter, we present the context in which the use of selection and compromise DSPs, in the conceptual phase of aircraft design, would be efficacious. We start by making some observations about aircraft design and the commonalty of constructs between it and the Decision Support Problem Technique (see Chapter 1). We postulate three templates for aircraft design; two for selection and one involving compromise. We present the conceptual framework for both selection and compromise DSPs and the mathematical constructs necessary for understanding the formulation of the compromise DSP. Problem statements for all three DSPs are also presented in this chapter. We end with the word formulation for the compromise DSP template for the conceptual design of subsonic jet transport aircraft.

## 2.1 AIRCRAFT DESIGN - SOME OBSERVATIONS

### 2.1.1 The Multi-disciplinary, Multi-level, Multi-dimensional Nature of Aircraft Design

It is probable that ever since man learned to stand erect he has been preoccupied with a yearning to shed his terrestrial shackles and fly in a controlled, predictable fashion [64]. However, since flight is the visible result of many branches of applied physics, positive advancement must be keyed to state-of-the-art engineering practices, mechanical design, and fabrication techniques. When the many early unsuccessful attempts at flight are reviewed, it becomes obvious that any mathematical theory of controlled flight with wings is dependent upon some theory of lift of inclined planes (wings). Thus, controlled aircraft flight had to await the development of appropriate mathematical tools to be used in conjunction with a deeper understanding of fluid dynamics. As a result, air displacement vehicles or balloons, provided the first real demonstration of atmospheric flight.

It is generally felt that by 1900 humankind was scientifically ready for controlled flight via aircraft incorporating lift generating surfaces (wings). The only technical obstacle that remained was the development of a gasoline engine and drive system superior to any then available. Two brothers from Dayton, Ohio, Orville and Wilbur Wright, were the producers of the first working prototype. The first recorded circular flight under power was made by Wilbur Wright on September 20, 1904, 121 years after the Montgolfier brothers first launched their air balloon [64].

Fortunately, the persistent efforts of talented mathematicians, physicists, and engineers penetrated the mysteries of flight, and aircraft design is no longer a hit-or-miss endeavor. Today, the aircraft design process is a blend of all the major engineering disciplines. An effective design involves the integration of aerodynamics, propulsion, flight control, structures and materials, avionics and the associated subsystems, blended in just the right way to produce a synergistic result. The design of a modern aircraft is a large undertaking requiring the team effort of many engineers having expertise in these areas. As the design takes shape, specialists are called in to design such subsystems as the crew station, landing gear, interior layout, equipment installation and, if appropriate, armament provisions. The completed aircraft design is a compromise of the best efforts and talents of many talented engineers and scientists.

### 2.1.2 The Aircraft Design Phases

Aircraft design, as is the design of any complex system or structure, is traditionally divided into three phases, namely,

- Conceptual Design Phase
- Preliminary Design Phase
- Detailed Design Phase.

These phases are discussed below [43].

**Conceptual Design Phase**: In this phase the general size and configuration of the aircraft is determined. Parametric trade studies are conducted using preliminary estimates of aerodynamics and weights to determine the best wing loading, wing sweep, aspect ratio, thickness ratio, and general wing-body-tail configuration. Different engines are considered and the thrust loading is varied to obtain the best airframe/engine match. The first look at cost and manufacturing possibilities is made at this time. The feasibility of the design to accomplish a given set of mission requirements is established, but the details of the configuration are subject to change. All of the work done during this phase is performed on paper.

**Preliminary Design Phase:** The best configuration in terms of cost and performance from the conceptual phase is now fine tuned through wind tunnel experiments and parametric testing. This is accomplished with a wind tunnel model capable of presenting the general configuration with provisions for variations in wing and tail planform and location. The design is starting to get locked in.

The engine is selected and the inlet/engine/airframe problems are considered in detail. Major loads, stresses, and deflections are determined along with considerable structural design. Aeroelastic, fatigue, and flutter analyses are performed and some of the structural components might be built and tested.

Refined weight estimates are made and a more thorough performance analysis is conducted. The design is now given serious manufacturing consideration with preliminary plans for jigs, tooling, and production methods. Refined cost estimates are also made in this phase.

Dynamic stability and control influences of the maneuvering systems are determined and analyzed. This enables the designers to make their first assessment of the handling qualities of the aircraft.

**Detailed Design Phase:** In this, the final design stage, the configuration is "frozen" or locked in. The detailed structural design is completed. All of the detail design and shop drawings of the mechanisms, joints, fittings, and attachments are completed. Interior layout is detailed as to location and mounting of equipment, hydraulic lines, ducting, control cables, and wiring bundles. All equipment and hardware items are specified. Finally, a complete cost analysis is performed based on the Work Breakdown Structure (WBS). It is now time for sheet metal bending for the prototype and component fabrication is started as soon as the shop drawings are released [43].

Our efforts are directed to the conceptual phase of aircraft design.

In summary, aircraft design involves teams of people who plan, structure and solve open-ended problems. They endeavor to use analysis, visualization and synthesis in complementary roles to obtain knowledge to make decisions that provide solutions to these open problems. Decisions include selection and compromise and are characterized by terms such as multi-leveled, multi-dimensional, satisficing*, multiple objectives, hard and soft information, etc. These terms are the same used to describe some of the paradigms on which the Decision Support Problem Technique is based (Section 1.1.1).

## 2.2 AIRCRAFT DESIGN IN THE CONCEPTUAL DESIGN PHASE

As indicated earlier in the text, the design of an aircraft is a large undertaking requiring the team efforts of many engineers having expertise in the areas of aerodynamics, propulsion, structures, flight control, performance and weights. Furthermore, as the selected design takes shape, other specialists are called in to develop the critical aircraft subsystems. Thus, the whole process requires the pulling together of many disciplines and talents to produce the best or optimum final aircraft design.

### 2.2.1 Planning, Structuring and Cost-Effectiveness

Typically, the key element in the three design phases is the design team leader or chief engineer, who acts as a technical referee or liaison between the different engineering groups. The chief engineer is the one who understands and appreciates all of the various disciplines involved in the design process. This individual is called upon to negotiate compromises between the design groups and to prevent any one group from driving the design, otherwise the final design could have excellent characteristics in some respects and at the same time be grossly inferior in other respects. Such a situation is humorously illustrated in Figure 2.1 titled "Dream Airplanes" [43], which gives an exaggerated rendition of what might happen if any one design group were allowed to take itself too seriously. Hence, the need for planning and structuring.

Prior to the 1970's, the performance of the aircraft was paramount and all design efforts were focused to give a vehicle displaying maximum performance/weight ratio. Cost was a major consideration only after the aircraft design was "locked in". In the 1970's the government and the aircraft industry became very cost conscious. The cost of aircraft systems was increasing dramatically and the chief measure of merit became minimum cost.

This emphasis on cost brought two outsiders into the design team: the cost analyst and the manufacturing expert. Thus, cost/performance trade-off results became vital considerations in design decisions. The new emphasis on maximum performance at minimum cost along with the current widespread availability of high speed digital computers has led many researchers in the aerospace industry to apply optimization methods to the design of aircraft. Two pieces of work were invaluable in understanding aircraft design and in creating the compromise DSP template that can be used to achieve maximum performance at minimum cost.

* We use it in design to describe an acceptable, less-than-optimal solution to a problem, which because of its complexity and/or magnitude cannot be characterized adequately by relatively simple laws of cause and effect and for which no exact or optimal solution can be obtained.

A completed airplane in many ways is a compromise of the knowledge, experience and desires of the many engineers that make up the various design and production groups of an airplane company.

It is only being human to understand why the engineers of the various groups feel that their part in the design of an airplane is of greater importance and that the headaches in design are due to the requirements of the other less important groups.

This cartoon "Dream Airplanes" by Mr. C. W. Miller, Design Engineer of the Vega Aircraft Corporation, indicates what might happen if each design or production group were allowed to take itself too seriously.

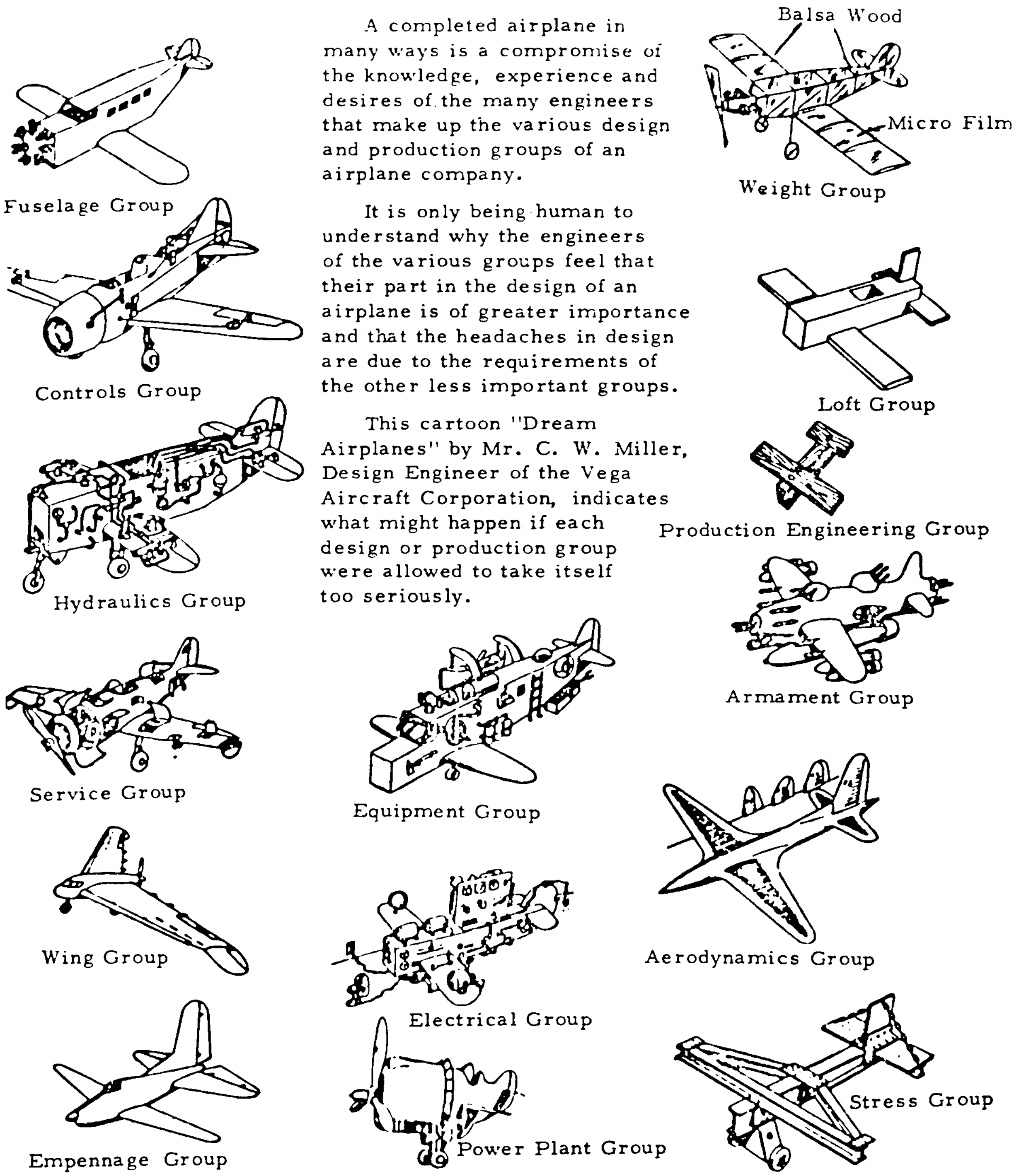



**FIGURE 2.1 -- DREAM AIRPLANES, [27]**

The first is a rapid method, described by Loftin [27], for estimating the size, weight, and required thrust of jet aircraft that satisfy specific performance objectives. The method developed is strictly for subsonic, jet propelled, aircraft intended for steady cruising flight. Extensive use is made of correlations of existing aircraft characteristics in terms of accepted design variables. The procedure is approximate, but yields acceptable results for conceptual design.

The second is the work on the preliminary design and evaluation of transport aircraft using nonlinear programming techniques by Sliwa and Arbuckle [56]. The basis for the procedure involves establishing a set of independent design variables that are of interest to the designer. The variables are adjusted until a minimum for a particular performance index (objective function) is found. The performance index is forced to satisfy a series of constraint functions that involve the selected design variables. Design variables are used to model geometry characteristics and mission parameters whereas constraints reflect federal regulations or flight stability requirements. The program allows the evaluation of new technologies to be incorporated into an aircraft design in an optimal fashion. The degree of detail in the analyses when the performance and the constraint functions are evaluated is at the preliminary design or classical aeronautics level. Thus, the precision in some phases of the calculations is in the neighborhood of 5-10 percent. While the predictive capabilities of the model are marginal, the accuracy of the relative comparison of designs is much better. Their program, OPDOT, is extremely suitable for evaluating the economic feasibility of an aircraft design. It is not possible, however, to directly trade-off economic and technical efficiencies inherent in the design. This work has been used to model the economic aspect of aircraft design in our compromise DSP template.

Sliwa and Arbuckle focus on aircraft economics. Loftin's rapid sizing procedure focuses far less upon the dollar efficiency of a given design and more upon the actual prediction of an aerodynamically acceptable aircraft configuration. The compromise DSP facilitates a direct trade-off between economic and technical efficiencies. In our compromise DSP template we have modeled the technical and economic efficiencies using relationships presented by Loftin [27] and Sliwa and Arbuckle [56,57], respectively.

### 2.2.2 Problem Definition

A natural point to start any design is at the beginning. The mission requirements are the beginning for aircraft design. They represent the intentions and goals the designer has in mind when first contemplating what the aircraft should physically be able to accomplish.

The mission requirements are extremely important as they drive the design and are the yardstick by which the success, or failure of the design is measured. Careful thought and research must go into establishing the mission requirements because if they are inappropriate, then the aircraft will be ineffective for its intended use.

Sometimes the mission requirements are established by the supplier based on market analyses to determine what the public's need or desires will be in the near future. At other times the mission requirements are established by the user, such as the military, commercial airlines, etc. No matter who defines the mission requirements the objectives must always be clearly defined. For example, the mission requirements usually identify the following:

- purpose - commercial transport, fighter, crop duster, etc.,
- payload - passengers, cargo, weapons, etc.,
- speed - maximum and minimum,
- range,
- endurance,
- field length - STOL, CTOL, etc.,
- cost - prototype, 300th production article, and
- maintainability - maintenance man hours per flight hour specified.

The mission requirements are then studied to identify the requirements that drive the design. For example, will the aircraft be range dominated, field length constrained or required to operate supersonically for extended periods or a combination of these? An early assessment of the driving requirement can help in the proper selection of the wing planform shape and size. The applicable specifications, standards, and regulations should be identified and complied with throughout the design process.

Once the mission requirements are resolved the designer starts the process of designing the aircraft in what is known as the conceptual design stage. However, before any formulas or analysis routines are considered, the mission requirements must be qualified by certain governmental specifications, standards, and regulations are identified as binding and therefore must be taken into consideration. The regulation of civil and commercial aircraft is administered by the Department of Transportation through the Federal Aviation Regulations (FAR), [1].

### 2.2.3 The Sizing Procedure

The DSP technique is a general design methodology and can be applied in all stages of design. However, the aircraft compromise Decision Support Problem developed in this report, is intended for use during the conceptual design phase. The objective of the conceptual design stage is to determine the overall size and configuration of the aircraft. Accordingly, the theory needed for this phase is not exact, but is accurate enough so that solutions obtained in the conceptual design stage can be accepted as an accurate scenario of the aircraft system. Therefore, preliminary estimates of aerodynamics, weights, and general wing-body configuration are acceptable using the limited theory presented in latter sections of this report.

For a traditional design process many assumptions have to be made in order to get started in the conceptual design phase. Before the initial aircraft sizing takes place estimates of the aircraft take-off weight, wing loading, and fuel weight first have to be determined. Later, during additional loops through the design process these values will be refined. The methods for determining these preliminary estimates will not be discussed in detail. Instead, the theory required to perform the higher level iterations is precisely that used for the aircraft compromise Decision Support Problem template and take precedence. The preliminary design estimates require time and effort to ascertain, and they will be of little value when the design is finished. This overhead design work can be eliminated because it is used only to start the traditional design process, and not for the final solution thereby having no relevance or use in the aircraft compromise template.

A rapid method for estimating the size, weight, and required thrust of jet aircraft that satisfy specific performance objectives is presented by Loftin [27]. The method developed is strictly for subsonic, jet propelled, aircraft intended for steady cruising flight. Extensive use is made of correlations of existing aircraft characteristics in terms of accepted design variables. The procedure is approximate, but yields acceptable results for conceptual design.

Loftin considers all jet aircraft to be designed to meet the following performance criteria:

- Airport performance
- FAR landing field length, missed approach requirement
- FAR take-off field length, second segment climb gradient
- Cruise performance
- Cruising speed in Mach number
- Range
- Payload.

The specification of these objectives combined with appropriate engine and aerodynamic data permit rapid estimation of the following aircraft parameters:

- Gross weight
- Fuel weight
- Empty weight
- Wing area and wing loading
- Engine thrust and thrust loading
- Cruise altitude.

An iterative design procedure by which an aircraft is sized to meet a given set of mission requirements is illustrated by Loftin, [27]. The procedure is illustrated in Figure 2.2 and is briefly described in this section. The blocks in the first column represent analysis methods for different flight conditions or performance objectives which are utilized in the first step toward sizing the aircraft. The landing field length block in the first column yields the output wing loading necessary to meet the required landing field length and the approach lift coefficient. The approach lift coefficient depends upon the type of high-lift system and is chosen on the basis of statistical data for current aircraft. The take-off field length yields an output curve of airplane thrust-to-weight ratio as a required take-off field length. The lift-off lift coefficient is again determined on the basis of statistical data for current, similar aircraft.

The second segment climb gradient criterion and the missed approach climb gradient criterion blocks pertain to regulations for emergency situations which follow loss of an engine in critical flight regimes. The aircraft lift-drag ratio for these two flight conditions is obtained using approximate methods. The cruise matching analysis block represents a relationship between take-off thrust to weight ratio as a function of wing loading. The defined thrust loading is sufficient for each wing loading to permit steady flight at the specified cruise Mach number and at the design lift coefficient which is usually near that for maximum lift-drag ratio. The altitude for cruise also comes from this analysis. The inputs to the cruise matching

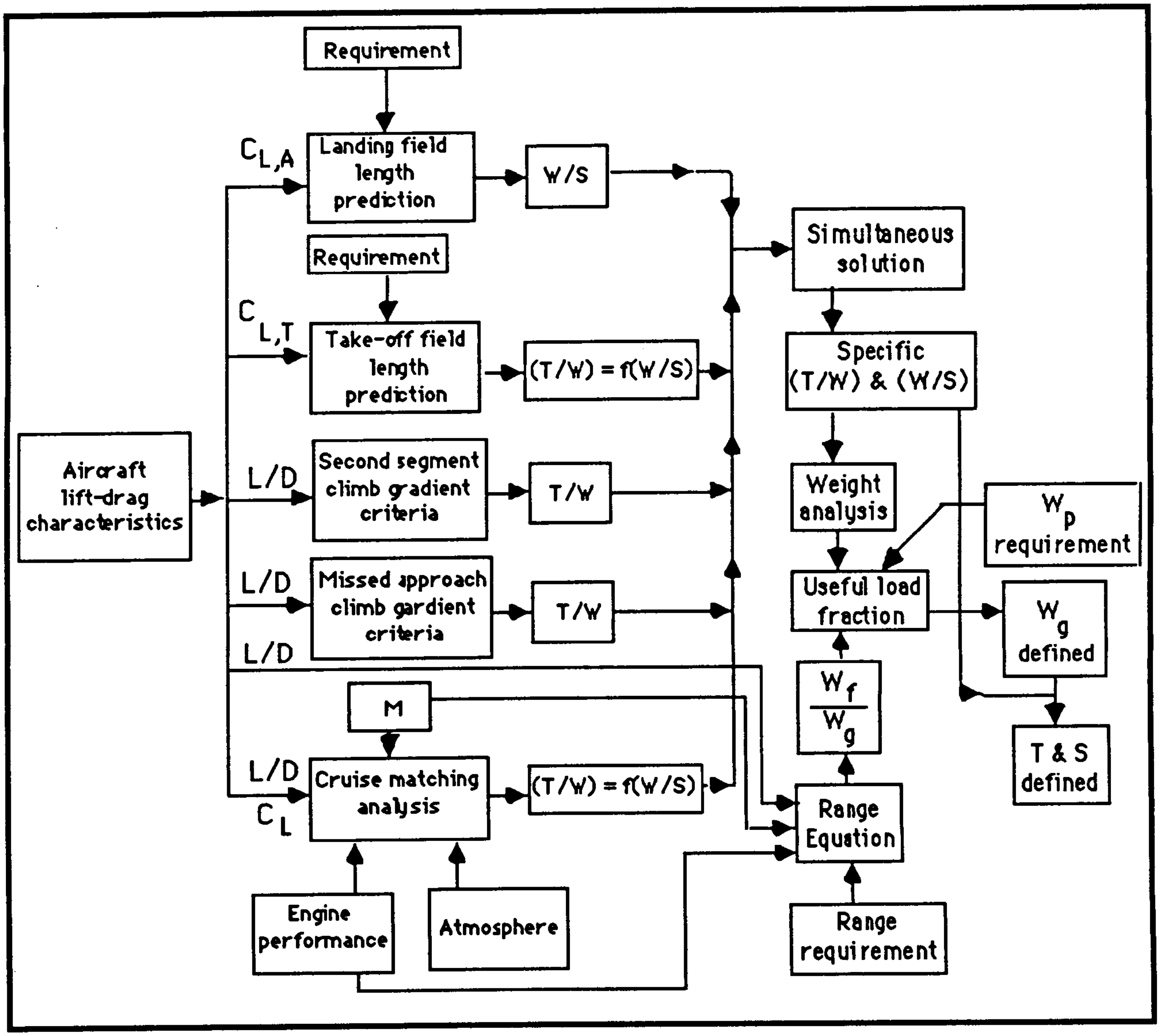



FIGURE 2.2 -- TRADITIONAL SIZING PROCEDURE, [27]

analysis are aircraft lift-drag ratio (L/D), engine performance, cruise Mach number (M), and characteristics of the atmosphere.

The outputs of the analyses represented by the first column constitute a set of relationships which, when considered simultaneously, yield values of wing loading and thrust loading that are required to meet the desired performance objectives. However, this process, being characteristic of traditional design methods, is fundamentally flawed. This procedure for designing aircraft will not exceed the objectives described by the mission requirements. Moreover, if a better design is sought, the designer must start at the beginning again, redefining the mission requirements to represent the intended better design, and proceed as though no previous work has been accomplished. As stated earlier, a compromise Decision Support Problem is used to seek the best possible design no matter what the initial objectives are, conflicting or otherwise. Whether the mission requirements are unrealistically high or modestly low, once the analyses procedures and design goals are represented as a compromise Decision Support Problem template the solution will converge to the best possible point with respect to designer's objectives. A computer-based post-solution sensitivity analysis feature provides information on the amount of improvement that can be achieved by modifying the goals and constraints. This information is provided as a matter of course.

### 2.2.4 The DSP Templates in Conceptual Design

As indicated in Chapter 1 the DSP Technique consists of four phases, namely, planning, structuring, solution and post-solution analysis. As indicated in Section 1.3.1 our focus in this report is limited to the development of templates for the conceptual phase of aircraft design.

A schematic of a very simple way in which the conceptual design of aircraft may be undertaken is shown in Figure 2.3. We assert that the conceptual design process starts with problem definition that leads to ideation that results in identifying alternative ways (concepts) of achieving the mission objectives. Ideally, a large number of concepts should be generated. At this stage most of the information will be soft and there should be many concepts. We envisage a preliminary selection DSP (Section 1.1.2) being formulated and solved to identify the more promising "top-of-the-heap" concepts. At this stage we expect engineering analysis to be used to convert the top-of-the-heap concepts into feasible alternatives. These alternatives will be characterized by both hard and soft information. We envisage a selection DSP (Section 1.1.2) being formulated and solved to identify one or two alternatives that should be further developed. This development involves improvement through modification and we believe that the compromise DSP is appropriate for this task. Iteration is necessary and is not precluded from the scenario just presented.

We recognize that preceding is an extremely idealized view of how conceptual design could be accomplished in practice - but it does, in our opinion, capture the essence of the process. An overview of the selection and compromise DSPs in the context of the conceptual design of aircraft follows.

## 2.3 SELECTION DECISION SUPPORT PROBLEMS

### 2.3.1 Selection in the Conceptual Design of Aircraft

Selection occurs in all stages of design. In the early stages there is almost no hard data; most of the data is soft. As the design process progresses the amount of hard data available increases. The principal distinction between selection in the stages is the ratio between the amount of hard and soft information that is available.

A preliminary selection decision support problem is formulated and solved when the amount of experience-based soft information far exceeds the amount of hard information available. A selection decision support problem is formulated and solved when meaningful hard information is available. In this report we describe the selection decision support problems in the context of conceptual design of aircraft.

**D E F I N E P R O B L E M**

RECOGNIZE NEED
EXAMINE PROBLEM
RECORD FIRST IMPRESSIONS
(See Wales et al.)

**I D E A T E**

GENERATE MANY CONCEPTS

**E V A L U A T E**

SELECT THE "TOP-OF-THE-HEAP" CONCEPTS
USING THE PRELIMINARY SELECTION DSP

**E N G I N E E R I N G**

CONVERT CONCEPTS TO FEASIBLE ALTERNATIVES

**E V A L U A T E**

SELECT A FEW FEASIBLE ALTERNATIVES
USING THE SELECTION DSP
FOR FURTHER DEVELOPMENT

**E N G I N E E R I N G**

DEVELOP SOME OF THE FEASIBLE ALTERNATIVES

**M O D I F Y**

IMPROVE DESIGNS THROUGH MODIFICATION
USING THE COMPROMISE DSP

**E V A L U A T E**

END CONCEPTUAL DESIGN START PRELIMINARY DESIGN
OF SUPERIOR ALTERNATIVE

FIGURE 2.3 -- CONCEPTUAL DESIGN IDEALIZATION

In the conceptual design stage, selection occurs in two major phases, namely,

- **Phase 1** - the generation and identification of potentially superior concepts based primarily on qualitative rather than quantitative information, and
- **Phase 2** - the identification, using insight-based 'soft' and science-based 'hard' information, of a very limited number of superior alternatives that should be developed further.

The two phases, in the context of conceptual design, are illustrated in Figure 2.4.

### 2.3.2 Types of Selection Decision Support Problems

Selection in design and management involves making a choice between a number of possibilities taking into account a number of measures of merit. These measures of merit may not all be of equal importance with respect to the decision. Some of the measures of merit may be quantified using 'hard' science-based information and others may be quantified using 'soft' information that is empirical in nature or derived from experience-based insight. The key issues are: there are a number of possibilities, there are a number of measures of merit and these are quantified using hard and soft information. We use the term **Decision Support Problem** [37,38] to draw attention to the fact that a numerical model is an approximation to the real-world and its solution is to be used to support human judgment.

The selection Decision Support Problem can be used in engineering in all stages of design. It can also be used in engineering management as a tool to resolve conflicting opinions. In both engineering and management there are two distinct types of selection: one that is based on the use of soft information (information derived from insight-based judgment) only and the other that makes use of both hard (information that can be quantified using some theory) and soft information. The process associated with the use of soft information only we call ***preliminary selection*** and the other we have named ***selection***. The role of the two in the DSP Technique is illustrated in Figure 2.5.

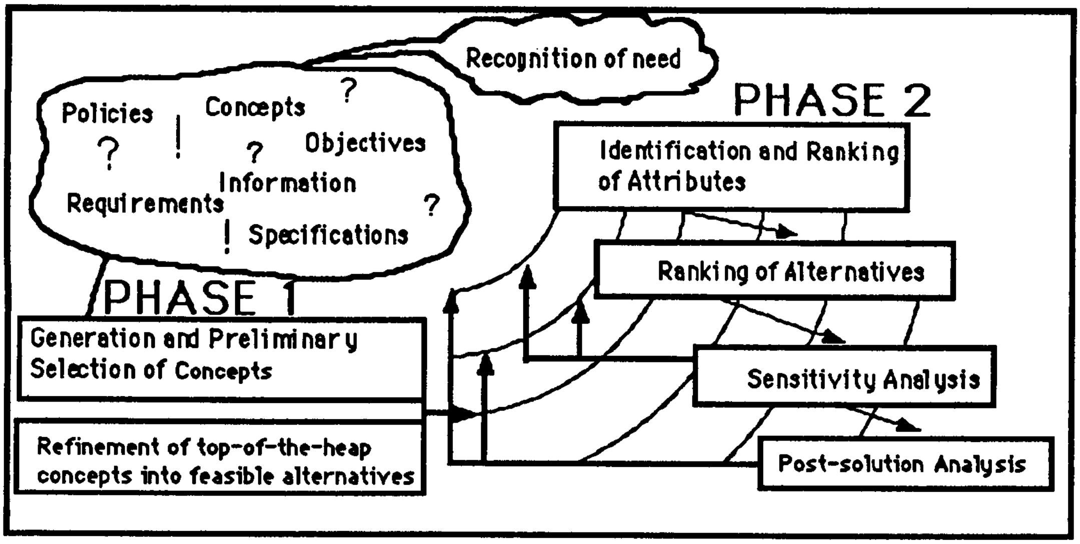



FIGURE 2.4 -- SCHEMATIC OF THE SELECTION PROCESS

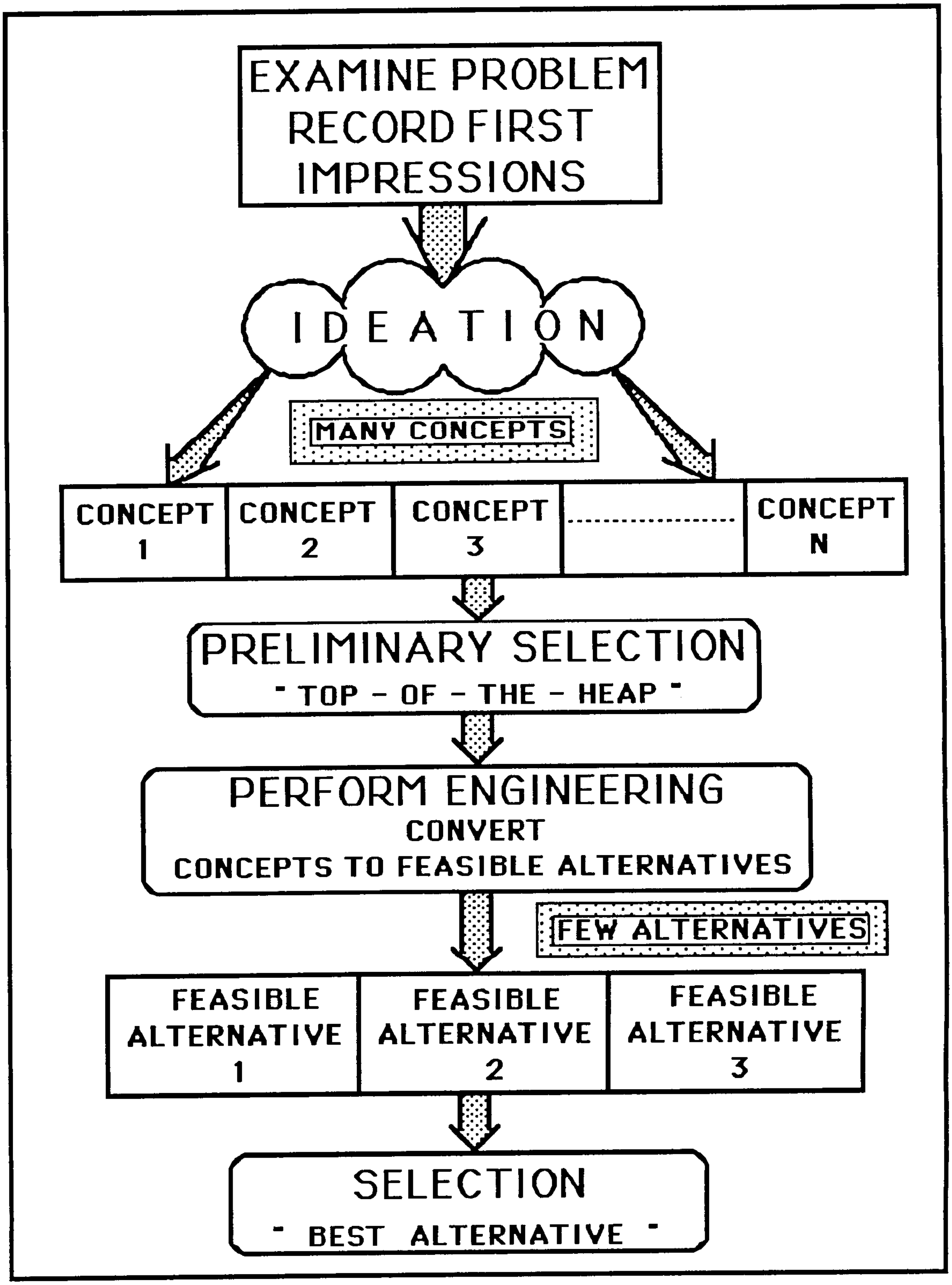



FIGURE 2.5 -- TWO TYPES OF SELECTION IN DESIGN

### 2.3.3 The Role of the Two Types of Selection in Design and Terminology

In ***preliminary selection*** we start with **concepts**; the end product of ideation (see Chapter 3). We evaluate the concepts based on **criteria.** The criteria are quantified using experience-based judgment and hence preliminary selection should normally be used to identify the top-of-the-heap concepts. The solution to the preliminary selection DSP involves the **rank ordering** of concepts. Therefore one cannot automatically infer, from the rankings, by how much one concept is preferred to another. Engineering is then 'performed' on the top-of-the-heap concepts (as many as one can afford) and the **concepts** become **feasible alternatives.**

In ***selection*** we start with **feasible alternatives.** We evaluate the feasible alternatives based on **attributes.** We use the selection DSP to help identify the best alternative. The solution to the selection DSP involves the **ordering** of alternatives. One can infer from the ranking by how much one alternative is preferred to another and therefore the best alternative can be identified.

Why different terms for similar items in the two types of selection? From experience, we find this is necessary to reduce confusion in communication. We always use the terms **concepts and criteria** in referring to **preliminary selection** and the terms **alternatives and attributes** in dealing with **selection.** For both types of selection we use the following terms:

**Relative importance**....establish the relative importance between criteria for preliminary selection and the relative importance between attributes in selection.

**Ratings**...we rate the concepts with respect to their criteria in preliminary selection and we rate the alternatives with respect to the attributes in selection.

**Rank**...we rank the concepts in descending order of preference in preliminary selection and we rank the alternatives in descending order of preference in selection.

In preliminary selection there are two types of criteria: **generalized** criteria and **specific** criteria. In preliminary selection the generalized criteria could be cost, reliability, maintenance, buildability. Each generalized criterion is qualified in terms of a number of specific criteria. For example, the specific criteria that qualify cost could be: the initial cost, the cost of maintenance, the cost of installation, the running cost, the cost of borrowing money, etc. In a similar manner generalized and specific attributes can be defined for selection.

### 2.3.4 Structure of the Selection DSPs

The decision support problem representing **preliminary selection** is stated as follows:

**Given** A set of ***concepts.***

**Identify** The principal ***criteria*** influencing selection.
The ***relative importance*** of criteria.

**Capture** Experience-based knowledge about the concepts with respect to a **datum** and the established criteria.

**Rank** The concepts in ***order of preference*** based on multiple criteria and their relative importance.

The decision support problem representing **selection** is stated as follows:

**Given** A set of ***alternatives.***

**Identify** The principal ***attributes*** influencing selection
The ***relative importance*** of attributes.
The ***feasible*** alternatives.

**Rate** The alternatives with respect to each attribute.

**Rank** The feasible alternatives in ***order of preference*** based on attributes and their relative importance.

Software to solve these problems has been written in BASIC for a 512K Macintosh. The software is called MacDSIDES. A version for the IBM PC/AT is under development.

### 2.3.5 An Example to Illustrate Selection in the Conceptual Design of Aircraft

We are amateurs in aircraft design. To explain our method we have used a problem from reference [27]. We have developed the problem for our use using information from [10,23,47,64]. A paraphrase of the problem follows.

> It is required to produce a design of a V/STOL aircraft capable of carrying either 12 passengers or 3000 pounds of payload a distance of 800 nautical miles at a speed greater than 400 knots. All major components should be available from distributors and have been proven reliable and safe from experience. (For example, powerplants, and avionic control systems that are considered radically new or untested in *in situ* operating conditions are not in line with this specification.) The ground area required for landing the vehicle should be rather small and of various terrain if possible.

The concepts are described and illustrated in Chapter 3. The method for formulating and solving these DSPs is also described in Chapter 3.

## 2.4 THE COMPROMISE DECISION SUPPORT PROBLEM

### 2.4.1 The Word Formulation

A compromise DSP can be stated in terms of the following system descriptors:

- Variables
  - system variables
  - deviation variables
- Constraints and goals
  - system constraints
  - system goals
- Bounds
  - on system variables
  - on deviation variables
- Objective
  - in terms of deviation variables.

The word formulation follows.

**Given**

A previously selected or existing concept (e.g., aircraft configuration).
Assumptions relating to the model (e.g., number of engines).
The goals of the design (e.g., maximize the range, minimize required thrust, etc.)

**Find**

The values of the system variables (wing span and area, fuselage diameter and length, installed thrust and take-off weight).
The values of the deviation variables (which indicate the extent to which the goals are achieved).

**Satisfy**

The system constraints that must be satisfied for feasibility (e.g., second segment climb gradient, wing loading, thrust loading, etc.),
The System goals that must be achieved as far as possible (e.g., range and endurance, etc.).
The upper and lower bounds on the system variables.

**Minimize**

The deviation of the system performance from that implied by the set of goals.

**Test**

The validity of the solution,
The sensitivity of the solution to the assumptions made and the information utilized.

The preceding formulation represents a **hybrid** formulation of an optimization problem. It incorporates concepts from both traditional mathematical programming formulations as well as goal programming (see Ignizio [15]), and also introduces some new ones. It is similar to goal programming in that the multiple objectives or goals are formulated as system goals and the objective function is solely a function of the goal deviation variables. However, the concept of having system constraints is retained from the traditional constrained optimization formulation. Special emphasis is placed on the bounds on the system variables unlike both the other formulations.

The preceding word formulation is different from the traditional constrained optimization formulation in that this formulation includes both deviation variables and system goals. Both the traditional optimization and the compromise DSP have a single objective function, but in the latter formulation, this objective is in terms of the deviation variables only. Multiple objectives, in the traditional formulation, are modeled as a weighted function of the system variables. In the compromise formulation the objectives are modeled as system goals involving both system and deviation variables. The objective, however, is a function of the deviation variables. In effect the traditional formulation is a subset of the compromise DSP - and as a result a lot more can be done with the compromise formulation. The results obtained using the traditional and compromise formulations will, of course, be different.

The phrases "Compromise Decision Support Problem" and "Goal Programming" [15] are synonymous to the extent that they refer to "Multiobjective Optimization" models; they both share the concept of deviation variables which measure the "goodness" of the solution with respect to the target values of goals. What distinguishes the compromise DSP formulation is the fact that it is tailored to handle common engineering design situations in which physical limitations manifest themselves as system constraints (mostly inequalities) and bounds. These constraints and bounds are handled separately from the system goals, contrary to the goal programming formulation in which everything is converted into goals. Unlike traditional optimization in both the compromise and goal programming formulations the multiple objectives are formulated as system goals. In the compromise formulation the set of system constraints and bounds defines the design space, and the set of system goals defines the aspiration space. For feasibility the system constraints and bounds must be satisfied, whereas the system goals are to be achieved as far as possible. The system goals model the aspirations of a design (mission requirements) for the designer.

### 2.4.2 System Descriptors

System descriptors are used to define the state of a system completely. Some of the descriptors are fixed parameters and do not change during the course of design. For example, the intended flight range will not change during the course of design. In this section, the system descriptors for a compromise DSP are presented. These are described with respect to Figure 2.6.

**System Variables and System Constraints**

System variables

$$\underline{X} = (X_1, X_2, \ldots, X_n), \quad X_i \geq 0 \quad .$$

System constraints

$$C_i(\underline{X}) \leq, \geq, \text{ or } = D_i(\underline{X}); \quad i = 1,2,3 \ldots m \quad .$$

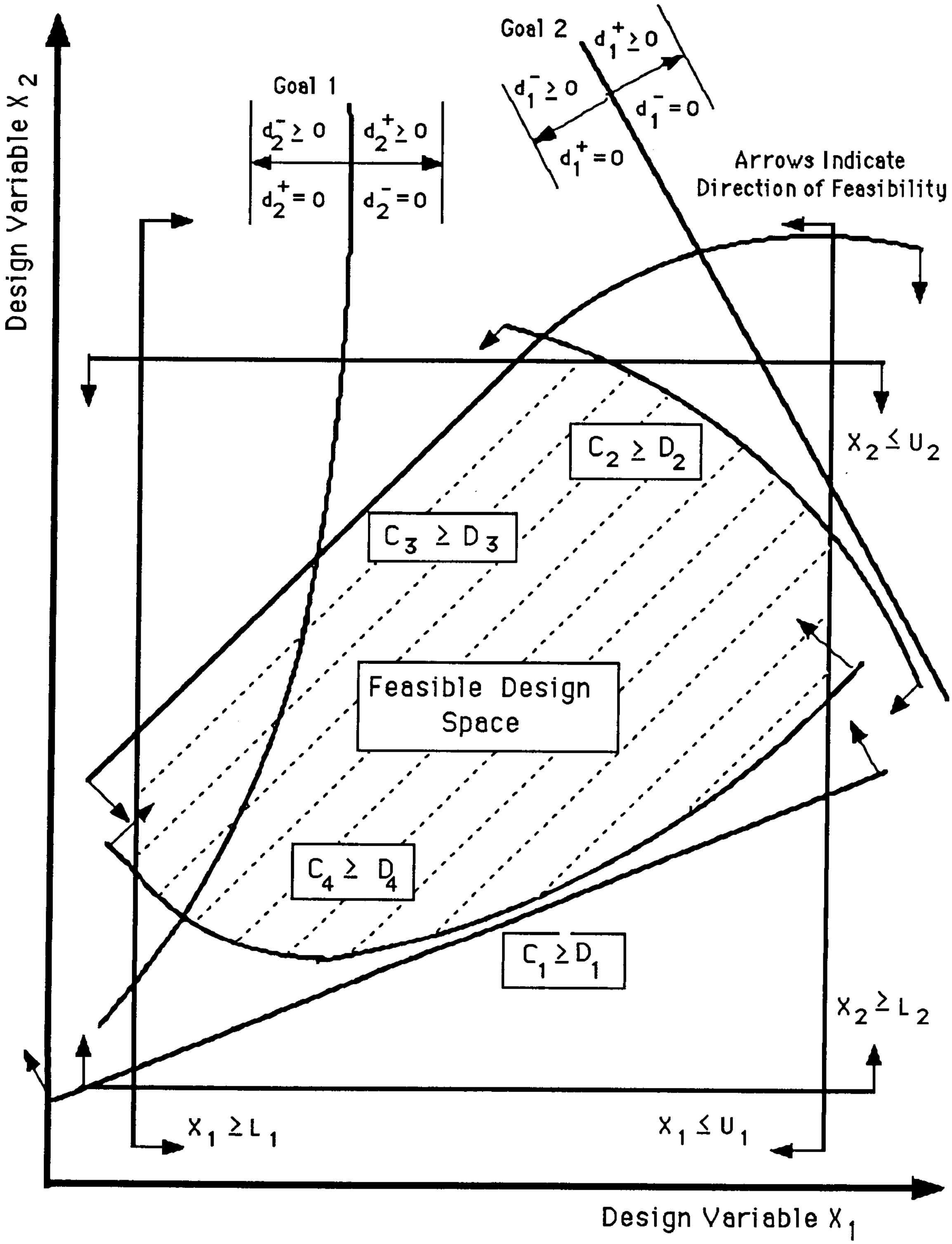



FIGURE 2.6 -- TYPICAL DESIGN SPACE FOR A TWO VARIABLE COMPROMISE DSP

Most engineering problems have at least two system variables. In general, a set of 'n' design variables is represented by $\underline{X}$ . These variables may be continuous, boolean (1 if TRUE, 0 if FALSE) or a combination of the two. System variables are, by their nature, independent of the other descriptors and can be changed as required by the designer to alter the state of the system. System variables associated in defining an artifact are always nonzero and positive. In Figure 2.6 the system variables $X_1$ and $X_2$, being independent, are represented by the abscissa and ordinate, respectively. In general, each member of the set $\underline{X}$ represents an axis of an 'n' dimensional space.

A system constraint is a constraint placed on the design. The set of system constraints must be satisfied for the feasibility of the design. Mathematically, system constraints are functions of system variables only. They are rigid and no violations are allowed. They relate the demand placed on the system $D(\underline{X})$ to the capability of the system, $C(\underline{X})$, to meet demand.

The set of system constraints may be all linear, nonlinear or consist of both linear and nonlinear functions. In engineering problems the system constraints are invariably inequalities. However, occasions which require equality constraints may arise. Equality functions, also, can be part of the set of system constraints. All system constraints shown in Figure 2.6 are inequalities.

**Deviation Variables and System Goals**

Deviation variables $d_i^-$ - underachievement of the $i^{th}$ goal
$d_i^+$ - overachievement of the $i^{th}$ goal.

System goals $A_i(\underline{X})/G_i + d_i^- - d_i^+ = 1; \; i = 1,2,....,m$

The set of system goals models the aspiration of a designer for the design. A system goal is always expressed as an equality. It relates the goal (aspiration level), $G_i$, of the designer to the actual achievement, $A_i(\underline{X})$, of the goal. It is possible that the designer's aspiration levels are inordinately high or the system constraints are much too restrictive to attain the desired levels of achievement. The deviation variables $d_i^-$ and $d_i^+$ are used to allow the designer a certain degree of latitude in making decisions. A particular goal may either be overachieved ($d_i^+ > 0$ and $d_i^- = 0$) or underachieved ($d_i^- > 0$ and $d_i^+ = 0$). The deviation variables therefore relate the actual performance of the design to the aspired level of performance. These variables serve to 'anchor' the aspiration levels to realistic achievement levels. The difference between a system variable and a deviation variable is that the former represents a distance in the $i^{th}$ dimension from the origin of the design space, whereas the latter has as its origin the surface of the system goal. This is illustrated in Figure 2.7. The value of the deviation variables are determined by the degree to which the $i^{th}$ goal is achieved, i.e.,

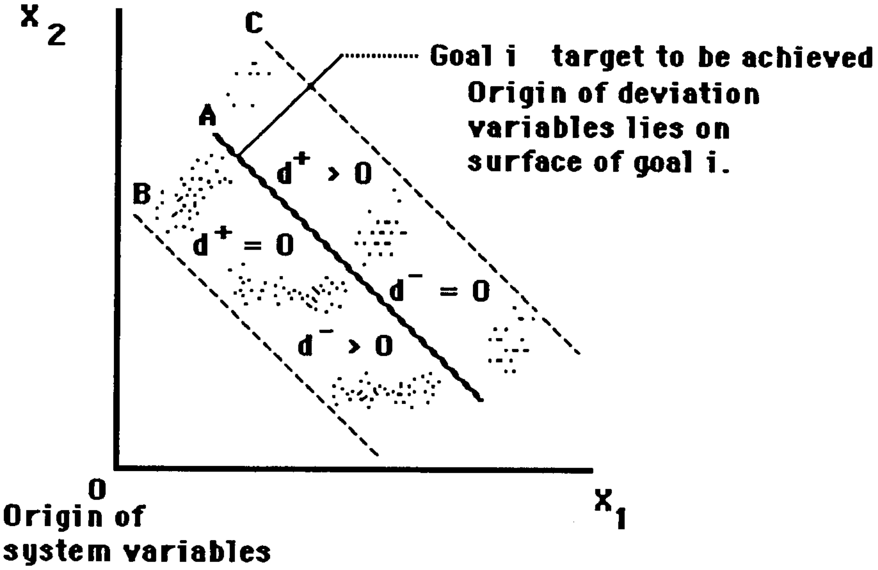
$$A_i(\underline{X})/G_i + d_i^- - d_i^+ = 1 \qquad [2\text{-}1]$$

where

$A_i(\underline{X})$ is the achievement and $G_i$ is the goal. When considering equation 2-1 the

| | | |
|---|---|---|
| SYSTEM VARIABLES: | $X_1$ , $X_2$... | Form the axes of the design space. |
| DEVIATION VARIABLES: | $d^-$ | The deviation variable that represents the underachievement of the goal. |
| | $d^+$ | The deviation variable that represents the overachievement of the goal. |

NOTE: Goals represented by lines A, B, C are parallel. The same holds true for nonlinear constraints.




| EQUATION FOR GOAL (LINE) A | | NUMERICAL EXAMPLE |
|---|---|---|
| 1 | $a_1X_1 + a_2X_2 = b_1$ | Say....$8X_1 + 7X_2 = 13$ |

**EQUATION FOR GOAL (LINE) B**

| | | |
|---|---|---|
| 1. | $a_1X_1 + a_2X_2 = b_2$ ; $b_2 < b_1$ | Say $8X_1 + 7X_2 = 10$ |
| 2. | $a_1X_1 + a_2X_2 + d_1^- = b_1$ ; $d_1^- \neq 0$ | $8X_1 + 7X_2 + d_1^- = 13$ ; $d_1^- = 3$ |
| 3. | $a_1X_1 + a_2X_2 + d_1^- - d_1^+ = b_1$ with $d_1^- > 0$, $d_1^+ = 0$ | $8X_1 + 7X_2 + d_1^- - d_1^+ = 13$ with $d_1^-=3$ , $d_1^+=0$ |

**EQUATION FOR GOAL (LINE) C**

| | | |
|---|---|---|
| 1. | $a_1X_1 + a_2X_2 = b_3$ ; $b_3 > b_1$ | Say $8X_1 + 7X_2 = 15$ |
| 2. | $a_1X_1 + a_2X_2 - d_1^+ = b_1$ ; $d_1^+ \neq 0$ | $8X_1 + 7X_2 - d_1^+ = 13$ ; $d_1^+ = 2$ |
| 3. | $a_1X_1 + a_2X_2 + d_1^- - d_1^+ = b_1$ with $d_1^- = 0$, $d_1^+ > 0$ | $8X_1 + 7X_2 + d_1^- - d_1^+ = 13$ with $d_1^- = 0$, $d_1^+ = 2$ |

**EQUATION FOR A FAMILY OF GOALS B THROUGH C**

| | | |
|---|---|---|
| 3. | $a_1X_1 + a_2X_2 + d_1^- - d_1^+ = b_1$ ; $d_1^-, d_1^+ \geq 0$ | $8X_1 + 7X_2 + d_1^- - d_1^+ = 13$ ; $d_1^-, d_1^+ \geq 0$ |

FIGURE 2.7 -- THE SYSTEM GOAL

following will be true:

| | |
|---|---|
| **if** $A_i > G_i$ (overachievement) | **then** $d_i^- = 0$ and $d_i^+ > 0$, |
| **if** $A_i = G_i$ (exact achievement) | **then** $d_i^- = 0$ and $d_i^+ = 0$, and |
| **if** $A_i < G_i$ (underachievement) | **then** $d_i^- > 0$ and $d_i^+ = 0$. |

The value of the $i^{th}$ deviation variable is dependent upon the value of $A_i(\underline{X})$ alone (since $G_i$ is fixed by the designer) which in turn is dependent upon the system variables $\underline{X}$. Further, at a point in the design space, only one of the deviation variables associated with a goal is greater than zero. The set of deviation variables can be all continuous, all boolean or some can be boolean and others continuous. Obviously, both the deviation variables associated with a particular system goal will be of the same type. If more than one goal exists, it is imperative that the goals be nondimensionalized such that the deviation variables, for a set of system goals, vary over the same range (for e.g., 0 to 1).

The system goal represents an equation for a family of either parallel linear or nonlinear functions. In Figure 2.7 goal i (represented by line A) is to be achieved. Assume that lines B and C represent the maximum acceptable excursion that is possible from the target goal. In other words the system variables can achieve any value in the shaded region. Three representations for lines B and C are shown in the figure, namely,

1 in terms of system variables,
2 in terms of the system variables and the non-zero deviation variable, and
3 in terms of the system variables and both the deviation variables.

In 1 the right hand sides for the equations for A, B and C are different. In 2 and 3 the right hand sides for both B and C are the same ($b_1$) however the deviation variables are different. In 3 both B and C are expressed in terms of the system variables and the two deviation variables. For B $d_1^-$ is non-zero and $d_1^+$ is zero. For C it is the other way around. Since, only one deviation variable, by definition, can be non-zero we are able to write the equation for the family of system goals B through C (see Figure 2.7). This is analogous to equation 2-1.

A more general form to the system goal given in equation 2-1, is

$$A_i(\underline{X})/G_i + d_i^- - d_i^+ = T_i \qquad [2\text{-}2]$$

The objective of an optimization problem may require **maximization** or **minimization** of a function. The objective of the optimization problem becomes a goal in the compromise DSP and the objective of the compromise DSP always represents the **minimization** of the deviation of the performance of the system from that implied by the goal. Therefore, in the compromise DSP:

a. To maximize $A_i(\underline{X})$ set $G_i$ to the maximum expected value of $A_i(\underline{X})$ so that the ratio $A_i(\underline{X})/G_i$ is less than 1, set $T_i = 1$ and minimize the deviation variable $d_i^-$. For example, if $A_i(\underline{X})$ is the reference stress then $G_i$ could be the yield stress. In this case the deviation variables will vary between 0 to 1.

b. To minimize $A_i(\underline{X})$ set $G_i$ to the minimum expected value of $A_i(\underline{X})$. Invert the first term of equation 2-2, flip the signs of the deviation variables and set $T_i = 1$. This gives equation 2-3.

$$G_i / A_i (\underline{X}) - d_i^- + d_i^+ = 1 \qquad [2\text{-}3]$$

Minimize the deviation variable $d_i^+$. The deviation variables will vary between 0 and 1.

c. If it is desired that $A_i(\underline{X}) = G_i$, and
   i) if the target value $G_i$ is always higher than $A_i(\underline{X})$), set $T_i = 1$ in equation 2-2 and minimize the sum $(d_i^- + d_i^+)$,
   ii) if the target value $G_i$ is always lower than $A_i(\underline{X})$), use equation 2-3 and minimize the sum $(d_i^- + d_i^+)$.

## Bounds

Bounds are specific limits placed on the magnitude of each of the variables. Each variable is associated with a lower and upper bound as a result of the limited capability of the system and based on the designer's judgment. In most engineering design optimization work done there has been a tendency to ignore bounds. It is necessary to place bounds on the system variables, i.e.,

$$\underline{L} \quad \leq \underline{X} \leq \quad \underline{U} \text{ and}$$

the bounds on the system variables demarcate the region in which a search is to be made for a feasible solution. Since the template is to be used in the design of artefacts the lower bound must be nonzero and positive.

If there are two or more system goals, it is imperative that all the deviation variables be dimensionless (or be of the same dimension) and it is desirable that they vary between a fixed range (e.g., 0 to 1). Invariably it is necessary to adjust the value of $G_i$ so that all deviation variables vary within a fixed range.

## The Objective

In the compromise DSP formulation the objective is to minimize the achievement function, $Z(\underline{d}^-, \underline{d}^+)$, which is always written in terms of the deviation variables.

The designer sets an aspiration level for each of the goals. It may be impossible to obtain a design that is up to the standards aspired. Hence, a compromise solution has to be accepted by the designer. It is desirable, however, to obtain a design whose performance matches the aspirations as closely as possible. This, in essence is the objective of a compromise solution. The difference between the goals and achievement is expressed by a combination of appropriate deviation variables, $Z(\underline{d}^-, \underline{d}^+)$. The function $Z(\underline{d}^-, \underline{d}^+)$ is also termed an 'achievement function' [15]. The magnitude of $Z(\underline{d}^-, \underline{d}^+)$ is an indication of the extent to which specific goals are achieved. All goals may not be equally important to a designer and the formulations are classified as Archimedean or Preemptive based on the manner in which importance is assigned to satisficing the goals. The achievement function for 'm' goals in the Archimedean formulation is

$$Z(\underline{d}^-, \underline{d}^+) = W_1 d_1^- + W_2 d_1^+ + \ldots\ldots + W_{(2m-1)} d_m^- + W_{2m} d_m^+$$

where the weights $W_1, W_2, \ldots\ldots, W_{2m}$ reflect the desire to achieve certain goals more than some others. In the Archimedean formulation, the weights $W_i$ are such that

$$\sum_{i=1}^{2m} W_i = 1 \text{ and } W_i \geq 0 \text{ for all i.}$$

The values of these weights are often based on estimates and designer preferences. As an example consider a three goal compromise DSP. In the Archimedean approach, the objective for the compromise DSP could be written in one of three ways:

a. If the relative value of minimizing both the under and the overachievement is known, then the objective can be written as:
$Z = W_1(d_1^- + d_2^- + d_3^-) + W_2(d_1^+ + d_2^+ + d_3^+)$
where $W_1 + W_2 = 1$ and $W_1, W_2 \geq 0$.

b. If the relative value of achieving each goal is known, then the objective for the compromise DSP can be written as:
$Z = W_1(d_1^- + d_1^+) + W_2(d_2^- + d_2^+) + W_3(d_3^- + d_3^+)$
where $W_1 + W_2 + W_3 = 1$ and $W_1, W_2, W_3 \geq 0$.

c. If it is a combination of the above, then
$Z = W_1(d_1^- + d_2^-) + W_2(d_1^+ + d_2^+) + W_3(d_3^- + d_3^+)$
where $W_1 + W_2 + W_3 = 1$ and $W_1, W_2, W_3 \geq 0$.

An example that illustrates the difference in the solution obtained by using the Preemptive and the Archimedean formulations is given in Figure 2.8. It may be difficult to come up with truly credible weights that attach more importance to one goal than the other for the Archimedean approach. A systematic approach for determining reasonable preferences is to use the schemes presented in [6,50,51]. In the preemptive approach, this difficulty is circumvented by rank ordering the goals and this is probably easier in an industrial environment or in the earlier stages of design. Goals are ranked lexicographically and an attempt is made to achieve a more important goal before other goals are considered. The achievement function, for instance, for a four goal problem, may look like

$$Z(\underline{d}^-, \underline{d}^+) = P_1(d_1^- + d_1^+ + d_2^-) + P_2(d_2^+ + d_3^- + d_3^+) + P_3(d_4^- + d_4^+)$$

where $P_1$ is preferred to $P_2$ which in turn is preferred to $P_3$ and so on. The deviation variables $d_1^-$, $d_1^+$, $d_2^-$ have to be minimized preemptively before variables $d_2^+$, $d_3^-$ , $d_3^+$ are considered and so on. The priorities represent rank, i.e., by how much one goal is preferred to another. No conclusions can be drawn with respect to the amount by which one goal is preferred or is more important than another. This approach is therefore suitable when there is little information available. For a simple problem with only two system variables, a graphical solution can be easily found by satisficing the goals in a logical manner. This is in contrast with the Archimedean approach in which the numerical evaluation of the objective function is required even for the simplest case.

### 2.4.3 An Overview of the Solution Algorithm

It has been shown, [36], that many different classes of DSPs arise in engineering design. There are two ways of providing the capability for solving a class of DSPs, namely.,

- organize a suite of algorithms, or
- develop a single algorithm.

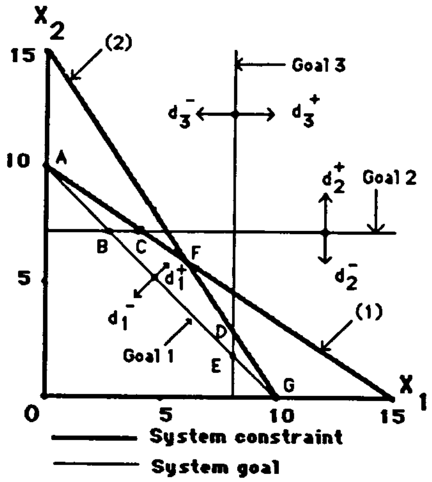
In either case, the suite of algorithms or the single algorithm must be capable of solving a wide range of formulations (see Figures 2 to 6, Table 1, reference [36]). We believe in solving the DSPs using optimization. Optimization algorithms fall into two categories, namely,

- solve the exact problem approximately, and
- solve an approximation of the problem exactly.

Gradient methods, pattern search methods, penalty function methods and barrier function methods fall into the first category whereas methods involving sequential linearization fall into the second category.

We have chosen the sequential linear programming approach because it has, in our opinion, the highest potential for being used to develop a single algorithm for solving a range of DSPs in engineering design and it also provides sensitivity information for the solution without extra calculations. The latter is particularly important for establishing the validity of DSPs that make use of both hard and soft information and in exploring the vicinity of the solution point. This sensitivity information, however, is only valid for the linear problem. For nonlinear problems and for those with both linear and nonlinear constraints, the sensitivity information is only valid for the final design and only for small changes in the variables.

| | |
|---|---|
| ***FIND*** | System variables |
| | $X_1$ , $X_2$ |
| | Deviation variables |
| | $d_1^-$, $d_1^+$, $d_2^-$, $d_2^+$, $d_3^-$, $d_3^+$ |
| ***SATISFY*** | System constraints |
| | $2X_1 + 3X_2 \leq 30$ ........ (1) |
| | $6X_1 + 4X_2 \leq 60$ ........ (2) |
| | System goals (dimensionless, normalized) |
| | $X_1/10 + X_2/10 + d_1^- - d_1^+ = 1$ ...(1g) |
| | $X_2/7 + d_2^- - d_2^+ = 1$ ...(2g) |
| | $X_1/8 + d_3^- - d_3^+ = 1$ ...(3g) |
| | Bounds omitted for now. |




***MINIMIZE*** Case a: Using the preemptive approach.

$$Z = P_1 d_1^- + P_2 d_2^- + P_3 d_3^- + P_4(d_1^+ + d_2^+ + d_3^+)$$

The priorities are **RANK-ORDERED**:

$P_1 >> P_2 >> P_3 >> P_4$ (indicate preference only)

Case b: Using the Archimedean approach.

$$Z = W_1 d_1^- + W_2 d_2^- + W_3 d_3^- + W_4(d_1^+ + d_2^+ + d_3^+)$$

where $W_1 = W_2 = W_3 = 1/3$ and $W_4 = 0$ (assumed values)

**SOLUTION**

Case A **Preemptive**.....the best solution is at point 'C'.

For system goal 1 alone, the better solutions are A, B, E & G (lie on the goal).

For system goals 1 and 2, taken together in that order, B >> A >> C. Note, both goals intersect at point B

For system goals 1, 2 and 3, taken together in that order, the ' optimum' solution is at point 'C'. If point C did not exist, the optimum would be at point B.

Case B **Archimedean**.....it follows from the following table that the best solution is at 'F' where Z is a minimum (Z=0.13).

| Acceptable Vertices (coordinates) | Value of Normalized Deviation Variable | | | | | | Objective Function |
|---|---|---|---|---|---|---|---|
| | $d_1^-$ | $d_1^+$ | $d_2^-$ | $d_2^+$ | $d_3^-$ | $d_3^+$ | 'Z' |
| A = (0, 10) | 0 | 0 | 0 | 0.42 | 1 | 0 | 0.333 |
| B = (3, 7) | 0 | 0 | 0 | 0 | 0.625 | 0 | 0.208 |
| C = (4.5, 7) | 0 | 0.15 | 0 | 0 | 0.438 | 0 | 0.146 |
| D = (8, 3) | 0 | 0.10 | 0.57 | 0 | 0 | 0 | 0.190 |
| E = (8, 2) | 0 | 0 | 0.71 | 0 | 0 | 0 | 0.238 |
| F = (6, 6) | 0 | 0.2 | 0.14 | 0 | 0.25 | 0 | 0.130 <--- |
| G = (10, 0) | 0 | 0 | 1 | 0 | 0 | 0.25 | 0.333 |

**FIGURE 2.8 -- DIFFERENCES IN SOLUTION**

Our algorithm is called ALP (Adaptive Linear Programming). A block diagram of the implementation of the ALP algorithm is shown in Figure 2.9. The user provides the input to the program in the form of a DSP template. This template consists of data and user provided Fortran routines. The data is used to define the problem size, the names of the variables and constraints, the bounds on the variables, the linear constraints and the convergence criteria. The Fortran routines are used to evaluate the nonlinear constraints, the objective function, to input data required for the constraint evaluation routines and the design-analysis routines, and to output results in a format desired by the user. Access is provided to a design-analysis program library from the analysis/synthesis cycle and also within the synthesis cycle. For the design of major systems, it is desirable to use the design-analysis interface associated with the analysis/synthesis cycles (e.g., structural design requiring the use of a finite element program). It has been found necessary to use both the interfaces for solving comprehensive hierarchical problems [58]. Once the nonlinear compromise DSP is formulated it is linearized in two stages using the scheme described in [31,36]. At each stage the solution of the linear programming problem is obtained by a Revised Dual Simplex algorithm. Two checks for determining whether or not to continue the solution process are made. Once a solution has been obtained a post-solution analysis can be performed using the algorithm described in [20,21,38]. The solution algorithm requires that all system variables are positive

The creation of templates for decision support is becoming easier as we acquire knowledge about decision making. This knowledge can be made available on a computer through knowledge-based expert systems. We are in the process of developing expert systems to support the formulation of the DSP, [18,19].

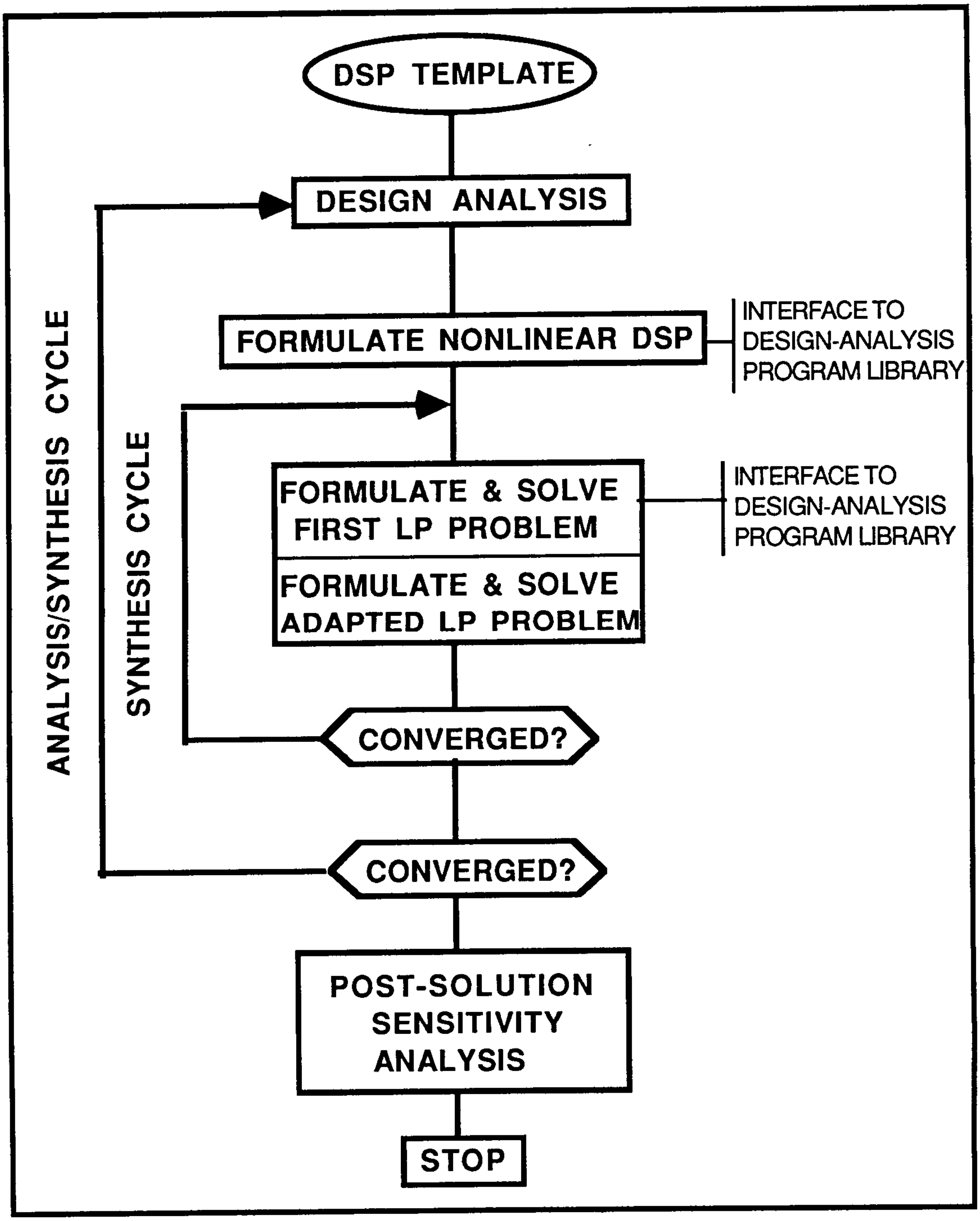



FIGURE 2.9 -- A SCHEMATIC OF THE ALP ALGORITHM

## 2.5 THE ANATOMY OF AN AIRCRAFT COMPROMISE DSP

### 2.5.1 The Compromise DSP Template for the Conceptual Design of Aircraft

In the mathematical formulation of the aircraft compromise DSP template, as indicated earlier, the design-analyses information (see blocks Figure 2.2) is based on the traditional sizing process. Figure 2.10 is the corresponding figure for the compromise DSP template. Details pertaining to the mathematical formulation of the compromise DSP are presented in Chapter 4.. Economic efficiency is not explicitly taken into account in the procedure illustrated in Figure 2.2. Since we do take this into account in our template economic efficiency is shown explicitly in Figure 2.10.

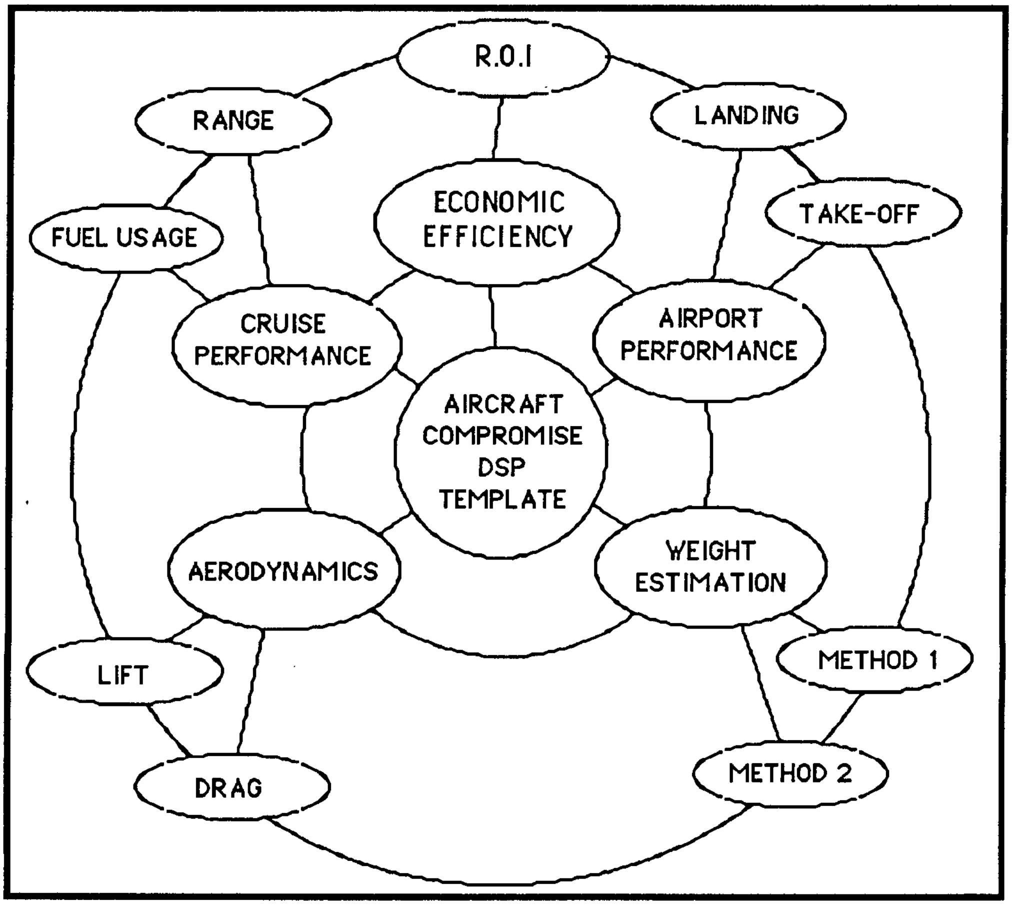



FIGURE 2.10 -- THE AIRCRAFT COMPROMISE DECISION SUPPORT PROBLEM TEMPLATE

In the compromise DSP, the system variables are not made firm sequentially but are determined concurrently. The solution to a compromise DSP represents an "optimal" balance between the technical and economic efficiencies that are used to model the aspirations for the design. The capability to optimally trade-off the conflicting requirements and aspirations concurrently is one of the principal advantages of the compromise DSP formulation. Further, the variables are determined taking into account the trade-offs between the system constraints, bounds and aspirations - concurrently. Hence, unlike Figure 2.2, there are no arrows in Figure 2.10 indicating precedence. Iteration when using the compromise DSP template is only necessary when the model (system constraints, system goals, bounds), design constants or the priorities associated with the aspiration function are altered. Hence, there is less iteration involved in obtaining a solution to the compromise DSP than there is in the traditional sizing procedure. These benefits must be weighed against the effort required in establishing the initial template.

In creating the compromise DSP template we have made use of design-analysis information that is used in the traditional sizing procedure. We have, in effect, synthesized the same information that is used in the traditional sizing process differently. We see our current work "augmenting" the traditional sizing procedure not replacing it. We do assert, however, that if we used exactly the same information and knowledge for the traditional and "augmented" sizing procedures the latter would provide a better aircraft design more quickly with fewer iterations.

### 2.5.2 The Problem Statement

A subsonic jet transport is to be designed. The system variables that must be determined are: wing span and area, fuselage diameter and length, installed thrust and take-off weight. The jet is to cruise at 35,000 feet and the number and type of engines have been selected and the specific fuel consumption rate is c.

Constraints should include all those used in traditional design. To satisfy the Federal Air Regulations (FAR) that govern the certification of all transport aircraft operated in the United States it is required that, for a N engined aircraft, the climb gradient and the second segment climb gradient be greater than $q_L$ and $q_{TO}$ degrees, respectively. To ensure that the aircraft is operational from many airports the take-off field length should be less than $S_{TO}$ ft and the landing field length should be as close to $S_{LTV}$ ft as possible. It is required that the range of the aircraft exceed R nautical miles.

It is desired that the aircraft should be cost-effective. This aspiration is modeled by seeking to maximize the endurance, range and useful load fraction by minimizing the fuel weight and the required thrust for cruise. Further, it is desirable that the airplane carry about $N_{PTV}$ passengers and provide a $ROI_{TV}$ % return on investment. It is also desirable that the missed approach climb gradient be as large as possible.

### 2.5.3 The Word Formulation

#### Given

The information provided in the problem statement. To simplify the design-analysis the take-off and landing speeds may be assumed to be the same. The principal references for design-analysis are [27,43,56]. Unknown values for parameters may be assumed to be the same as those of similar aircraft.

### Find

The values of the independent **system variables:**

| | |
|---|---|
| Wing area | $S$ |
| Installed thrust | $T_i$ |
| Fuselage length | $l$ |
| Take-off weight | $W_{TO}$ |
| Wing span | $b$ |
| Fuselage diameter | $d$ |

The values of the **deviation variables** associated with
- the landing field length goal
- the missed approach climb gradient goal
- the endurance goal
- the cruise range goal
- the useful load fraction goal
- the weight matching goal
- the number of passengers goal
- the return on investment goal

### Satisfy

The **system constraints:**
- The thrust required for cruise, $T_R$, must be less than the installed thrust, $T_i$.
- The fuel weight must be greater than a minimum required for a given fuel consumption rate and range.
- The thrust for cruise, $T_R$, must be greater than or equal to drag, D.
- The missed approach climb gradient must be greater than $q_L$ degrees with one engine operable.
- The take-off field length must be less than $S_{TO}$.
- The second-segment climb gradient must be greater than $q_{TO}$ degrees with one engine inoperable.
- The range must be greater than R.
- The wing loading must be within the range of values for existing aircraft.
- The thrust loading must be within the range of values for existing aircraft.
- The wing area to fuselage area ratio must be within the range of values for existing aircraft.
- The fuselage form factor must be within the range of values for existing aircraft.
- The aspect ratio must be within the range of values for existing aircraft.

The **system goals:**
- The landing field length should be around $S_{LTV}$.
- The missed approach climb gradient should be around $q_{LTV}$ with ($q_{LTV} > q_L$)

The endurance should around $E_{TV}$.
The cruise range should be around $R_{TV}$.
The useful load fraction should be around $U_{TV}$.
The weight matching[1] routine should be as exact as possible.
The passenger carrying capacity should be close to $N_{PTV}$.
The return on investment should be close to $ROI_{TV}$

The **bounds:**
Upper and lower bounds on the system and deviation variables.

**Minimize**

The difference between the aircraft performance that is achievable and that which is sought.

In the very early stages it may be difficult to quantify some of the target values for the system goals, for example, $E_{TV}$, $R_{TV}$, $U_{TV}$, $N_{PTV}$, $ROI_{TV}$. It is appropriate, until more is known, to assign a high numerical value to these targets (in effect seeking to maximize aspiration). It is recommended that as more is known these targets are assigned realistic and appropriate values.

The development of the mathematical form of the compromise DSP template and its solution are presented in Chapters 4 and 5, respectively. The insight gained by solving the template formulation posed in this chapter is included in Chapter 6.

## 2.6 OUR WORK IN THE CONTEXT OF AIRCRAFT DESIGN

We are amateurs in aircraft design and it is therefore not our intention to imply that aircraft design is being done or should be done in the way described in this chapter. Our strength is in developing the approaches and software that supports human judgment in decision making. We are therefore confident that the use of the selection and compromise DSPs in aircraft design and the management of design, after further development, will be efficacious. The status of our current activities in discipline-independent decision making is summarized in [19].

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[1] Two empirical weight estimation routines have been used. Both give different results. Lacking experience as to which routine is better we decided to use both routines by introducing a "weight-matiching" goal. The goal reflects our desire that the design is one that minimizes the difference in the weight estimate using the two routines.

# CHAPTER 3
## THE SELECTION DECISION SUPPORT PROBLEMS

Selection occurs in all stages of design. In the early stages there is almost no hard data; most of the data is soft. As the design process progresses the amount of hard data available increases. The principal distinction between selection in the stages is the ratio between the amount of hard and soft information that is available.

A preliminary selection Decision Support Problem is formulated and solved when the amount of experience-based soft information far exceeds the amount of hard information available. A selection decision support problem is formulated and solved when meaningful hard information is available. In this report we describe selection decision support problems in the context of conceptual design of aircraft.

In the conceptual design stage, selection occurs in two major phases, namely,

**Phase 1** - the identification of potentially superior concepts based primarily on qualitative rather than quantitative information, and
**Phase 2** - the identification, using insight-based 'soft' and science-based 'hard' information, of a very limited number of superior alternatives that should be developed further.

In Chapter 2 an idealized view of the process of design in the conceptual phase and the role and structure of the two types of selection DSPs is presented. In this chapter a practical approach to design, based on the concept of selection, is presented. A reader is advised to focus on the process described rather than the technical details of the example.

## 3.1 SELECTION IN CONCEPTUAL DESIGN

In the conceptual design stage selection occurs in two major phases, namely,

phase 1 - the identification of potentially superior concepts based primarily on qualitative rather than quantitative information, and
phase 2 - the identification, using insight-based 'soft' and science-based 'hard' information, of a very limited number of superior alternatives that should be developed further.

A preliminary selection DSP is formulated and solved in Phase 1 whereas a selection DSP is formulated and solved in Phase 2. **Preliminary selection** involves the selection of the "top-of-the-heap" concepts for further development into feasible alternatives. **Selection** involves the ranking, based on multiple attributes, of the feasible alternatives in order of preference. The role of these two types of selection in conceptual design and the terminology associated with each are described in Section 2.3.

The selection Decision Support Problems (DSPs) were described in Chapter 2. The methods for formulating and solving both the preliminary selection and selection Decision Support Problems are presented in this chapter. An overview of the process and the steps involved in formulating and solving the two types of DSPs is presented in Figure 3.1. The process itself is described in Sections 3.2.1 and 3.3.1, respectively. To facilitate understanding of the underlying principles the procedures are explained as if a person was doing the work by hand using pencil and paper. An aircraft design problem presented in [10] is used by way of example. The technical details to support our use of the problems are taken from books on aircraft design [12,23,47,64]. We are novices when it comes to aircraft design; the reader is therefore advised to focus on the method of selection rather than the technical details of the example. These examples are presented in Sections 3.2.2 and 3.3.2 A summary of the steps involved in formulating the selection DSPs is presented in Appendix A and information on creating scales in Appendix B. The software for solving both types of selection DSPs has been implemented in BASIC for an Apple Macintosh. This software is called MacDSIDES. Information on using the MacDSIDES is presented in reference[34,35].

## 3.2 PHASE 1 - THE PRELIMINARY SELECTION DECISION SUPPORT PROBLEM

The role and structure of the preliminary selection DSP is given in Chapter 2, Section 2.3. The method of Pugh [48] forms the basis of the algorithm developed for solving the preliminary selection DSP. In this section, the formulation and solution is described and this is followed by an example. A summary of the steps and important points of the process is presented in Appendix A.1.

### 3.2.1 Preliminary Selection - Formulation and Solution

In Phase 1, some choices are made that narrow the field of contending design concepts down to a few "top-of-the-heap" concepts. These choices are made

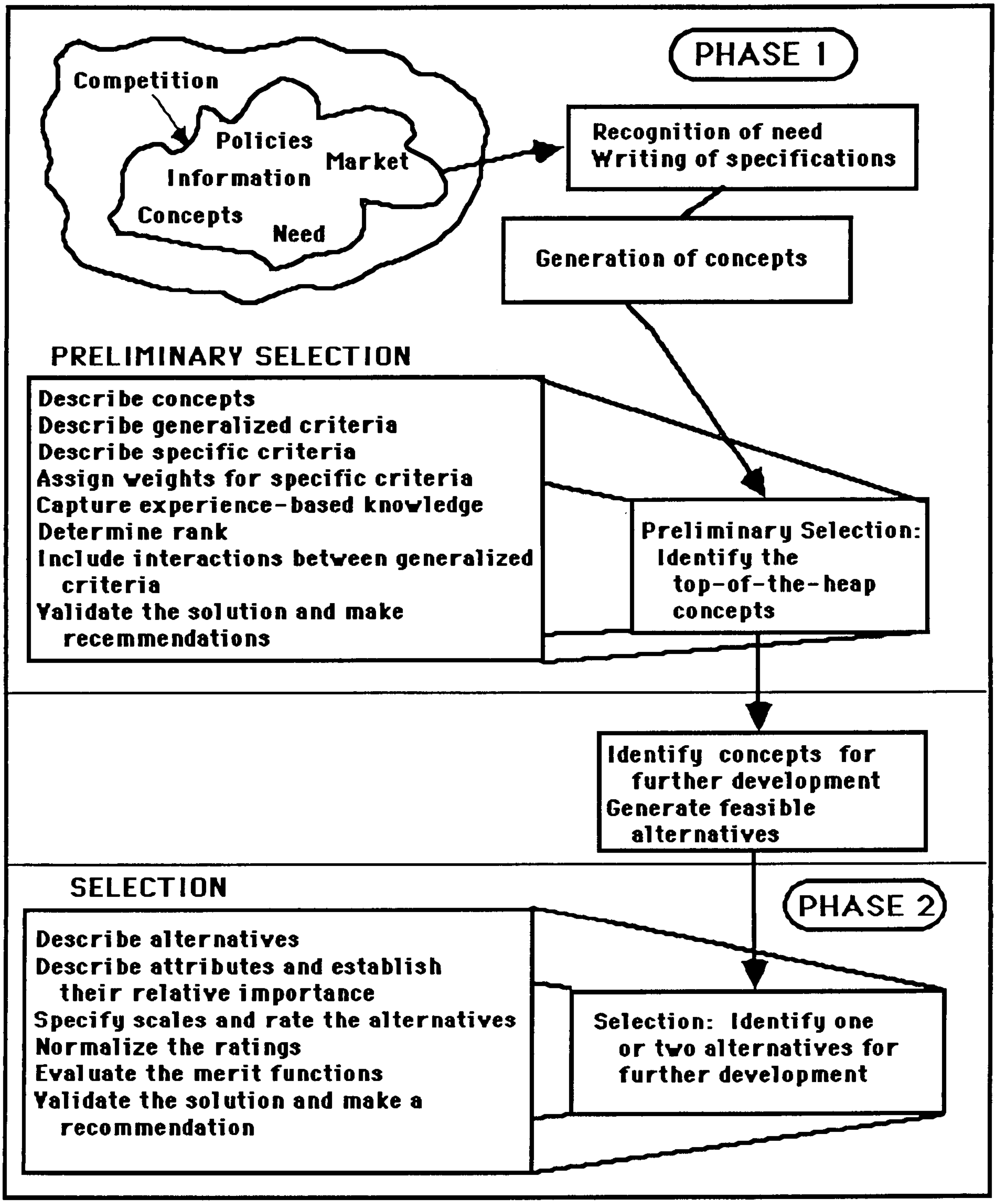



FIGURE 3.1 -- SCHEMATIC OF THE SELECTION PROCESS

against a set of criteria, specified by the designer, as to the preferred performance of the design. This process is shown schematically in Figure 3.1.

The recognition of need is the basis for initiating the design process. The need may arise owing to policy decisions or functional requirements. The need may be for the design of a system or a subsidiary part of a system. Before a detailed design of a concept is performed, it is necessary to generate many concepts so as not to overlook the deficiencies or merits of a particular alternative. A systematic approach for structuring creative thought to generate alternatives is necessary. Such an approach avoids possible confusion caused by the vast amount of information that may be generated. These approaches are well documented in [2,3,14,45]. Allen [2] deals with idea generation (conceptual block busting). The book is excellent. Wales [65] provides a believable practical approach for recognizing need and arriving at an initial definition of the problem. The approach we follow in the DSP Technique is presented in [38, Unit 2].

Let us assume that the competing concepts are known and information about them are available. Let us also assume that most of this information is soft. In design, the following steps serve as a set of guidelines to aid the design team identify a set of feasible alternatives. If the concepts are submitted by different companies for evaluation, the same procedure will facilitate the identification of the top-of-the-heap concepts and just possibly the selection of the superior one. A seven-step procedure to accomplish these tasks is presented. In Figure 3.2 schematic of the seven steps is presented.

**Step 1 Describe the concepts and provide acronyms.** Draw sketches of the embryonic concepts for the problem. Concepts should be presented in the form of sketches for easy understanding. The complexity for each of these sketches should be maintained at the same level so as not to bias one concept in favor of another. Describe each concept in words, set forth the advantages and disadvantages of each concept and provide meaningful acronyms (something more meaningful than concept 1, concept 2, etc.).

**Step 2 Describe each generalized criterion and provide acronyms and specify the relative importance of the specific criteria.** The criteria usually emerge from the needs defined in the problem statement. For each generalized criterion describe the specific criteria and provide acronyms. For example, a generalized criterion called "Cost of Product" could be qualified in terms of the specific criteria that measure design cost, material cost, maintenance cost, etc.

A criterion represents a quality of the desired solution and this quality must be quantifiable. The relative importance of the criteria should not be considered when identifying the criteria. A criterion that is not taken into consideration in this step will have no affect on the selection process. The selection process could thus yield an alternative which will perform well in all aspects save that of the ignored criterion. Therefore, the set of criteria defined must be comprehensive, understandable, unambiguous and serve the needs of the design. The criteria should be independent of each other and each should measure a single quality of the concepts.

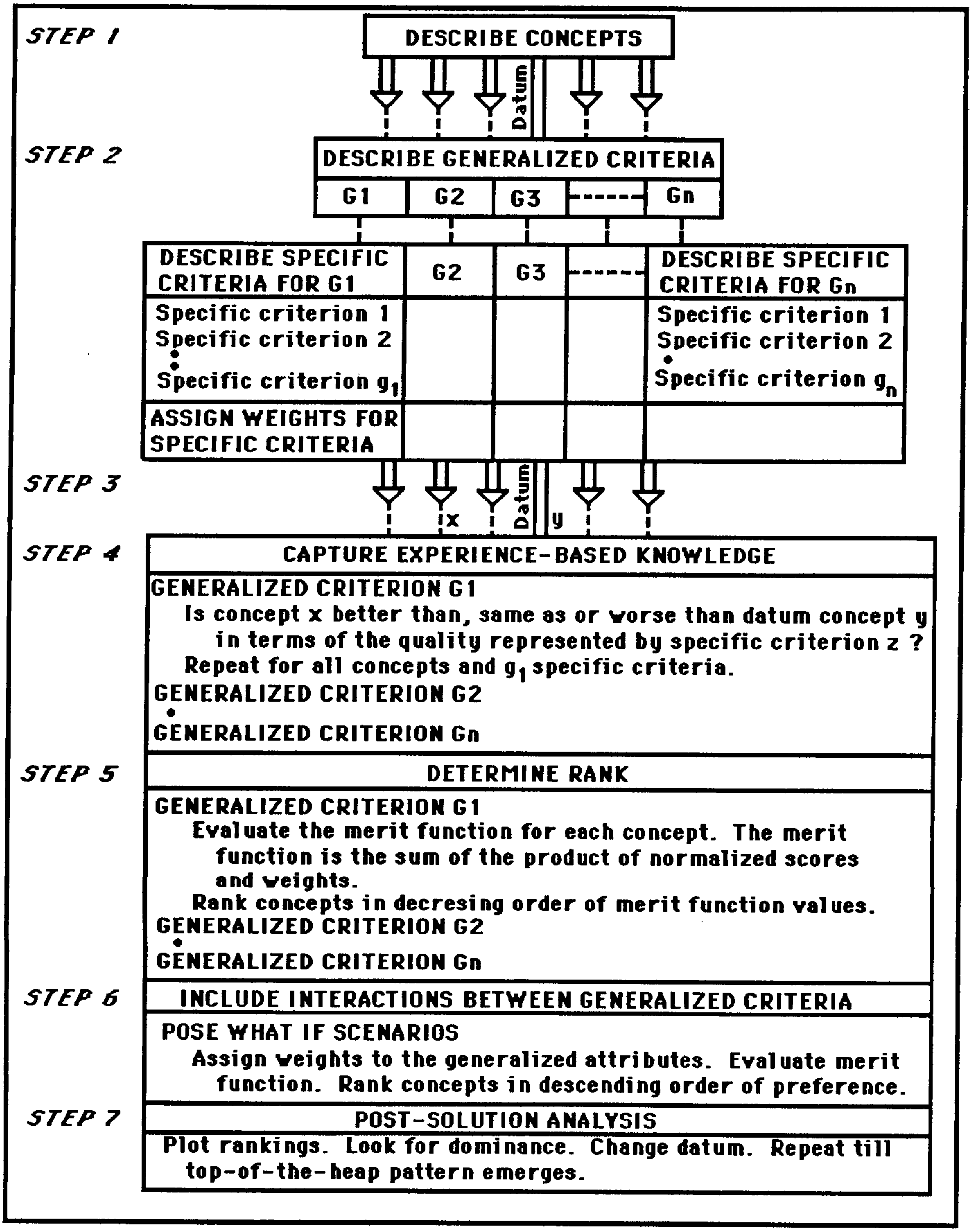



FIGURE 3.2 -- STEPS IN PRELIMINARY SELECTION

Rank the specific criteria, associated with each generalized criterion, in order of importance (see Appendix B). Determine the normalized weighting constant that reflects the relative importance of each specific criterion within its generalized criterion.

Step 3 **Choose a datum with which all other concepts will be compared.** A design that is favored to win is an appropriate initial choice.

Step 4 **Capture experience-based knowledge through comparison of concepts.** For each generalized criterion answer the following question:

With respect to specific criterion z, is concept x better than, same as, worse than the datum concept y? Enter a score: +1, 0 or -1 for a better than, same as and worse than answer, respectively.

Step 5 **Evaluate the merit function for each concept within each generalized criterion and determine rank.** Multiply each entry (step 3) by the corresponding weight (step 2) to obtain a score. For each concept add these scores and normalize to obtain the merit function value for the concept. Order the concepts in decreasing order of normalized merit function values. This order represents the quality of each of the concepts with respect to each generalized criterion.

It is recommended that an initial run be made with the assumption that all the generalized criteria are equally important. If these results are counter-intuitive runs with other datums are appropriate. Using other datums as a matter of course is likely to eliminate bias from the comparisons. This, however, becomes extremely time consuming.

Step 6 **Include interactions between generalized criteria and compute the overall merit and determine overall rank.** Based on the perception of the future pose 'what if' scenarios: optimistic, pessimistic, realistic, etc. Assume that a larger number indicates preference. Determine the weights, to be associated with each generalized criterion, that are representative for each scenario. The weights must sum to 1. Multiply the normalized merit function values by the corresponding weight. Sum and normalize to get the overall merit function value for each concept. Order the concepts with respect to these merit function values.

Step 7 **Post-solution analysis: Determine the top-of-the-heap concepts.** Plot the overall merit function values for each concept. Plot the scenario number on the x-axis and the normalized merit function value on the y-axis. Analyze the plot. Look for dominance. Determine whether any of the concepts can be discarded. Determine another datum. Repeat steps 4 through 7. Stop when you see a top-of-the-heap pattern emerge.

This seven-step procedure yields a set of potentially superior concepts. These concepts are refined and turned into feasible alternatives. These alternatives are used as input for the selection DSP. A program has been developed by the Systems Design Group on the Apple Macintosh that proceeds from Step 3 (selection of a datum) to Step 7, yielding a set of superior concepts to be used in Phase 2. The user manual is included in references [35,36].

### 3.2.2 An Example to Illustrate the Preliminary Selection of Concepts

The problem statement for the preliminary selection DSP is presented in Section 2.3.5. The problem has been taken from reference [10] and we have developed the problem using information from [10,23,47,64].

Aircraft design is extremely complex and time intensive. In what follows we present an extremely brief summary of the steps - to highlight some aspects of the method. Major considerations have been omitted or glossed over. In practice a significant amount of effort will need to be invested in a project of this type and there would invariably be a substantial report that is generated.

**Step 1 Describe the concepts and provide acronyms**
Assume that a number of concepts were generated. Further, assume that after careful scrutiny it was decided to restrict the choice to eight. Rough sketches of these embryonic concepts have been drawn and specific details are maintained at the same level of complexity for all the concepts. These sketches are presented in Figures 3.3A and B The descriptions of the eight concepts follow:

**TWTE** (Tandem Wing, Tandem Engine) - This concept features two tandem fan engines located on either side of the fuselage for a total of four engines. These engines also provide lift by a type of vector thrust. The wing layout is a pair of tandem wings which combine to make for a small easily parked craft.
**CWTN** (Conventional Wing, Tilt Nacelle) - Here, a conventional wing is paired with two cruise turbo jets and two lift/cruise turbo fans.
**CWLE** (Conventional Wing, Lift Engines) - This concept relies on 4 stowable lift turbo fans for takeoff and landing, and two jets for cruising slung underneath the conventional wings.
**CNAW** (Canard Augmentor Wing) - Two turbo fans are placed at the rear of a canard wing configuration. The exhaust of the fans is blown over the rear wing to augment its lift.
**HELI** (Helicopter) - This concept is a conventional helicopter, with gas turbine engines.
**TWLE** (Tandem Wing, Lift Engine) - The small overall area of the tandem wings is combined with one lift engine and two tilt nacelles.
**TTVT** (Twin Tail, Vector Thrust) - A twin tail design with fuselage pod and clamshell doors provides easy cargo access. Two vector thrust engines provide lift and cruise thrust.
**CWAW** (Conventional Augmentor Wing) - A conventional transport layout is provided with augmentor wing technology for V/STOL capability via two engines mounted on the conventional wing.

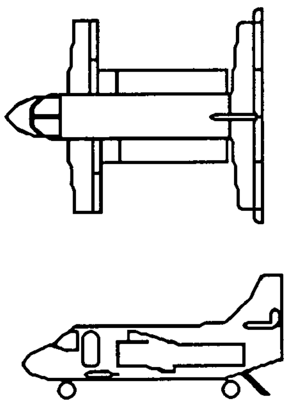


FIGURE A -- TANDEM WING,F TANDEM ENGINE (TWTE)

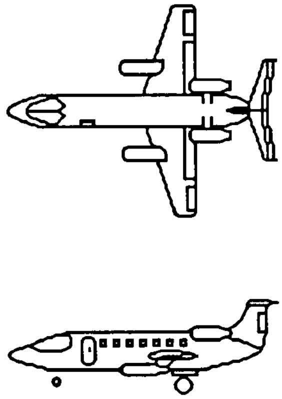


FIGURE B -- CONVENTIONAL WING, TILT NACELLE (CWTN)

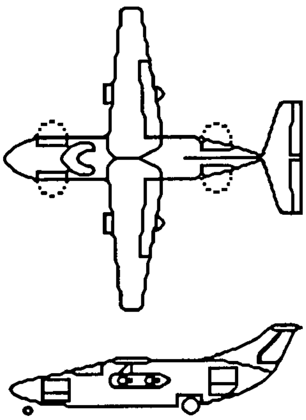


FIGURE C -- CONVENTIONAL WING, LIFT ENGINE (CWLE)

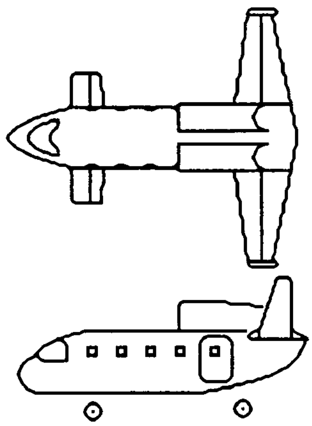


FIGURE D -- CANARD AUGMENTOR WING (CNAW)

FIGURE 3.3a -- V/STOL AIRCRAFT CONCEPTS

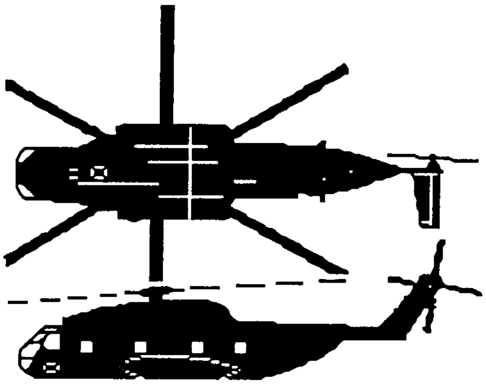


FIGURE E -- HELICOPTER (HELI)

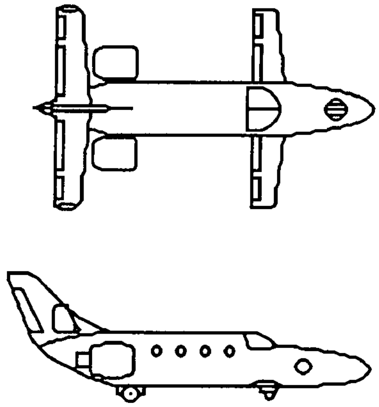


FIGURE F -- TANDEM WING, LIFT ENGINE (TWLE)

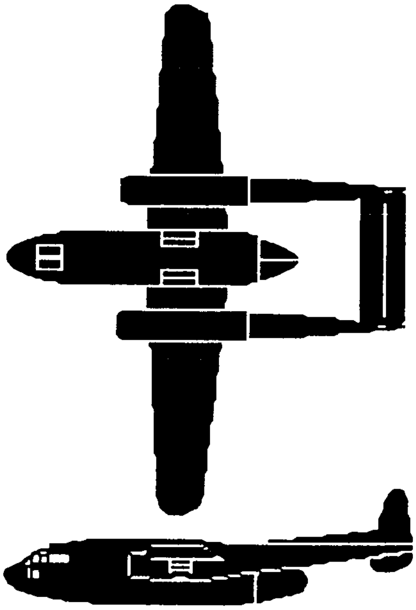


FIGURE G -- TWIN TAIL, VECTOR THRUST (TTVT)

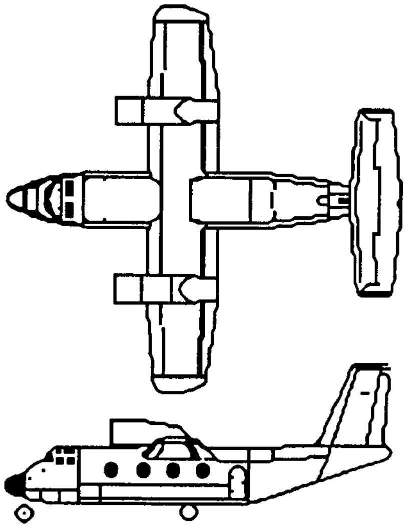


FIGURE H -- CONVENTIONAL AUGMENTOR WING (CWAW)

FIGURE 3.3b -- V/STOL AIRCRAFT CONCEPTS

**Step 2 Describe each generalized criterion, provide acronyms and weighting constants for the specific criteria.** Since this design is for a commercial aircraft the following generalized criteria have been identified: safety, performance, economics and market potential. The specific criteria for each of the generalized criteria are shown in Table 3.1. The attribute listing technique [38,Unit 2] was used to create the specific criteria for this project. For this illustrative example descriptive titles for each of the specific criteria have been used instead of acronyms. For the initial iteration it is assumed that all the specific criteria are equally important. For brevity, the description of the attributes has been combined with the the viewpoint and is presented in Step 4.

**Step 3 Choose a datum with which all other concepts will be compared.** Concept number 1, TWTE (tandem wing - tandem engine) is chosen as the initial datum. There is no special reason for choosing one concept over another as the initial datum in this example. However, in applying the preliminary selection method one might pick as the initial datum either the concept one perceives the most likely to succeed or the most controversial concept or the concept most like an existing design.

**Step 4 Compare the concepts.** The end result of the comparison of each of the concepts with the datum are summarized in Table 3.1. It is necessary to record the underlying reasons for the decisions. This is extremely important. In practice, this task requires a lot of gathering of information, discussion and involves considerable time and effort. In the summary that follows more detail is provided for the first generalized.criterion (by way of illustration) than the others. In practice, the level of detail that is provided must be the same for all cases.

<u>Generalized Criterion: Safety</u>

**Engine out safety in STOL.** Does the design have a backup in case of a single engine failing in short takeoff and landing? The datum has equivalent safety to the other concepts except CNAW and CWAW which might have problems due to the augmentor wing engine mounting. Hence, a '0' is assigned for all concepts except CNAW and CWAW which have been assigned a -1.

**Engine out safety in VTOL.** Does the design have a backup in case of a single engine failing in vertical takeoff and landing? The datum concept has 4 engines. Most of the other concepts have only two engines. The CWLE concept, which has several lifting engines is equivalent to the datum. Hence a -1 is assigned for all concepts except CWLE which is equivalent to the datum and is hence assigned a '0'.

**Simplicity of design.** Is the design concept simple in terms of mechanicals? The CNAW, helicopter, the TTVT and the CWAW have the same complexity of mechanicals as the datum. The others are more complex.

**Reliability.** Here reliability is based on the fewest things that can go wrong. This includes number of engines and the use of tried technology. Thus, CNAW and TTVT are rated more reliable since they have few engines and less complex lift mechanisms. Also, vector thrust has been proven on the Harrier fighter aircraft.

| | TWTE | CWTN | CWLE | CNAW | HELI | TWLE | TTVT | CWAW |
|---|---|---|---|---|---|---|---|---|
| **SAFETY** | | | | | | | | |
| Engine out safety in STOL | 0 | 0 | 0 | - | 0 | 0 | 0 | - |
| Engine out safety in VTOL | 0 | - | 0 | - | - | - | - | - |
| Simplicity of mechanicals | 0 | - | - | 0 | 0 | - | 0 | 0 |
| Reliability | 0 | - | - | + | 0 | - | + | - |
| Score | 0 | -3 | -2 | -1 | -1 | -3 | 0 | -3 |
| Normalized score | 1 | 0 | 0.33 | 0.67 | 0.67 | 0 | 1 | 0 |
| **PERFORMANCE** | | | | | | | | |
| Range versus Payload | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 |
| Ground effects | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Achieveability of minimum cruise speed | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 |
| Achieveability of stability | 0 | + | + | 0 | - | 0 | + | + |
| Score | 0 | +1 | +1 | 0 | -3 | 0 | +1 | +1 |
| Normalized score | 0.75 | 1 | 1 | 0.75 | 0 | 0.75 | 1 | 1 |
| **ECONOMICS** | | | | | | | | |
| Cost | 0 | 0 | - | + | + | + | + | 0 |
| Power matching | 0 | 0 | + | + | + | 0 | + | + |
| Technology Utilization | 0 | + | + | 0 | + | + | + | 0 |
| Score | 0 | +1 | +1 | +2 | +3 | +2 | +3 | +1 |
| Normalized score | 0 | 0.33 | 0.33 | 0.67 | 1 | 0.67 | 1 | 0.33 |
| **MARKET POTENTIAL** | | | | | | | | |
| Cargo accessibility | 0 | - | - | - | 0 | - | + | + |
| Passenger comfort | 0 | - | - | 0 | - | 0 | 0 | 0 |
| Landing surface restrictions | 0 | 0 | 0 | + | + | 0 | 0 | + |
| Parking space | 0 | - | - | - | 0 | 0 | - | - |
| Noise | 0 | 0 | + | 0 | - | 0 | + | 0 |
| Score | 0 | -3 | -2 | -1 | -1 | -1 | +1 | +1 |
| Normalized score | 0.75 | 0 | 0.25 | 0.5 | 0.5 | 0.5 | 1 | 1 |
| **OVERALL SCORES AND RANKS** | | | | | | | | |
| **Sum of Scores** | 2.50 | 1.33 | 1.91 | 2.59 | 2.17 | 1.92 | 4.0 | 2.66 |
| **Ranks** | 4 | 8 | 7 | 3 | 5 | 6 | 1 | 2 |

(Column group heading: CONCEPTS)

Legend: A '-' implies '-1' and a '+' implies '+1'

**TABLE 3.1 -- PRELIMINARY SELECTION: SCORES AND RANKS**

<u>Generalized Criterion: Performance.</u>

**Range versus payload.** Can the design be expected to meet the range and payload specifications?

**Ground effects.** Will the design have undesirable ground effects in V/STOL?

**Cruise speed.** Can the design be expected to meet the minimum cruising speed specification?

**Achieveability of stability.** Will the design require less work to achieve stability?

<u>Generalized Criterion: Economics.</u>

**Cost.** This includes design, construction and maintenance costs. The simpler and more conventional designs are favored here.

**Power matching.** Will the engine combination in the design concept allow for simple power matching between VTOL and level flight?

**Technology utilization.** Does the concept employ VTOL technology that has been proven?

<u>Generalized Criterion: Market Potential</u>

**Cargo accessibility.** Does the concept allow for easy access for loading and unloading cargo.

**Passenger comfort.** How comfortable for passengers can the design concept expect to be?

**Landing restriction.** Is the design concept capable of landing at hardened and non-hardened landing sites?

**Parking space.** Will the concept require a minimum of parking space?

**Noise.** Will the design concept generate less noise in takeoff and landing than the other concepts?

**Step 5 Evaluate the merit function for each concept within each generalized criterion.** The "Score" and the "Normalized Score" (i.e., the merit function value) for each of of the concepts with respect to the four generalized criteria are computed and are shown in Table 3.1. In this case, the scores are normalized using equation 3.1. Any reasonable normalization scheme could have been used. Based on the normalized scores the rank of each of the aircraft, on the basis of a particular generalized criterion, can be ascertained.

**Step 6 Include interactions between generalized criteria.** Equal weights were assigned for each of the generalized criteria and the 'Sum of Scores' and 'Ranks' are also shown in Table 3.1. On this basis, the four best concepts are the TTVT, CWAW, CNAW and TWTE concepts. In this case, since the TTVT concept received the highest overall rank it would be appropriate to use it as the next datum. The results shown in Table 3.3 and Figure 3.4 are after using the two datums and it will therefore not be possible for the reader to establish the correspondence between the information presented in Table 3.1 and the results in Table 3.3.

Five scenarios for the relative importance of generalized criteria were created. In the first four each of the generalized criterion in turn is made to dominate the other criteria. The fifth scenario represents our best estimate of the relative importance of the generalized criteria. The scenarios and normalized total scores are shown in

Tables 3.2 and 3.3 respectively. The overall values of the merit function are plotted in Figure 3.4.

**Step 7 Post-solution analysis: determine the top-of-the-heap concepts.** In Table 3.3 the top three concepts for each of the scenarios are shown in bold. It is seen that the Twin Tail Vector Thrust (TTVT, Figure 2.3G) "the winner" in all the scenarios. It is premature, however, to declare it the winner because only soft experience-based insight was used in preliminary selection. It is important that the top-of-the-heap concepts be identified and the selection DSP is formulated and solved.

| Generalized Criterion | Scenario Number | | | | |
|---|---|---|---|---|---|
| | One | Two | Three | Four | Five |
| Safety | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 |
| Performance | 0.2 | 0.4 | 0.2 | 0.2 | 0.3 |
| Economics | 0.2 | 0.2 | 0.4 | 0.2 | 0.2 |
| Market Potential | 0.2 | 0.2 | 0.2 | 0.4 | 0.3 |

**TABLE 3.2 -- SCENARIOS FOR THE RELATIVE IMPORTANCE OF GENERALIZED CRITERIA**

| Concept | | Scenario Number | | | | |
|---|---|---|---|---|---|---|
| No. | Name | One | Two | Three | Four | Five |
| 1 | TWTE | **0.680** | 0.610 | 0.480 | **0.630** | 0.620 |
| 2 | CWTN | 0.187 | 0.307 | 0.253 | 0.187 | 0.247 |
| 3 | CWLE | 0.397 | 0.420 | 0.414 | 0.370 | 0.395 |
| 4 | CNAW | **0.629** | **0.636** | **0.640** | 0.626 | **0.631** |
| 5 | HELI | 0.566 | 0.443 | **0.643** | 0.563 | 0.503 |
| 6 | TWLE | 0.383 | 0.513 | 0.517 | 0.503 | 0.508 |
| 7 | TTVT | **0.980** | **0.960** | **0.980** | **0.980** | **0.970** |

**TABLE 3.3 -- PRELIMINARY SELECTION: NORMALIZED OVERALL SCORES**

It is seen, from Table 3.3, that the TTVT, CWAW and CNAW concepts do consistently well, placing in the top four, while the TWTE places in the top four in four out of five scenarios. The CWTN and CWLE concepts score low consistently. The HELI concept does well in some scenarios (notably, Scenario Three, where cost is most important) but since it it is very difficult to build helicopters that will cruise at the minimum required speed it will not be considered further. The TWLE concept falls below the HELI concept and so will also not be considered further.

By looking at the numbers shown in bold in Table 3.3 it may appear that TTVT, CWAW and CNAW are the top-of-the-heap concepts for Phase 2 of the selection process. From Figure 3.4, it is seen that TWTE is in the running with CWAW and CNAW. It is also clear from the figure that TWTE performs badly when the generalized criterion economics dominates. We have therefore decided to use four top-of-the-heap concepts, namely, TTVT (twin tail, vector thrust), CWAW (conventional augmentor wing), CNAW (canard augmentor wing), TWTE (tandem wing, tandem engine)].

In practice, at this stage, some engineering work should be undertaken to develop more information and ensure that the four top-of-the-heap concepts are indeed feasible. We will, for the purpose of illustration, assume that this has been done and the four concepts go into Phase 2 as feasible alternatives.

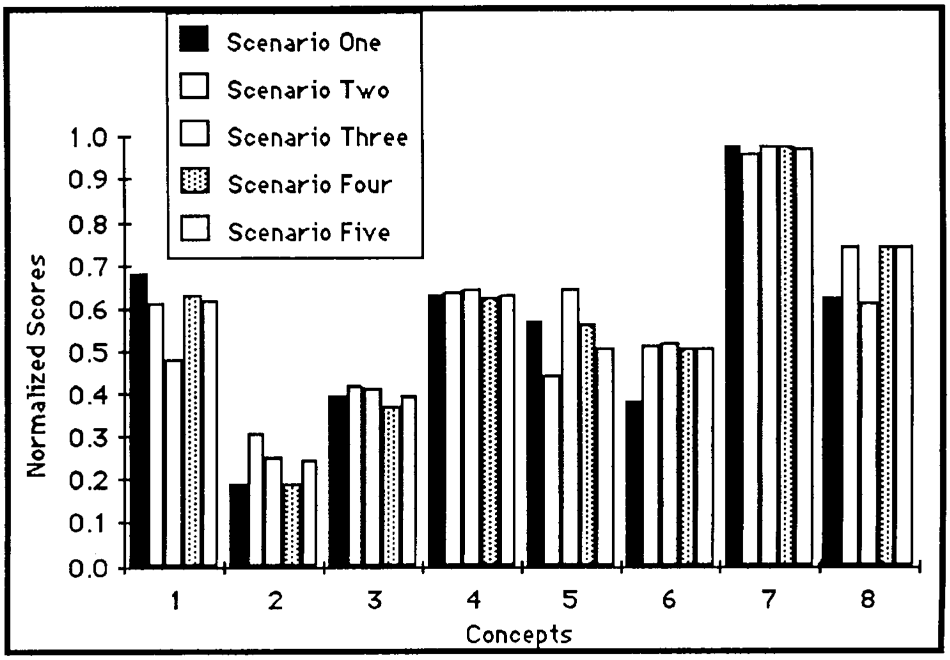



**FIGURE 3.4 -- PRELIMINARY SELECTION: GRAPHICAL REPRESENTATION OF THE SCORES**

## 3.3 PHASE 2 - THE SELECTION DECISION SUPPORT PROBLEM

The selection DSP facilitates the ranking of alternatives based on multiple attributes of varying importance. The order indicates not only the rank but also by how much one alternative is preferred to another. In the selection DSP both science-based "hard" information and experience-based "soft" information can be used. The structure of the selection DSPs is given in Section 2.3.4. The steps associated with the selection DSP are explained in Section 3.3.1. An example based on the top-of-the-heap concepts identified in Section 3.2.2 is presented in Section 3.3.2. The aircraft example is for illustrative purposes only. The process is illustrated in Figure 3.1 and a summary of cogent points associated with the formulation and solution process is given in Appendix A.2.

### 3.3.1 Selection - Formulation and Solution

**Step 1 Describe the alternatives and provide acronyms.** Assume that a number of concepts have been generated and these have been narrowed down in Phase 1 that is described in the preceding section. Assume that the concepts have been developed into alternatives. Provide drawings of the alternatives. The complexity for each of these drawings should be maintained at the same level so as not to bias one alternative in favor of another. Describe each alternative in words, set forth the advantages and disadvantages of each and provide meaningful acronyms (something more meaningful than alternative 1, alternative 2, etc.).

**Step 2 Describe each attribute, specify the relative importance of the attributes and provide acronyms.** Since the alternatives are known, the next step in solving the selection DSP is the identification of attributes by which the alternatives are to be judged. These attributes will vary from one problem to another depending on the needs of each problem. The attributes usually involve a refinement of the criteria used in preliminary selection. An attribute represents a quality of the desired solution and this quality must be quantifiable. The relative importance of attributes are not considered in this time. The designer should be careful about ignoring a relevant attribute regardless of its relative importance compared to other attributes. An attribute which is not taken into consideration in this step will have no affect on the selection process. The selection process could thus yield an alternative which will perform well in all aspects save that of the ignored attribute. Therefore, the set of attributes defined must be comprehensive, understandable, unambiguous and serve the needs of the design.

There are two ways of determining the relative importance, $I_j$, of the attributes, namely, the ranking method and the method of comparison. Both are described in detail in Appendix B, Section B.3. The method of comparison involves much more effort. Therefore, in the very early stages of the design process (or when the quality and amount of information do not warrant the extra effort) the use of the ranking method is recommended.

**Step 3 Specify scales, rate the alternatives with respect to each attribute and normalize.** There are four types of scales, namely, ratio, interval, ordinal [50] and composite. The choice of a particular type of scale to model an attribute depends on the nature of available information. The ratio scale is used for an attribute for which physically meaningful numbers are available, e.g., cost, power, speed, etc. The ordinal scale is used to model an attribute that can only be qualified in words. An ordinal scale is appropriate for attributes like aesthetic appeal, color, etc. The interval scale is used in two ways. Firstly, it is used to model attributes in which the zero is relative, e.g., temperature, efficiency, etc. Secondly, it is used to transform the quality captured by the ordinal word scale into a numerical interval scale. The composite scale is used for a generalized attribute that is generated as the result of computations. The results could come from a relative importance analysis, a subordinate selection problem or other analytical means.

The ratio scale is used to quantify attributes for which physically meaningful numbers are available, e.g., length, mass, cost, power, speed, etc. A ratio scale is used to measure physical quantities. The numbers used in a ratio scale are generally science-based, computable or measurable and are therefore categorized as "hard" information. It is important that the ratio scales are established independently of the set of alternatives being considered. It is necessary to specify the upper ($A_j^{max}$ for the $j^{th}$ attribute) and lower ($A_j^{min}$ ) bounds for the ratio scale and indicate whether a larger or smaller number indicates preference. Specification of the upper and lower bounds for the ratio scale is imperative. The bounds should indicate the most desirable outcome and the minimum outcome that is acceptable. The bounds should be specified after very careful consideration. For attributes on the ratio scale the measured or computed number associated with each alternative becomes its rating.

Interval scales are created for attributes for which only qualitative or "soft" information is available. Safety, reliability, complexity, simplicity are some examples of attributes measured on an interval scale. The creation of interval scales is justified when a designer is able to rank-order preference for a particular alternative with respect to a particular attribute. If a designer is unable to indicate (even qualitatively) by how much a particular alternative is preferred over another then the ranking method (Appendix B, Section B.3.1) for creating the interval scale is recommended. If a designer is able to express some degree of preference between the alternatives then the method of comparison should be used to create the scales (see Appendix B, Section B.3.2 and B.3.3). If a designer is able to clearly articulate a definite and measurable degree of preference then a scale together with the associated ratings may be specified (see Section 3.3.2, Step 3). It is pointed that this option must be exercised with great care. The upper and lower bounds on the interval scale correspond to the maximum possible outcome and the lowest acceptable outcome. The interval scale and bounds provide a means for quantifying different levels of aspiration a designer has for the design. The scale, therefore, should be established independently of the alternatives being considered.

Once the ordinal and interval scales are established, the rating, $A_{ij}$, of alternative 'i' with respect to the attribute 'j' begins. For attributes on the ratio scale the measured or computed number associated with each alternative becomes its rating. For an attribute on an interval scale a rating needs to be assigned and justified. The justification of each rating is extremely important and the set of justifications is called a 'viewpoint'.

Ratio scales are seldom converted to interval scales. Ordinal scales must be converted to interval scales to be used in the solution process.

**Step 4 Normalize the ratings.** The attribute ratings, $A_{ij,}$ are on scales that are not uniform. For example, for some attributes a larger rating would indicate a preference whereas for others a lower rating would indicate preference. Further, it is unlikely that the upper and lower bounds on the scales are the same. Hence, it is necessary to convert the attribute ratings to scales that are uniform. This is achieved by converting the attribute rating, $A_{ij}$, to a normalized rating, $R_{ij}$. The normalized scales range from 0 to 1 with a higher number indicating a preference.

There are different ways to effect normalization. One way for normalizing an attribute rating for alternative 'i' with respect to attribute 'j' is :

$$R_{ij} = \frac{A_{ij} - A_j^{min}}{A_j^{max} - A_j^{min}} \tag{3.1}$$

where $A_j^{min}$ and $A_j^{max}$ in both formulae represent the lowest and highest possible values of the alternative rating $A_{ij}$.

The preceding formulation is for the case where the larger value of an attribute rating represents preference. If a smaller value of an attribute rating represents preference, the normalized rating, $R_{ij,}$ is defined as

$$R_{ij} = 1 - \frac{A_{ij} - A_j^{min}}{A_j^{max} - A_j^{min}} \tag{3.2}$$

In cases where the normalized ratings for all the alternatives turn out to be the same, that attribute may be dropped from further consideration.

**Step 5 Evaluate the merit function for each alternative.** A merit function combines all the individual ratings of attributes together using proper weights defined in step 1. There are several methods for modeling the merit function (see Table 3.4).

The most frequently used model, however, is the linear model

$$MF_i = \sum_{j=1}^{n} I_j R_{ij} \quad i = 1, \ldots, m \tag{3.3}$$

where
m = number of alternatives
n = number of attributes
$I_j$ = relative importance of jth attribute
$R_{ij}$ = rating of alternative i for the attribute j
$MF_i$ = value of merit function for alternative i

| Model | Type | Comment |
|---|---|---|
| 1 | Linear Additive $MF_i = \sum_j I_j R_{ij}$ | All values are treated similarly. |
| 2 | Higher Order Additive $MF_i = \sum_j I_j \lvert\log(R_{ij})\rvert$ | Weights the smaller merit functions' contributions more than those of the larger ones. |
| 3 | Product $MF_i = \prod_j I_j R_{ij}$ | The product may result in errors for zero values of either $I_j$ or $R_{ij}$. |

TABLE 3.4 -- MODELS FOR MERIT FUNCTION

In most applications, it is better to start with a linear model. When the cost and time spent in developing and implementing more complex methods are taken into account, it may be that the greater sophistication will not be justified. For most practical purposes, the linear model should be sufficient [39].

**Step 6 Post-solution sensitivity analysis.** Post-solution analysis of the selection DSP consists of two types of activities, namely, validation of the solution and sensitivity analysis which includes both sensitivity of the solution to changes in the attribute weights and sensitivity of the solution to changes in the attribute ratings. These activities are very important because of the nature and quality (hard or soft) of the information being used.

### Validation

Having ranked all the alternatives in order of decreasing merit function values, the designer is able to identify the best and some of the better alternatives. In general, when the number of alternatives is fairly large the rankings will naturally divide alternatives into several groups of alternatives for which the merit function values are comparable. Alternatives in the same group usually have some characteristics in common. These characteristics should be examined and, if they are desirable, should be included as additional attributes for the selection. This is to assure that no important attribute is left out as a result of which some alternatives are ranked lower than they should have been. Also, a re-examination of the relative weights, attribute ratings and the numerical calculations is necessary to ensure that no biased judgments of numerical errors occur in any step. Validation of the solution is very important especially when the highest ranked alternative is unexpected.

### Sensitivity analysis

In applications where the number of alternatives is large, it is very likely that the values of the merit functions of the top two or three alternatives are almost equal. In such cases it is necessary that a sensitivity analysis be performed. Therefore, the sensitivity analysis consists of determining the effect on the solution of small changes in the relative importances of attributes and also to changes in the attribute ratings.

**Sensitivity to changes in the attribute importances.** During the selection process, the weights for the attributes are derived using judgment which entirely depends on the experience, knowledge and preference of each individual. For this reason, the sensitivity to the change in the relative weights of attributes needs to be performed. This can be done by re-examining and changing the relative importance of the attributes in (see Table B.1 for example) or changing the preferences within a comparison (see Tables B.2 and B.3 by way of example) and determining the effect of that change on the merit function. The top ranked alternative which is not affected by small changes in the weights of attributes is the best alternative and should be selected. When the ranking is altered by the changes in the weights of attributes, a decision may be made to perform the sensitivity analysis of the attribute ratings or the designer may consider including other attributes and then resolve the selection DSP.

**Sensitivity to the changes in the attribute ratings.** As stated before, the ratings may be derived subjectively or directly from the available quantitative information. In the former case, it is possible that errors in ratings occur. Hence, the sensitivity of the solution to changes in attribute ratings needs to be found. This can be done by studying the change in the merit function value effected by changes in the attribute ratings (e.g. ± 5%).

Consider a change of $\pm\delta$ in the rating $R_{ij}$ in attribute j of alternative i. The change in the merit function of that alternative will be

$$\delta\, MF_i = \pm\, \delta\, I_j\, R_{ij}.$$

The new merit function will be

$$MF_i^{new} = MF_i^{old} + \delta\, MF_i$$

The alternatives are then ranked again and if the top-ranked alternative remains unchanged, the solution is considered stable. If the top-ranked alternative is changed, the sensitivity of the merit function to other ratings needs to be evaluated further. In some cases, addition or redefinition of attributes may be necessary.

### 3.3.2 An Example to Illustrate the Selection Decision Support Problem

In Section 3.2.2 the top-of-the-heap concepts for the V/STOL aircraft were identified. It is assumed that the concepts have been developed into feasible alternatives and and a selection DSP, to identify the best concept, is to be solved. Again it is pointed out that aircraft design is extremely complex and time intensive. In what follows we present an example for illustrative purposes only.

**Step 1 Describe the alternatives and provide acronyms**
The feasible alternatives are:

**TWTE** (Tandem Wing, Tandem Engine) - This concept features two tandem fan engines located on either side of the fuselage for a total of four engines. These engines also provide lift by a type of vector thrust. The wing layout is a pair of tandem wings which combine to make for a small easily parked craft.

**CNAW** (Canard Augmentor Wing) - Two turbo fans are placed at the rear of a canard wing configuration. The exhaust of the fans is blown over the rear wing to augment its lift.

**TTVT** (Twin Tail, Vector Thrust) - A twin tail design with fuselage pod and clamshell doors provides easy cargo access. Two vector thrust engines provide lift and cruise thrust.

**CWAW** (Conventional Augmentor Wing) - A conventional transport layout is provided with augmentor wing technology for V/STOL capability via two engines mounted on the conventional wing.

**Step 2 Describe each attribute, specify the relative importance of the attributes and provide acronyms.** The following attributes have been identified for use in solving the selection DSP:

**Payload** (PLOD): Useful load in pounds the aircraft can carry above its own weight. Ratio scale. Range of rating values: 500 to 8000 lbs. A larger number indicates preference.

**Range** (RNGE): Distance in nautical miles the aircraft can carry the payload. Ratio scale. Range of rating values: 500 to 1500 nautical miles. A larger number indicates preference.

**Simplicity** (SIMP): The designs requiring the least number of moving parts and make use of existing technology are judged to be the simplest.

Ordinal converted to interval scale. Range of rating values: 0 - 10. A larger number indicates preference.

**Power Matching** (PMCH): The design that has the best capability to match vertical takeoff power to level flight power is judged to be the best. Composite scale (relative importance). Range of rating values: 0 - 1. A larger number indicates preference.

**Cargo Access** (CACC): The design that gives the best access for loading and unloading cargo is preferred. Ordinal converted to interval scale. Range of rating values: 0 - 10. A larger number indicates preference.

**Landing Restriction** (LRES): The design that can land on any surface is preferred. Composite scale (relative importance). Range of rating values: 0 - 1. A larger number indicates preference.

**Parking Area** (PARK): The parking area in square feet is determined by multiplying the wingspan by the length of the aircraft. A smaller space is desired. Ratio scale. Range of rating values: 200 to 2000 square feet. A smaller number indicates preference.

**Stability** (STAB): The more stable the craft, the more marketable it is. Interval scale. A larger number indicates preference. Range of rating values: 0 - 10.

**Engine Out Safety** (ESAF): Those designs that have better chances of surviving a single engine failure in take-off and landing are preferred. Composite scale (relative importance). Range of rating values: 0 - 1. A larger number indicates preference.

As indicated in Step 2, there are two ways of determining the relative importance of the attributes, namely, the ranking method and the method of comparison. The methods have been described in Appendix B.2 and for the example problem the relative importances using both methods have been computed and presented in Table B.8. Note that the relative importances determined, using three methods, are different.

**Step 3 Specify scales, rate the alternatives with respect to each attribute and normalize.** Attributes of Payload and Parking Space are measured in physical units and are therefore evaluated using a ratio scale. The attributes Power Matching and Engine out Safety are rated on a composite scale and all other attributes on an interval scale. Examples of two of the interval scales are presented in Table 3.5. The implicit assumption underlying the specification of these scales is that the designer is able to clearly articulate a definite and measurable degree of preference. As indicated earlier this option must be exercised with great care. An example of the composite scale is presented in Table 3.6. The comparison method (see Appendix B.2) has been used for creating this scale. For brevity the viewpoint associated with the table is omitted. The attribute ratings, the bounds, the type of scale and the preference for higher or lower numbers are shown in Table 3.7. The upper and lower bounds for the scales were specified in Step 2. As indicated earlier the bounds for the ratio scales must be established after very careful consideration.

| ATTRIBUTE 3 - SIMPLICITY<br>Description | Rating |
|---|---|
| Very simple - two fixed engines, no unusual moving parts. | 10 |
| Simple - two engines with variable positioning | 7 |
| Complex - more than two engines with variable positioning | 4 |
| Very complex - two or more engines, variable positioning, complicated flap arrangement, stowed lift engines. | 1 |

| ATTRIBUTE 5 - CARGO ACCESSIBILITY<br>Description | Rating |
|---|---|
| Best - large entry way, at front or rear, door/ramp | 10 |
| Adequate - Side entry, medium to large entry | 6 |
| Limited - Small entry in side, high undercarriage | 2 |

**TABLE 3.5 -- EXAMPLES OF THE CREATION OF INTERVAL SCALES**

| Power Matching | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Decision Number | | | | | | | | | | |
| Alternative | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Score/Rating |
| **CNAW** | 1 | 1/2 | 1/2 | 1 | | | | | | | 3/10 = 0.3 |
| **TWTE** | 0 | | | | 0 | 0 | 1 | | | | 1/10 = 0.1 |
| **TTVT** | | 1/2 | | | 1 | | | 1/2 | 1 | | 3/10 = 0.3 |
| **CWAW** | | | 1/2 | | | 1 | | 1/2 | | 1 | 2/10 = 0.2 |
| **Dummy** | | | | 0 | | | 0 | | 0 | 0 | 0/10 = 0.0 |

Note: Viewpoint must be included.

**TABLE 3.6 -- EXAMPLE OF THE CREATION OF COMPOSITE ATTRIBUTE RATINGS**

| Alternatives | PLOD | RNGE | SIMP | PMCH | CACC | LRES | PARK | STAB | ESAF |
|---|---|---|---|---|---|---|---|---|---|
| | Attributes | | | | | | | | |
| **CNAW** | 3500 | 1000 | 9 | 0.3 | 6 | 0.35 | 1500 | 1 | 0.15 |
| **TWTE** | 6200 | 800 | 1 | 0.1 | 8 | 0.1 | 518 | 4 | 0.4 |
| **TTVT** | 5000 | 900 | 7 | 0.3 | 10 | 0.2 | 1480 | 2.5 | 0.3 |
| **CWAW** | 3500 | 1000 | 10 | 0.3 | 8 | 0.35 | 1023 | 2.5 | 0.15 |
| U. Bound | 8000 | 1500 | 10 | 1 | 10 | 1 | 2000 | 10 | 1 |
| L. Bound | 500 | 500 | 0 | 0 | 0 | 0 | 200 | 0 | 0 |
| Units | [lbs] | [nm] | - | - | - | - | [sq ft] | - | - |
| Type | R | R | O-I | C | O-I | C | R | I | C |
| Preference | H | H | H | H | H | H | L | H | H |

R - Ratio, I - Interval, O-I - Ordinal converted to interval, C - Composite
H - High numbers indicate preference; L - Low numbers indicate preference

**TABLE 3.7 -- ATTRIBUTE RATINGS ($A_{ij}$)**

**Step 4 Normalize Ratings.** Since larger numbers indicate preference for attributes, equation 3.1 is used to normalize the ratings for all attributes except parking space. For parking space, since smaller numbers represent preference, the ratings are normalized using equation 3.2. The normalized ratings are shown in Table 3.8.

**Step 5 Evaluate the merit function for each alternative.**
The merit function values are calculated using equation 3.3, the normalized ratings (Table 3.8) and the normalized relative weights of the attributes Table B.2. The merit function values together with their percentage differences are presented in Table 3.9. It is clear from Table 3.9 that the difference in the merit function values for Conventional Augmentor Wing (CWAW) and the Twin Tail Vector Thrust (TTVT) alternatives is very small. Therefore these alternatives should be considered equivalent.

**Step 6 Post-solution sensitivity analysis.**
Reviewing the ratings, we see that the TWTE alternative is very poorly rated in simplicity and power matching. The TWTE alternative has the best rating for payload cargo capacity parking, atability and engine out saftey. It is probably a good alternative but is not appropriate for the scenario under consideration. If, however, work was done on the TWTE alternative to reduce the complexity of the aircraft and improve its rating for power matching it would be a very competitive option. The CNAW alternative rated well on simplicity and landing restrictions but did relatively poorly on payload, cargo capacity, engine out safety and stability. In a scenario where payload is relatively less important and simplicity very important this alternative could be a viable option. The TTVT alternative does reasonably well

across all attributes except parking. The CWAW alternative also does reasonably well across all attributes except payload and engine out safety. Hence, the two top alternatives require further engineering to discern which is actually the best alternative. This type of result is not uncommon. We can tell that we need to specify new attributes that better demonstrate the differences between the two alternatives. We can also recognize the need for iteration; a further cycle involving engineering analysis and selection.

| Alternatives | Attributes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | PLOD | RNGE | SIMP | PMCH | CACC | LRES | PARK | STAB | ESAF |
| CNAW | 0.4 | 0.5 | 0.9 | 0.3 | 0.6 | 0.35 | 0.28 | 0.1 | 0.15 |
| TWTE | 0.76 | 0.3 | 0.1 | 0.1 | 0.8 | 0.1 | 0.82 | 0.4 | 0.4 |
| TTVT | 0.6 | 0.4 | 0.7 | 0.3 | 1.0 | 0.2 | 0.29 | 0.25 | 0.3 |
| CWAW | 0.4 | 0.5 | 1.0 | 0.3 | 0.8 | 0.35 | 0.54 | 0.25 | 0.15 |

**TABLE 3.8 -- NORMALIZED ATTRIBUTE RATINGS ($R_{ij}$)**

| Alternatives | Merit function Values | Percent Difference Between the Best and Others | Overall Rank |
|---|---|---|---|
| CWAW | 0.504 | 0.0 | 1 |
| TTVT | 0.493 | 2.2 | 2 |
| CNAW | 0.430 | 14.7 | 3 |
| TWTE | 0.413 | 18.1 | 4 |

**TABLE 3.9 -- MERIT FUNCTION VALUES AND FINAL RANKINGS FOR THE ALTERNATIVES**

**Sensitivity to changes in the attribute importances**

The Canard Augmentor Wing (CNAW) and the Tandem Wing, Tandem Engine (TWTE) alternatives, however, are close to the top choices. Thus a sensitivity analysis is required to determine the effect on the solution of small changes in the values of the relative importances and also to changes in the attribute ratings. To evaluate the sensitivity of the solution to changes in the relative importance of the attributes the following steps are necessary:

- Pick the best and the second best alternatives for further analysis.

- Increase or decrease the relative importance of **each** attribute by a certain amount (say 5%) so as to affect the merit function of the second ranked alternative favorably with respect to the first ranked alternative.
- Compute the revised merit functions.
- Accept/re-evaluate problem results based on comparison and judgment.

We have established earlier that the top two alternatives are equivalent and therefore is not likely to yield interesting information. From looking at the merit function values it appears that the alternatives are divided into two groups with CWAW in one and TWTE in the other. A closer examination of the ratings for these two alternatives reveals that they are strong on different attributes and there may be an interesting result.

For this example, the current attribute importance vector (see Table B.2) is (0.16, 0.04, 0.18, 0.2, 0.11, 0.02, 0.09, 0.07, 0.13). The normalized ratings for alternatives CWAW and TWTE (see Table 3.8) are (0.4, 0.5, 1.0, 0.3, 0.8, 0.35, 0.54, 0.25, 0.15) and (0.76, 0.3, 0.1, 0.1, .8, 0.1, 0.82, 0.4, 0.4), respectively. Modify the attribute importance vector by 5% as shown:

[0.16x1.05, 0.04x.95, 0.18x.95, 0.2x.95, 0.11x1, 0.02x.95, 0.09x1.05, 0.07x1.05, 0.13x1.05]

or

[0.168, 0.038, 0.171, 0.19, 0.11, 0.019, 0.085, 0.074, 0.137]

This combination of modifications will be the most conducive to an increase in the merit function of alternative TWTE with respect to alternative CWAW, since it takes advantages of the areas where TWTE is strong and minimizes the importance of those areas where it is weak compared to CWAW. In this instance, the revised merit functions are as follows:

$$M'_{CWAW} = 0.499 \text{ and } M'_{TWTE} = 0.427.$$

Since the merit function for CWAW is still more than that for the TTVT, the solution is accurate within a 5% error margin. By way of information, the corresponding values for the other alternatives are:

$$M'_{CWAW} = 0.488 \text{ and } M'_{CNAW} = 0.418$$

$$M'_{CWAW} = 0.500 \text{ and } M'_{TTVT} = 0.498.$$

**Sensitivity of solution to changes in alternative ratings**

To determine the sensitivity of the solution to changes in alternative ratings we try and determine whether there could be an instance of alternative TWTE being chosen over alternative CWAW, if there were an error of 5% in any of the rankings. The steps are as follows:

- Pick the best and second best alternatives for analysis.
- Increase the rating of attribute j for alternative i by 5%. Calculate the merit function. Decrease the rating by 5% (from the original value) and calculate the merit function. Repeat for other attributes for changes of 5% in each alternative rating.

Accept/re-evaluate selection DSP sensitivity analysis based on comparison and judgment.

This is a very tedious task if it has to be done by hand. The highest merit function value (after affecting a 5% increase for every attribute rating in turn) is plotted in Figure 3.5. So also are the corresponding lowest merit function values. The merit function values from Table 3.9 are labelled "No change" in Figure 3.5.

To look for a switch compare, say, the 5% decrease plot for CWAW with the 5% increase plot for TTVT; they appear to be close. To investigate this further look at Table 3.10. In column two of Table 3.10 the merit function values obtained after decreasing the rating of CWAW for each of the attributes in turn is presented. In column three is the merit function value of TTVT (from Table 3.9). In column four the merit function values obtained after increasing the rating of TTVT for each of the attributes in turn is presented. Clearly, a 5% decrease in a single attribute rating for CWAW is not going to result in TTVT comining out on top (compare $M_{TTVT}$ = 0.493 with the numbers for CWAW in column two). It is also evident from the numbers shown in Table 3.10 that a switch in the ranks of CWAW and TTVT will occur if there is a 5% decrease in the rating of CWAW **and** a 5% increase in the rating of TTVT on the attribute simplicity. In the same way a 5% change in the rating on cargo capacity for the two alternatives results in the merit function values being identical. Hence, alternatives CWAW and TTVT are chosen for further engineering and re-evaluation. It is recommended that particular attention be paid to simplicity and cargo accessibility in the next design iteration.

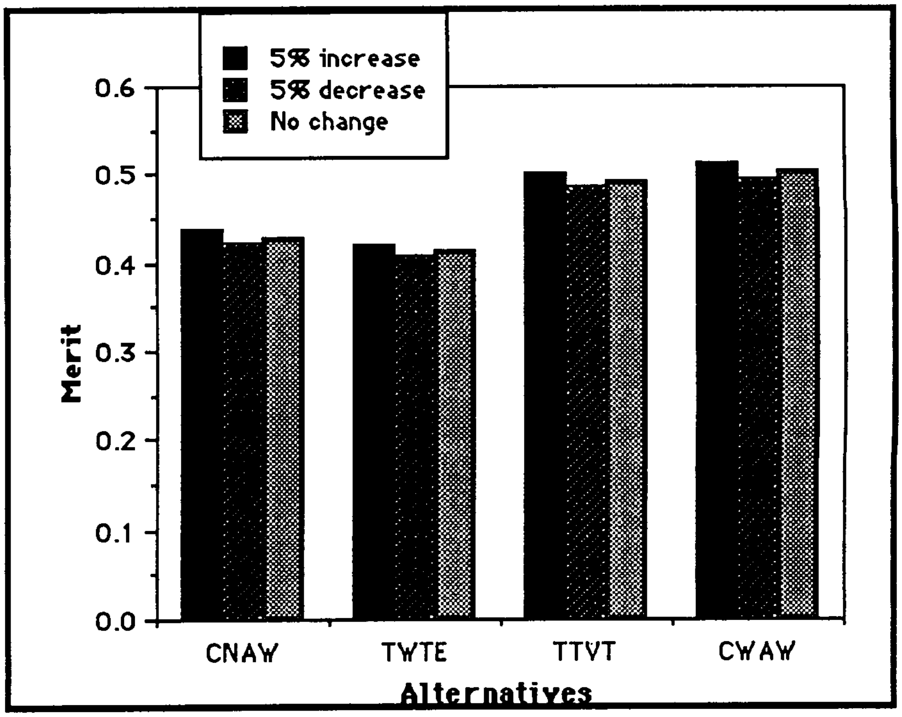



FIGURE 3.5 -- VARIATIONS IN MERIT FUNCTION VALUES

| 5% decrease/increase with respect to: | CWAW 5% dec. | TTVT M = 0.493 | TTVT 5% inc |
|---|---|---|---|
| Payload | 0.500 | | 0.499 |
| Range | 0.502 | | 0.495 |
| Simplicity | **0.495** | | **0.500** |
| Power Matching | 0.501 | | 0.496 |
| Cargo Accessibility | **0.499** | | **0.499** |
| Landing Site Restrictions | 0.503 | | 0.494 |
| Parking Space | 0.506 | | 0.490 |
| Stability | 0.503 | | 0.494 |
| Engine Out Safety | 0.503 | | 0.495 |

**TABLE 3.10 -- MERIT FUNCTION VALUES FOR 5% CHANGE IN ALTERNATIVE RATINGS**

Since the emphasis in this chapter is placed on the process rather than the results consider the following scenario:

> Assume that the top two alternatives have been closely examined particularly with respect to the two attributes listed earlier. Let us also assume that the results presented in Table 3.10 have been obtained after this re-examination. In other words there is some degree of confidence in the differences that are apparent in the table. How are these numbers to be interpreted?

For this case the interpretation follows. The conventional augmentor wing (CWAW) alternative is dominant over the twin tail, vector thrust (TTVT) aircraft. Even in the worst case for the CWAW, the merit value ($M'_{CWAW} = 0.495$) is larger than the merit function value for TTVT ($M_{TTVT} = 0.493$). It is unlikely that there is a 5% decrease and a simultaneous increase in the rating associated with simplicity for the two aircraft. Therefore, the Conventional Augmentor Wing aircraft is recommended for further development.

The V/STOL aircraft design is used as an example to illustrate the design process from concept to selection of an alternative for further development. The same process could be applied in the conceptual and preliminary design stages of other types of aircraft and engineering systems in general. The designer would merely replace the alternatives and attributes with ones that are pertinent to the particular problem.

## 3.4 ON THE IMPLEMENTATION OF THE SELECTION DSP TEMPLATES

The selection DSPs are useful tools in engineering synthesis. It is important to remember that the DSPs can at best support human judgment; they should never be viewed as a means of replacing human judgment. They do, however, provide an ordered, rational means for making a choice throughout the process of design.

The results can be only as good as the model and the care with which it has been created and exercised. The number of decimal points used to arrive at and report a decision should be commensurate with the level of confidence that a designer has in the model. The real power of the method lies in the fact that it can be used at any point in a project where choices are being made.

We are confident in recommending the use of the preliminary selection DSP. In selection, however, the proposed method of normalizing and using both ratio and interval scales in calculating the merit function can be severely criticised. One remedy is to convert all ratio to interval scales and thence compute the merit function values. This has been suggested by Saaty [51,52]. We believe that this solution is appropriate when there is more soft information than hard information available (for example, in management science and in the early stages of the design process). Saaty [51,52] has presented a very good and mathematically sound method that can be used for creating interval scales and also for converting ratio scales into interval scales. We are in the process of integrating this into the MacDSIDES system. This, however, only addresses part of the problem.

Our current approach is suitable when hard information dominates the selection process. In the intermediate case, that is, when there is a fair amount of both hard and soft information available there are currently two options available, namely, convert all ratio scales to interval scales or the approach presented in this chapter. We are reluctant to recommend converting ratio scales to interval scales and then solving the selection DSP because in doing so some very important technical knowledge is invariably lost. We believe that our current approach is suitable, in the intermediate case, if used by knowledgeable engineers with caution. We are at this time developing one of the ideas presented by Saaty that, if implemented, would provide a better way for making use of hard and soft information.

We recognize that in practice the problem of selection in aircraft design is far more complex than is depicted in the examples described in this chapter. We therefore suggest that a reader focus on the process of selection and not just the example problem. Recommendations for improving these templates are made in Chapter 7.

# CHAPTER 4
## MATHEMATICAL FORM OF THE COMPROMISE DSP FOR AIRCRAFT DESIGN

In this chapter the mathematical form of the compromise Decision Support Problem template for a subsonic jet transport is presented. The problem is stated in Section 2.5.2 and the template illustrated in Figure 2.10. The word formulation for the template is presented in Section 2.5.3. As indicated in Section 2.5.1 we are making use of the design-analysis information that is used in a traditional sizing procedure and a schematic of the information is given in Figure 2.2. The mathematical form for the constraints and goals that constitute the technical requirements and aspirations are based on the work of Loftin [27] and Nicolai [43]. The economic analysis is modeled after that created for Program OPDOT by Sliwa and Arbuckle [56]. The template presented in the chapter is generic for subsonic jet transports. The terms used are defined in the nomenclature and the text. The template is validated in Chapter 5 using the Boeing 727-400 as an example.

## 4.1 AIRPORT PERFORMANCE

Methods for estimating the FAR landing field length and take-off field length are presented in this section based on the work of Nicolai [43]. As will be seen, these field lengths contain certain safety margins to allow for emergency situations. The one engine inoperative climb characteristics are also considered in relation to the FAR requirements for the missed approach situation on landing and the second segment climb gradient following take-off. The field lengths presented are for subsonic commercial transport aircraft and are based on the requirements set forth in FAR part 25.

### 4.1.1 Landing Field Length

The landing field length is defined by the Federal Air Regulations for transport category aircraft. It is measured, see Figure 4.1, horizontally, from the point at which the aircraft is 50 ft above the landing surface, in steady gliding flight at an approach speed not less than 1.3 times the stalling speed, to the point at which the aircraft is brought to a complete stop on a hard, dry smooth runway surface [27]. The FAR landing field length is obtained by dividing the measured landing distance by 0.6 in order to account for the possibility of variations in approach speed, touchdown point, and other deviations from standard procedures, thus increasing the overall length. The FAR landing field length as defined in Figure 4.1 always appears in specifications for transport aircraft designed to the criteria of FAR part 25.

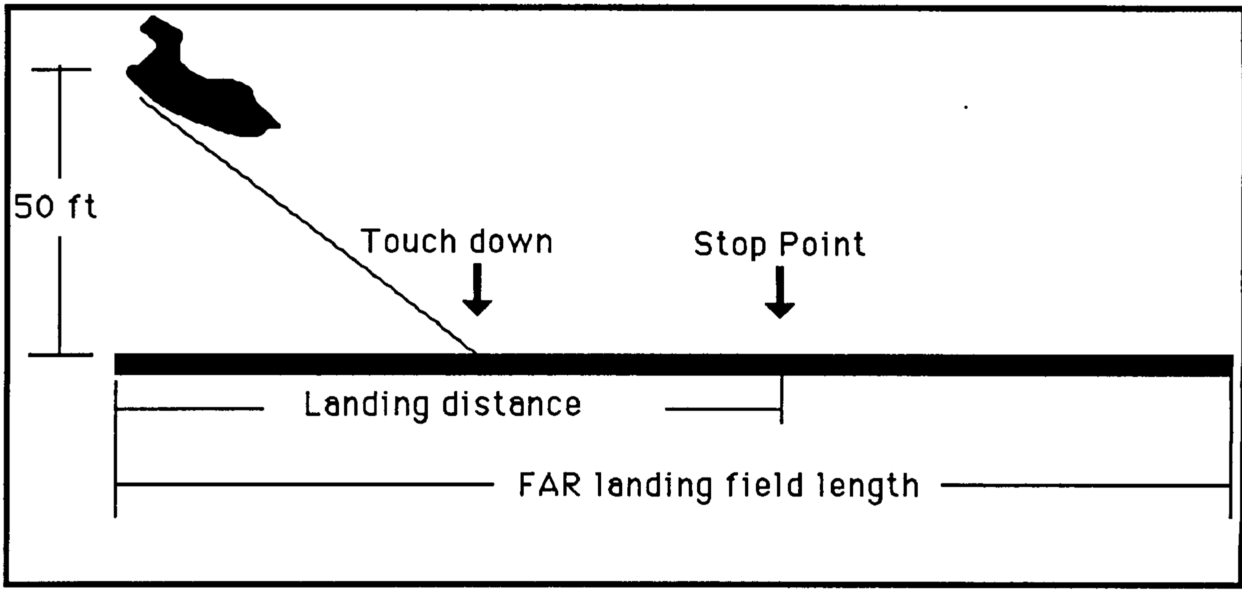



**FIGURE 4.1 -- FAR LANDING FIELD LENGTH DEFINITIONS**

The wing loading of the aircraft influences the landing and take-off distances through the stall speed, $V_{stall}$,

$$V_{stall} = (W/S)\ (2/\rho C_{Lmax}). \qquad [4\text{-}1]$$

Nicolai [43] suggests that the landing distance is dependent upon a "landing parameter", LP:

$$LP = (W/S)\ /\ \rho\ C_{Lmax}. \qquad [4\text{-}2]$$

This landing parameter can be developed into a more accurate expression for the landing field length, $S_L$,

$$S_L\ = 118\ (W/S)\ /\ (\ \rho\ C_{Lmax}) + 400, \qquad [4\text{-}3]$$

where $S_L$ is in feet.

The landing field length needs to be modeled as both a system constraint and a goal in the compromise DSP. The system constraint ensures that the maximum value is not violated. The system goal is an expression of the aspiration (lower than the system constraint) that a designer has for this particular attribute of the design. In this case it is desirable that the aircraft is able to land field of length less than some maximum specified value; hence the landing field length as a system constraint. It is also desirable that the aircraft have a landing field length less than the maximum specified value; in this case the landing field length is modeled as a system goal.

If $S_L$ and $S_{LTV}$ are the maximum and the target value of the landing field length ($S_{LTV} < S_L$), respectively - the system constraint and the system goal are as follows.

---

$$118[(W_{TO}\ \text{-}W_{fuel}\ /\ S)\ /\ (\ \rho\ C_{Lmax})\ ] + 400 \leq S_{L,} \qquad \textbf{[4-3.C]*}$$

---

$$118[(W_{TO}\ \text{-}W_{fuel}\ /\ S)\ /(\ \rho\ C_{Lmax})\ ] + 400\}\ /\ S_{LTV} + d_1^- -\ d_1^+ = 1 \qquad \textbf{[4-3.G]**}$$

---

The difference in the way $S_L$ is determined in the traditional process (see Section 2.2.3 and Figure 2.2) and using the compromise DSP template is important. In the traditional design process $S_L$ is a returned value independent of the mission requirements. In other words, even though the mission requirements have already been stated such that the landing field length must be less than a certain value there is no means to provide for this requirement. If the value exceeds required value the designer must perturb the values of W, S, and $C_{Lmax}$ until they satisfy the mission

* System constraint in compromise DSP template for aircraft design.

** System goal in compromise DSP template for aircraft design.

requirement. The decision as to what should be changed and by how much, rests on the experience-based insight of the designer. Hopefully, the design will improve a little, but there is no means to ensure this. In fact, it is highly unlikely that the designer can visualize how the weight, wing area, and maximum lift coefficient (which, by the way, is a function of about six other variables) can be changed to ensure the aircraft is meeting FAR regulations for other criteria which are functions of these same variables. More importantly, using the traditional approach, it is not possible to obtain a value for the landing field length that reflects the use of all the excess capability of the aircraft system. Utilizing the excess capability of a system constraint or system goal while simultaneously ensuring that no other system constraints are being violated and all other system goals are being met ,is one of the principal advantages of the using a compromise Decision Support Problem for the conceptual design of aircraft. The distinction made with respect to the determination of the landing field length using the traditional sizing approach and the compromise DSP template is generic; it is equally applicable to the determination of other parameters.

### 4.1.2 Missed Approach

Although not listed with the primary operational criteria, the approach phase of flight presents some interesting design problems that are worth exploring. Stability and controllability are both important at this time and should remain fairly constant over a broad range of relatively low speeds. Because of its importance, the missed approach must also be considered in relation to the landing maneuver. The missed approach is a situation in which the aircraft is on final approach to a landing but does not land for one of several reasons; instead, power is applied and the aircraft climbs, usually to circle the airport and initiate another landing approach. Federal Air Regulations for transport category aircraft require the installation of sufficient thrust so that the aircraft can climb from a missed approach, in the approach configuration, at a specified gradient with one engine inoperative and at maximum landing weight. The specified climb gradients are 2.7 degrees for four engine aircraft, 2.4 degrees for three engine aircraft, and 2.1 degrees for two engine aircraft [27].

A simple relationship for estimating the thrust required to meet the wave-off climb gradient requirement is derived by balancing the forces along the flight path. The resulting equation is

$$T = D + W \sin \gamma, \qquad [4\text{-}4]$$

where:

- T is the engine thrust, [lb],
- D is the aircraft drag, [lb],
- W is the aircraft weight, [lb], and
- $\gamma$ is the flight-path angle, degrees.

However, for small values of the flight path angle, $\sin \gamma$ is approximately equal to $\dot{\gamma}$, expressed in radians, which in turn represents the climb gradient in percent, divided by 100. In other words, $q_L$, the climb gradient in percent is approximately equal to the climb gradient, $\gamma$, in degrees. With this simplification and dividing by the aircraft weight, equation [4-4] takes the form

$$T/W = 1/(L/D) + q_L, \qquad [4\text{-}5]$$

where (L/D) is the lift-drag ratio of the aircraft in the approach configuration. In order for the climb gradient criterion to be satisfied with one engine inoperative, the thrust to weight ratio with all engines operating is determined from a modification of equation [4-5]. If N is the number of engines, the required thrust to weight ratio with all engines operating is given by the expression:

$$T/W = \{N/(N-1)\}\ \{1/(L/D) + q_L\}, \qquad [4\text{-}6]$$

where for the wave-off, the weight W should be the maximum landing weight.

The climb gradient associated with the missed approach on landing needs to be modeled as both a system constraint and a goal in the compromise DSP. The system constraint ensures that the minimum requirement is met. The system goal is an expression of the aspiration (higher than the system constraint) that a designer has for the design. In this case the aircraft must have a climb gradient with one engine inoperable larger than some minimum specified value; hence the range as a system constraint. It is also desirable that the aircraft have a climb gradient greater than the minimum specified value; in this case the climb gradient is modeled as a system goal. If $q_L$ is the minimum value of the climb gradient and $q_{LTV}$ is the target value for the climb gradient ($q_{LTV} > q_L$) then the system constraint and a system goal are as follows:

$$T/W\,[(N-1)/N] - 1/(L/D) \geq q_L. \qquad \mathbf{[4\text{-}6.C]}$$

$$\{T/W\,[(N-1)/N] - (L/D)^{-1}\} / q_{LTV} + d_2^- - d_2^+ = 1 \qquad \mathbf{[4\text{-}6\ G]}$$

### 4.1.3 Take-off Field Length

The FAR take-off field length, often called the FAR balanced field length, contains certain inherent safety features to account for situations associated with engine failure. This take-off field length is defined in several ways. Briefly, if an engine should fail during take-off before a critical speed, called the decision speed $V_1$, the pilot is offered the option of two safe courses of action. The pilot may elect to continue the take-off on the remaining engines, in which case, the take-off distance is defined as the distance from the point where the take-off run is initiated to the point where the aircraft has reached an altitude of 35 ft. Alternatively, the pilot may elect to use thrust reversers and apply full brakes. The decision speed is chosen in such a way that the sum of the distance required to accelerate to $V_1$ and then decelerate to a stop is the same as the total distance for the case in which the take-off is continued following engine failure. If an engine should fail before $V_1$ is reached, the aircraft is usually brought to a stop on the runway. If, however, an engine fails at a speed greater than $V_1$ the take-off is continued. The distances are based on smooth, hard, dry runway surfaces. An idealization of the FAR take-off length is shown in Figure 4.2.

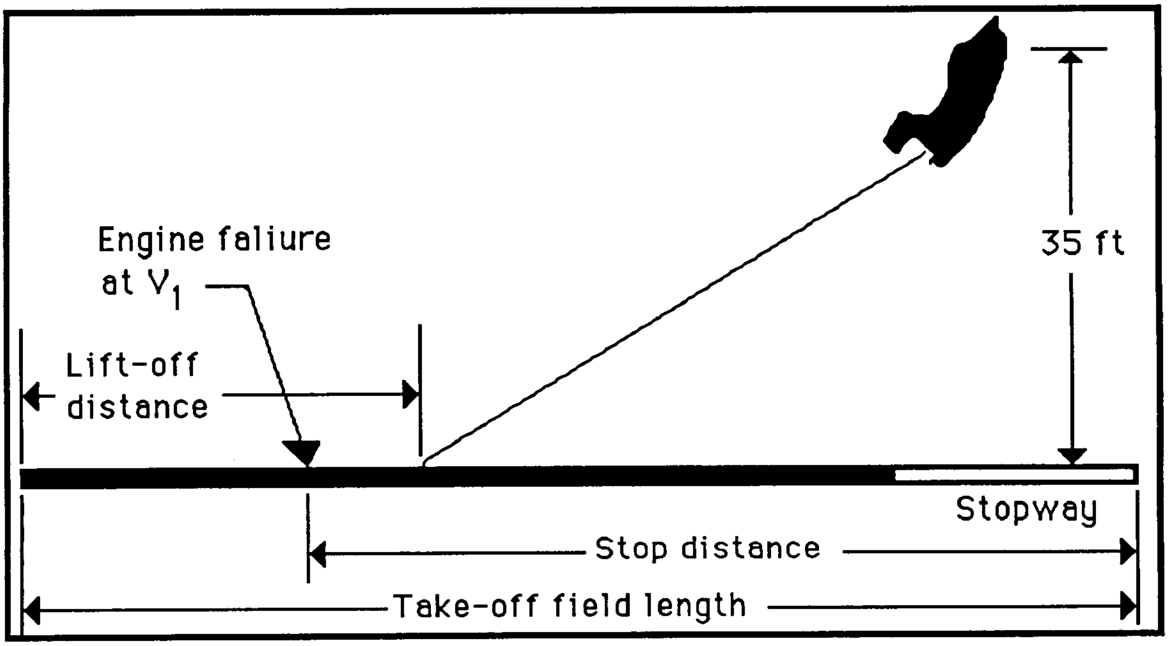



**FIGURE 4.2 -- FAR TAKE-OFF FIELD DEFINITION, [27]**

It is assumed, for the following, that the aerodynamic drag during take-off roll and the rolling friction resulting from the contact between the aircraft wheels and the ground are negligible. The following physical relations are used to obtain an expression for the take-off distance, $S_{TO}$, required to accelerate to the lift-off speed corresponding to the lift coefficient $C_{L,lo}$ at lift-off:

$$S_{TO} = V_{lo}^2 / 2a, \qquad [4\text{-}7]$$

$$T_o / W_{TO} = a / g, \text{ and} \qquad [4\text{-}8]$$

$$V_{lo} = \{W_{TO} / [S\, C_{L,lo} (\rho/2)]\}, \qquad [4\text{-}9]$$

where:

| | |
|---|---|
| $a$ | is the average acceleration of aircraft along ground, [ft/sec$^2$], |
| $\rho$ | is the atmospheric density, [slugs/ft$^2$], |
| $g$ | is the acceleration due to gravity, [ft/sec$^2$], |
| $V_{lo}$ | is lift-off speed corresponding to $C_{LM}$, [knots], and |
| $T_o/W_{TO}$ | is the aircraft thrust to weight ratio with all engines operating, expressed in terms of maximum take-off gross weight and maximum sea level static thrust. |

Equations [4-7], [4-8] and [4-9] are combined to give the following expression,

$$l_{T,g} = K / (\sigma\, C_{L,lo})\, (W_{TO}/S) / (T_o/W_{TO}), \qquad [4\text{-}10]$$

where:

$K = 1 / (\sigma_o\, g)$,
$\sigma = \rho/\rho_o$, and

$\rho_o$ is the atmospheric density for standard sea level conditions. The length $l_{T,g}$ defined by equation [4-10] is the ground run to lift-off (zero aerodynamic drag and rolling friction is assumed). The actual ground run distance is somewhat larger than that given by equation [4-10]. A reasonable assumption to make is that for the class of aircraft considered, the FAR take-off field length should bear a nearly constant relationship to the ground run with all engines operating. On the basis of this assumption, a close correlation is expected between the FAR take-off field length, $l_T$, and the parameter,

$$\frac{(W_{TO}/S)}{S\, C_{L,T}\ \ (T_o/W_{TO})}\ .$$

Nicolai [43] develops this relationship between the take-off distance and the take-off parameter and gives the following approximate expression,

$$S_{TO} = 20.9[(W_{TO}/S) / (C_{Lmax}\, (T_i/W_{TO}) + 87[(W_{TO}/S)\ 1/C_{Lmax}]^{1/2}. \qquad [4\text{-}11]$$

This expression is more accurate than equation [4-10]. Using Nicolai's relationship, it is seen that a short take-off distance can be achieved with a high wing loading if $C_{Lmax}$ and $T_i/W_{TO}$ are large. Although the above definition for take-off field length is simply an equation for determining the length, if it is converted into a system constraint then we can pick a take-off field length value and ensure that the aircraft does not exceed (or does not go below) this value. In the compromise DSP, the corresponding take-off field length is modeled as a constraint and it has the following form,

$$20.9[(W_{TO}/S) / (C_{Lmax}\, (T_i/W_{TO}) + 87[(W_{TO}/S)\ 1/C_{Lmax}]^{1/2} \le S_{TO}. \qquad \textbf{[4-11.C]}$$

### 4.1.4 Second Segment Climb Gradient

Another factor which must be considered in relation to the take-off maneuver is the FAR second segment climb gradient requirement. The second segment climb is that portion of the flight path, following take-off, conducted at $V_2$, which extends from an altitude of 35 to 400 ft, (see Figure 4.2). The Federal Air Regulations require that sufficient thrust be installed in the aircraft so that in the event of an engine failure, the following second segment climb gradients, $\gamma$, may be sustained, that is, 3 degrees for four engine aircraft, 2.7 degrees for three engine aircraft, and 2.4 degrees for two engine aircraft. The aircraft must satisfy these requirements with flaps in the take-off position but with the landing gear retracted. The required thrust to weight ratio with all engines operating is similar to the equation for the missed approach condition, with the exception being the weight of the aircraft and the lift to drag ratio for the different operational modes.

For small values of the flight path angle, sin $\gamma$ is approximately equal to $\gamma$, expressed in radians, which in turn represents the climb gradient in percent, divided by 100. In other words, $q_{TO}$, the second segment climb gradient in percent is approximately equal to the climb gradient in degrees. With this simplification, the second segment climb gradient is represented as a system constraint in the following DSP formulation:

$$T/W_{TO}\,[(N-1)/N] - 1/(L/D) \geq q_{TO}\,. \qquad \textbf{[4-12.C]}$$

## 4.2 CRUISE MATCHING

A cruise matching analysis provides a method for matching the engine to the airframe in such a way as to permit cruising in a specified manner. The cruising criterion is for the pertinent engine and airframe characteristics to be matched in such a way as to permit achievement of a specified design range at a given cruising Mach number for a minimum amount of fuel. There are two aspects of cruise matching, namely, the range and performance at the cruising altitude.

### 4.2.1 The Range

The quantitative relationship between the range, the significant aircraft and engine characteristics, and the fuel used during cruising flight is given by the well known Brequet range equation [27],

$$R = V\,(L/D)\,/\,c\;\;\{\ln\,[1 - (W_f/W_{TO})\,]^{-1}\,\}, \qquad [4\text{-}13]$$

where:

| | |
|---|---|
| R | range, [ nautical miles], |
| V | speed, [knots], |
| L/D | aircraft lift-drag ratio, |
| c | engine specific fuel consumption [lb/hp-hour], |
| $W_f$ | aircraft fuel weight, [lb], and |
| $W_{TO}$ | aircraft gross take-off weight, lb. |

The range needs to be modeled as both a system constraint and a goal in the compromise DSP. The range system constraint ensures that the minimum requirement is met. The range system goal is an expression of the aspiration (higher than the system constraint) that a designer has for this particular attribute of the design. In this case the aircraft must have a range larger than some minimum specified value; hence the range as a system constraint. It is also desirable that the aircraft have a range greater than the minimum specified value; in this case the range is modeled as a system goal. If R is the minimum range and $R_{TV}$ is the desired target value for the range ($R > R_{TV}$) then the system constraint and a system goal are as follows:

$$V\,(L/D)\,/\,c\ \ \{\ \ln\,[1 - (W_f/W_{TO})\,]^{-1}\ \} \geq R. \qquad \textbf{[4-13.C]}$$

$$V\,(L/D)\,/\,c\ \ \{\ \ln\,[1 - (W_f/W_{TO})\,]^{-1}\ \}\,/\,(R)_{TV} + d_3^- - d_3^+ = 1 \qquad \textbf{[4-13.G]}$$

The parameter V (L/D)/c is often called the Brequet factor which is designated by the symbol B. Equation [4-13] can be written in a more useful form:

$$W_f/W_{TO} = 1 - \exp(-R/B), \qquad [4\text{-}14]$$

which explicitly gives the fuel fraction necessary for a specified range. According to equation [4-14], the desired range is achieved with the minimum fuel fraction when the aircraft is flown at the maximum value of the Brequet factor, B. The Brequet factor can also be written in the form,

$$B = V\,(L/D)\,/\,c = a\,M\,(L/D)\,/\,c, \qquad [4\text{-}15]$$

where:

a speed of sound, [ft/sec], and
M Mach number.

The speed of sound decreases with altitude until the tropopause (35,000 ft) is reached after which it remains constant with further increases in altitude up to about 105,000 ft.

### 4.2.2 Steady State Performance

In this section, a method for modeling the steady-state performance is presented. A large portion of an aircraft's mission profile is considered as steady-state (equilibrium) or as a series of near steady-state conditions. For the methods presented in this section, the aircraft is considered as a point mass system with horizontal and vertical translation degrees of freedom and subject to aerodynamic, propulsive, and gravity forces. The force diagram is shown in Figure 4.3 where the lift and drag forces are normal and parallel to the free stream velocity respectively, $i_T$ is the angle (usually small) between the wing cord line and the thrust vector and a is the flight path angle.

During level unaccelerated flight the flight path angle, a, is zero and all external forces acting on the aircraft are in balance. Thus, summing forces normal and parallel to $V_B$ (the free stream velocity axis), we have

$$L + T\sin(\alpha + i_T) = W\cos(\Upsilon), \text{ and} \qquad [4\text{-}16]$$

$$T\cos\,(\alpha + i_T) = W\sin(\Upsilon) + D. \qquad [4\text{-}17]$$

Since $\gamma = 0$ and $(\alpha + i_T)$ is usually small during this flight condition, the scalar equations representing level unaccelerated flight are

$$W \approx L = C_L qS, \text{ and} \tag{4-18}$$

$$T \approx D = (C_{Do} + KC_L^2)qS, \tag{4-19}$$

where: $q = 1/2(\rho_\infty V_\infty^2)$ is the dynamic pressure, and S is the reference wing planform surface area for $C_L$ and $C_D$

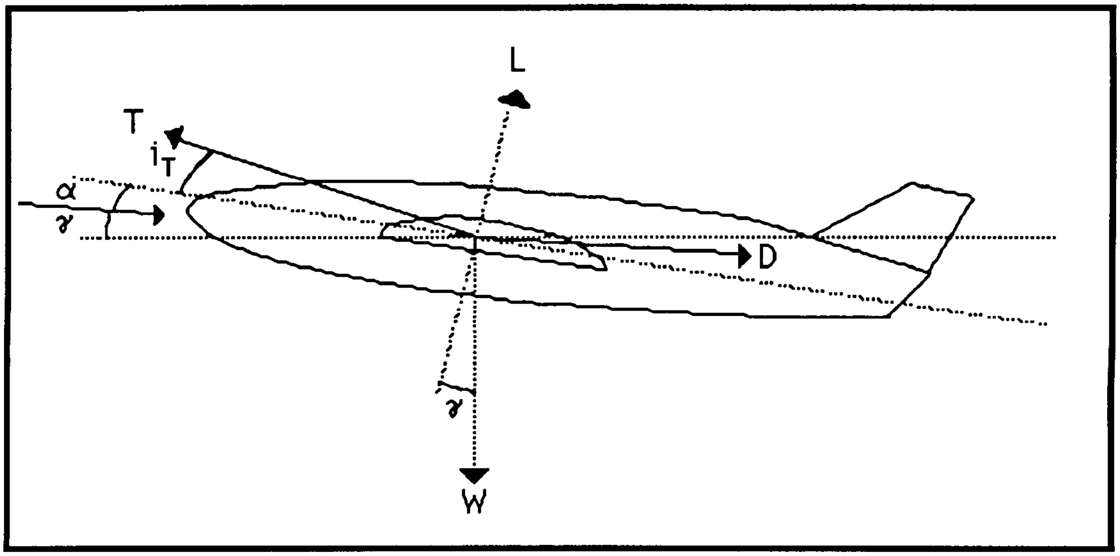



FIGURE 4.3 -- THE FORCES ACTING ON AN AIRCRAFT

(usually the total planform area). Since L = W, the $C_L$ the aircraft must fly at is expressed as

$$C_L = W / qS. \tag{4-20}$$

From equation [4-19], the drag determines the thrust required $T_R$,

$$T_R = D = C_{Do}\, qS + KW^2/qS. \tag{4-21}$$

Hence, by expressing this requirement as a system constraint, it can be ensured installed value of the total thrust is greater than the required value. Hence, the system constraint is

---

$$T_i / T_R \geq 1. \tag{4-22.C}$$

---

From equation [4-21] the power required for an aircraft is

$$P_R = DV = T_R V = (C_{Do} + KC_L^2)\,(W/C_L)\,(2W/\rho C_L S)^{1/2}. \qquad [4\text{-}23]$$

This may be introduced as a constraint in a later version of the template.

## 4.3 AERODYNAMIC PERFORMANCE

Lift and drag data for an aircraft through the Mach number range of its flight envelope are necessary for performance analysis. In this section, a review of the fundamental aerodynamic ideas relative to lift and drag are presented. This is followed by an explanation of methods for estimating the aerodynamics of wing-body combinations and their transformation into the appropriate system and goal constraints. Some of the constraints have been derived but not used in the template. The information on these constraints is included; it may be of use in the future.

### 4.3.1 Drag Due to Lift

The total drag coefficient for a wing-body combination is expressed as

$$C_D = (C_{Do})_{wing} + (C_{Do})_{body} + \Delta C_{Do} + \Delta C_{DL}, \qquad [4\text{-}24]$$

where: $\Delta C_{Do}$ is the zero lift drag coefficient due to miscellaneous protuberances, and $\Delta C_{DL}$ is the drag coefficient due to lift. The wing-body $C_{DL}$ is primarily due to the wing. Hence, it is assumed that the wing-body $C_{DL} \approx$ wing $C_{DL}$. The method for determining $C_{DL}$ that follows makes use of the wing geometry, but can be made to represent the entire wing-body $C_{DL}$ when referenced to the total planform area.

In subsonic flow, the total drag coefficient for the wing is expressed as

$$C_D = C_{Dmin} + K'C_L^2 + K''(C_L - C_{Lmin})^2. \qquad [4\text{-}25]$$

The terms containing K' and K" are the drag due to lift. The K' term in equation [4-25] is the inviscid drag due to lift called the induced drag. This drag results from the vortices trailing off of a finite wing inducing a downwash at the wing aerodynamic center. The K" term is the viscous drag due to lift due to flow separation and increased skin friction. This drag results from the viscous nature of the fluid causing the separation point on the upper surface to move forward from the trailing edge as the wing rotates to higher angles of attack and the region of adverse pressure gradient spreads. There is also an increase in skin friction occurring in the leading edge region due to the local super velocities associated with increasing lift.

The $C_{Lmin}$ term is the lift coefficient for minimum drag coefficient $C_{Dmin}$. For cambered airfoils, $C_{Lmin} \neq 0$ and is approximately equal to the $C_L$ for $a = 0$. For symmetric airfoils, $C_{Lmin} = 0$ and equation [4-25] is expressed as

$$C_D = C_{Do} + KC_L^2, \qquad [4\text{-}26]$$

where K = K' + K" and is called the drag due to lift factor. $C_{Do}$ is the zero lift drag coefficient. It is pointed out that $C_{Do} \approx C_{Dmin}$ for wings with cambered airfoils and the terms $C_{Do}$ and $C_{Dmin}$ are often used interchangeably. Equations [4-25] and [4-26] which display the parabolic behavior of $C_D$ with $C_L$ are valid only up to moderate values of $C_L$. At a $C_L$ called the "break $C_L$", $C_{LB}$, the drag coefficient ceases to be parabolic with $C_L$. The flow phenomena involved here is not too well understood.

The induced drag factor K' is given as

$$K' = 1/(\pi Ae), \qquad [4\text{-}27]$$

where "e" is called the wing efficiency factor. It corrects the finite wing theory result for taper ratio, sweep and body effects on the span loading. The "e" factor is determined from the following equation:

$$e = e'[1 - (d/b)^2], \qquad [4\text{-}28]$$

where d/b is the body diameter to wing span ratio (see Figure 4.4). The e' factor has been formulated by Weissinger in Nicolai [43]. An average value to use for the conceptual stage is e' = 0.96. The factors K' and K" are not dependent on Mach number for subsonic speeds, so K = K' + K".

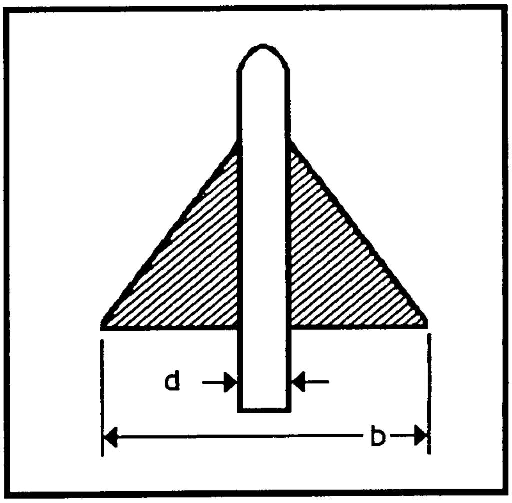



**FIGURE 4.4 -- DEFINITION OF FUSELAGE FINENESS RATIO**

The subsonic wing $C_{Do}$ is primarily skin friction. The expression for $(C_{Do})_{wing}$ based upon the reference area $S_{ref}$ is given by

$$(C_{Do})_{wing} = C_f[1 + L(t/c) + 100(t/c)^4]\, R\, S_{wet} / S_{ref}, \qquad [4\text{-}29]$$

where:

L is the airfoil thickness location parameter.

C - 2

L=1.2 for max (t/c) located at $x \geq 0.3c$, and
L =2.0 for max (t/c) located ar $x \leq 0.3c$.

t/c is the maximum thickness ratio of the airfoil.
$S_{wet}$ is the wetted area of the wing ($2S_e$).
$S_e$ is the exposed planform area, ft$^2$.
R is the lifting surface correlation factor , and
$C_f$ is the turbulent flat plat skin friction coefficient.

At subsonic speeds, the body $C_{D_o}$ of smooth slender bodies is primarily skin friction. The body $C_{D_o}$, referenced to the maximum cross-sectional area $S_B$ is given as

$$(C_{Do})_{body} = (C_{Df})_B + C_{Db}, \qquad [4\text{-}30]$$

where: $C_{Df}$ is the skin friction coefficient, and $C_{Db}$ is the base pressure coefficient. The body $C_{Df}$ is expressed as

$$(C_{Df})_B = C_f[1 + 60 + (l_B/d)^3 + 0.0025\,(l_B/d)\,]\, S_S / S_B, \qquad [4\text{-}31]$$

where: $S_S$ is the wetted area of the body surface, and $(l_B/d)$ is the body fineness ratio as defined below.

The $C_f$ is the turbulent skin friction coefficient and is determined in the same manner as the wing subsonic skin friction. The reference length is the body length $l_B$.

The base pressure coefficient is expressed as

$$C_{Db} = 0.029\,(d_b/d) / [\,(C_{Df})_B]^{1/2}. \qquad [4\text{-}32]$$

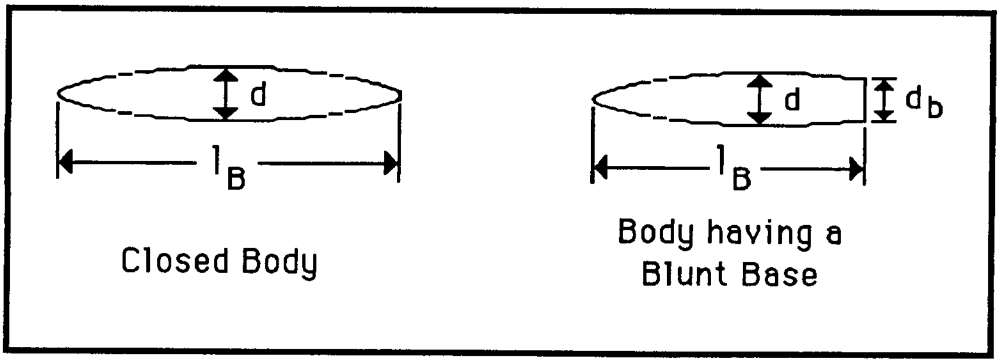



**FIGURE 4.5 -- GENERALIZED FUSELAGE DEFINITIONS**

The designer should avoid blunt base bodies if at all possible because the $C_{Db}$ term can become quite large. If a jet engine exhaust completely fills the base region, then the base drag is zero.

The problem of estimating the wing-body combination $C_{Do}$ is one of properly accounting for the mutual interference effects of one component on the other. The problem is extremely complicated and requires a fairly accurate picture of the flow field interactions. However, this information is not available at the conceptual design stage. Correction studies have been conducted on wing-body interference [11]. These indicate that the wing-body interference effects amount to about ± 5% for subsonic flow. It would be hard, indeed almost certainly incorrect, to argue that the $C_{Do}$ of the components is accurate to within 5%. Thus, the wing-body subsonic $C_{Do}$ could be assumed to simply be the sum of the components, that is,

$$(C_{Do})_{wing\text{-}body} = (C_{Do})_{wing} + (C_{Do})\, S_B / S_{ref} + \Delta C_{Do}, \text{ and} \qquad [4\text{-}33]$$

is based upon $S_{ref}$.

### 4.3.2 Minimum Drag and Maximum L/D

The total drag coefficient for an uncambered aircraft is expressed as

$$C_D = C_{Do} + KC_L^2, \text{ and}$$

the total drag as

$$D = (\, C_{Do} + KC_L^2)\, qS. \qquad [4\text{-}34]$$

The total drag could be represented as a goal constraint in the compromise Decision Support Problem, and if the target value is selected properly the drag can be held to a minimum. If $D_{TV}$ is the target value for the drag, the corresponding goal constraint has the following form:

---

$$\{(C_{Do} + KC_L^2)\, qS\} / D_{TV} + d^- - d^+ = 1. \qquad \mathbf{[4\text{-}34.G]}$$

---

The aircraft's drag was not used as a constraint for this template. It takes experience to be able to determine what a good target value for drag is.

### 4.3.3 Determination of the Optimum Drag Coefficient

To obtain the value of $C_L$ that minimizes the total drag the following operation is performed:

$$\partial D/\partial C_L = 0, \qquad [4\text{-}35]$$

with $q = (W/S) / C_L$. Differentiating equation [4-34] with respect to $C_L$ gives $C_{Do} = KC_L^2$. In other words, the zero lift drag coefficient is equal to the drag due to lift. From this relationship the $C_L$ for minimum drag or the optimum $C_L$ is found to be

$$C_{Lopt} = (C_{Do} / K)^{1/2}. \qquad [4\text{-}36]$$

Another useful and interesting value to find for $C_L$ is the one that maximizes L/D or $C_L/C_D$. In other words the following operation is performed:

$$\partial( C_L/C_D ) / \partial C_L = 0. \qquad [4\text{-}37]$$

This operation yields the value for maximum L/D as

$$C_L = (C_{Do} / K)^{1/2}; \qquad [4\text{-}38]$$

the same value as for minimum drag. This gives the expression for $(L/D)_{max}$ as

$$(L/D)_{max} = 1 / [2(C_{Do}K]^{1/2}. \qquad [4\text{-}39]$$

The total drag coefficient for a cambered airfoil is expressed as

$$C_D = C_{Dmin} + K'C_L{}^2 + K''(C_L - C_{Lmin})^2. \qquad [4\text{-}40]$$

The $C_L$ for maximum L/D or minimum drag is

$$C_{Lopt} = \{ [C_{Dmin} + KC_{Lmin}{}^2] / [K' + K''] \}^{1/2}. \qquad [4\text{-}41]$$

### 4.3.4 Endurance or Loiter

The aircraft endurance or loiter is expressed (in hours) by

$$E = (L/D)\ (1/C)\ \ln(W_i/W_f). \qquad [4\text{-}42]$$

From equation [4-42] it is observed that in order to obtain maximum endurance for a given weight change (i.e., given the amount of fuel), the aircraft should fly at that altitude and Mach number such that the endurance parameter (L/D) (1/C) is a maximum. The designer should be aware that maximum endurance is not necessarily at that velocity for $(L/D)_{max}$ because C is dependent upon Mach number and altitude and a different velocity could give a larger value for (L/D) (1/C). However, the velocity for $(L/D)_{max}$ is close (within 10%) of the velocity for maximum endurance. The fuel fraction , $W_f/W_i$ , can be determined using equation [4-45]. For the mission this fuel fraction becomes

$$W_f/W_i = 1 - W_{fuel}/W_{TO}$$

Endurance is modeled as a system goal only in the template. If $E_{TV}$ is the target value of the endurance the system goal is:

---

$$\{(L/D)\ (1/C)\ \ln[(1- W_{fuel}/W_{TO})^{-1}]\}/ E_{TV} + d_4^- - d_4^+ = 1. \qquad \textbf{[4-42.G]}$$

---

## 4.4 EMPIRICAL AND STATISTICAL REQUIREMENTS

Some of the quantitative relationships employed in the compromise template are based on correlations of characteristics of present day turbojet - turbofan powered aircraft. These correlations are in terms of fundamental aircraft design parameters, and constrain the aircraft design to within the range of existing aircraft. Technical feasibility is ensured through the use of these constraints in that demands placed on the aircraft performance do not exceed the capabilities of existing aircraft. The intent is not to restrict certain values to be conservative, but rather to confine the design so as not to go beyond capacity of present day technology.

### 4.4.1 Weight Prediction

In the conceptual design of aircraft it is difficult to predict weight accurately because of required assumptions that are based on very little information. The actual propulsion, avionics, instruments, landing gear, materials, etc. are still undetermined, and introduce uncertainty into the weight prediction. There are numerous correlations for predicting weight, and which, if any, is best to use is not clear. Therefore, two different weight analyses are employed, and when a degree of closeness between the two is obtained, weight matching is said to have been achieved.

Consider the take-off weight, $W_{TO}$, to be made up of

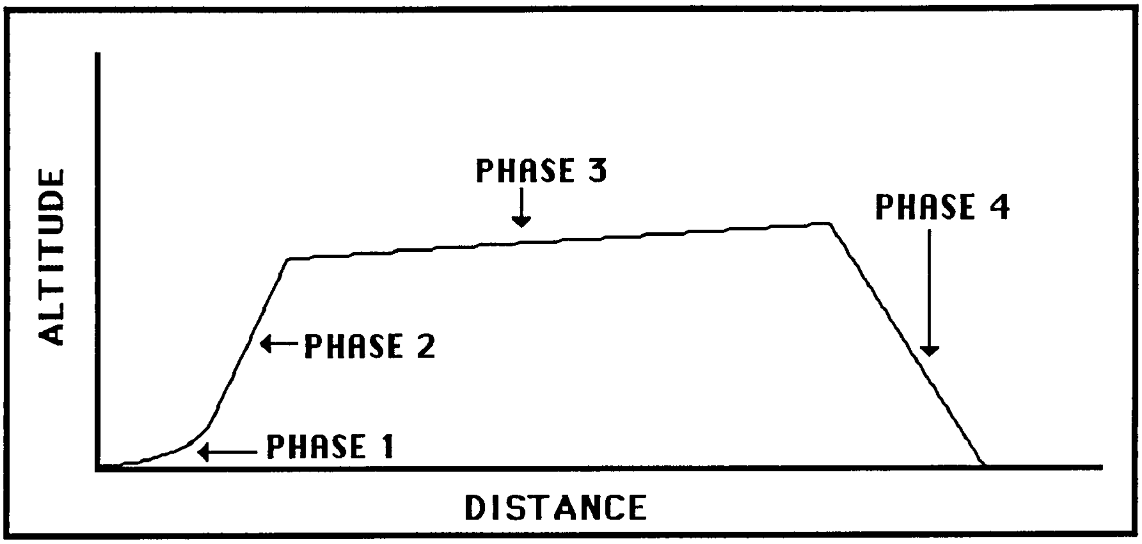
$$W_{TO} = W_{fuel} + W_{payload} + W_{empty} \, . \qquad [4\text{-}43]$$

The payload weight, $W_{payload}$, includes all expendable fixed weight items. In addition to the actual payload it includes nonexpendable (crew and equipment) and expendable (passengers, baggage, food and drink) fixed weight items. Payload is a function of the number of passengers, which is a function of the two system variables, fuselage length and diameter. The payload weight is not a function of $W_{TO}$, and can be removed from the aircraft and it would still be ready to fly. For example, the passengers, cargo, ammunition are all expendable, whereas the crew and equipment are not. Payload weight is an objective that is clearly defined in the mission requirements and is a fixed number independent of $W_{TO}$. However, the payload weight is related to the number of passengers on the aircraft plus a fixed amount for expendables. We were unable to find the estimated weight per passenger for transport aircraft design in the literature. The average passenger weight was estimated to be in the vicinity of 160 lbs, and it was decided that the passenger may carry on a maximum of 40 lbs. of baggage. This allows for a total estimated average weight per passenger of 200 lbs. This number appears large, but whenever total passenger weight is is less than estimated an aircraft could take on more cargo. The payload weight in equation [4-43] is quantified as follows:

$$W_{payload} = 200.0 \, N_p + W_{fixed} \qquad [4\text{-}44]$$

where: $N_p$ is the number of passengers and $W_{fixed}$ is the weight of the expendables.

In equation [4-43] $W_{empty}$ is the operating empty weight of the aircraft which includes primarily the structure, the engine(s), and equipment. $W_{fuel}$ is the weight of the fuel required for the mission plus reserves. The fuel weight is calculated through the definition of the flight profile defined in mission requirements. The flight is divided into four phases, and the fuel fraction with respect to the take-off weight for each is calculated. The following four phases define the mission profile used in the compromise template.




phase 1 - engine start and take-off
phase 2 - accelerate and climb to cruise velocity
phase 3 - cruise to destination
phase 4 - loiter

**FIGURE 4.6 -- MISSION PROFILE**

The fuel fraction for each can be determined, and the individual weight ratios for each phase, $W_{i+1}/ W_i$, upon multiplication together give the complete mission fuel fraction [43]. The fuel fraction for the mission is defined as

$$W_f/W_i = (W_4/W_3)(W_3/W_2)(W_2/W_1) \text{ therefore,}$$

$$W_f/W_i = \{\exp[R(c/V)/(L/D)]\}^{-1}. \qquad [4\text{-}45]$$

From the fuel fraction, the fuel weight is defined as

$$W_{fuel} = (1 + \text{reserve} + \text{trapped})(1 - (W_f / W_i)) W_{TO}. \qquad [4\text{-}46]$$

From the above expression the calculated empty weight is [43]

$$(W_{empty})_{calculated} = W_{TO} - W_{fuel} - W_{payload}, \qquad [4\text{-}47]$$

where $W_{payload}$ is defined in equation [4-44].

The required empty weight determined from historical data on transport aircraft (based on conventional metal structures) as a function of take-off weight is [43]

$$(W_{empty})_{required} = 1.0377(W_{TO})^{0.9362}. \qquad [4\text{-}48]$$

When the relative difference between the calculated empty weight and the required empty weight is

$$| (W_{empty})_{calculated} - (W_{empty})_{required} | / \{(W_{empty})_{required}\} \leq 10\%, \qquad [4\text{-}49]$$

a matching of the two different weight analyses is achieved. This weight matching to within 10% is an introduction to 'slop' in aircraft design. The aircraft weights are extremely important in the calculation of other aircraft technical analyses. Therefore, a weight matching goal constraint of 1% is used to ensure that this is met. This is an important goal, because if the aircraft weight is off then all the analyses and constraints involving the aircraft weight will also be off. Because of this fact, this goal should always be given a high priority. The weight matching goal for the template is

$$| (W_{empty})_{calculated} - (W_{empty})_{required}| / \{(W_{empty})_{required}\} + d_5^- - d_5^+ = 1\% \qquad \mathbf{[4\text{-}49.G]}$$

An important weight prediction technique described by Loftin [27] is an aircraft's useful load fraction, U. The useful load is the difference between the empty weight established when the airplane is completed by the manufacturer and the gross weight, which is the maximum legal flying weight. Useful load can make or break a new airplane intended for the serious business and pleasure markets. In view of this, every new design must provide as much flight performance and and safety as possible at minimum empty weight. The useful load fractions for different jet aircraft vary from 0.58 to 0.30, [43], but most are in the vicinity of 0.45 to 0.50. The following equation is for the useful load fraction with $W_{payload}$ defined in equation [4-44]:

$$U = (W_{payload} + W_f) / W_{TO} \qquad [4\text{-}50]$$

A large useful load fraction is desired and this can be factored into the compromise DSP template as a system goal, namely,

$$\{(W_{payload} + W_f) / W_{TO}\} / U_{TV} + d_6^- - d_6^+ = 1. \qquad \mathbf{[4\text{-}50.G]}$$

### 4.4.2 Form Factors

The form factor, $FF_{wing}$, for wing surfaces is determined from

$$FF_{wing} = 1 + 60(t/c)^4 + K(t/c)\,, \qquad [4\text{-}51]$$

where (t/c) is the thickness ratio of the airfoil [46]. This factor is useful for predicting wing drag characteristics. The value of K is bounded between 1.2 (for conventional airfoils) and 2.0 for advanced airfoils which generally have their maximum thickness much farther aft than do conventional airfoils. The constant 60 used in equation [4-49] represents conventional airfoils. A value of 100 is recommended for laminar type flows. For conventional aircraft the wing form factor lies within the range of $0.9 \leq FF \leq 1.25$. Thus, two constraints can be defined to help ensure a reasonable wing shape based upon drag considerations. They are

$$1 + 60(t/c)^4 + K(t/c) \geq FF_{wing,\,min} = 0.9 \text{ , and} \qquad \textbf{[4-51.C.a]}$$

$$1 + 60(t/c)^4 + K(t/c) \leq FF_{wing,\,max} = 1.25 \text{ .} \qquad \textbf{[4-51.C.b]}$$

Since t/c is a design constant for this version of the template, the wing form factors were not necessary and therefore removed.

The form factor for fuselage and tank shapes is given by

$$FF_{fuse} = 1 + 60/(l/d)^3 + 0.0025\,(l/d)\,, \qquad [4\text{-}52]$$

where l/d is the fineness ratio of the body in question [46]. For non-circular bodies, the fineness ratio is determined using the length and the root-mean-square of the width and height. A survey was conducted and it was found that similar transport aircraft had fuselage form factors within the range $0.85 \leq FF_{fuse} \leq 1.1$. After running the initial template results, it was found that only the maximum $FF_{fuse}$ was necessary to design an aircraft. The constraint describing the fuselage shape based upon drag characteristic was developed and is given as

$$1 + 60/(l/d)^3 + 0.0025\,(l/d) \leq FF_{fuse,\,max} = 1.1 \text{ .} \qquad \textbf{[4-52.C]}$$

### 4.4.3 Wing and Thrust Loading

The take-off wing loading, $(W/S)_{TO}$ is a very important parameter as it governs the sizing of the wing and weighs heavily in the dominant performance features of the aircraft. The range, stall speed, minimum acceleration time, landing and take-off lengths, are all critically influenced by the wing loading. For example, good cruise efficiency drives the $(W/S)_{TO}$ to high values whereas good maneuverability requires a low $(W/S)_{TO}$. Since this template is for transport aircraft, a higher $(W/S)_{TO}$ is desired for efficiency since a transport aircraft rarely, if ever, is required to perform aggressive actions. Low values of the wing loading drastically increase the take-off field length for transport aircraft where the installed thrust to weight ratio is much lower than for combat aircraft. Since the dominant mission phase of the aircraft being modeled by this template is for cruising, an appropriate range for the wing loading is $80 \leq (W/S)_{TO} \leq 140$. This requirement takes the form of the following two system constraints:

$$(W/S)_{TO} \geq 80, \text{ and} \qquad \textbf{[4-53.C.a]}$$

$$(W/S)_{TO} \leq 140\,. \qquad \textbf{[4-53.C.b]}$$

The thrust loading, $W_{TO}/T_i$, exercises a great deal of influence in determining the lift coefficients and the lift to drag ratio which virtually all performance characteristics are a function of. The take-off and landing field lengths are also heavily dependent on $W_{TO}/T_i$. The inverse of this relationship is a simple estimation of the attainable acceleration upon take-off, and accordingly is a very important design factor. As the take-off run gets under way there is nothing so satisfying as pushing the throttle down and feeling the seat back give your spine a good shove. This is acceleration at work, and the amount available can be very critical for operation out of short fields. Similar reasons as stated above for the wing loading apply for the thrust loading as well. The range in which $W_{TO}/T_i$ is expected to be for conventional transport aircraft is $2.5 \leq W_{TO}/T_i \leq 5.0$. From this requirement, two system constraints for confining the ratio of take-off weight to installed thrust to realizable values are defined as

$$W_{TO}/T_i \leq 5\text{, and} \qquad \textbf{[4-54.C.a]}$$

$$W_{TO}/T_i \geq 2.5\,. \qquad \textbf{[4-54.C.b]}$$

### 4.4.4 Aspect Ratio

The effect of aspect ratio, $b^2/S$, (for definition see Figure 4.4) upon induced drag is considerable. At the comparatively high lift coefficients required during climb, increasing the wing aspect ratio will lower the induced drag, which intern releases power to increase the climb rate. However, too high of an aspect ratio is unpractical for general aviation use from both structural weight and ground handling considerations. It is also apparent that high aspect ratio is not important to aircraft designed primarily for high-speed cruise operation at low values of lift coefficient. At a speed requiring a $C_L$, induced drag changes very slightly whether the wing aspect ratio is 4, 8, or 20. Some compromise is necessary, and finalizing the design within a range of acceptable aspect ratios is required. Existing transport aircraft employ aspect ratios within the range $7 \leq b^2/S \leq 10.5$. This design information is represented as two system constraints:

$$b^2/S \leq 10.5\text{, and} \qquad \textbf{[4-55.C.a]}$$

$$b^2/S \geq 7. \qquad \textbf{[4-55.C.b]}$$

### 4.4.5 Airfoil Thickness Ratio vs. Mach Number

Critical Mach number, $M_{CR}$ of an airfoil usually represents the maximum speed attainable for high subsonic aircraft due to the increase in thrust required for flight past $M_{CR}$. The designer strives to design so that this upper speed limit is pushed as far back as possible on subsonic aircraft. Ideally, the $M_{CR}$ should be larger than the fuselage $M_{CR}$. All aircraft components have a $M_{CR}$, and flight past this limit is accompanied by a large increase in drag. The individual component drag increases are additive for the most part and their sum at any Mach number represents the minimum thrust required for a vehicle to accelerate past that Mach number. Therefore, by having the wing and fuselage drag increases peak at different Mach numbers, the thrust requirement is lessened, [43].

The relationship of t/c vs. Mach number is represented as a system goal in the compromise aircraft Decision Support Problem. If $(M)_{TV}$ is the target value for the Mach number, the corresponding goal has the form of

$$[0.94 - (t/c)] / (M)_{TV} + d^- - d^+ = 1. \qquad \textbf{[4-56.G]}$$

The preceding goal was formulated by the authors for the first version of the template [9,30]. The airfoil thickness and Mach number parameters were design constants for the version presented in this report. The reasons for the removal of this goal are discussed briefly in Section 4.7.

## 4.5 ECONOMIC EFFICIENCY

Good designs are those that represent an optimal trade-off between technical and economic efficiencies. This by no means guarantees commercial success of the design. In our template we model economic considerations through two system goals. The first reflects the desirability of the aircraft having a certain number of seats and the second the desirability of an appropriate return on investment.

### 4.5.1 The Number of Passengers

Some of the preceding constraints and goals are aimed at lowering the fuel weight. This deals with the cost side of the ledger. The other side of the ledger requires the modeling of benefits, namely, the earning capacity of the aircraft. Commercial transport aircraft income is a function of the number of passengers carried, or the volume available for payload. For passenger service, the number of seats is determined by specifying the width of each seat, aisle, and cockpit, and equipment requirements. If $N_p$ represents the number of passengers and it is assumed that each passenger seat requires 22 inches for width, 43 inches for depth, and a single aisle is included requiring 24 inches for width then the desired income is reflected by the following goal [43]:

$$\{[0.867\, l_b\, ((D / 1.83) - 1)] / 3.75\} / N_p + d_7^- - d_7^+ = 1, \qquad \textbf{[4-57.G]}$$

### 4.5.2 Return on Investment

Return on investment, ROI, has been generally regarded as the richest of the available economic variables [56]. Direct operating cost suffers from an ambiguity in that the methods of calculation adhere to no universally accepted standard at the present time. As previously indicated, an augmented version of a standard industry model is being used in this template. However, there remains the issue of which method represents the proper breakdown of direct operating costs and indirect operating costs. Since ROI involves complete accounting of all costs, ROI avoids this issue and is therefore used to model a mojor part of the economic efficiency of the aircraft.

A simple return on investment is calculated in the following manner [57]:

$$ROI = [( I - DOC - IOC ( 1 - tx ) U ) / 0.9C_{A\$} ] \times 100 \quad [4\text{-}58]$$

Hourly income, I, minus direct and indirect operating costs, DOC and IOC, is the profit per hour. Determining the after-taxes profit using tx as the tax rate and multiplying by the annual utilization, U, and then dividing by the airplane purchase price minus the ten percent investment tax credit, $0.9C_{A\$}$ yield the annual return on investment.

If $ROI_{TV}$ is the desired return on investment, then the system goal is:

$$ROI / ROI_{TV} + d_8^- - d_8^+ = 1 \quad \textbf{[4-59G]}$$

Additionally, another economic parameter that is calculated is the income required, $I_{req}$, per flight for a $ROI_{TV}$ return on investment. It basically involves solving for I in equation [4-58] and converting to a per flight basis:

$$I_{req} = [ 0.9C_{A\$}(ROI) (0.01) / ( 1 - tx ) U + DOC + IOC ] \; k \quad [4\text{-}60]$$

where k is a conversion factor from annual income to per flight income [56].

A fundamental problem in using annual return on investment is trying to determine the income term for equation [4-58]. It requires predicting the impact of price and traffic growth upon supply and demand. The assumption that trying to maximize airline ROI is equivalent to optimizing the transport manufacturer's profitability is typically used and relied upon in this analysis. Even so, major complaints about using airline ROI are that it requires modeling income, which is different for each city-pair and each airline, and it requires airline income statistics as a function of the important design parameters which are not readily available to the designer. Since a major portion of ROI is the income generated by the transport airplane, the simple formulas used for estimating this in the past tended to negate the accuracy of the rest of the analysis. It has been shown that relatively minor modifications to the assumptions used for developing the income result in significantly different implications during trade-off studies [56].

Economic design constants used in this template are not those used by Boeing in the design of its aircraft. We have based our work on that incorporated in Program OPDOT [56]. Hence, the study is based on figures for 1979. The computation of the DOC is based on a method developed by American Airlines [5,56]. Aircraft development and production costs are calculated according to Nicolai [43] and [5]. Aircraft maintenance costs were estimated from industry statistics [4,5,29]. The indirect operating cost computation is based on a method developed at Lockheed [63]. Where possible and appropriate we used information from Steiner [62]. The implementation of these computations is patterned after that used in Program OPDOT and [5]. Further details are provided in Appendix C.

## 4.6 THE MATHEMATICAL FORM OF THE COMPROMISE DSP

The mathematical problem is a restatement of the word problem. The mathematical formulation exhibits a one-to-one correspondence to the word formulation presented in Chapter 2.

## Given

Airport performance requirements
Cruise altitude
Data on similar subsonic transport aircraft
Density of air at sea level and 35000 ft
Federal air regulations
Mission requirements
Specific fuel consumption
Take-off and landing speed
Economic constants and considerations

## Important Relationships and Equations

$C_L = W/qS$ [Lift coefficient during cruise]
$C_L = W_{TO} / (qS)$ [Lift coefficient at take-off]
$C_{Do} = (C_{Do})_{wing} + (C_{Do})_{body}$ [Zero lift drag coefficient]
$(C_{Do})_{wing} = C_f[1+L''(t/c) + 100(t/c)^4]\, R''\, S_{wet}/S_{ref}$
where:
L" is the airfoil thickness location parameter,
L = 1.2 for max t/c located at $x \geq 0.3c$, and
L = 2.0 for max t/c at $x < 0.3c$.
$(C_{Do})_{body} = (C_{Df})_B + C_{Db}$
$(C_{Df})_B = C_f[1 + 60/(l_B/d)^3 + 0.0025(l_B/d)]\, S_s/S_B$
$C_{Db} = 0.029 / [(C_{Df})_B]^{1/2}$
$(C_{Do})_{total} = \{C_f[1+L''(t/c) + 100(t/c)^4]\, R''\, S_{wet}/S_{ref}\} + \{C_f[1 + 60/(l_B/d)^3 + 0.0025(l_B/d)]\, S_s/S_B\} + 0.029 / \{Cf[1 + 60/(l_B/d)^3 + 0.0025(l_B/d)]\, S_s/S_B\}^{1/2} + DC_{Do}$
$C_D = C_{Do} + KC_L^2$ [Total drag coefficient]
$e = e'[1 - (d/b)^2]$
$e' = 0.96$
$K = 1/\pi Ae$
$K' = (1 + \delta)/\pi Ae$ (for symmetric wings $\delta$=0)
$q = 1/2\, (\rho V_\infty^2)$ or $= 1/2\, (\rho M^2 a^2)$
$L/D = C_L/(C_{Do} + K\, C_L^2)$
$(L/D)_{max} = 1/2\, (C_{Do}\, K)^{-1/2}$
$T_R = C_{Do} qS + KW^2/qS$
$W_f/W_i = \{\exp\, [R\, (c/V) / (L/D)\, ]\, \}^{-1}$
$W_f/W_i = \{\exp\, \{(Rc/Ma)(5280/3600)\, [\, (W_{TO}/(1/2\, \rho\, M^2\, a^2\, S)) / ( C_{Do} + K\, (W_{TO}/(1/2\, \rho\, M^2\, a^2\, S))^2 )\, ]^{-1}\, \}\, \}^{-1}$
$(W_e)_{required} = 1.0377(W_{TO})^{0.9362}$
$(W_e)_{assumed} = W_{TO} - W_{fuel} - W_{payload}$
$W_{fuel} = (1 + reserve + trapped)\, ( 1 - W_f/W_i)W_{TO}$

## Find

| The values of the **system variables** | | Units |
|---|---|---|
| Wing area, | $S$ | [$ft^2$] |
| Installed thrust, | $Ti$ | [lb] |
| Fuselage length, | $l$ | [ft] |
| Take-off weight, | $W_{TO}$ | [lb] |
| Wing span, | $b$ | [ft] |
| Fuselage diameter, | $d$ | [ft] |

The values of the **deviation variables** associated with
the landing field length goal,
the missed approach climb gradient goal,
the cruise range goal,
the endurance goal,
the useful load fraction goal,
the weight matching goal,
the number of passengers goal, and
the return on investment goal.

## Satisfy **Units Eq.No.**

The **system constraints**

The thrust required for cruise climb ratio must be greater than 1. [-]

$T_i / T_R \geq 1$ [4-22]

The fuel weight must be greater than a specific minimum for range requirements. [lbs]

$(1 + \text{reserve} + \text{trapped})\ (1 - W_f/W_i)W_{TO} \geq W_{fuel}$ [4-46]

Thrust for cruise must be greater than or equal to drag. [lbs]

$\{(C_{Do} + KC_L{}^2)qS\} \geq D$ [4-34]

The missed approach climb gradient must be greater than $q_L$ percent with one engine inoperable. [%]

$(T_i/W_{TO} - W_{fuel})\ [(N-1)/N] - (L/D)^{-1} \geq q_L$ [4-6]

The take-off field length must be less than $S_{TO}$ ft. [ft]

$20.9[(W_{TO}/S) / (C_{Lmax}\ (T_i/W_{TO}) + \ 87[(W_{TO}/S)\ 1/C_{Lmax}] \leq S_{TO}$ [4-11]

The second segment climb gradient must be greater than $q_{TO}$ percent with one engine inoperable. [%]

$(T_i/W_{TO})[(N-1)/N] - (L/D)^{-1} \ \geq q_{TO}$ [4-12]

The range must be greater than R nautical miles. [nm]

$(0.943)\ aM/[2c(C_{Do}\ K)^{1/2}]\ \ln[(1 - W_{fuel}/W_{TO})^{-1}] \ \geq R$ [4-13]

The wing loading must be within the range of values for similar existing aircraft. [nmu][1]

$80 \leq W_{TO}/S < 140$ [4-53]

$W_{TO} - 140\, S \leq 0$

$W_{TO} - 80\, S \geq 0$

The thrust loading must be within the range of values for existing aircraft. [-]

$2.5 \leq W_{TO}/T_i \leq 5$ [4-54]

$W_{TO} - 5\, T_i \leq 0$

$W_{TO} - 2.5\, T_i \geq 0$

The wing area to fuselage area ratio must be within the range of values for existing aircraft. [-]

$13.5 \leq 4S/\pi\, d^2 \leq 25$

$4S/\pi\, d^2 - 25 \leq 0$

$13.5 - 4S/\pi\, d^2 \leq 0$

The fuselage form factor must be within the range of values for existing aircraft. [-]

$0.85 \leq 1 + 60/\{(l_B/d)^3\} + 0.0025(l_B/d) \leq 1.1$ [4-52]

$1 + 60/\{(l_B/d)^3\} + 0.0025(l_B/d) - 1.1 \leq 0$

$0.85 - 1 + 60/\{(l_B/d)^3\} + 0.0025(l_B/d) \leq 0$

(Only the maximum fuselage form factor was used in this template.)

The aspect ratio must be within the range of values for existing aircraft. [-]

$7 \leq b^2/S \leq 12$ [4-55]

$b^2/S - 12 \leq 0$

$7 - b^2/S \leq 0$

### The **system goals**[2]

The landing field length

$\{118[((W_{TO} - W_{fuel}) / S) / (C_{Lmax})] + 400\} / (S_L)_{TV} + d_1^- - d_1^+ = 1.$ [4-3]

The missed approach on landing with one engine inoperable

$\{(T_i/W_{TO} - W_{fuel})\, [(N-1)/N] - (L/D)^{-1}\} / q_{LTV} + d_2^- - d_2^+ = 1.$ [4-6]

The cruise range

$\{(0.943)\, aM/[2c(C_{Do}\, K)^{1/2}]\ \ln[(1 - W_{fuel}/W_{TO})^{-1}]\} / R_{TV} + d_3^- - d_3^+ = 1.$ [4-13]

Endurance or loiter

1 "nmu" refers to no meaningful units.

2 It is important that the systm goals are normalized so that the maximum values of the deviation variables are reasonably close.For this template, the deviation variables are nonnegative and less than two.

Useful load fraction

$\{(W_{payload} + W_{fuel})/W_{TO}\} / U_{TV} + d_5^- - d_5^+ = 1.$ [4-50]

Weight matching

$|(W_{empty}) - (W_{empty})_{required}| / (W_{empty})_{required} + d_6^- - d_6^+ = 1.$ [4-49]

The number of passengers

$\{[0.867\ l_B\ ((d/1.83) - 1)]/3.75\} / N_{pTV} + d_7 - d_7^+ = 1.$ [4-57]

The return on investment

$(ROI) / ROI_{TV} + d_8^- - d_8 = 1.$ [4-60]

The **bounds** on the **system variables**

| | | | | | |
|---|---|---|---|---|---|
| Wing area | $[S]_{min}$ | ≤ | $[S]$ | ≤ | $[S]_{max}$ |
| Installed thrust | $[Ti]_{min}$ | ≤ | $[Ti]$ | ≤ | $[Ti]_{max}$ |
| Fuselage length | $[l]_{min}$ | ≤ | $[l]$ | ≤ | $[l]_{max}$ |
| Fuselage diameter | $[d]_{min}$ | ≤ | $[d]$ | ≤ | $[d]_{max}$ |
| Take-off weight | $[W_{TO}]_{min}$ | ≤ | $[W_{TO}]$ | ≤ | $[W_{TO}]_{max}$ |
| Wing span | $[b]_{min}$ | ≤ | $[b]$ | ≤ | $[b]_{max}$ |

**Minimize**

The sum of the **deviation variables**

$$Z = P_1(d_1^- + d_1^+) + P_2(d_2^- + d_2^+) + P_3(d_3^- + d_3^+) + P_4(d_4^- + d_4^+) + P_5(d_5^- + d_5^+) + P_6(d_6^- + d_6^+) + P_7(d_7^- + d_7^+) + P_8(d_8^- + d_8^+)$$

The preceding formulation is solved using the DSIDES System using the preemptive approach (Section 2.4.2). The priorities, $P_i$ , reflect rank order preference for the achievement of the system goals, that is, one knows that goal A is preferred to goal B but one does not know by how much.

## 4.7 ON THE DEVELOPMENT OF THE AIRCRAFT COMPROMISE DSP TEMPLATE

The creation of this template involved a number of false starts, forays into blind alleys and a tremendous amount of work. A template was postulated by Marinopoulos in December 1986. One of the most time consuming tasks was to determine some of the design constants. Some were obtained from text books, others by talking to people in the know, and the rest had to be determined by exercising the template repeatedly. We had to also experiment with the goal priorities. This too involved exercising the template extensively.

The template proposed by Marinopoulos [30] was validated by Bradberry, Entrekin and Jackson [9]. This template included two more system variables (Mach number and airfoil thickness ratio) than the one described in this report. Further, this template did not include the rate of return goal. On analysis of the results presented in [9,30] it became clear that the Mach number and the airfoil thickness ratio should, at this time, be treated as design constants. This is justified on the basis that most subsonic medium range transport aircraft travel at relatively the same speed - approximately 0.8 Mach. It is not that critical whether a transport cruises at 0.78 or 0.82 Mach. The maximum airfoil thickness ratio is usually chosen at the beginning of the design process, and it usually is the lowest possible thickness without being supercritical which is 0.10 or less. We were unable to find information that would support the creation of system constraint and goals that involved the airfoil thickness. It is entirely possible that the aircraft thickness ratio should and could be treated as a sytem variable in the future. By fixing the cruise Mach number to 0.8 and airfoil thickness ratio to 0.12 it was possible to drop (from the template proposed by Marinopoulos) three technically weak constraints, namely, the wing form factor constraint, wing form factor system goal and the airfoil thickness ratio versus Mach number system goal.

Much was learned in the creation of the compromise DSP template - some of it through time consuming trial and error. We learned that wing configuration and weight related parameters essentially governed the design. Fuel consumption and range contributed to a lesser extent. The fuselage length was relatively unaffected. This is understandable because of the emphasis, in the earlier version of the template, being on achieving technical efficiency for the aircraft. Consistently, in the early runs, the fuselage length would be shorter in proportion to the wing span than is the case for similar aircraft. This led to the generation of a fuselage volume constraint that was formulated in terms of the number of passengers. This constraint proved to be a crude estimate but was effective in varying the fuselage length. The problem with this constraint was that it was not verifiable and was difficult to apply accurately to a wide range of aircraft configurations. Further, design runs for various aircraft configurations revealed that the nonlinearity of the fuselage volume constraint created a condition were the number of desired passengers for a given configuration could not be accurately represented. This led to the generation of a linear fuselage to passenger number relation. This constraint proved to be more effective and allowed for fine-tuning the parameters that affect the length of the fuselage.

The validation of the template proposed in this chapter is described in Chapter 5. In Chapter 6 the use of the template in the design of a Boeing 747-200 type airplane is described and a critical evaluation is included in Chapter 7. A listing of the template and a sample output are included in Appendices C and D, respectively.

# CHAPTER 5
## CASE STUDY - BOEING 727-200
### A Trade-off Between Technical and Economic Efficiencies

In Chapter 2, a general word formulation of a compromise DSP template for the design of subsonic jet transports in the conceptual stage of design is presented. Based on the word formulation, in Chapter 4, a general mathematical formulation of the compromise DSP template is developed and presented. In this chapter t template is particularized for a Boeing 727-200 subsonic jet transport. This template has been exercised and to the extent possible - validated.

As part of the validation process three questions are posed and answered, namely,:

- Can the template be used to design subsonic jet transport?
- In what ways should the template and the associated software be improved?
- How can the template be used in the conceptual design of aircraft in general?

During the course of this project two versions of the template were developed. The first is documented by Marinopoulos in [30] and the second (together with the differences from the first) by Jackson in [16]. Some of the differences between the two versions are described in Section 4.7. In this chapter, however, only the second version of the template is presented.

## 5.1 THE VALIDATION OF THE PROPOSED COMPROMISE DSP TEMPLATE

The problem statement and the general form of the compromise DSP template is presented in Sections 2.5.2 and 2.5.3, respectively. The general mathematical form of the template is presented in Section 4.6. As part of the validation process four questions are posed and answered, namely,

1. Can the template be used in the conceptual design of subsonic jet transport?
2. In what ways should the template be improved?
3. How can the template be used in the conceptual design of aircraft in general?
4. In what ways should the associated software be improved?

An answer to the first question is extremely important. A first step in answering this question necessitates our showing that the design obtained using this template is reasonable and correct in the context of what is known and already achieved. In other words, we need to show that given the same problem statement the design obtained by exercising the template is similar to a design (obtained by conventional means) that has been implemented. Therefore, the problem statement (Section 2.5.2) and the general formulation (Sections 2.5.2 and 4.6) of the template needs to be particularized and then exercised. This is done in the remainder of this section. The second step in answering the first question and laying the basis for answering the next two questions is to exercise the template and to report on it. This is covered in Section 5.2. Answers to the second and third questions are presented in Sections 5.3.and 5.4, respectively. The fourth question is addressed in Chapter 7.

### 5.1.1 Particularization of the DSP Template - The Boeing 727-200 Airplane

The Boeing 727-200, Figure 5.1, is a three-engined subsonic jet transport aircraft designed for short to medium ranges and short runway operations. It is considered to be one of the most successful jet transport aircraft ever produced. The aircraft is popular with the airlines because it can be operated profitably over various range segments and passenger load requirements. The 727 design was originally laid out in 1959 and 1960 - almost thirty years ago. The airplane is no longer in production, but as of September 1978 almost 1400 had been produced and the equivalent of ten billion 1978 dollars passed through the Boeing Aircraft Company.

The Boeing 727-200 airplane has been chosen as the airplane to be designed using our template. Due to its world-wide popularity a lot of information has found its way into the literature. In the light of the success of the airplane, J. E. Steiner (chief engineer of the design team) said, "While we no doubt did a good many things wrong, it would seem we must have done some things right" [62]. We therefore feel comfortable in assuming that the 727-200 design is somewhat of an "optimum" design and this design is not "sitting" in some isolated hollow (or on some isolated peak) in the design space. This is important for the initial attempt at using an untested template for designing an aircraft.

The Boeing 727-200 mission requirements and design criteria are summarized in Tables 5.1 to 5.4. One of the problems faced by the designers was to achieve a

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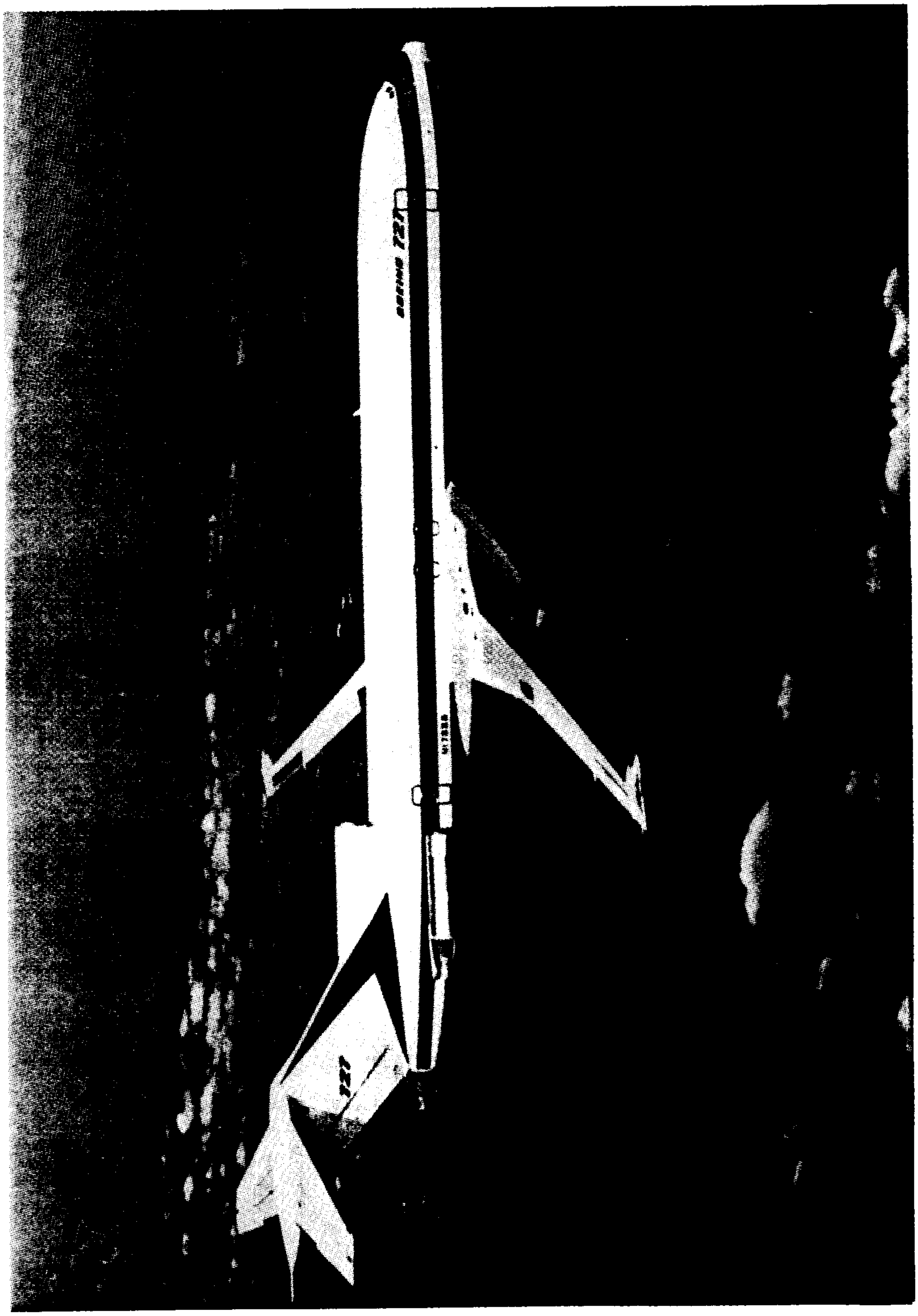

FIGURE 5.1 --.THE BOEING 727-200 AIRPLANE

compromise between economics and performance [62]. The Boeing engineers wanted the smallest possible wing to decrease direct operating cost and also wanted low approach speed, short field length for operation - plus excellent flight handling characteristics. The maximum landing field length was fixed for the Boeing 727 by LaGuardia's runway 4-22. This was the only instrument runway at LaGuardia and it had a length of 4860 feet (it has been lengthened since then) [62].

The Boeing 727-200's system variables and the upper and lower bounds used in exercising the template are listed in Table 5.1. These values were difficult to ascertain due to the many different versions of this aircraft; wherever possible the actual Boeing information was used. For the 727-200, the take-off weight varies between 175,000 to 220,000 lbs. depending on its options. The value chosen was 210,000 lbs.[29]. Aircraft can fly many different ranges according to the payload. Transport aircraft are designed to achieve a maximum range for the desired payload. For the maximum mission requirements, a payload of 41,000 lbs. and a range of 2900 nautical miles is listed for the Boeing 727-200.

| SYSTEM VARIABLES | BOUNDS | BOEING 727-200 |
|---|---|---|
| 1. WING AREA ($ft^2$) | $1{,}200 \leq S \leq 2{,}500$ | 1,700 |
| 2. INSTALLED THRUST (lbs) | $27{,}750 \leq T_i \leq 55{,}000$ | 48,000 |
| 3. FUSELAGE LENGTH (ft) | $105 \leq L \leq 150$ | 136 |
| 4. TAKE-OFF WEIGHT (lbs) | $140{,}000 \leq W_{TO} \leq 250{,}000$ | 210,000 |
| 5. WING SPAN (ft) | $85 \leq b \leq 140$ | 108 |
| 6. FUSELAGE DIAMETER (ft) | $10 \leq d \leq 20$ | 12.8 |

**TABLE 5.1 -- SYSTEM VARIABLES AND BOUNDS FOR THE BOEING 727-200 COMPROMISE DSP TEMPLATE**

The mission requirements for the Boeing 727-200 are summarized in Tables 5.2 and 5.3. The right hand side values for the system constraints are presented in Table 5.2, whereas the target values for the system goals are presented in Table 5.3. The design constants used in this case study are presented in Table 5.4. The design constants are relatively the same for aircraft of comparable size and mission and have been principally taken from Loftin [27].

A problem statement for the designers of the Boeing 727-200 could have read, in part, as follows:

> A three engined subsonic jet transport is to be designed. To ensure that the aircraft is operational from many airports the take-off field length should be less than 6,500 ft and the landing field field length should be as close to 4,500 ft as possible. It is required that the range of the aircraft exceed 2,000 nm.

| SYSTEM CONSTRAINTS | | REQUIREMENTS | | |
|---|---|---|---|---|
| 1. FUEL WEIGHT | $[W_{fuel}]$ | ≥ | 40,000 | lbs |
| 2. THRUST FOR CRUISE | $[T_R]$ | ≥ | 9,000 | lbs |
| 3. SECOND SEGMENT CLIMB | $[q_{TO}]$ | ≥ | 2.7 | percent |
| 4. TAKE-OFF FIELD | $[S_{TO}]$ | ≤ | 6,500 | ft |
| 5. WING TO FUSELAGE AREA RATIO | | ≥ | 12.5 | |
| 6. WING TO FUSELAGE AREA RATIO | | ≤ | 15 | |
| 8. WING ASPECT RATIO | | ≥ | 7.20 | |
| 9. WING ASPECT RATIO | | ≤ | 10.50 | |
| 10. THRUST FOR CRUISE CLIMB TO DRAG RATIO | | ≥ | 1.0 | |
| 11. MISSED APPROACH | $[q_L]$ | ≥ | 2.4 | percent |
| 12. RANGE | [R] | ≥ | 2,000 | nm |

Note: System constraints must be satisfied for feasibility

**TABLE 5.2 -- SYSTEM CONSTRAINTS FOR THE BOEING 727-200 COMPROMISE DSP TEMPLATE**

| SYSTEM GOALS | | ASPIRATIONS | |
|---|---|---|---|
| 1. LANDING FIELD | $[S_{LTV}]$ | 4,500 | ft |
| 2. MISSED APPROACH | $[q_{LTV}]$ | 7.2 | percent |
| 3. RANGE | $[R_{TV}]$ | 2,400 | nm |
| 4. ENDURANCE | $[E_{TV}]$ | 0.03 | |
| 5. USEFUL LOAD FRACTION | $[U_{TV}]$ | 0.5 | |
| 6. WEIGHT MATCHING | | 0.10 | |
| 7. NUMBER OF PASSENGERS | $[N_{PTV}]$ | 190 | |
| 8. RETURN ON INVESTMENT | $[ROI_{TV}]$ | 15.0 | percent |

Note: System goals are to be achieved as far as possible

**TABLE 5.3 -- SYSTEM GOALS FOR THE BOEING 727-200 COMPROMISE DSP TEMPLATE**

| DESIGN CONSTANTS | TEMPLATE VALUE | |
|---|---|---|
| 1. KINEMATIC VISCOSITY AT 35,000 FT | 0.00046 | |
| 2. AIRFOIL THICKNESS LOCATION PARAMETER | 1.2 | |
| 3. LIFTING SURFACE CORRELATION FACTOR | 1.1 | |
| 4. WING WETTED/PLANFORM AREA RATIO | 2.0 | |
| 5. ATMOSPHERIC DENSITY AT 35,000 FT | 0.000737 | slugs/cu ft |
| 6. SPEED OF SOUND AT 35,000 FT | 973.1 | ft/sec |
| 7. MAXIMUM LIFT COEFFICIENT | 2.6 | |
| 8. SPECIFIC FUEL CONSUMPTION | 0.9 | lb/lb-hr |
| 9. PLANFORM EFFICIENCY CONSTANT | 0.96 | |
| 10. NUMBER OF ENGINES | 3.0 | |
| 11. MACH NUMBER | 0.80 | |
| 12. AIRFOIL THICKNESS RATIO | 0.12 | |
| 13. FIXED PAYLOAD | 5000 | lbs |

**TABLE 5.4 -- DESIGN CONSTANTS FOR BOEING 727-200 COMPROMISE DSP TEMPLATE**

It is desirable that the airplane carry about 190 passengers, have a useful load fraction of 0.5, an endurance of 0.03, a range of 2,400 nm and provide a 15% return on investment. It is also desirable that the missed approach climb gradient be as large as possible.

At this early stage of design the variables to be determined are the wing span and area, fuselage diameter and length, installed thrust and take-off weight. The solution should provide information on the size of the aircraft based on geometrical parameters, aerodynamic considerations and the Federal Air Regulations. The solution should also provide information on the costs involved.

### 5.1.2 Cases, Goal Priorities and Scenarios

The template has been extensively exercised. In this report only three interesting studies are presented, namely,

- Case A: A Technically Efficient Aircraft
- Case B: A Technically Efficient Aircraft Influenced by Economics
- Case C: A Technically and Economically Efficient Aircraft.

Another study involving a Boeing 747-like aircraft is summarized in Chapter 6.

In Case A the Return on Investment system goal is suppressed during the execution of the template. The resulting Return on Investment, however, is computed but it does not influence the design itself. In Cases B and C the Return on Investment goal is included during the execution of the template and it influences the design. The Return on Investment goal, in Case B, is given a relatively low priority and the resulting design is a technically efficient design that has been influenced by the Return on Investment. In Case C the Return on Investment goal is given a relatively high priority and the resulting design shows signs of being a technically and economically efficient design. The goal priorities used in the three cases are shown in Table 5.5

| SYSTEM GOAL | PRIORITIES Case A | Case B | Case C |
|---|---|---|---|
| LANDING FIELD LENGTH | 5 | 5 | 6 |
| MISSED APPROACH CLIMB | 6 | 6 | 7 |
| ENDURANCE | 4 | 4 | 5 |
| CRUISE RANGE | 2 | 2 | 3 |
| USEFUL LOAD FRACTION | 7 | 7 | 8 |
| WEIGHT MATCHING | 3 | 3 | 4 |
| PASSENGER CAPACITY | 1 | 1 | 1 |
| RETURN ON INVESTMENT | | 8 | 2 |

**TABLE 5.5 -- GOAL PRIORITIES FOR CASES**

To test the correctness of the template and the comprehensiveness of the formulation three different designs are used as starting designs for the solution process for each of the three cases. A target design is identified. If the template is adequate then the final design using any of the starting designs should be similar to a target design. If it is found that no matter what the starting design the process converges to essentially the same target design we should be able to alter the mission profile (say for a new jet transport) and view resulting design with some degree with confidence.

In our case the target design is the Boeing 727-200 airplane. Different starting designs give rise to "scenarios". These together with the target design are presented in Table 5.6. Scenario One is representative of a good educated guess at the target design. The starting design of Scenario Two is grossly infeasible; it is close to the lower bounds specified in the template. The starting design of Scenario Three is infeasible; it is close to the upper bounds placed on the variables.

| SYSTEM VARIABLES | | SCENARIO One | Two | Three | 727-200 |
|---|---|---|---|---|---|
| 1. WING AREA | ($ft^2$) | 1,600 | 1,250 | 2,100 | 1,700 |
| 2. INSTALLED THRUST | (lbs) | 40,000 | 28,000 | 54,000 | 48,000 |
| 3. FUSELAGE LENGTH | (ft) | 125 | 108 | 145 | 136 |
| 4. TAKE-OFF WEIGHT | (lbs) | 220,000 | 150,000 | 240,000 | 210,000 |
| 5. WING SPAN | (ft) | 120 | 90 | 140 | 108 |
| 6. FUSELAGE DIAMETER | (ft) | 15 | 11 | 19 | 12.8 |

Notes:
Scenario One: Starting design represents a good educated guess
Scenario Two: Starting design is close to the lower bounds
Scenario Three: Starting design is close to the upper bounds

TABLE 5.6 -- SCENARIOS FOR THE BOEING 727-200 COMPROMISE DSP TEMPLATE

## 5.2 CONVERGENCE TO THE TARGET DESIGN

By convergence we mean the attainment of the target design for a particular starting design. This is described and illustrated graphically for Case A. For the other cases convergence is described but not illustrated. It was found that it was not possible to obtain the target design using Scenario Three for both Cases B and C. Upon investigation of Case B we found that the template and our validation strategy had to be altered slightly. Both the template and Scenario Three were modified and the template for Case B exercised. This time the design converged to the target design. Instead of just presenting the results associated with the template that resulted in convergence to the target design we have presented our work chronologically to highlight the process of knowledge acquisition and the evolutionary nature of template refinement. It is noted that it was not possible to obtain convergence to the target design in Case C using Scenario Three and a remedy has been suggested.

### 5.2.1 Case A - Design of a Technically Efficient Aircraft

As indicated earlier, in this case, the Return on Investment goal was not allowed to influence the outcome of the results. For all three scenarios the system variables converged to what is essentially the target design (see Table 5.7). The maximum difference between the design obtained by exercising the template and the target design is 3 percent; an extremely small number.

A summary of the values of the dependent variables is given in Table 5.8. In Table 5.8 values for some of the dependent variables are summarized for the three scenarios and the target Boeing 727-200 design. There is good agreement between these values. The system variables differed by less than 3 percent from the target design. A range and payload of 2,900 nm and 41,000 lbs respectively was sought and a range of 2913 nm. and a payload of 43,000 lbs was achieved. This is remarkably close; the difference being insignificant in the range and in less than 5 percent in the payloads. Weight matching is well within its specified target. It is only necessary to achieve a closeness of 10 percent, but it averages to approximately 6 percent. All the values computed in the economic analysis were compared against a similar aircraft design in [56]. They were all comparable except for the fuel cost which was slightly higher for the template design. This could be reduced by reducing the price of fuel or by reducing the specific fuel consumption factor. This, however, is not necessary for this comparative study.

The design histories of the variables are shown in Figures 5.2 to 5.7. Scenarios One and Two converged to the target design in 6 design cycles. At first glance it appears from the graphs that Scenario Three has also converged to the target design at design cycle 6. A closer examination reveals that this is not the case. In Scenario Three it took 11 design cycles to achieve convergence to the target design. Of particular interest is the jump evidenced in design cycle 7 of Scenario Three for all the system variables.

The jump in the values of the system variables between design cycles 6 and 7 was unexpected. It appears that the design at the end of design cycle 5 was feasible but the design at the end of design cycle 6 was not. It appears that in an attempt to improve the design in design cycle 6, the solution algorithm "overcompensated" and the resulting design ended up being infeasible. In design cycle 7, the algorithm sought to correct this by increasing the wing span and wing area. Hence, an increase in the take off weight which then necessitates an increase in the installed thrust. This appears to be logical. Overcompensation can be attributed to two sources: the nature of the solution algorithm (see Chapter 2, Section 2.4.3) or the incompleteness of the template. There is little that can be done about the former. It is interesting to note, however, that the solution did converge to the target design albeit after another 5 design cycles. The issue of the possible incompleteness of the template is taken up again in Section 5.4.

| SYSTEM VARIABLES | | SCENARIO | | | |
|---|---|---|---|---|---|
| | | One | Two | Three | 727-200 |
| 1. WING AREA | ($ft^2$) | 1700 | 1700 | 1702 | 1700 |
| 2. INSTALLED THRUST | (lbs) | 46,716 | 46,584 | 46,763 | 48,000 |
| 3. FUSELAGE LENGTH | (ft) | 132 | 132 | 132 | 136 |
| 4. TAKE-OFF WEIGHT | (lbs) | 206,240 | 205,810 | 205,758 | 210,000 |
| 5. WING SPAN | (ft) | 110.8 | 110.6 | 110.7 | 108 |
| 6. FUSELAGE DIAMETER | (ft) | 13.2 | 13.1 | 13.2 | 12.8 |

**TABLE 5.7 -- RESULTS FOR CASE A - SYSTEM VARIABLES**

| DEPENDENT VARIABLES | | SCENARIO One | Two | Three | 727-200 |
|---|---|---|---|---|---|
| 1. ASPECT RATIO | | 7.22 | 7.20 | 7.20 | 7.20 |
| 2. RANGE | (nm) | 2913 | 2913 | 2913 | 2900 |
| 3. PAYLOAD WEIGHT | (lbs) | 43,000 | 42,600 | 43,000 | 41,000 |
| 4. NUMBER OF PASSENGERS | | 190 | 188 | 190 | 189 |
| 5. FUEL WEIGHT | (lbs) | 52,284 | 52,208 | 52,212 | 50,000 |
| 6. WING LOADING | | 121 | 121 | 121 | 123 |
| 7. LANDING FIELD | (ft) | 4509 | 4500 | 4494 | 4500 |
| 8. USEFUL LOAD FRACTION | | 0.46 | 0.46 | 0.46 | 0.43 |
| 9. WEIGHT MATCHING | | 0.06 | 0.06 | 0.06 | 0.09 |
| 10. TAKE-OFF FIELD | (ft) | 4898 | 4892 | 4868 | ≤6500 |
| 11. CRUISE THRUST | (lbs) | 10,011 | 10,000 | 10,001 | ~ |
| 12. ENDURANCE | | 0.02 | 0.02 | 0.02 | ~ |
| 13. FUSELAGE FORM FACTOR | | 1.08 | 1.08 | 1.08 | ~ |
| 14. DOC/BLOCK HOUR | | 2152 | 2148 | 2150 | ~ |
| 15. TOTAL COST/BLOCK HOUR | | 3010 | 2999 | 3008 | ~ |
| 16. REVENUE/BLOCK HOUR | | 4121 | 4078 | 4122 | ~ |
| 17. RETURN ON INVESTMENT | | 0.102 | 0.100 | 0.103 | ~ |

Note
~ - Not able to obtain

**TABLE 5.8 -- RESULTS FOR CASE A - DEPENDENT VARIABLES**

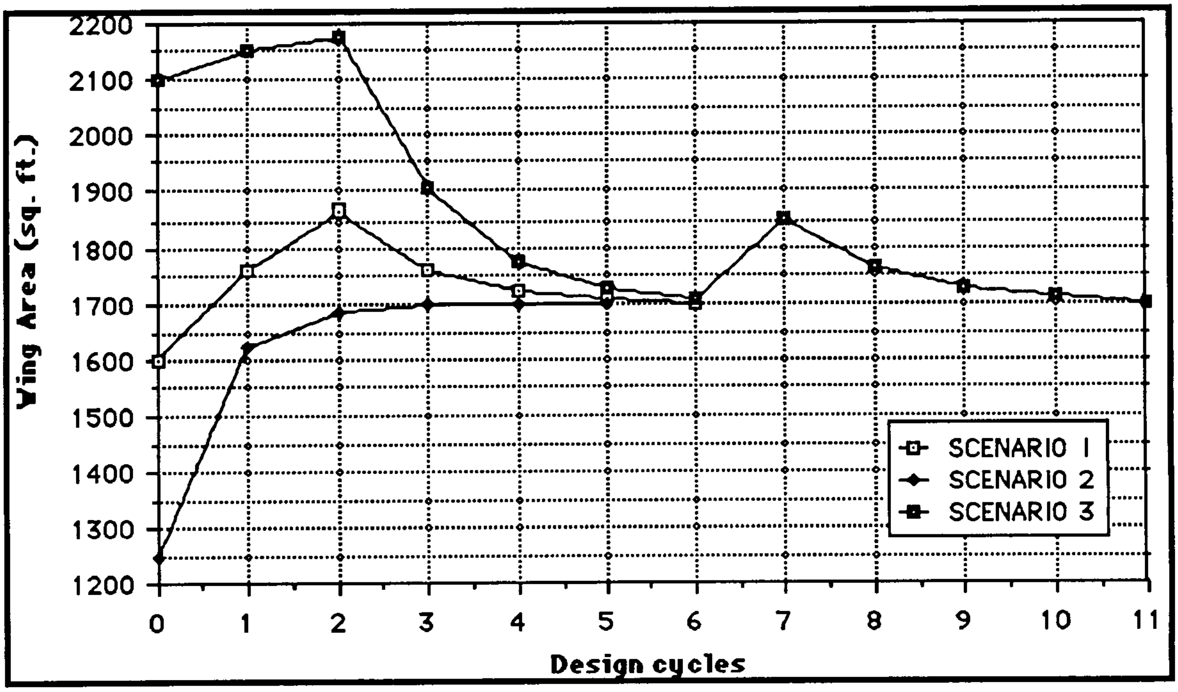


FIGURE 5.2 -- DESIGN HISTORY CASE A - WING AREA

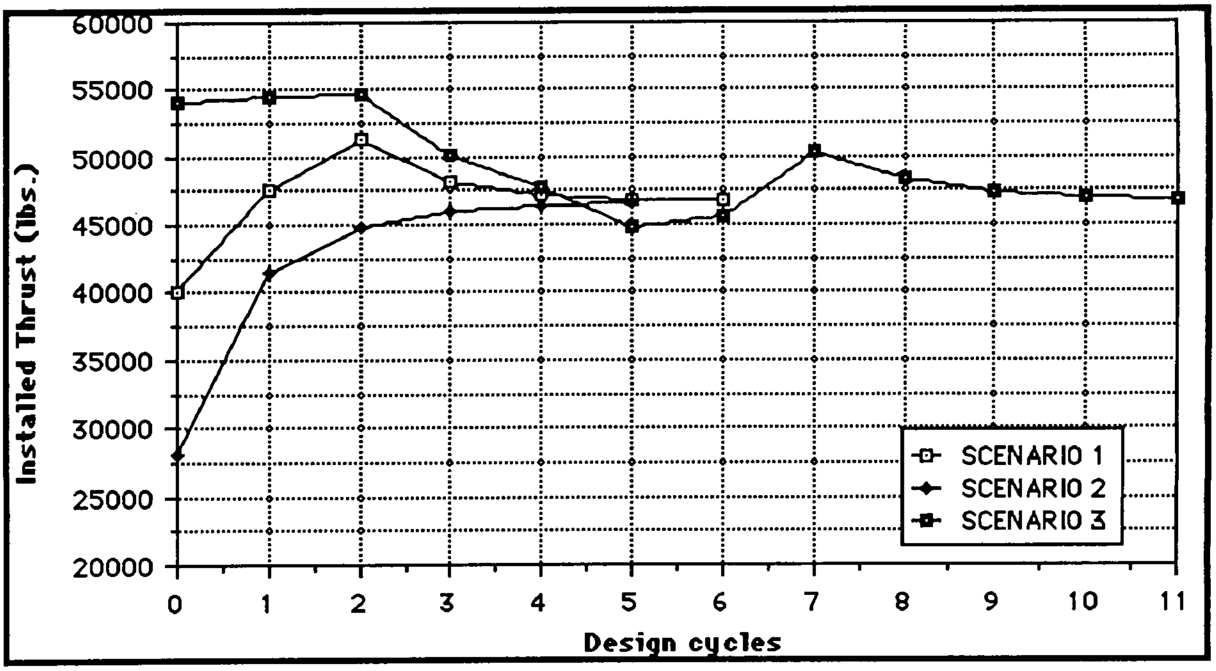


FIGURE 5.3 -- DESIGN HISTORY CASE A - INSTALLED THRUST

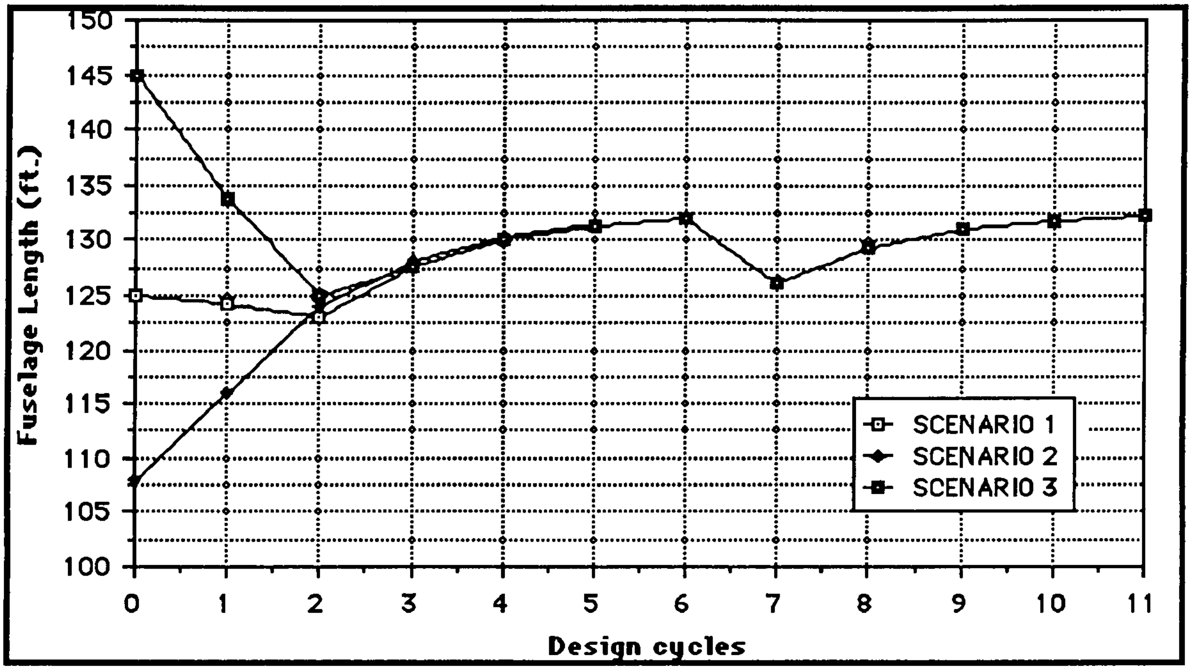


FIGURE 5.4 -- DESIGN HISTORY CASE A - FUSELAGE LENGTH

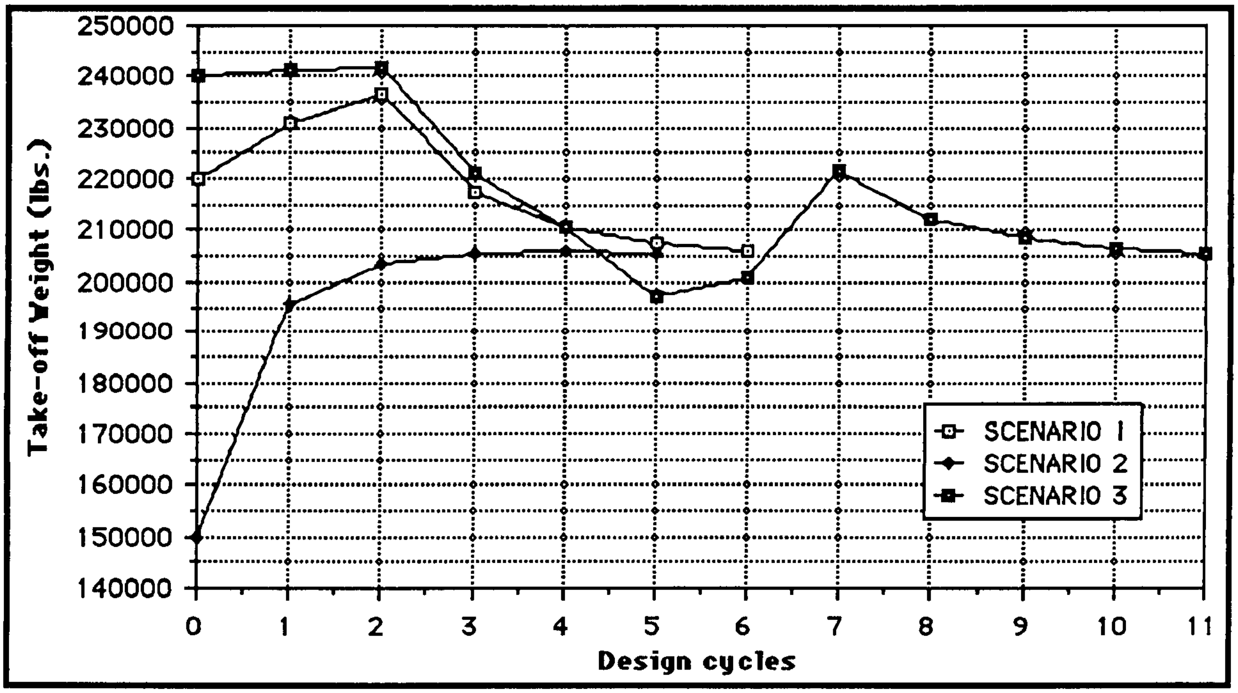


FIGURE 5.5 -- DESIGN HISTORY CASE A - TAKE-OFF WEIGHT

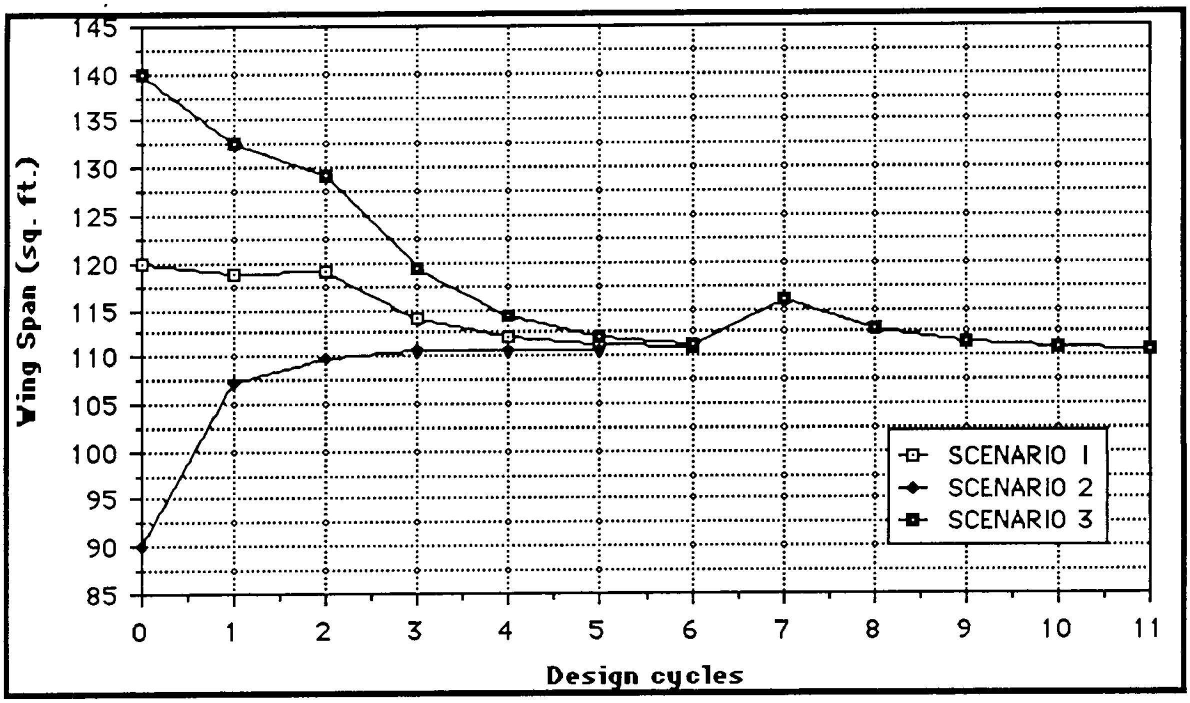


FIGURE 5.6 -- DESIGN HISTORY CASE A - WING SPAN

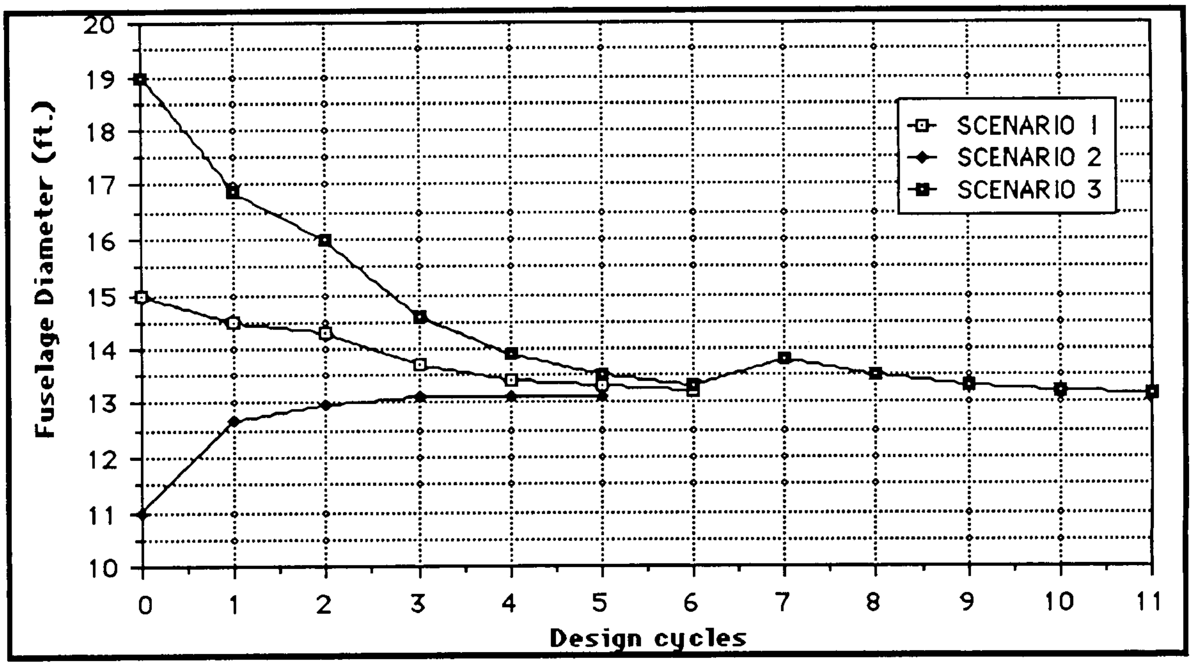


FIGURE 5.7 -- DESIGN HISTORY CASE A - FUSELAGE DIAMETER

### 5.2.2 Case B - The Design of a Technically Efficient Aircraft Influenced by Economics

In Cases B the Return on Investment goal is included during the execution of the template and it influences the design. The Return on Investment goal is, however, given a very low priority and the resulting design is a technically efficient design that has been influenced by the Return on Investment goal.

In Case B, Scenarios One and Two converged to the target design. The results are summarized in Tables 5.9 and 5.10. It was not possible to obtain a solution for Scenario Three. For the first two scenarios the variable design history is similar to that shown in Figures 5.2 to 5.7 and have therefore not been plotted. The output for Case B Scenario Two is shown in Appendix D.

Why was it not possible to obtain convergence to the target design for Scenario Three? After numerous runs, it was found that the return on investment goal was forcing the fuselage diameter to a higher value than before. This is logical because the return on investment is a function of revenue which in turn is a function of the function of the volume and this volume is governed by the fuselage diameter. The value of the fuselage diameter was reduced in the starting design from 19 to 11 feet and the resulting design is listed in Tables 5.11 and 5.12 under Scenario Three A. Obtaining a solution when the initial value of the fuselage diameter for Scenario Three is reduced from 19 to 11 feet is explained as follows. The high starting value of the fuselage diameter resulted (in the earlier design cycles of Scenario Three) in some poor trade-offs between the goals resulting in the failure to obtain a result. This is of course attributed to the introduction of the rate of return goal in Case B. The design obtained in Scenario Three A is a high profit design (return on investment is about 18%) but it is not the target design.

In exercising the template we also found that for this case the end solution was dependent on the starting solution. We noted from the design of Scenario Three A that the wing loading was at its lower bound. Wing loading is a function of take-off weight. Most of the constraints and goals involve the take-off weight and it is therefore probably the most important variable in this formulation. We reduced the take-off weight of the starting design from 240,000 to 200,000 lbs and we found that convergence to the target design was achieved. These results are shown as Scenario Three B in Tables 5.11 and 5.12.

We are both delighted and concerned with the implications of the results obtained in Scenarios Three A and B. We are delighted that we were able to achieve convergence to the target design using three different starting solutions and that the resulting return on investment was lower than what we expected (15%) but was still a reasonable 10%. And now to register our concern. The deviation variables associated with each goal provide a measure of the difference (for that particular goal) between that which is achieved and that which is sought The sum of the deviation variables represents the difference between the aspirations (as modeled by the system goals) and that which is achieved (see Section 2.4.2). In multiobjective optimization in general and the compromise DSP in particular it is always possible that there is more than one design with the same minimum value of the sum of the deviation variables. In such instances even though the values of the system variables are significantly different, the designs, from the standpoint of the achievement function, are equivalent. This is our concern. The resolution of the

| SYSTEM VARIABLES | | SCENARIO One | Two | Three | 727-200 |
|---|---|---|---|---|---|
| 1. WING AREA | ($ft^2$) | 1700 | 1700 | * | 1700 |
| 2. INSTALLED THRUST | (lbs) | 46,716 | 46,584 | * | 48,000 |
| 3. FUSELAGE LENGTH | (ft) | 132 | 132 | * | 136 |
| 4. TAKE-OFF WEIGHT | (lbs) | 206,240 | 205,810 | * | 210,000 |
| 5. WING SPAN | (ft) | 110.8 | 110.6 | * | 108 |
| 6. FUSELAGE DIAMETER | (ft) | 13.2 | 13.1 | * | 12.8 |

Note:
* Did not converge

TABLE 5.9 -- RESULTS FOR CASE B - SYSTEM VARIABLES

| DEPENDENT VARIABLES | | SCENARIO One | Two | Three | 727-200 |
|---|---|---|---|---|---|
| 1. ASPECT RATIO | | 7.22 | 7.20 | * | 7.20 |
| 2. RANGE | (nm) | 2913 | 2913 | * | 2900 |
| 3. PAYLOAD WEIGHT | (lbs) | 43,000 | 42,600 | * | 41,000 |
| 4. NUMBER OF PASSENGERS | | 190 | 188 | * | 189 |
| 5. FUEL WEIGHT | (lbs) | 52,284 | 52,208 | * | 50,000 |
| 6. WING LOADING | | 121 | 121 | * | 123 |
| 7. LANDING FIELD | (ft) | 4509 | 4500 | * | 4500 |
| 8. USEFUL LOAD FRACTION | | 0.46 | 0.46 | * | 0.43 |
| 9. WEIGHT MATCHING | | 0.06 | 0.06 | * | 0.09 |
| 10. TAKE-OFF FIELD | (ft) | 4898 | 4892 | * | ≤6500 |
| 11. CRUISE THRUST | (lbs) | 10,011 | 10,000 | * | ~ |
| 12. ENDURANCE | | 0.02 | 0.02 | * | ~ |
| 13. FUSELAGE FORM FACTOR | | 1.08 | 1.08 | * | ~ |
| 14. DOC/BLOCK HOUR | | 2152 | 2148 | * | ~ |
| 15. TOTAL COST/BLOCK HOUR | | 3010 | 2999 | * | ~ |
| 16. REVENUE/BLOCK HOUR | | 4121 | 4078 | * | ~ |
| 17. RETURN ON INVESTMENT | | 0.102 | 0.100 | * | ~ |

Note
~ Not able to obtain
* Did not converge

TABLE 5.10 -- RESULTS FOR CASE B - DEPENDENT VARIABLES

| SYSTEM VARIABLES | | SCENARIO One | Three A | Three B | 727-200 |
|---|---|---|---|---|---|
| 1. WING AREA | ($ft^2$) | 1700 | 2171 | 1706 | 1700 |
| 2. INSTALLED THRUST | (lbs) | 46,716 | 39,974 | 46,743 | 48,000 |
| 3. FUSELAGE LENGTH | (ft) | 132 | 128 | 132 | 136 |
| 4. TAKE-OFF WEIGHT | (lbs) | 206,240 | 174,710 | 205,660 | 210,000 |
| 5. WING SPAN | (ft) | 110.8 | 125.6 | 110.8 | 108 |
| 6. FUSELAGE DIAMETER | (ft) | 13.2 | 15.0 | 13.2 | 12.8 |

**TABLE 5.11 -- RESULTS FOR CASE B - SYSTEM VARIABLES**

| DEPENDENT VARIABLES | | SCENARIO One | Three A | Three B | 727-200 |
|---|---|---|---|---|---|
| 1. ASPECT RATIO | | 7.22 | 7.26 | 7.20 | 7.20 |
| 2. RANGE | (nm) | 2913 | 2917 | 2913 | 2900 |
| 3. PAYLOAD WEIGHT | (lbs) | 43,000 | 47,600 | 42,800 | 41,000 |
| 4. NUMBER OF PASSENGERS | | 190 | 213 | 189 | 189 |
| 5. FUEL WEIGHT | (lbs) | 52,284 | 44,092 | 52,196 | 50,000 |
| 6. WING LOADING | | 121 | 80 | 120 | 123 |
| 7. LANDING FIELD | (ft) | 4509 | 3130 | 4482 | 4500 |
| 8. USEFUL LOAD FRACTION | | 0.46 | 0.52 | 0.46 | 0.43 |
| 9. WEIGHT MATCHING | | 0.06 | 0.00 | 0.06 | 0.09 |
| 10. TAKE-OFF FIELD | (ft) | 4898 | 3311 | 4856 | $\leq$6500 |
| 11. CRUISE THRUST | (lbs) | 10,011 | 8993 | 9998 | ~ |
| 12. ENDURANCE | | 0.02 | 0.02 | 0.02 | ~ |
| 13. FUSELAGE FORM FACTOR | | 1.08 | 1.08 | 1.08 | ~ |
| 14. DOC/BLOCK HOUR | | 2152 | 1949 | 2149 | ~ |
| 15. TOTAL COST/BLOCK HOUR | | 3010 | 2874 | 3003 | ~ |
| 16. REVENUE/BLOCK HOUR | | 4121 | 4621 | 4100 | ~ |
| 17. RETURN ON INVESTMENT | | 0.102 | 0.181 | 0.102 | ~ |

Note
~ Not able to obtain

**TABLE 5.12 -- RESULTS FOR CASE B - DEPENDENT VARIABLES**

problem of distinguishing between different designs with equivalent achievement is conceptually simple and involves the addition of system constraints and/or goals that in effect act as tie-breakers between equivalent designs. Although the fix is conceptually simple it requires, on the part of template developer, a fair degree of insight into the practical nature of trade-offs in aircraft design. Further information is provided in Section 5.4

### 5.2.3 Case C - Design of a Technically and Economically Efficient Aircraft

In Case C the Return on Investment goal is included in the template. It is given a high enough priority to result in a design that could represent a reasonable trade-off between technical and economic efficiencies.

In Case C Scenarios One, Two and Three B have been used. The results are presented in Tables 5.13 and 5.14. In this case the designs are similar but not identical to the target design. The designs obtained by Scenario One and Two are close to the target design. It was not possible, however, to fine-tune the template for Scenario Three to achieve convergence to the target design. The design of Scenario One has a higher (with respect to the Scenario Two design) wing span, aspect ratio, range and take-off weight but a lower return on investment. Of the three designs, the design of Scenario Three B has the lowest take-off weight and highest fuselage diameter and hence, the highest return on investment. It appears (as was described in Section 5.3.2 for Case B) that the lack of convergence to the target design stems from the incompleteness of the template resulting in the inability to make a distinction between different designs with equivalent achievements. It appears that this problem manifests itself only when the starting design is close to the upper bounds as is the case in Scenario Three. Quite clearly this calls for further investigation..

The introduction with a high priority of the return on investment goal resulted in an increase in the useful load fraction (see Scenarios Two and Three B) and a decrease in the value of the system variable take-off weight. This trade-off is logical.

The designs of Scenarios One and Two are narrow-bodied aircraft similar to the Boeing 727-200. The design of Scenario Three B is wider and shorter than the designs of Scenarios One and Two. The wider aircraft has a lower take-off weight but a higher wing span and wing area than its narrow-bodied counterpart. This combination of weight, wing span and wing area accounts for the lower take-off and landing field length requirements. The return on investment for the wider aircraft is higher than its narrow-body counterparts. This probably explains the emergence of wide-bodied jets in the 1970's. Modern aircraft have a wing loading ratio of about 120. This is the case for the designs of Scenario One and Two. The wing loading ratio for the Scenario Three design is 80 and on the low side for modern aircraft. The lower bound for this ratio should be raised to 100.

| SYSTEM VARIABLES | | SCENARIO One | Two | Three B | 727-200 |
|---|---|---|---|---|---|
| 1. WING AREA | ($ft^2$) | 1686 | 1695 | 2172 | 1700 |
| 2. INSTALLED THRUST | (lbs) | 45,372 | 42,025 | 44,279 | 48,000 |
| 3. FUSELAGE LENGTH | (ft) | 132 | 133 | 116 | 136 |
| 4. TAKE-OFF WEIGHT | (lbs) | 202,390 | 184,960 | 174,940 | 210,000 |
| 5. WING SPAN | (ft) | 118.3 | 110.5 | 125.1 | 108 |
| 6. FUSELAGE DIAMETER | (ft) | 13.3 | 13.1 | 14.9 | 12.8 |

**TABLE 5.13 -- RESULTS FOR CASE C - SYSTEM VARIABLES**

| DEPENDENT VARIABLES | | SCENARIO One | Two | Three B | 727-200 |
|---|---|---|---|---|---|
| 1. ASPECT RATIO | | 8.31 | 7.20 | 7.20 | 7.20 |
| 2. RANGE | (nm) | 2961 | 2913 | 2915 | 2900 |
| 3. PAYLOAD WEIGHT | (lbs) | 43,200 | 42,800 | 43,200 | 41,000 |
| 4. NUMBER OF PASSENGERS | | 191 | 189 | 191 | 189 |
| 5. FUEL WEIGHT | (lbs) | 48,363 | 46,925 | 44,280 | 50,000 |
| 6. WING LOADING | | 120 | 109 | 80 | 123 |
| 7. LANDING FIELD | (ft) | 4546 | 4096 | 3129 | 4500 |
| 8. USEFUL LOAD FRACTION | | 0.45 | 0.48 | 0.50 | 0.43 |
| 9. WEIGHT MATCHING | | 0.07 | 0.04 | 0.02 | 0.09 |
| 10. TAKE-OFF FIELD | (ft) | 4896 | 4424 | 3332 | ≤6500 |
| 11. CRUISE THRUST | (lbs) | 9025 | 8997 | 9028 | ~ |
| 12. ENDURANCE | | 0.01 | 0.02 | 0.02 | ~ |
| 13. FUSELAGE FORM FACTOR | | 1.08 | 1.08 | 1.14 | ~ |
| 14. DOC/BLOCK HOUR | | 2060 | 2004 | 1933 | ~ |
| 15. TOTAL COST/BLOCK HOUR | | 2916 | 2852 | 2786 | ~ |
| 16. REVENUE/BLOCK HOUR | | 4146 | 4100 | 4144 | ~ |
| 17. RETURN ON INVESTMENT | | 0.115 | 0.124 | 0.141 | ~ |

Note
~ Not able to obtain

**TABLE 5.14 -- RESULTS FOR CASE C - DEPENDENT VARIABLES**

## 5.3 A CRITICAL EVALUATION OF THE RESULTS

Based on the material presented in the previous section answers to the following questions are provided in this section :

1. Can the template be used in the conceptual design of subsonic jet transport?
2. In what ways should the current template be improved?

It appears by looking at all the designs the one obtained for Case A Scenario Two is closest to the target design, that is, the Boeing 727-200 aircraft. We were unable to get specific information on the return on investment for the Boeing 727-200. According to our template the "implicit" return on investment of the Boeing 727-200 aircraft is 10 percent. It would have been an interesting exercise to re-run Cases B and C with the goal of achieving a return on investment of 10 percent. Unfortunately this has not been done.

It is recalled that we had difficulty in achieving convergence to the target design for Scenario Three in all three cases. It is clear that the modeling of the economic aspirations for the designs is inadequate and needs to be refined. This is analyzed and a few recommendations ensue.

The system variables for Scenario Two for all the Cases were normalized with respect to the system variables of the Case A Scenario Two design. A plot of these values is shown in Figure 5.8.

The designs obtained for Case A and Case B are almost the same which indicates that the return on investment goal did not really affect the designs that were obtained. This is logical because the return on investment goal was given a low priority in Case B. For Case C the return on investment was given a high priority and the introduction of the return on investment goal has made a difference to the designs that were obtained. This is also logical. It is observed that all the system variables for the three cases are the same except for take-off weight and installed thrust. In Case C the take-off weight and thrust are 10 percent lower and the return on investment 2.4 percent greater than the two other cases. A possible explanation for this difference is the 'slop' introduced in the aircraft's weight matching (see Section 4.4.1). The Case A and B designs are credited with a weight matching of only 0.06 whereas a weight matching of 0.02 is achieved in Case C. This 'slop' in the weight matching is a weakness in the technical part of the template that the return on investment goal is able to exploit. The effect of the target value for the weight matching goal on convergence needs to be investigated

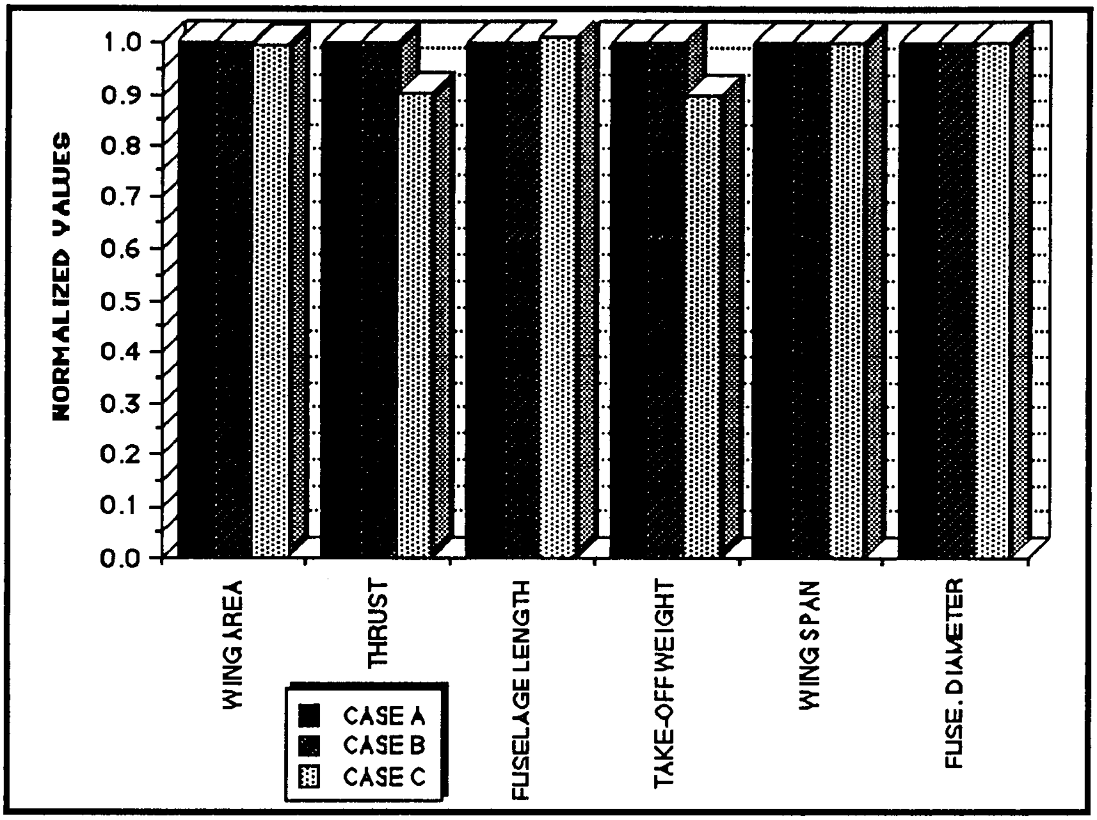


FIGURE 5.8 -- A COMPARISON OF THE NORMALIZED RESULTS OF THE THREE CASES

As indicated earlier, the deviation variables associated with each goal provide a measure of the difference (for that particular goal) between that which is achieved and that which is sought The sum of the deviation variables represents the difference between the aspirations (as modeled by the system goals) and that which is achieved (see Section 2.4.2). It is entirely possible for designs that are characterized by widely varying values of the system variables to have the sums of the deviation variables be the same. In the compromise DSP formulation designs with the same sum of the deviation variables are deemed to be equivalent. The resolution of this problem is conceptually simple and involves the addition of system constraints and/or goals that in effect act as tie-breakers between equivalent designs. Although the fix is conceptually simple it requires, on the part of template developer, a fair degree of insight into the practical nature of trade-offs in aircraft design.

It is clear that it is not possible using the current template to adequately distinguish between equivalent designs when Scenario Three is used. The return on investment is a ratio. Hence, it is possible for two widely different designs (e.g., a large and a small aircraft) to have the same return on investment. In essence, for the return on investment, the revenue contributes to the numerator and the investment to the denominator. One way to refine the template is to place a constraint on the direct operating cost and introduce a system goal for the money available for investment.

The additional constraint will affect the take-off weight and hence the payload and revenue. The additional goal provides a means for putting a cap on the investment that is needed. One such possibility would be a goal for a certain direct operating cost. Another way to refine the template is, for a given investment level, to minimize the direct operating cost and maximize the return on investment. This should result in the smallest high profit aircraft possible. The values of some of the interesting variables for Scenario Three for the three cases are tabulated in Table 5.15. These designs are different but in the context of the preceding discussion equivalent. As indicated earlier, the designs for Cases A and B reflect a narrower and longer aircraft than the design for Case C. Two additional bits of information are provided in the table, namely, the fuselage length to diameter ratio and the cost to revenue ratio. The both ratios decrease as the design moves towards a wide-body design. To avoid the occurrence of equivalent designs it may be appropriate to introduce both these ratios as goals and seek to minimize them. In ship design the ratios between the principal dimensions and form coefficients play an extremely important role in determining the design of a vessel and hence in the formulation of the compromise DSP template, [28]. The inclusion of such ratios as system constraints and/or goals, in our opinion, needs to be investigated.

| Variables | | Case A | Case B | Case C | 727-200 |
|---|---|---|---|---|---|
| WING AREA | ($ft^2$) | 1702 | 1706 | 2172 | 1700 |
| INSTALLED THRUST | (lbs) | 46,763 | 46,743 | 44,279 | 48,000 |
| FUSELAGE LENGTH | (ft) | 132 | 132 | 116 | 136 |
| TAKE-OFF WEIGHT | (lbs) | 205,758 | 205,660 | 174,940 | 210,000 |
| WING SPAN | (ft) | 110.7 | 110.8 | 125.1 | 108 |
| FUSELAGE DIAMETER | (ft) | 13.2 | 13.2 | 14.9 | 12.8 |
| WING LOADING | | 121 | 120 | 80 | 123 |
| LANDING FIELD | (ft) | 4494 | 4482 | 3129 | 4500 |
| USEFUL LOAD FRACTION | | 0.46 | 0.46 | 0.50 | 0.43 |
| WEIGHT MATCHING | | 0.06 | 0.06 | 0.02 | 0.09 |
| TAKE-OFF FIELD | (ft) | 4868 | 4856 | 3332 | ≤6500 |
| CRUISE THRUST | (lbs) | 10,001 | 9998 | 9028 | ~ |
| TOTAL COST/BLOCK HOUR | | 3008 | 3003 | 2786 | ~ |
| REVENUE/BLOCK HOUR | | 4122 | 4100 | 4144 | ~ |
| RETURN ON INVESTMENT | | 0.103 | 0.102 | 0.141 | ~ |
| LENGTH/DIAMETER | | 10 | 10 | 7.78 | |
| COST/REVENUE | | 0.730 | 0.732 | 0.672 | |

Note
~ Not able to obtain

TABLE 5.15 -- SELECTED VARIABLES - ALL CASES
SCENARIO THREE

Can the template be used in the conceptual design of subsonic jet transport? The answer is in two parts. The template at this time is not mature enough to be used for the conceptual design of jet transports. It is ready, after some refinement, to be used as a tool for gaining an understanding of the interaction between the system constraints and goals. It is important to note that it is easy to particularize the template for other mission requirements; it is only necessary to alter the values for some of the parameters listed in Tables 5.1 to 5.4. It was indicated in Section 1.2 that templates for the preliminary design of ships have been created and are successful [28,59,60]. Work is underway on introducing explicit economic considerations into the template. A preliminary report has been prepared by Emmons [13]. The templates for ship design are incorporated in the AUSEVAL system [60]. These templates are currently being particularized for warships for use in the Directorate of Naval Ship Design, Canberra, Australia. Having been through the exercise of developing a compromise DSP template for aircraft and having already done it for ships we find much similarity in both. In the light of our success with ships and the work reported here we feel confident about the efficacy of developing a set of compromise DSP templates for the conceptual design of aircraft. It is clear, in our minds, that the potential for the use of the compromise DSP template in the conceptual design of aircraft has been established. The question "In what ways should the template be improved?" has been answered in earlier part of this section. Our principal recommendation is that the template needs to be modified as indicated in this section, exercised and then generalized.

## 5.4 A LESSON LEARNED - A STRATEGY FOR THE DESIGN OF TECHNICALLY AND ECONOMICALLY EFFICIENT AIRCRAFT

We define design as the process to convert information that characterizes the requirements and aspirations for a product into knowledge about the product itself [37]. The premise that the principal role of any process is to convert information that characterizes the requirements and aspirations for a product into knowledge about the product itself implies that this conversion is accomplished in stages. In traditional design we have given names to the stages, e.g., feasibility, conceptual, preliminary, detail, etc. In the Decision Support Problem Technique the names and the number of stages, from the standpoint of the information that is necessary for making decisions in each of the stages, is not important. What is important is that:

- the types of decisions being made (e.g., selection, compromise, etc.) are the same in all stages, and
- the amount of hard information increases as the knowledge about the product increases.

Ideally, we would like to see a set of templates established in the conceptual phase evolve and provide support for making decisions throughout the design process. The question we, therefore, need to address is:

> How should the use of the compromise DSP template change in, say, the conceptual phase of aircraft design?

This is what is outlined in this section..

Assume that we are in the conceptual phase of design (see Figure 2.3) and are at a point where type of aircraft to be designed is known and we are ready to improve the early conceptual designs through modification (see Figure 2.3). Assume also that a general compromise DSP template is available for the particular aircraft type.

We recognize that the eventual aircraft design will represent a balance (we hope optimal) between technical and economic efficiencies. We need to make a distinction between direct and indirect measures of efficiency. For example, return on investment and the landing field length are direct measures of economic and technical efficiencies, respectively. Payload is a direct measure of technical efficiency and an indirect measure of economic efficiency whereas direct operating costs may be just the opposite. These distinctions are important because at this early stage some measures are easier to quantify than others.

**Step 1: Design of a Technically Efficient Aircraft**
Generally, we believe, at this early stage there are more <u>direct</u> measures of technical efficiency than there are of economic efficiency that can be quantified and used in a template. If this indeed is the case we recommend identifying the technically efficient aircraft first. This means running the compromise DSP template without the influence of the direct measures of economic efficiency (for example, the return on investment). This is what we attempted to do in Case A. In Case A using direct measures of technical efficiency and some indirect measures of economic efficiency (for example, low fuel weight, long range, high useful load fraction, etc.) we obtained a feasible technically efficient design. Economic analysis was done after the design was obtained. The economic analysis in this case is used to pose "what if" questions to gain an understanding of the behavior of the technical part of the template and hence refine it. Exercizing this template also facilitates the establishment of the priorities to be given to the different technical goals. With limited resources identification of those constraints that need to be refined or developed and then added to the template is important.

**Step 2: Design of a Technically Efficient Aircraft Influenced by Economics**
At some time in the design process there is sufficient technical information known about the airplane that meaningful measures of economic efficiency can be formulated. From experience with both ships and aircraft we have learnt that the introduction of these direct measures of technical efficiency has to be done in steps; for example as was done in Case B. This involves introducing the direct measures of economic efficiency with a low priority in the hierarchy of goals and using as one of the starting designs the best of Case A. We believe, from experience, that the introduction of economic efficiency into the template will highlight weaknesses in the modelling of the technical part. These weaknesses are easier to identify and fix if the knowledge gleaned from Case A is available. This is the template utilizing the aircraft's return on investment as the lowest priority goal.

**Step 3: Design of a Technically and Economically Efficient Aircraft**
At some time in the design process there is sufficient and accurate enough information to seek an optimal trade-off between the economic and technical efficiencies. This is the time to invoke Case C.

In all the preceding steps a study of the design history of the variables and the active constraints yields a wealth of information that can be effectively used to gain knowledge about the trade-offs. Iteration between the three cases is always a possibility, is recommended and is quite easy using DSIDES. A post-solution capability has been developed to facilitate the post-design analysis of complex engineering templates [20,21]. Unfortunately, we were unable to use this work in this project.

# CHAPTER 6
## THE BOEING 747 AIRPLANE AND RECOMMENDATIONS FOR IMPROVEMENT OF TEMPLATE

In Chapter 2, a general word formulation, of a compromise DSP template for the design of subsonic jet transports in the conceptual stage of design, is presented Based on the word formulation, in Chapter 4, a general mathematical formulation of the compromise DSP template is developed and presented. In Chapter 5 the template is particularized for a Boeing 727-200 subsonic jet transport and has been to the extent possible - validated.

As indicated earlier, during the course of this project two versions of the template were developed. The first is documented by Marinopoulos in [30] and the second (together with the differences from the first) by Jackson in [16]. Some of the differences between the two versions are described in Section 4.7. Bradberry, Entrekin and Jackson were involved in implementing the template proposed by Marinopoulos on the computer. As a result of this work we learnt about some shortcomings that were fixed and have been briefly described in Chapter 4, Section 4.7. It is the fixed version of the template that was subsequently extended by Jackson to include economic efficiency and has been reported on in Chapter 5. In April 1985, we were in the process of confirming the soundness of the template proposed by Marinopoulos - and were extremely excited by this prospect. The student team in the excitement of the moment got carried away and posed a very intriguing question:

Can the compromise DSP template be used to design a Boeing 747 airplane?

The answer to this question is presented in this chapter. It is pointed out that the original template (without fixes) has been used in this study. Further, the student team developed an answer to the question over a period of three weeks (in the last month of the academic year) as a "surprise present" for their professor ! Hence, only qualitative conclusions can be drawn. Recommendations for improving the template are also included.

## 6.1 THE BOEING 747-200

The problem statement and the general form of the compromise DSP template is presented in Sections 2.5.2 and 2.5.3, respectively. The general mathematical form of the template is presented in Section 4.6. The template used in this study, however, is of earlier vintage and is documented in [9,30,33]. The differences between the two templates are presented summarized in Chapter 4, Section 4.7. The question that is posed is:

> Given that we know that the template appears to be usable for designing a Boeing 727 type of aircraft can it be used for designing a larger aircraft, say, an aircraft with the mission requirements embodied in the Boeing 747-200?

An affirmative answer to this question is important. The Boeing 747-200 is a successful aircraft. The most striking feature of the Boeing 747-200 is its "bulbous nose" and its large size (see Figure 6.1). With it Boeing entered the era of subsonic "wide-bodied" transports. The Boeing 747-200 incorporated many technological advances of the day including an improved wing that had a thinner airfoil profile. When it was introduced the Boeing 747-200 was the largest jet transport aircraft constructed of its day, [27, pp. 67]. The Boeing 727-200 is a medium-haul aircraft whereas the Boeing 747-200 is a long-haul aircraft. Both aircraft designs have been successful and incorporated the technology of the day. An affirmative answer to the question posed earlier, in our opinion, is indicative of the inherent capability of our DSP-based approach to accommodate technological change and respond to changing requirements.

The first step towards obtaining an answer to the question is identical to that undertaken for the Boeing 727-200 case study. This involves particularizing the problem statement (Section 2.5.2) and the general formulation (Sections 2.5.2 and 4.6) of the template - and exercising it. This is described in Section 6.2. Recommendations for improving the template are presented in Section 6.3.

## 6.2 THE BOEING 747-200 AND THE COMPOMISE DSP TEMPLATE

Specific performance requirements dictate the size, weight, and power to be installed in the aircraft. Methods for estimating design parameters and for studying the effects of changes in performance requirements and configuration variables on these design parameters are of great importance to the aircraft design process. As indicated we had no expertise in aircraft design at the start of the project. Much of the understanding of aircraft design was obtained through extensive reading of published information However, a modicum of appreciation of its complexity and some understanding of the interaction between the variables, constraints and goals were only achieved through the template validation process using the Boeing 727-200 aircraft as an example. This experience proved invaluable.

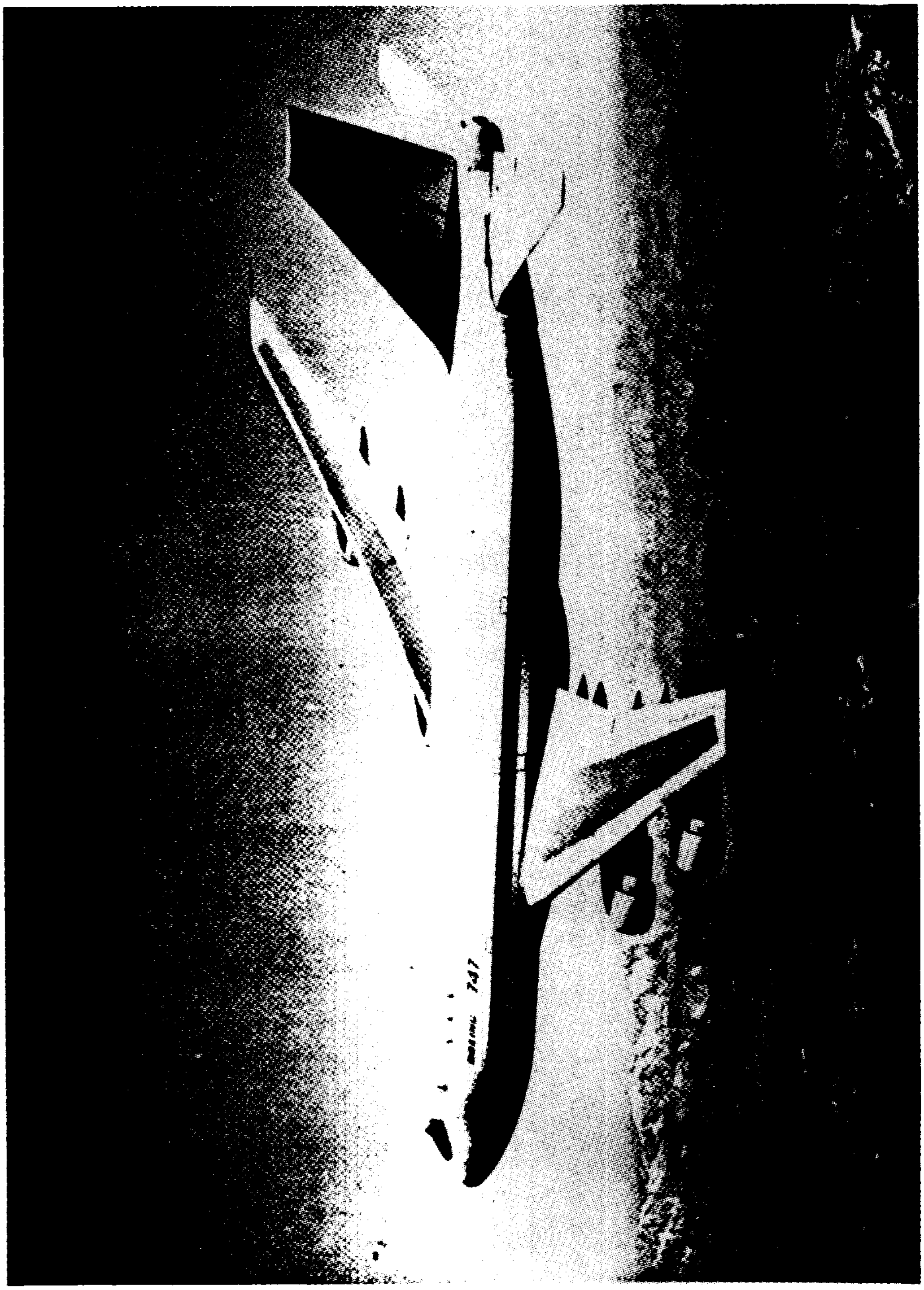

FIGURE 6.1 -- THE BOEING 747-200 AIRPLANE

### 6.2.1 Particularization of the Compromise DSP Template for the Boeing 747-200

The Boeing 747-200, Figure 6.1, is a four-engined subsonic, wide-bodied jet aircraft designed for long-haul intercontinental operations. Our positive experience with the template in the 727-200 case study gave us some confidence in assuming that a reasonably accurate representation of the knowledge used for aircraft design was embodied in the template. We made a starting assumption that since the Boeing 747 had the same pedigree as the Boeing 727; the 747 was just a larger version of the 727. This implies that the knowledge embodied in the template is (for the most part) equally applicable to both types of aircraft. In other words all fuselage, wing sizing and weight parameters and ratios used to design the Boeing 727-200 are equally applicable to the Boeing 747-200.

The variables and bounds are summarized in Table 6.1. The mission requirements used in this study are summarized in Tables 6.2 and 6.3. The actual mission requirements for the Boeing 747 could not be obtained from the literature. Some of the information used in these tables is therefore taken from Loftin [27, pp 94]. The right hand side values for the system constraints are presented in Table 6.2, whereas the target values for the system goals are presented in Table 6.3. The design constants used within this case study are presented in Table 6.4. The design constants are relatively the same for aircraft of comparable size and mission and have been principally taken from Loftin [27].

The requirements that changed from the Boeing 727-200 study affect the system constraints associated with fuel weight, second segment climb, take-off field length, the lower bound on aspect ratio, missed approach, and range (compare Tables 5.2 and 6.2). The target values for the system goals that changed from the previous study affect the system goals associated with landing field length, range, number of passengers, and Mach number (compare Tables 5.3 and 6.3). The goal for the Mach number was increased from 0.80 to 0.88 to reflect the use of an improved airfoil design. The other changes are self explanatory. Since the 747-200 wing incorporates an improved airfoil design, the planform efficiency factor was increased to 0.98 and the lifting surface correlation factor was decreased to 0.91. The skin friction coefficient was increased slightly to account for the increased aircraft size requirements. The maximum lift coefficient associated with the improved airfoil design is somewhat less than that of the Boeing 727-200 and is dependent upon the type of high lift devices used. With the improved airfoil design the Boeing 747-200 sacrifices a certain amount of lift while increasing the critical Mach number of the airfoil, which is the reason for a maximum lift coefficient value of 2.2. The numerical values for the wing factors were obtained after experimenting with the template. A brief description of the effort involved is given in the next section.

A problem statement for the designers of the Boeing 747-200 could have read, in part, as follows:

> A four engined subsonic jet transport is to be designed. To ensure that the aircraft is operational from many airports the take-off field length should be less than 9,500 ft and the landing field length should be as close to 5,500 ft as possible. It is required that the range of the aircraft exceed 4,000 nm.

| SYSTEM VARIABLES | BOUNDS | BOEING 747-200 |
|---|---|---|
| 1. WING AREA ($ft^2$) | $4,200 \leq S \leq 7,200$ | 5,500 |
| 2. INSTALLED THRUST (lbs) | $90,000 \leq T_i \leq 250,000$ | 180,000 |
| 3. FUSELAGE LENGTH (ft) | $170 \leq L \leq 250$ | 225 |
| 4. CRUISE MACH NUMBER | $0.75 \leq M \leq 0.95$ | 0.85 |
| 5. TAKE-OFF WEIGHT (lbs) | $520,000 \leq W_{TO} \leq 850,000$ | 778,000 |
| 6. MAXIMUM THICKNESS RATIO OF AIRFOIL | $0.10 \leq TC \leq 0.15$ | 0.12 |
| 7. WING SPAN (ft) | $160 \leq b \leq 240$ | 195.7 |
| 8. FUSELAGE DIAMETER (ft) | $10 \leq d \leq 40$ | 22 |

TABLE 6.1 -- SYSTEM VARIABLES AND BOUNDS FOR THE BOEING 747-200 COMPROMISE DSP TEMPLATE

| SYSTEM CONSTRAINTS | | REQUIREMENTS | | |
|---|---|---|---|---|
| 1. FUEL WEIGHT | $[W_{fuel}]$ | $\geq$ | 300,000 | lbs |
| 2. THRUST FOR CRUISE | $[T_R]$ | $\geq$ | 9,000 | lbs |
| 3. SECOND SEGMENT CLIMB | $[q_{TO}]$ | $\geq$ | 3.0 | percent |
| 4. TAKE-OFF FIELD | $[S_{TO}]$ | $\leq$ | 9,500 | ft |
| 5. WING TO FUSELAGE AREA RATIO | | $\geq$ | 13.5 | |
| 6. WING TO FUSELAGE AREA RATIO | | $\leq$ | 15.0 | |
| 7. FUSELAGE FORM FACTOR | | $\geq$ | 1.0830 | |
| 8. WING FORM FACTOR | | $\geq$ | 1.1560 | |
| 9. WING ASPECT RATIO | | $\geq$ | 6.80 | |
| 10. WING ASPECT RATIO | | $\leq$ | 8.50 | |
| 10. THRUST FOR CRUISE CLIMB TO DRAG RATIO | | $\geq$ | 1.0 | |
| 12. MISSED APPROACH | $[q_L]$ | $\geq$ | 2.7 | percent |
| 13. RANGE | $[R]$ | $\geq$ | 4,000 | nm |

Note: System constraints must be satisfied for feasibility

TABLE 6.2 -- SYSTEM CONSTRAINTS FOR THE BOEING 747-200 COMPROMISE DSP TEMPLATE

| SYSTEM GOALS | | ASPIRATIONS | |
|---|---|---|---|
| 1. LANDING FIELD | [$S_{LTV}$] | 5,500 | ft |
| 2. MISSED APPROACH | [$q_{LTV}$] | 7.2 | percent |
| 3. RANGE | [$R_{TV}$] | 5,500 | nm |
| 4. ENDURANCE | [$E_{TV}$] | 0.03 | |
| 5. USEFUL LOAD FRACTION | [$U_{TV}$] | 0.5 | |
| 6. WEIGHT MATCHING | | 0.308 | |
| 7. WING FORM FACTOR | | 1.1560 | |
| 8. NUMBER OF PASSENGERS | [$N_{PTV}$] | 565 | |
| 9. MACH NUMBER | | 0.88 | |

Note: System goals are to be achieved as far as possible

TABLE 6.3 -- SYSTEM GOALS FOR THE BOEING 747-200 COMPROMISE DSP TEMPLATE

| DESIGN CONSTANTS | TEMPLATE VALUE | |
|---|---|---|
| 1. KINEMATIC VISCOSITY AT 35,000 FT | 0.00046 | |
| 2. AIRFOIL THICKNESS LOCATION PARAMETER | 1.2 | |
| 3. LIFTING SURFACE CORRELATION FACTOR | 0.91 | |
| 4. WING WETTED/PLANFORM AREA RATIO | 2.0 | |
| 5. ATMOSPHERIC DENSITY AT 35,000 FT | 0.000737 | slugs/cu ft |
| 6. SPEED OF SOUND AT 35,000 FT | 973.0 | ft/sec |
| 7. MAXIMUM LIFT COEFFICIENT | 2.2 | |
| 8. SPECIFIC FUEL CONSUMPTION | 0.9 | lb/lb-hr |
| 9. PLANFORM EFFICIENCY CONSTANT | 0.98 | |
| 10. NUMBER OF ENGINES | 4.0 | |

TABLE 6.4 -- DESIGN CONSTANTS FOR BOEING 747-200 COMPROMISE DSP TEMPLATE

It is desirable that the airplane carry about 565 passengers, have a useful load fraction of 0.5, an endurance of 0.03, a range of 5,500 nm. It is also desirable that the missed approach climb gradient be as large as possible.

At this early stage of design the variables to be determined are the wing span and area, fuselage diameter and length, installed thrust and take-off weight, cruise Mach number, and the maximum thickness ratio of airfoil. The solution should provide information on the size of the aircraft based on geometrical parameters, aerodynamic considerations and the Federal Air Regulations.

### 6.2.2 Establishing the Boeing 747-200 as the Target Design

As indicted earlier the Boeing 747-200 wing is considerably different from that of the Boeing 727-200. It was therefore necessary to fine-tune the template. The template was exercised several times using the Boeing 747-200 as the initial design, together with its mission requirements but with the Boeing 727-200 airfoil parameters. If the right information is embedded in template then when the template is exercised the initial (Boeing 747-200) design should be returned as the target design. These runs, however, resulted in aircraft designs with wing thickness ratios greater than 0.14, wing areas greater than 6000 sq ft, wing spans greater than 200 ft, aspect ratios greater than 7.5, and Mach numbers lower than 0.82. The weight and fuselage parameters were consistently close those of the Boeing 747-200. In effect we were getting designs for the Boeing 747 based on the Boeing 727 technology. To improve upon this the application of an improved airfoil configuration was chosen to be the next step. We proceeded by making adjustments to the wing lifting surface correlation factor and planform efficiency constant. This resulted in a decreased aspect ratio, a decreased wing area, a decreased wing span, a decreased wing thickness ratio, and an increased Mach number. These characteristics were precisely what is to be expected to be gained from a more efficient airfoil. When there was little or no difference between the input Boeing 747 design and the design obtained using the template it was assumed that the right knowledge for designing a Boeing 747 like airplane was embodied in the template and the Boeing 747 became the "target" design.. It was then assumed that the Boeing 747-200 represented an optimum design. This design was therefore established as the 'target' design to be found, with widely different starting designs, using the aircraft DSP template.

### 6.2.3 Sets, Scenarios and Goal Priorities

To test the correctness of the template and the comprehensiveness of the formulation three different designs are used as starting designs for the solution process for each of the three cases. A target design is identified. If the template is adequate then the final design using any of the starting designs should be similar to a target design. If it is found that no matter what the starting design the process converges to essentially the same target design then we should be able to alter the mission profile (say for a new jet transport) and view resulting design with some degree with confidence.

| SYSTEM VARIABLES | | SCENARIO One | Two | Three | 747-200 |
|---|---|---|---|---|---|
| 1. WING AREA | ($ft^2$) | 4,500 | 5,000 | 7,000 | 5,500 |
| 2. INSTALLED THRUST | (lbs) | 150,000 | 160,000 | 200,000 | 180,000 |
| 3. FUSELAGE LENGTH | (ft) | 180 | 200 | 240 | 225 |
| 4. CRUISE MACH NUMBER | | 0.80 | 0.85 | 0.93 | 0.85 |
| 5. TAKE-OFF WEIGHT | (lbs) | 675,000 | 725,000 | 840,000 | 778,000 |
| 6. MAXIMUM THICKNESS RATIO OF AIRFOIL | | 0.14 | 0.13 | 0.10 | 0.12 |
| 7. WING SPAN | (ft) | 170 | 185 | 230 | 195.7 |
| 8. FUSELAGE DIAMETER | (ft) | 16 | 18 | 35 | 22 |

Notes:
Scenario One: Starting design is close to the lower bounds
Scenario Two: Starting design represents a good educated guess
Scenario Three: Starting design is close to the upper bounds

**TABLE 6.5 -- SCENARIOS FOR THE BOEING 747-200 COMPROMISE DSP TEMPLATE**

| SYSTEM GOAL | PRIORITIES 747-200 | 727-200 |
|---|---|---|
| LANDING FIELD LENGTH | 4 | 5 |
| MISSED APPROACH CLIMB | 5 | 6 |
| ENDURANCE | 8 | 4 |
| CRUISE RANGE | 7 | 2 |
| USEFUL LOAD FRACTION | 1 | 7 |
| WEIGHT MATCHING | 6 | 3 |
| PASSENGER CAPACITY | 3 | 1 |
| AIRFOIL FORM FACTOR | 9 | |
| MACH. NO./ AIRFOIL THK. | 1 | |

**TABLE 6.6 -- GOAL PRIORITIES**

In our case the target design is the Boeing 747-200 airplane. Different starting designs give rise to "scenarios". These together with the target design are presented in Table 6.5. The starting design of Scenario One is grossly infeasible; it is close to the lower bounds. Scenario Two is representative of a good educated guess at the target design. The starting design of Scenario Three is is representative of a highly overdesigned aircraft but it is still infeasible; it is close to the upperbounds placed on the variables. The goal priorities are listed in Table 6.6. By way of comparison the priorities for Case A for the Boeing 727-200 is also shown in the table.

Convergence to the target design is said to have occurred if it satisfies two criteria, namely,

- the percentage difference in the sum of the deviation variables between the designs obtained from two concurrent design cycles is less than a specified value, and
- the percentage difference between the system variables of the two designs is also less than a specified value

Two sets of results are presented. For the first set (Set A, Figures 6.7 and 6.8) the convergence limits on both criteria were set at 5 percent. The convergence criteria were then reset to 1 percent. The second set of results, Set B, with the tighter convergence limits are shown in Figures 6.9 and 6.10. To conserve computer time the template designs of Set A were used as the starting designs for Set B.

### 6.2.4 Can the Template be used to Design a Boeing 747-200?

The results presented in Tables 6.7 to 6.10 provide support for an affirmative answer to the question. Each of the scenarios converges to about 5% of the target design, that is, the Boeing 747-200 configuration. The design histories for all the variables were plotted and they are similar in form to those shown by Marinopoulos [30]. They are not germaine to the conclusions and are not reproduced here.

One obvious conclusion that can be drawn from this study is the subsonic constraints and goals, in the conceptual stage, apply equally to the Boeing 727 and the Boeing 747. The template appears to be a good way to represent knowledge about a particular domain of application. Care, however, must be exercised in using the template beyond the range of applicability. It is expected that the template will evolve with time. This evolution will involve both the scope (more variables, constraints and goals) and also the design-analysis information that is used. At some stage, some important empirical relationships will be replaced by more rigorous ones that involve mathematical analysis within the solution process. This requires access to a design-analysis library. Access to this library has been facilitated through two interfaces (see Figure 2.9).

| SYSTEM VARIABLES | SCENARIO One | Two | Three | 747-200 |
|---|---|---|---|---|
| 1. WING AREA ($ft^2$) | 5,580 | 5,566 | 5,605 | 5,500 |
| 2. INSTALLED THRUST (lbs) | 156,980 | 157,084 | 156,998 | 180,000 |
| 3. FUSELAGE LENGTH (ft) | 220.4 | 220.8 | 223.1 | 225 |
| 4. CRUISE MACH NUMBER | 0.87 | 0.88 | 0.89 | 0.85 |
| 5. TAKE-OFF WEIGHT (lbs) | 782,580 | 780,734 | 782,489 | 778,000 |
| 6. MAXIMUM THICKNESS RATIO OF AIRFOIL | 0.12 | 0.12 | 0.12 | 0.12 |
| 7. WING SPAN (ft) | 197,2 | 197.2 | 198.6 | 195.7 |
| 8. FUSELAGE DIAMETER (ft) | 21.8 | 21.8 | 22.1 | 22 |

TABLE 6.7 -- RESULTS SET A - SYSTEM VARIABLES

| DEPENDENT VARIABLES | SCENARIO One | Two | Three |
|---|---|---|---|
| 1. ASPECT RATIO | 6.97 | 6.98 | 7.04 |
| 2. RANGE (nm) | 5,552 | 5,554 | 5,559 |
| 3. PAYLOAD WEIGHT (lbs) | 150,000 | 150,000 | 150,000 |
| 4. NUMBER OF PASSENGERS | 556 | 555 | 572 |
| 5. FUEL WEIGHT (lbs) | 324,767 | 322,872 | 320,865 |
| 6. WING FORM FACTOR | 1.1659 | 1.1659 | 1.1556 |
| 7. LANDING FIELD (ft) | 4,801 | 4,812 | 4,818 |
| 8. USEFUL LOAD FRACTION | 0.61 | 0.61 | 0.60 |
| 9. TAKE-OFF FIELD (ft) | 7,337 | 7,318 | 7,303 |
| 10. CRUISE THRUST (lbs) | 39,991 | 39,857 | 39,862 |
| 11. ENDURANCE | 0.03 | 0.03 | 0.03 |
| 12. FUSELAGE FORM FACTOR | 1.0834 | 1.0828 | 1.0838 |
| 13. MISSED APPROACH (deg) | 9.99 | 10.00 | 9.90 |
| 14. SECOND SEG. CLIMB (deg) | 4.55 | 4.58 | 4.57 |

TABLE 6.8 -- RESULTS SET A - DEPENDENT VARIABLES

| SYSTEM VARIABLES | | SCENARIO One | Two | Three | 747-200 |
|---|---|---|---|---|---|
| 1. WING AREA | ($ft^2$) | 5,575 | 5,585 | 5,601 | 5,500 |
| 2. INSTALLED THRUST | (lbs) | 156,979 | 156,907 | 156,878 | 180,000 |
| 3. FUSELAGE LENGTH | (ft) | 221.2 | 220.9 | 222.9 | 225 |
| 4. CRUISE MACH NUMBER | | 0.88 | 0.87 | 0.88 | 0.85 |
| 5. TAKE-OFF WEIGHT | (lbs) | 781,624 | 782,913 | 782,635 | 778,000 |
| 6. MAXIMUM THICKNESS RATIO OF AIRFOIL | | 0.12 | 0.12 | 0.12 | 0.12 |
| 7. WING SPAN | (ft) | 197.5 | 197.5 | 198.5 | 195.7 |
| 8. FUSELAGE DIAMETER | (ft) | 21.8 | 21.8 | 22.1 | 22 |

TABLE 6.9 -- RESULTS SET B - SYSTEM VARIABLES

| DEPENDENT VARIABLES | | SCENARIO One | Two | Three |
|---|---|---|---|---|
| 1. ASPECT RATIO | | 7.04 | 7.02 | 6.99 |
| 2. RANGE | (nm) | 5,556 | 5,555 | 5,555 |
| 3. PAYLOAD WEIGHT | (lbs) | 150,000 | 150,000 | 150,000 |
| 4. NUMBER OF PASSENGERS | | 569 | 569 | 558 |
| 5. FUEL WEIGHT | (lbs) | 322,607 | 322,374 | 322,601 |
| 6. WING FORM FACTOR | | 1.1647 | 1.1647 | 1.1647 |
| 7. LANDING FIELD | (ft) | 4,805 | 4,801 | 4,816 |
| 8. USEFUL LOAD FRACTION | | 0.60 | 0.60 | 0.60 |
| 9. TAKE-OFF FIELD | (ft) | 7,316 | 7,312 | 7,326 |
| 10. CRUISE THRUST | (lbs) | 39,887 | 39,879 | 39,888 |
| 11. ENDURANCE | | 0.03 | 0.03 | 0.03 |
| 12. FUSELAGE FORM FACTOR | | 1.0835 | 1.0836 | 1.0829 |
| 13. MISSED APPROACH | (deg) | 9.93 | 9.94 | 9.96 |
| 14. SECOND SEG. CLIMB | (deg) | 4.56 | 4.56 | 4.57 |

TABLE 6.10 -- RESULTS SET B - DEPENDENT VARIABLES

## 6.3 SOME IMPROVEMENTS FOR THE TEMPLATE

There are three principal limitations in the template, namely, weight analysis, fuel estimation and tail sizing. The weight and the fuel weight estimation routines need to be significantly improved. The system variables need to be increased to accommodate the horizontal and vertical stabilizer dimensions and the aft-most center of gravity in cruise. It is recommended that the detailed mission analysis routine that is used in OPDOT [56] be included in this template. This will permit the formulation of goals to minimize fuel consumption in taxi, initial climb, climb to cruise, cruise, descent and landing.

An accurate estimate of the weight is very important and is for the most part proprietory information. In this template empirical relations from Nicolai [43] have been used. These are, however, credited to the General Dynamics Corporation. A detailed weight estimate and the weight distribution are important for determining the aircraft's center of gravity. The center of gravity of the aircraft governs the placement of the wing, tail and landing gear and hence its inclusion in the template is warranted.

It is recommended that design of the control surfaces in the conceptual stage be based on static stability and control condiderations. The inclusion of the design of the horizontal and vertical control surfaces will facilitate the determination of the aircraft layout and balance. The horizontal surface (aft tail or canard) is used for longitudinal stability and control. Typically, an aircraft is designed for a particular level of stability and is then sized for adequate longitudinal control. Constraints and/or system goals, for designing the horiziontal control surface, may be developed that take into account the following:

- Trim drag: The trim drag during cruise should be less than 10 percent of the total aircraft drag. Many designers limit it to 5 percent for range dominated transports.

- Take-off rotation: The take-off rotation to climb $C_L$ should be checked. The horizontal control surface must have enough control power to rotate about the main landing gear to the take-off attitude.

- High $\alpha$, low speed: The condition of low speed approach for landing with power at idle, flaps down and high angle of attack is often a critical condition for sizing the control surface. This condition often determines the most forward position of the center.of gravity of the aircraft.

The vertical tail is sized to give adequate static directional stability. An empirical relation to determine the surface area is given in Nicolai [43]. This may be adequate. The lift coefficients used in the template are over-estimated for the engine-out performance constraints. The missed approach climb gradient and the second segment climb gradient are engine-out performance requirements specified by the Federal Aviation Regulations, FAR [1]. Our error may be in assuming the value of the lift coefficient to be the maximum during this occurrence. This needs to be investigated and fixed.

Recommendations for future work are presented in Chapter 7.

# CHAPTER 7
## CLOSURE

In this chapter the work that has been done is analyzed and recommendations for further development presented.

## 7.1 HAS THE PRINCIPAL GOAL BEEN ACHIEVED?

As indicated in Chapter 1 our principal goal was to demonstrate the efficacy of using selection and compromise DSPs in aircraft design. With this in mind we started work on two fronts, namely,

- developing the selection DSP methodology and associated computer software, and
- creating and validating selection and compromise DSP templates.

Has the principal goal been achieved? The answer is a qualified yes.

An ideal design scenario involving preliminary selection, selection and compromise is shown in Figure 2.1. The role of the two selections and compromise in conceptual design is explained in Chapter 2, Section 2.3.3. A problem statement involving aircraft selection is the subject of Section 2.3.5. A problem statement and a general word formulation for the conceptual design of a subsonic transport is given in Section 2.5.2. The reasons for our choice of the Boeing 727-200 as the focus of our study are give in Chapter 5, Section 5.1.1. It was our intention to use this airplane for illustrating both selection and compromise. Unfortunately, we lacked expereince and were unable to find the right type of information to support the creation of selection templates for the Boeing 727-200 airplane. Hence, for selection, we relied on a paper study that was the outcome of a student competition [10]. We found sufficient information to create a general compromise template for the design of subsonic jet transports to particularize it for the Boeing 727-200 aircraft, for example, [27,43,56,61]. Hence, in our case, the solution of the preliminary selection DSP feeds into the selection DSP but the solution of the selection DSP does not feed into the compromise DSP. Conceptually we see no problem in demonstrating the link between selection and compromise in the scenario shown in Figure 2.1. Since we are unable to demonstrate this through example our answer to the question of attaining our principal goal is a qualified yes.

## 7.2 ACHIEVEMENTS, SHORTCOMINGS AND RECOMMENDATIONS

For selection (see Chapter 3) only the potential of the process in aircraft design is evident. Two types of selection DSPs are proposed, namely, preliminary selection and selection. The templates do provide a basis for developing and incorporating rigorous measures for modeling and trading off economic and technical efficiencies that are inherent in aircraft at this early stage in design. The templates are not sufficiently complete, however, to be useful in the real-life design of subsonic transports. It is shown that the output from the preliminary selection DSP can indeed be used as input for the selection DSP. Both types of selection involve multiple attributes and both facilitate trade-offs between technical and economic efficiencies. Post solution sensitivity analysis is particularly important in cases where decisions are based on soft information, the decision models are evolving and there is seldom enough time or resources for them to be completed. In practice, the development of the decision models ceases when the key players are ready to make their decision; this always precludes the development of a complete and comprehensive decision model. Hence, in this report, emphasis is placed on explaining post solution analysis and in communicating a flavor of the types of "what-if" questions that can be posed and answered. To facilitate correct formulation of the templates the cogent points associated with the formulation of each type of selection are listed in Appendices A.1 and A.2. The creation of scales and weights using soft information is covered in Appendix B. The software for selection, MacDSIDES, has been developed for the Apple Macintosh and has already been used, in industry, on projects involving the conceptual design of oil tools, offshore structures and ships. A PC-DSIDES is currently under development. Recommendations for the further development of method are presented in Chapter 3, Section 3.4.

The compromise DSP formulation is described in detail in Chapter 2 and points that are important for correctly formulating these DSPs are summarized in Appendix A.3. A generic template for the design of subsonic jet transports has been developed (see Chapters 2 and 4). It has been particularized for a Boeing 727-200 aircraft and validated. Can the template be used in the conceptual design of subsonic jet transports? The answer is yes. The validation process is described in Chapter 5. Three cases involving the Boeing 727-200 have been run:

- Case A: A Technically Efficient Aircraft
- Case B: A Technically Efficient Aircraft Influenced by Economics
- Case B: A Technically and Economically Efficient Aircraft

In addition to the conclusions, an attempt has been made to depict the evolutionary nature of template development and validation, and a feeling for the effort involved (see Section 5.4). The compromise DSP template was particularized (quite easily) for a Boeing 747-like aircraft. This is the subject of Chapter 6. An aircraft with strikingly similar (within 5%) to the Boeing 747 was the result. Creating the initial template takes time but modifications and extensions involve relatively little effort. Our success with the template for the Boeing 747 is indicative of the inherent capability of our DSP-based approach to accommodate technological change and respond to a change in mission requirements. The compromise DSP facilitates the modeling of requirements (as system constraints) and aspirations (as system goals). In Chapter 5, the trade-off between economic and technical efficiency on the design has been shown. We believe that the compromise DSP template (see Chapter 4) is sufficiently complex, comprehensive and realistic that it can be used for validation purposes. We feel comfortable with results (see Chapters 5 and 6) to conclude that the efficacy of using the method and the template in the conceptual design of aircraft has been demonstrated and warrants further support for development. Recommendations for improving the template are presented in Chapter 6, Section 6.3.

What is needed to increase confidence in the principal conclusion? Two issues need to be addressed, namely, the state of the software and the state of the template. Each is discussed in turn - first for selection and then for compromise.

We are confident in recommending the use of the preliminary selection DSP. In selection, however, the proposed method of normalizing and using both ratio and interval scales in calculating the merit function can be severely criticized. One remedy is to convert all ratio scales to interval scales and thence compute the merit function values. This has been suggested by Saaty [51,52]. We believe that this solution is appropriate when there is more soft information than hard information available (for example, in management science and in the early stages of the design process). Saaty [51,52] has presented a very good and mathematically sound method that can be used for creating interval scales and also for converting ratio scales into interval scales. We are in the process of integrating this into the MacDSIDES system. However, this addresses only part of the problem.

Our current approach is suitable when hard information dominates the selection DSP. In the intermediate case, that is, when there is a fair amount of both hard and soft information available there are currently two options available, namely, convert all ratio scales to interval scales or the approach presented in this chapter. We are reluctant to recommend converting ratio scales to interval scales and then solving the selection DSP because in doing so some very important technical knowledge is invariably lost. We believe that our current approach is suitable, in the intermediate case, if used by knowledgeable engineers with caution. We are at this time developing one of the ideas presented by Saaty that, if implemented, would provide a better way for making use of hard and soft information.

The selection templates, as stated earlier, do provide a basis for developing and incorporating rigorous measures for modeling and trading off economic and technical efficiencies that are inherent in aircraft at this early stage in design. The templates are not sufficiently complete, however, to be useful in the real-life design of subsonic transports. A real-life template for this activity, in our opinion, can only be developed if industry is involved. Support for this is strongly urged.

Version 4.6 of the DSIDES System was used in this project. This version had a number of limitations. These have been described by Kamal [18] and subsequently corrected in Version 4.73. Tools are needed to help a person develop templates. For example, identifying the starting solution during the template development phase is time consuming and at times very difficult. Once the template is fully developed the problem of identifying a starting solution vanishes. This feature and others that help the template developer need to be added. The software for post solution analysis has been developed by Karandikar [20]. Unfortunately, it was not possible to use it in this project. It is recommended that this feature of the program be exercised on the Boeing 727-200 template.

The compromise DSP template can be improved. These improvements are discussed in Chapter 6, Section 6.3. In summary it is recommended that the weight estimation and the modeling of economic efficiency be refined and the capabilities for detailed mission analysis be added. Further, it is recommended that the effect of the center of gravity and the design of the control surfaces at the tail be included. None of these improvements are likely to reverse the principal conclusion arrived at in this report; they will only reinforce the principal conclusion.

The principal benefit of implementing the recommendations regarding the templates is that this action will facilitate a better understanding of the issues involved and hence make it easier to use these templates in practice. In selection this will result in an understanding of the criteria and attributes and an identification of the type and quality of information needed to arrive at a decision. In compromise, the implementation of the recommendations will foster a better understanding of the interactions between the augmented set of variables, constraints and goals. Both are essential for facilitating the use of these templates by industry.

## 7.3 FUTURE WORK

The recommendations presented in Section 7.2 are those that affect the quality of the results and conclusions associated with the current study. In this section areas of work that are broader in scope are identified and discussed.

### 7.3.1 Development of the Domain Dependent Templates

There is a vast amount of technical information available in the public domain, for example [27,43,56,57,61,62,63], that can be used to refine the formulation of the compromise DSP template and to create new ones. We recommend that this work be undertaken at a university with a program in aeronautical engineering and also where there work is already underway on developing a design assistant for aircraft design. Incidentally, this excludes the University of Houston because we do not have a program in aeronautical engineering. The immediate benefit of this development will be a tool that is continually being updated and can be used in a teaching environment to help budding aircraft designers get a feel for the interactions that are driven by both technical and economic efficiency. With the encouragement of Brian Robson, the Director of Naval Ship Design, Canberra this is being done for ships using the AUSEVAL System [59] at the University of New South Wales, Sydney, Australia. The development of this type of capability for aircraft design and its use in teaching will provide a strong impetus for the design assistant, after the incorporation of proprietary information, to be used by different companies.

### 7.3.2 Development of the Domain Independent DSIDES Software

There are three aspects associated with the development of the domain independent software DSIDES, namely, the development of utilities, an intelligent knowledge base and the development of the capability to solve decision support problems that involve hierarchy.

The analysis and synthesis of engineering systems are generally too complex to be handled as a single problem. This necessitates designing the overall system by first decomposing the system into subsystems. If the system is then designed in parts (sequentially), there is no guarantee that an overall superior design will be reached. Thus, it becomes necessary to develop a methodology that will facilitate the determination of a superior design of a hierarchical system. A hierarchical system is a system that contains multiple levels of interaction between a parent system and the associated subsystems. The hierarchical design of a system can be modeled using a network of DSPs.

An engineering artifact can be represented by a hierarchy of a parent system and subsystems. Our views on this are summarized in a recent publication[1]. At each level of the hierarchy the design process involves decisions which are qualified by the following assertions:

- Some decisions are separable and therefore can be made concurrently

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1 See Shupe J.A, J.K. Allen, D. Muster and F. Mistree, "Decision-Based Design: Some Concepts and Research Issues", Expert Systems: Design and Management of Manufacturing Systems, (Ed. A. Kusiak), Taylor and Francis, June 1988, Chapter 1.

- Some decisions are inseparable and the input of decision "i" is the output of decision "i-1" and thus the decisions can be made sequentially (See Figure 7.1a).
- Some decisions are inseparable and are coupled and the output of one is the input of another (see Figures 7.1b and 7.1c). In this case the decisions could be made either sequentially (start with a reasonable guess for the first output of "i") or concurrently (using optimization).

Coupled hierarchical decision support problems permit the entire hierarchy to be formulated and solved as a single DSP. Hence, the interactions between the decisions are strongly linked, creating a tight bond between subsystems solved by the problem.

The following types of coupled problems have been identified:

1- Coupled compromise-compromise problems
2- Coupled selection-compromise problems
3- Coupled selection-selection problems

What is the current status of development? Hierarchical DSPs of the first type have been developed for the concurrent design of a ship hull and its propeller, Smith [58], and structural systems, Shupe, et al. [55]. Type 2 hierarchical DSPs have been developed and solved for the layout of a barge and the hull [59] and structural systems (the concurrent selection of the material and determination of dimensions) Kuppuraju, et al. [24]. Bascaran [8] has postulated and solved with difficulty a type 2 hierarchical DSP for the design of thermal energy systems. This work is important in that it is indicative of the problems that occur and remain to be solved in developing the capability to include the effects of hierarchy in design.

We now believe that we were successful to the extent reported in the earlier papers - only because the engineering system that we dealt with (in that case structures) involved information from a single discipline. From the subsequent work involving the design of thermal system [8], ships [59], an idealized drill casing subjected to a pseudo shock load [18] and composite materials we have come to recognize that we know very little about the behavior of hierarchical DSPs involving the design of systems that are governed by technical factors whose roots are in different disciplines. This represents the first focus of our current developmental efforts.

The third type of hierarchical DSP has many applications particularly in the very early stages of design. Consider a hypothetical engineering system that can be subdivided into three subsystems. To simplify the problem assume that each subsystem can be ordered from a catalog. Further, assume that the number of alternatives for each of the subsystems has been narrowed (by a human or expert system or both) to 3, 5 and 4, respectively and the number of attributes governing the choice of each alternative is 5, 3 and 4, respectively. We know how to solve selection DSPs and we can therefore pick the best alternative for each of the subsystems. The problem with this approach is that the interaction between the subsystems has not been taken into account resulting in a poor choice of subsystems for the system. Unfortunately, this or a variation of this approach is used all too often in practice. The interactions between the subsystems must be

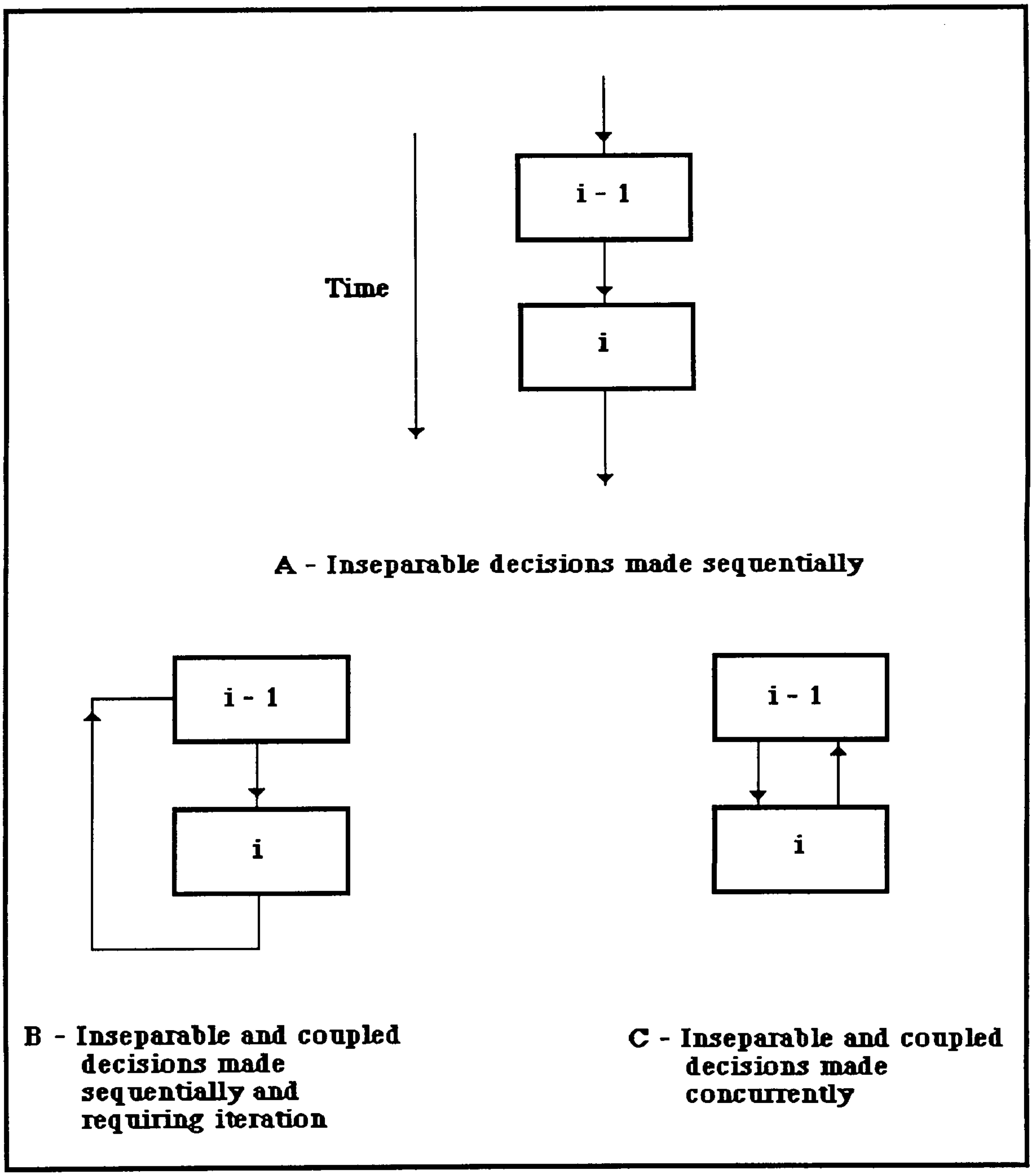


FIGURE 7.1 -- SERIES OF DECISIONS

taken into account. Conceptually, the formulation of coupled selection-selection problems is similar to the other two types of coupled problems. There are, however, certain aspects that have been identified which need to be resolved before a problem with several coupled selection problems and numerous alternatives can be actually implemented and solved. This represents the second focus of our current developmental effort.

What are some of the possibilities of using hierarchical DSPs in aircraft design? For purposes of illustration consider an aircraft to be divided into three subsystems, namely, the wing, the engine and the fuselage. Assume further that there are two possible wing forms and three different engines and three possible seating arrangements. The question could well be put: What is the best layout for the airplane based on, say, four different mission requirements? In this case the solution involves the formulation of a type 3 hierarchical DSP. Now assume that the wings and the engines still have to be selected but there is sufficient information to determine the fuselage dimensions. Now, the answer to the same question requires the formulation and solution of a type 2 hierarchical DSP. On the other hand, a fuselage with a width of 18 feet may be worthless when five seats across measures 17 feet and six seats across measures 19 feet and the hierarchical problem may quite well be altered to select the fuselage and the engine but to design the wing (another type 2 hierarchical DSP).

Aircraft are designed so that after the initial introduction different versions for a larger payload or a longer range are introduced Can this be handled using the DSPs? The answer is yes. Once the compromise DSP template is developed an airplane using the primary mission requirements is designed. Typically the wing for this aircraft is larger than that which is required. Given that the wing is fixed and say three engines are available the fuselage can be designed for the two new mission requirements (longer range or larger payload) using a type 2 hierarchical DSP.

Work is underway at the University of Houston to demonstrate the efficacy of using the hierarchical DSP in materials tailoring. We have had success in formulating and solving the compromise DSP for designing a pressure vessel using composite materials based on both strength, function and manufacturing requirements. A type 2 hierarchical DSP has also been formulated and solved for selecting the type of composite material to be used in addition to determining the design of the pressure vessel. These developments are significant for aircraft design. Strength considerations could also be taken into account at a relatively early stage of the design of the aircraft. Further, materials tailoring capabilty could be exploited not for the design of the aircraft as a whole but just for the wing. Our efforts in developing the capability for materials tailoring represents the third focus of our current developmental activities.

## 7.4 CONCLUDING REMARKS

It is not our intention, in this report, to suggest that we have a method for aircraft design but to indicate that we may have some tools that have some untapped potential in providing decision support for aircraft designers. At the start of the project we had no knowledge of how aircraft were designed nor any knowledge of the sources of information. On the completion of this project we are at best novices at aircraft design. Our knowledge has been gleaned from books, talking to a few involved in aircraft design and through exercising the templates. Some of our assumptions may be naive. Some of our conclusions, in the eyes of an experienced designer, may be "old hat" and maybe even wrong. We accept this possibility and hope that this does not detract from our principal conclusion, namely, that there is untapped potential for using selection and compromise Decision Support Problems in aircraft design.

An experienced aircraft designer might well ask: " What is to be gained from redesigning the good old Boeing 727-200 or redoing a paper study (that was done by students) involving aircraft selection? After all aircraft have been successfully designed and built for many years without the use of Decision Support Problems - so what's new?" Yes, we have used existing information but organized it in a manner that supports human judgment and hence may contribute to an increase in the efficiency and effectiveness of the designer. This is particularly important at the dawn of, what some futurists call, the Information Age. Intelligent design assistants are under development at various centers around the world. It is generally accepted that "intelligent" computer-based design assistants will become available - albeit, initially, for very limited and specific design tasks. The development of knowledge representation schemes, inference algorithms and machine learning is based on the notion that knowledge can be obtained from experts; a time consuming and difficult process. Another way is to provide this knowledge through machine learning from simulation; a nearly impossible task with the current status of machine learning.

Central to the development of the DSP Technique and the DSIDES System is the development of a scheme to represent design information in a knowledge base. This requires the conceptual categorization of knowledge in terms of representation as well as the role it plays in capturing the DSP process and domain specific information about the artefact. The knowledge base includes two types of knowledge: knowledge about the process of design and knowledge about the product being designed. The knowledge about the process (procedural knowledge), in our case, is embodied in the Decision Support Problem Technique for design. On the other hand, declarative knowledge is a set of facts represented (usually) according to the protocol defined by procedural knowledge. This knowledge is embodied in a DSP template.

The information and knowledge associated with an entire class of DSPs is stored as a template on the computer. A template, is the representation of the mathematical forms of a class of DSPs on the computer. Once a template within a domain for a class of problems is developed it can be used to formulate specific DSPs in this domain by using a subset of information from the template or through the addition of information to the template. These templates, we believe, provide a basis for providing knowledge for intelligent design assistants. The knowledge that is sought can be obtained through "intelligent" simulation involving a designer and a tool like DSIDES. This scheme lies in between the two schemes, for acquiring knowledge, listed earlier. The DSP templates are meant to evolve with time and we have provided some proof of this by extending the Boeing 727 template to design a Boeing 747 like aircraft (see Chapters 5 and 6). We therefore believe that our work is important in the context of being able to (on a continuing basis) use/structure existing information to help in the process of creating knowledge for intelligent design assistants or expert systems. Specifically, this includes, creating and modifying heuristics and/or rules of thumb. At the other end of the spectrum a tool like DSIDES could be used to do away with rules of thumb and replace them with analysis that is more rigorous.

The development of DSIDES is linked inextricably to the development of the Decision Support Problem Technique. The DSP Technique is based on a particular view of the world and a set of paradigms. It includes four phases, namely, planning, structuring, solution and post-solution analysis. The current DSIDES package can can only be used to solve selection, compromise and hierarchical DSPs. At this time there is no computer-based support available for the planning and structuring phases of the DSP Technique. A very limited capability for post-solution analysis has been included in the DSIDES System. Therefore, our focus in this report has been on investigating the use of Decision Support Problems (as opposed to the DSP Technique) in aircraft design. The DSPs represent fundamental decision blocks and can always be uncoupled from the DSP Technique and can therefore be integrated into any design method. Since the focus is not on the DSP Technique but the DSPs only an overview of the DSP Technique is given in Chapter 1. Further information is available in [37,38]. We have, however, provided an in-depth treatment of the selection and compromise DSPs.

The report is long and we have been pedantic and repetitious at times. This is a direct consequence of our experience in dealing with practicing engineers and other developers. We have been repetitious and perhaps succumbed to lecturing - but this is only to emphasize a point and to facilitate concept absorption. We have tried, in this report, to make clear what we are trying to achieve, how far we have succeeded and to provide enough information for others who may want to build on our work to do so. The paradigms from which we operate and their ramifications are very important (see Section 1.1.1). For example, we use the phrase Decision Support Problem to convey our desire to support human judgment not replace it. We do use optimization techniques to obtain solutions not *of* optimization problems but *for* Decision Support Problems. Our solutions are not optimal designs or optimal solutions - but rather potential designs that represent trade-offs (we hope optimal) between economic and technical efficiencies. Except in routine design, information is rarely complete or comprehensive enough to warrant always worrying about obtaining a "true optimum". Hence, we believe in providing decision support to practicing engineers that result in "satisficing" solutions - not solutions that are globally optimal. In the same vein, since we are interested in providing decision support for the design of artifacts we are not concerned that we restrict the system variables of a compromise DSP to be independent, positive and non-zero. Parameters that assume negative values are dependent variables and may manifest themselves as system constraints, goals or target values. There are many things that may appear, at first glance, to be part of the familiar but are not. For example, the modeling of the design and aspiration spaces in the compromise DSP formulation requires that the "objective" (of what may appear to be a "traditional" nonlinear optimization problem), always be a sum of the deviation variables. There are sound reasons that we require that certain things be done. For example we require bounds, that are independent of the attributes, to be specified when the scales are created for use in selection and we only accept rank-ordered responses in preliminary selection. There are certain things that just cannot be accommodated - even if it is permissible in other well-known schemes. We require that two deviation variables be used to model each system goal in a compromise DSP. One cannot expect to get a solution by removing a deviation variable from the formulation of a system goal and permitting the remaining one to assume non-zero values. Yes, there are some limitations but these represent the price one pays for achieving the capability to model and optimally trade-off technical and economic considerations in design. We have made clear the domain of application of the DSPs and care should be exercised in using these tools or attempting to modify them for use in domains that are not supported by the paradigms on which they are based.

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# APPENDIX A:
## SUMMARY AND STEPS FOR FORMULATING SELECTION AND COMPROMISE DECISION SUPPORT PROBLEMS

In this appendix a summary of the important points and the necessary steps for formulating and solving selection and compromise Decision Support Problems is presented. For the preliminary selection DSP the steps are presented for the case where the generalized criteria are characterized by one specific criterion only. The formulation and solution of the DSPs involve four phases (planning, structuring, solution and post-solution sensitivity analysis) and six steps. The phases are illustrated in Figure 1.1 and the process is covered in detail in references [37,38].

A solution to a DSP does not guarantee a superior solution - the adage garbage in garbage out still applies. It is extremely easy to get a false sense of security because one is using a computer program to process numbers. The quality of the solution is a function of the person making use of these tools. A good description of the problem and the documentation of the reasons for making choices is extremely important. In this appendix, therefore, a cogent summary of these points is presented.

## A.1 THE PRELIMINARY SELECTION DSP

In this section a summary (details in Chapter 3, Section 3.2) of the important points and the necessary steps for formulating a preliminary selection DSP are presented. Assume that the problem statement has been written. The problem statement must be written in sufficient detail to provide the basis for developing the preliminary selection DSP. The concepts and the principal criteria that will influence the decisions should be summarized in this statement. The problem statement is different from the word problem in that problem statement is unstructured (no key words) and similar to an executive summary whereas the word problem is structured in terms of the keywords - Given, Identify, Rank, etc. The word problem together with some pointers follows.

**GIVEN** The concepts.
Provide a sketch of each concept.
Describe each concept, list the advantages and disadvantages and provide acronyms.

**IDENTIFY** The criteria.
Describe each criterion. Remember, the criteria must be independent of each other. Each criterion must measure only one quality.

**CAPTURE** The experience-based insight.
Compare each concept against the concept chosen as the datum. A better concept receives a +, while a worse concept is given a - score. A zero is given for ties.

**RANK** The concepts in order of their scores.
Total the + scores and the - scores to see which concepts are the "top-of-the-heap" in this iteration.
Choose the concept with the best score to be the next datum.

**ITERATE** until it is clear which concepts are at the top-of-the-heap. This includes trying several different scenarios involving different weights for each general criterion. It may also involve modifying the problem statement and the criteria. The concepts that consistently come out at the top become the top-of-the-heap concepts.

**VALIDATE** the results through critical examination and convince yourself of their correctness. Document insight....**MAKE YOUR RECOMMENDATION.**

## A.2 THE SELECTION DSP

In this section a summary (details in Chapter 3, Section 3.3) of the important points and the necessary steps for formulating a selection DSP are presented. Assume that the problem statement has been written. Recall that the problem statement must provide the basis for developing the selection DSP. The alternatives, the attributes, etc. that will influence the decisions should be summarized in this statement. The problem statement is different from the word problem in that problem statement is unstructured (no key words) and similar to an executive summary whereas the word problem is structured in terms of the keywords Given, Identify, Rank, etc. The specification of the bounds and the documentation of the reasons underlying your choices is of paramount importance.

**GIVEN** The alternatives.

Provide a sketch of each alternative, if appropriate.
Describe each alternative and list the pros and cons.

**IDENTIFY** The attributes.

Describe each attribute. Remember, the attributes must be independent of each other. Each attribute must measure only one quality. Indicate whether the information is hard (quantitative, ratio scale) or soft (qualitative, interval scale). Remember attributes specified on an ordinal scale are converted to interval scales.

The relative importance of attributes with respect to each other.

Two methods for determining the relative importance of the attributes have been presented; use the appropriate method for the case in hand. Justify the decisions when using the 'Ranking Method'. Present the viewpoint and check for cycling when using the 'Reciprocal Pairwise Comparison Method'. Both methods result in a scale in which a larger number indicates preference.

The scale for each attribute.

Describe the nature of the information for each attribute. You seldom need to create a scale for those attributes that are rated on a ratio scale. Indicate clearly whether a larger or smaller number indicates preference. Specify the bounds. Be prepared to compare alternatives in pairs and to justify and document the reasons for your choice. The documentation of the reasons underlying your choices should be clear enough that your colleague (who is not necessarily familiar with the details of the problem), is able to read the description and then is able to offer a reasonable rating or argument.

**RATE** The alternatives with respect to each attribute.

For attributes rated on a qualitative (interval) scale make pair-wise comparisons and document your viewpoint. For attributes rated on a quantitative (ratio) scale allocate a rating. Justify the allocation of a particular attribute rating (value from a scale) to an alternative.

**RANK** The alternatives in order of preference.

Normalize the ratings. Transform the ratings into decision matrices. Convert all the matrices of decisions to a matrix of normalized priorities. Evaluate the merit function for each alternative.

**POST-SOLUTION ANALYSIS**

Validate the results: Critically examine the results and convince yourself of their correctness.
Perform an intelligent sensitivity analysis. Should the attributes be redefined? Is there a basis for combining the features of some of the alternative and creating a new alternative? Should the problem be resolved?
Document insight.......**MAKE YOUR RECOMMENDATION.**

## A.3 THE COMPROMISE DSP

In this section a summary (details in Chapter 2, Section 2.4) of the important points and the necessary steps for formulating a compromise DSP are presented. Assume that the problem statement has been written. Recall that the problem statement must provide the basis for developing the compromise DSP. The system variables should be clearly identified and the basis for the system constraints and goals should be clearly explained in this statement. Every goal has two deviation variables associated with it and they need to be specified to obtain a solution using the DSIDE System. The system variables are always positive and nonzero. The problem statement is different from the word problem in that problem statement is unstructured (no key words) and similar to an executive summary whereas the word problem is structured in terms of the keywords Given, Find, Satisfy, Minimize. The compromise DSP includes both system and deviation variables, system constraints and goals. The objective or achievement function for the compromise DSP is written in terms of the deviation variables only. A summary of the structure and important points with respect to problem formulation follows. A "checklist" for the formulation is presented in Figure A.1.

**GIVEN** The following information:

1. The assumptions on which the DSP is based.
2. a The independent system variables.
   b The deviation variables associated with each of the goals.
3. a The system constraints. These are formulated using independent system variables only.
   b The system goals. These are formulated using independent system variables and deviation variables. There are two deviation variables associated with each goal.
4. The achievement function which is formulated using deviation variables only.

**FIND** The value of the system variables.
The value of the deviation variables.

**SATISFY** System constraints <u>MUST</u> be satisfied for feasibility.
These constraints are specified using system variables.
These constraints are generally inequalities.
It is advisable to make these constraints nondimensional by normalizing so that all system constraint function values are roughly of the same order of magnitude.

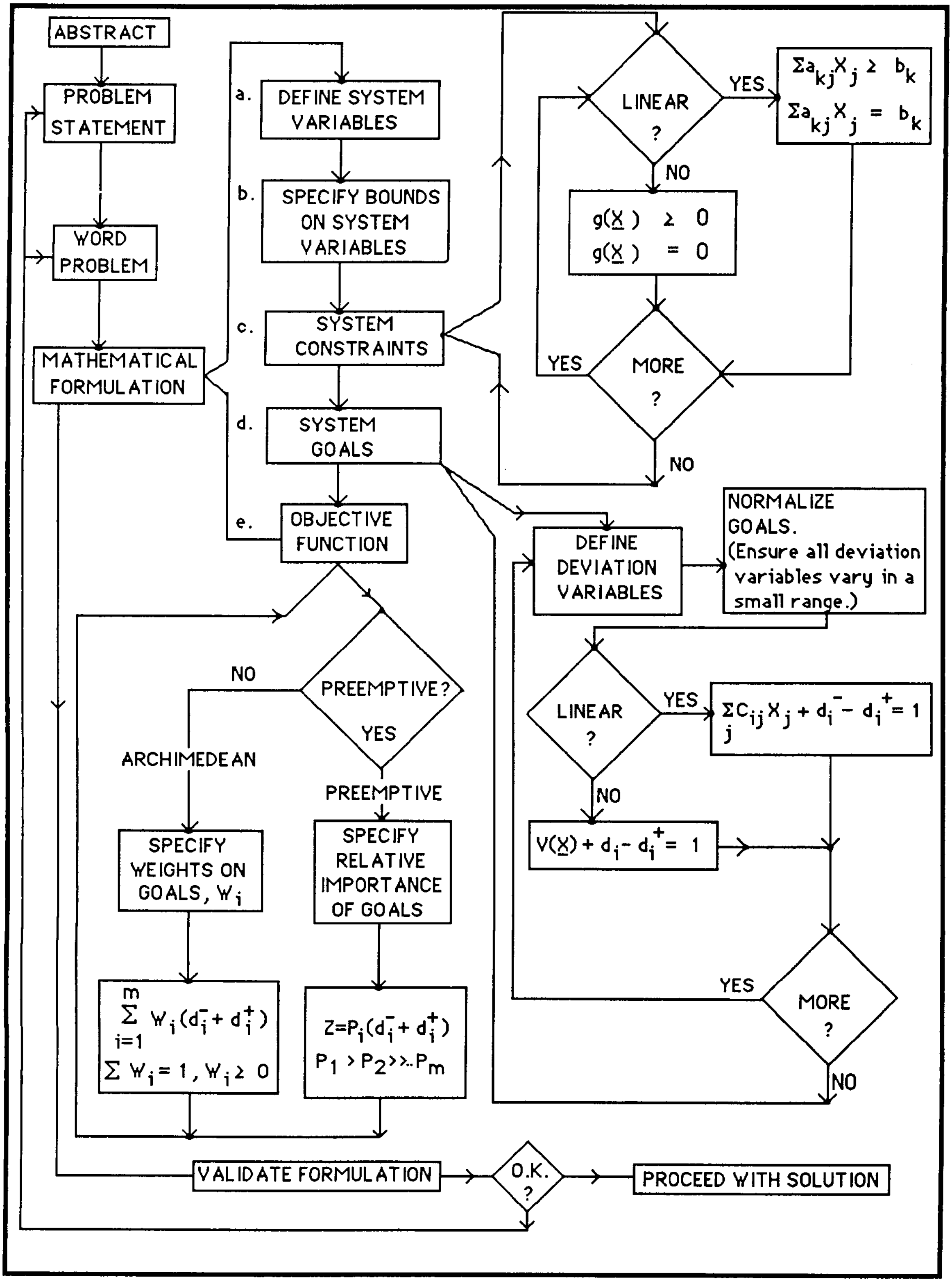


FIGURE A.1 -- STEPS FOR FOR FORMULATING A COMPROMISE DSP

System goals

It is desirable but not necessary for these to be satisfied at the 'optimum'.

Unlike traditional optimization multiple objectives are represented as a set of system goals. The goals are specified using system variables and deviation variables. There will be two deviation variables for each system goal, i.e., one to represent the underachievement of the goal and the another to represent the overachievement of the goal.

These system goals will **ALWAYS** be formulated as equalities.

If there is more than one goal it is **IMPERATIVE** that the goals are made nondimensional by normalizing so that the values of the deviation variables for the set of system goals vary between the same range (e.g. 0 to 1 or 0 to 100, etc.)

Bounds on system variables

Specify the lower and the upper bounds on **ALL** system variables.

**MINIMIZE** An achievement function that is specified using **ALL** the deviation variables. There are two forms of the achievement function, viz., pre-emptive and Archimedean. Both are defined as sums (different functions though) of deviation variables. A solution in the preemptive case reflects an attempt by the algorithm to maximize the number of goals that are attained. A solution obtained using the Archimedean formulation reflects an attempt to achieve all of the goals (simultaneously) as far as possible. Hence, the result could be different for the two formulations.

**POST SOLUTION ANALYSIS**

Validate the results: Critically examine the results and convince yourself of their correctness.

Perform an intelligent sensitivity analysis. Should the system constraints and/or goals be modified? Should the priorities be changed? Should the problem be re-solved? What are the active constraints? Should the specified ratios between system variables be altered?

Document insight.......**MAKE YOUR RECOMMENDATION.**

# APPENDIX B:
## SCALES AND WEIGHTS USING SOFT INFORMATION

Scales have to be created and used to model experience-based judgment in both the selection and compromise Decision Support Problems. The methods for creating the scales are simple. Their effectiveness on design is a function of the degree of care and the quality of knowledge with which the creator of the scale is imbued. The creation of scales is an extremely important task and it must be undertaken with great care. In this appendix information on how to create scales and determine weights using experience-based judgment is presented.

## B.1 INTERVAL SCALES AND THEIR USE IN DECISION SUPPORT PROBLEMS

In preliminary selection interval scales are used in specifying the relative importance of the generalized criteria. An interval scale may also be used to assign weights to the specific criteria within a particular generalized criterion. In the selection DSP interval scales are used to establish the relative importance between attributes and also to provide a means for quantifying preferences that are rooted in experience-based insight (soft information). In the compromise DSP interval scales are used to model the weights used in the achievement function.

There are four types of scales, namely, ratio, interval, ordinal [50] and composite. The choice of a particular type of scale to model an attribute depends on the nature of available information. The ratio scale is used for an attribute for which physically meaningful numbers are available, e.g., cost, power, speed, etc. The ordinal scale is used to model an attribute that can only be qualified in words. An ordinal scale is appropriate for attributes like aesthetic appeal, color, etc. The interval scale is used in two ways. Firstly, it is used to model attributes in which the zero is relative, e.g., temperature, efficiency, etc. Secondly, it is used to transform the quality captured by the ordinal word scale into a numerical interval scale. The composite scale is an interval scale but with a twist. The composite scale is used to model the collective preference associated with a number of related sub-attributes.

Interval scales are created for attributes for which only qualitative or "soft" information is available. Safety, reliability, complexity, simplicity are some examples of attributes measured on an interval scale. The creation of interval scales is justified when a designer is able to rank-order preference for a particular alternative with respect to a particular attribute. If a designer is unable to indicate (even qualitatively) by how much a particular alternative is preferred over another then the ranking method (see Section B.3.1) for creating the interval scale is recommended. If a designer is able to express some degree of preference between the alternatives then the method of comparison should be used to create the scales (see Section B.3.2). If a designer is able to clearly articulate a definite and measurable degree of preference then a scale together with the associated ratings may be specified (see Chapter 3, Section 3.3.2, Step 3). It is pointed that this option must be exercised with great care.

The simplest way of rating alternatives for a soft attribute is to rank order the alternatives. This will quickly show the best as well as the worst alternative is and everything in between. This will work when a decision can be made based on only one attribute. This invariably is not the case in engineering. The problem with rank ordering is that there is no notion of the "distance" between ratings. In terms of preference, how far apart are the first and second alternatives? Is the third alternative, in terms of preference, as far from second as the second is from the first? These questions cannot be answered through rank-ordering, yet the information is necessary for DSPs with multiple attributes. Hence, we need some quantitative means of representing differences of preference. This is accomplished by creating an interval scale. Thus, we must have some means of creating an interval scale; a scale that provides an interval or measure of preference between ratings.

## B.2 THE CREATION OF INTERVAL SCALES

Riggs [49] presents three methods for developing interval scales:

- Churchman-Ackoff Method
- Standard Gamble Method
- Rating Forms

These are presented as given by Riggs [49] with some modifications in order to conform to their use in the decision support problems. Saaty [50] has developed a very good and mathematically sound method that can be used for rating alternatives on attributes based on soft information. This is presented in the context of determining the relative weights of attributes in Section B.3.3.

A numerical rating system is only as good as the rationale exercised in its use. A **decision maker should be prepared to convince a questioner that the judgment was correct.** The rating form approach, at this time, is the most common one used for creating interval scales for use in formulating the DSPs. As indicted in Chapter 3 we are in the process of implementing the method suggested by Saaty into the MacDSIDES system.

### B.2.1 The Churchman-Ackoff Method

Churchman and Ackoff offer a procedure for quantifying intangibles in which the developed values are assumed to be additive. A decision maker is asked first to rank the items and then to assign numbers between 1.0 and 0.0 to alternative outcomes according to the approximate intensity of preference. Thus, a rating for outcomes from alternatives W, X, Y and Z might appear as,

| X | Z | W | Y |
|---|---|---|---|
| 1.0 | 0.8 | 0.4 | 0.3 |

Now the sum of the values for Z, W and Y ($0.8 + 0.4 + 0.3 = 1.5$) is compared with the rating for X (1.0). In order to show a distinct preference for X, its rating must exceed the sum of all lower-ranked ratings ($X > Z + W + Y$). If the ratings do not conform to the rule, they are changed as little as possible in making them conform. The new value assignment might be,

| X | Z | W | Y |
|---|---|---|---|
| 1.0 | 0.6 | 0.2 | 0.1 |

where $1.0 > 0.6 + 0.2 + 0.1$.

Next the value for Z is compared to the sum of W and Y. The values above confirm a preference for Z, since 0.6 > 0.2 + 0.1. The sequence ends with a preference shown for W over Y, with 0.2 > 0.1.

There are many sets of numbers that conform to the procedure and show the same order of preference but different intervals:

| X | Z | W | Y |
|---|---|---|---|
| 1.0 | 0.97 | 0.02 | 0.01 |
| 1.0 | 0.34 | 0.32 | 0.01 |
| 1.0 | 0.04 | 0.02 | 0.01 |

The procedure by itself does not assure that a legitimate interval scale has been developed. It systematizes the judgment process, but accuracy is still a function of the decision maker's conscientiousness.

### B.2.2 The Standard Gamble Method

Another procedure designed to yield an interval scale is called the standard gamble method. The top and bottom levels of the scale are mentally fixed by visualizing the perfect outcome of the criterion for a 1.0 rating, and the worst possible outcome for a 0.0 rating. Then the alternative being rated is compared to the extreme examples. The comparison is made like a lottery: The decision maker selects acceptable odds for a gamble between having a perfect outcome (1.0) against the worst outcome (0.0) ***or*** having the certain outcome of the alternative. The mental gymnastics required to conduct this mental lottery are difficult to master, but the scale boundaries for the best and worst outcomes make the ratings comparable for all alternatives.

To further describe the standard gamble method, assume graduate schools are being compared. One of the criteria is prestige, an attribute with no natural measurements. The first step is to select the most prestigious school imaginable, and give it a rating of 1.0. The next step is to select a school with the least possible prestige for the 0.0 rated outcome. The best and worst limits are not established by the set of alternatives being considered: that is, the upper and lower bounds must be established not by the alternatives that are being considered but by the best and worst **possible** outcomes. For example, it might not be possible to attend the most prestigious institution but it still needs to be used to set the upper limit. Then a theoretical lottery matches the preference for the top school (1.0) over the lowest (0.0) against surely attending the school being rated.

The lottery takes the form of a specific query aimed at each school being rated: "What probabilities of going to the 1.0 rated school instead of the 0.0 school would I accept to make the gamble equivalent to surely going to school X (X is the school being rated)." An answer of 0.4 indicates indifference between attending school X and having 3 chances in 10 of attending the top school (which means there are 7 chances in 10 of attending the worst school). A rating of 0.5 shows no preference between school X and a 50 percent chance of going to either the top or bottom school. The selected probabilities become the ratings for each alternative. In this example with two schools rated at 0.3 and 0.5, if there were a third school with a rating of 0.9, this school would be preferred over the other two alternatives by the intervals given by the lotteries (0.6 and 0.4, respectively).

### B.2.3 The Rating Form

A standardized rating form which has written descriptions of each level of desirability is the most commonly used method for rating intangibles. The scales typically run from 0 to 10 with explanations of the attributes expected at each interval. Well-composed rating forms define, in easily understood language, the outcome that qualifies an alternative for each numbered rating.

Rating forms with similar characteristics have been developed to evaluate recurring decision situations. For example, government agencies engaged in research solicit bids from internal and outside investigators for conducting studies. A request for proposals (RFP) contains a statement of the technical requirements of the work and requests bidders to provide cost estimates, time schedules, and proof of competence. The replies are then evaluated by a board according to how well they meet the criteria of acceptance. A typical guideline for assigning numerical ratings for each criterion or attribute is given below.

| Ratings Interval | Ordinal | Description |
|---|---|---|
| 10 9 | Very good | Has a high probability (over 80%) of exceeding all the requirements expressed in the RFP for the criterion |
| 8 7 6 | Normal | Will most (50-80%) likely meet the minimum requirements and scope of work established in the RFP |
| 5 4 3 | Below normal | May fail (30-50% probability of success) to meet the stated minimum requirements but is of such a nature that it has the correction potential |
| 2 1 0 | Unacceptable | Less than 30 percent chance of success. Cannot be expected to meet the stated minimum requirements and is of such a nature that drastic revision is necessary for correction |

**TABLE B.1 -- A TYPICAL RATING FORM**

While using a rating form, it is important to keep referring to a mental standard that conforms to each level. In the RFP evaluation, the standards are defined in writing. In personnel rating forms the standards result from experiences with the performance of people how were previously rated in each category. Each decision maker has a different interpretation of what constitutes perfection, based on personal views and past exposures. <u>It is not vital</u> that all decision makers have the same absolute limits for their interval scale; it is vital that they are consistent in applying their own scale among alternatives. To facilitate consistency of ratings it is vital that the description of each interval include wherever possible numerical qualification (e.g., the percentage chance of success in the example). Note that it may be tempting at times to create one rating form and use it for creating scales for many attributes. This is invariably not possible to do. In general a different rating form will be needed for creating interval scales for for different attributes.

## B.3 DETERMINING WEIGHTS FOR THE RELATIVE IMPORTANCE OF CRITERIA AND ATTRIBUTES

When more than one attribute exists, relative importances or relative weights must be assigned to the attributes. This process is generally based on experience and insight and requires very careful consideration. There are many ways to develop weights [6,49,50]. We present three ways to capture the insight of the designer and once captured, use the insight to develop the relative importances. All three have been used to determine the relative importance of attributes for the aircraft example. Note that the weights obtained using the methods are not the same. If the problem is reasonably small (e.g., a problem solved as a classroom exercise) a computer is not essential for the first two methods; it is essential for the third.

The ranking method and the comparison methods can also be used to create composite scales. The comparison method has been used for determining the composite scale for power matching in the example (see Table 3.6). All three methods can also be used to determine the weights associated with the achievement of the goals (for the compromise DSP) when the Archimedean approach is used.

### B.3.1 The Ranking Method

In this method, the attributes are ranked in order of importance. The least important attribute gets the lowest rank and the lowest assigned weight. The second least important attribute gets the second lowest rank and the second lowest assigned weight, and so on. Then the weights are normalized.

The advantage of this method is that it is easy to apply and very suitable when the number of attributes is not too large (say up to 20). Also, when the available information (e.g. in the early stages of design) is not adequate but some decisions have to be made this method is very useful. The disadvantage of this method however, is that when the number of attributes defined is large, ranking of attributes becomes rather difficult. Another disadvantage of this method is that the difference in weights between successive attributes is the same. Such a scale may not be realistic. In this method it is important that the reasons supporting the ranking are given. Further, it is imperative that the ranks ascribed to different attributes are recorded and presented as a viewpoint. In Table B.2, the relative importance of the attributes, using the ranking method, for the aircraft problem are derived. The viewpoint has been omitted in the interest of brevity.

### B.3.2 The Comparison Method

In the comparison method, the preference between each pair of attributes is compared, and a viewpoint is established. Assume that there is a selection problem with nine attributes identified: 1 through 9. For this problem, there are 36 decisions to be made. The viewpoint represents these 36 decisions qualitatively (Table B.3). This qualitative viewpoint is changed to a quantitative value. For each comparison, the preferred attribute is assigned one point and the other attribute is assigned a zero. In the case where two attributes are equally important, both attributes are assigned 1/2 point each. It is only possible to award 0, 1 or 1/2 point, since the basis of this method is done pairwise for all the attributes. Then the points obtained by each attribute are totalled. The attribute which gets the highest score is the more important attribute. The scores are then normalized (see Table B.4). It is extremely important to present the viewpoint. This is been done after a fashion in Table B.3 In practice the viewpoint needs to be more substantial than that presented in Table

| | Attribute (j) | Rank | Normalized Relative Importance |
|---|---|---|---|
| 1 | Payload, or useful load | 7 | 7/45 = 0.156 |
| 2 | Range | 2 | 2/45 = 0.044 |
| 3 | Simplicity of design | 8 | 8/45 = 0.178 |
| 4 | Power matching | 9 | 9/45 = 0.200 |
| 5 | Cargo accessibility | 5 | 5/45 = 0.111 |
| 6 | Landing site restrictions | 1 | 1/45 = 0.022 |
| 7 | Parking area | 4 | 4/45 = 0.089 |
| 8 | Achieved stability | 3 | 3/45 = 0.067 |
| 9 | Engine out safety | 6 | 6/45 = 0.133 |

Notes: The larger numbers indicate preference.
Normalized relative importance is computed by dividing the rank by the sum of the ranks.

**TABLE B.2 -- EVALUATION OF NORMALIZED RELATIVE IMPORTANCE OF ATTRIBUTES**

B.3. The information in Table B.4 is of no value without the supporting information from Table B.3 and a substantial viewpoint. In our opinion a decision maker should be able to convince others who read the report that the judgment used is correct. The advantage of this method over the ranking method is that comparing two attributes at a time is easier than ranking all attributes at once. This method, however, can result in intransitivity or cycling (i.e., attribute A > attribute B > attribute C > attribute A where > indicates preference). Cycling can be avoided by adding a new relevant attribute or refining the definition of equal preferences. Saaty [50,51] has proposed a check for ascertaining and correcting inconsistencies. This

| Decision Number | Attributes | Decision | Viewpoint |
|---|---|---|---|
| 1 | 1,2 | 1>2 | Payload is more important than most of the attributes since it is a measure of the earning capability of the craft. It falls behind Simplicity and Power Matching. |
| 2 | 1,3 | 3>1 | |
| 3 | 1,4 | 4>1 | |
| 4 | 1,5 | 1>5 | |
| 5 | 1,6 | 1>6 | |
| 6 | 1,7 | 1>7 | |
| 7 | 1,8 | 1>8 | |
| 8 | 1,9 | 1>9 | |
| 9 | 2,3 | 3>2 | Range affects the problem less since there is a minimum range required and all alternatives are capable of meeting that requirement. It is only more important than Landing Restriction. |
| 10 | 2,4 | 4>2 | |
| 11 | 2,5 | 5>2 | |
| 12 | 2,6 | 2>6 | |
| 13 | 2,7 | 7>2 | |
| 14 | 2,8 | 8>2 | |
| 15 | 2,9 | 9>2 | |
| 16 | 3,4 | 4>3 | Simplicity is very important since it has an effect on design, construction and maintenance costs. |
| 17 | 3,5 | 3>5 | |
| 18 | 3,6 | 3>6 | |
| 19 | 3,7 | 3>7 | |
| 20 | 3,8 | 3>8 | |
| 21 | 3,9 | 3>9 | |
| 22 | 4,5 | 4>5 | Power Matching is most important since it measure economic and technical efficiency of the design. |
| 23 | 4,6 | 4>6 | |
| 24 | 4,7 | 4>7 | |
| 25 | 4,8 | 4>8 | |
| 26 | 4,9 | 4>9 | |
| 27 | 5,6 | 5>6 | Cargo Accessibility is fairly important to the operation of the aircraft. It is in the middle of importance. |
| 28 | 5,7 | 5>7 | |
| 29 | 5,8 | 5>8 | |
| 30 | 5,9 | 9>5 | |
| 31 | 6,7 | 7>6 | Landing Restrictions is the least important since in this category the alternatives are almost equal. |
| 32 | 6,8 | 8>6 | |
| 33 | 6,9 | 9>6 | |
| 34 | 7,8 | 7>8 | Parking is another important operational attribute. |
| 35 | 7,9 | 9>7 | |
| 36 | 8,9 | 9>8 | Engine Out Safety is third in importance. |

Notes: The symbol > indicates preference.
The numbers of the attributes correspond to those listed in Table B.2.

**TABLE B.3 -- ESTABLISHING A VIEWPOINT WITH THE COMPARISON METHOD**

Comparisons
Decision Number (from Table B.3)

| Attribute | 1 | | | | | | | | 9 | | | | | | | 16 | | | | | | 22 | | | | | 27 | | | | 31 | | | 34 | | 36 | Score |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 6 |
| 2 | 0 | | | | | | | | 0 | 0 | 0 | 1 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | 1 |
| 3 | | 1 | | | | | | | 1 | | | | | | | 0 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | | | | | | 7 |
| 4 | | | 1 | | | | | | | 1 | | | | | | 1 | | | | | | 1 | 1 | 1 | 1 | 1 | | | | | | | | | | | 8 |
| 5 | | | | 0 | | | | | | | 1 | | | | | | 0 | | | | | 0 | | | | | 1 | 1 | 1 | 0 | | | | | | | 4 |
| 6 | | | | | 0 | | | | | | | 0 | | | | | | 0 | | | | | 0 | | | | 0 | | | | 0 | 0 | 0 | | | | 0 |
| 7 | | | | | | 0 | | | | | | | 1 | | | | | | 0 | | | | | 0 | | | | 0 | | | 1 | | | 1 | 0 | | 3 |
| 8 | | | | | | | 0 | | | | | | | 1 | | | | | | 0 | | | | | 0 | | | | 0 | | | 1 | | 0 | | 0 | 2 |
| 9 | | | | | | | | 0 | | | | | | | 1 | | | | | | 0 | | | | | 0 | | | | 1 | | | 1 | | 1 | 1 | 5 |
| Total score | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 36 |

| Attribute $j$ | Relative Importance $I_j$ |
|---|---|
| 1 Payload, or useful load | 6/36 = 0.167 |
| 2 Range | 1/36 = 0.020 |
| 3 Simplicity of design | 7/36 = 0.194 |
| 4 Power matching | 8/36 = 0.222 |
| 5 Cargo accessibility | 4/36 = 0.111 |
| 6 Landing site restrictions | 0/36 = 0.0 |
| 7 Parking area | 3/36 = 0.083 |
| 8 Achieved stability | 2/36 = 0.056 |
| 9 Engine out safety | 5/36 = 0.139 |

Note: The numbers of the attributes correspond to those listed in Table B.2.

**TABLE B.4 -- RELATIVE IMPORTANCE OF ATTRIBUTES USING THE COMPARISON METHOD**

should help eliminate the problem of cycling. This feature is in the process of being incorporated into the MacDSIDES system.

In small problems, a dummy attribute is introduced so that the least important attribute exerts some influence on the evaluation of alternatives. Without the dummy attribute, the least important attribute may be assigned no score at all which is the same as not taking that attribute into consideration. However, a dummy attribute is not needed when the number of attributes is large. In this case, the attribute which receives no score at all may be considered unimportant and therefore may be eliminated. The number of comparisons that need to be made in this comparison method depends on the number of attributes used. For a problem with n attributes, the number of comparisons is ${}^{n+1}C_2$

where

$$ {}^{n+1}C_2 = (n+1)!/(n-1)!\ 2! $$

and

$$ n! = n\ (n-1)(n-2)\ \ldots\ (3)(2)(1). $$

### B.3.3 The Reciprocal Pairwise Comparison Matrix Method

This approach has been proposed by Saaty, [50]. It has some elements of both the standard gamble and rating forms. We recommend its use in determining the relative importance of attributes, rating alternatives on attributes characterized by soft information and in determining the weights for the achievement function of the compromise DSP. The method, however, is difficult to implement by hand and is suitable for use on a computer. In the following the method is explained context of determining the relative importance of attributes:

- The rating form, for this case, is set up to capture the degree of preference a decision maker has for one attribute over another (see Table B.5). The structure of the rating forms of Tables B.1 and B.5 is the same. The former is used to rate alternatives. The latter is used to elicit preferences between a pair of attributes. The interval scale in the former varies from o to 10 whereas, in the latter, it varies from 1 to 9. Saaty has given the mathematical justification and proof as to why the scale should vary from 1 to 9 in reference [50]. The ordinal scale and the viewpoint are also shown in the rating forms.

- A decision maker is asked to compare the attributes in pairs enter the ordinal scale and pick up the corresponding value (preference level) on the interval scale. Tabulate the preference levels and their reciprocals in a decision matrix (described later) and note the reasons in the form of a "viewpoint".

- A measure of the level of consistency of the decisions is obtained by determining the maximum eigenvalue of the decision matrix, whereas the corresponding normalized maximum eigenvector provides the weights that reflect the relative importance of each attribute.

| Ratings Interval | Ordinal | Viewpoint |
|---|---|---|
| 1 | Equal preference | The two attributes are equally important. |
| 3 | Slight preference | Based on experience there is a slight preference for attribute i over attribute j. |
| 5 | Medium preference | Based on experience attribute i is preferred to attribute j. |
| 7 | Strong preference | Attribute i is strongly favored over Attribute j; its dominance is demonstrated in practice. |
| 9 | Absolute preference | The preference of one concept over another is of the highest possible order. |
| 2, 4, 6, 8 | | Intermediate values When compromise is needed between adjacent ratings. |

**TABLE B.5 -- DESCRIPTION OF THE SCALE FOR DECISIONS**

The decision matrix $\underline{A}$ has the following form:

$$\underline{A} = \begin{vmatrix} 1 & a_{12} & & a_{1n} \\ 1/a_{12} & 1 & & a_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ 1/a_{1n} & 1/a_{2n} & & 1 \end{vmatrix} \qquad \text{(B.1)}$$

An element $a_{ij}$ is the number (from Table B.2) corresponding to the preference expressed, by a human being, for attribute i over attribute j. Hence, the reverse preference, i.e., the preference for attribute j over attribute i is $1/a_{ij}$. The preferences are entered in the upper triangle and the reverse preferences are entered in the lower triangle of the decision matrix. The diagonal element $a_{ii}$ is unity. All elements of the decision matrix are nonzero and positive.

Let us assume, for the moment, that there are n attributes $(A_1,...,A_n)$ and that we know the answer, i.e., we know the relative weights of the attributes. Assume that each attribute is represented by one everyday garden variety stone. Since we know the weights of the attributes we know the weight $(w_1,...,w_n)$ of each of the n stones. Let us form a matrix, $\underline{A}$, of pairwise ratios whose rows give the ratios of the weights of each stone with respect to all others:

$$\underline{A} = \begin{vmatrix} w_1/w_1 & w_1/w_2 & & w_1/w_n \\ w_2/w_1 & w_2/w_2 & & w_2/w_n \\ . & . & \cdots & . \\ . & . & \cdots & . \\ w_n/w_1 & w_n/w_2 & & w_n/w_n \end{vmatrix} \qquad \text{(B.2)}$$

Note we have assumed that we know the weights of the stones with certainty in equation B.2. Hence, if we multiply this matrix by the transpose of the vector of weights, $\underline{w}^T = (w_1, w_2, \ldots, w_n)$ we obtain the vector $n\,\underline{w}$, where n represents the number of stones (attributes) being compared. The problem can now be expressed as:

$$\underline{A}\,\underline{w} = n\,\underline{w} \tag{B.3}$$

It is well known that this mathematical problem has a nonzero solution only if n is an eigenvalue of the matrix $\underline{A}$. Furthermore, $\underline{A}$ has unit rank since every row is a constant multiple of the first row. Thus all the eigenvalues $\lambda_i$, i = 1, 2, ..,n of $\underline{A}$ are zero except one.

It is also known that

$$\sum_{i=1}^{n} \lambda_i = \text{sum of the diagonal elements of } \underline{A} = n$$

Therefore, only the largest eigenvalue is nonzero:

$$\lambda_{max} = n; \text{ and}$$
$$\lambda_i = 0 \text{ for } \lambda_i \neq \lambda_{max}$$

and the original vector of weights is represented by the eigenvector corresponding to the maximum eigenvalue, $\lambda_{max}$, of the matrix of decisions $\underline{A}$.

In this case, the matrix $\underline{A}$ is consistent, it satisfies the property

$$a_{ij}\, a_{jk} = a_{ik}$$

which means that if we are given a row of $\underline{A}$, we can reconstruct the whole matrix $\underline{A}$ by using this relation; only n-1 values are needed to do so. Once the matrix is formed the vector of weights can be extracted from any of the columns of the matrix $\underline{A}$ after normalizing it by the sum of its elements.

Let us return to the decision matrix, $\underline{A}$, (equation B.1) that has been formed by comparing the attributes in pairs and the preference levels picked from Table B.2. Since human judgment is involved in creating the decision matrix it is entirely likely that $a_{ij}$ deviates from the known ratios $w_i/w_j$ and hence equation B.3 is not valid. We know, however, that in any matrix small perturbations in the coefficients result in small perturbations in the eigenvalues. We therefore affirm that if the diagonal of our new decision matrix $\underline{A}$ consists of ones ($a_{ii} = 1$) and the variations of the $a_{ij}$ are small, the largest eigenvalue, $\lambda_{max}$, will be close to n, and the remaining eigenvalues will be close to zero (although they might take complex form). So in order to find the vector of relative weights, we must find the vector $\underline{w}$ that satisfies

$$\underline{A}\,\underline{w} = \lambda_{max}\,\underline{w} \tag{B.4}$$

To make $\underline{w}$ unique we normalize its entries by dividing each entry by the sum of all components of the vector. Hence,

$$\sum_{i=1}^{n} w_i = 1$$

Despite their best efforts people's feelings and preferences are inconsistent and intransitive. (An example of intransitivity is: A is preferred to B, B is preferred to C and C is preferred to A.) Hence, it is unlikely that the decision matrix $\underline{A}$ (equation B.1) will be consistent. Being aware of this fact and knowing that inconsistency cannot be eliminated what we need is a measure for the error introduced due to human inconsistency. The decision matrix $\underline{A}$ is consistent if and only if $\lambda_{max} = n$ and we know because humans are involved that $\lambda_{max} \geq n$. This suggests using $\lambda_{max} - n$ as an index of departure from consistency. Saaty suggests using the following consistency index:

$$C.I. = (\lambda_{max} - n) / (n - 1) \qquad \text{(B.5)}$$

After performing many experiments Saaty concluded that if C.I. is smaller than 0.1 the level of consistency in human judgment reflected in the decision matrix is acceptable. Otherwise, we have to go back and reconsider our decisions. Consistency can always be mathematically forced but this is not advised since it might distort the answer to our problem. Improved judgment based on experience is the preferred alternative.

As an illustration consider the relative importance of attributes for the aircraft example. There are nine attributes identified: 1 through 9. For this problem, there are 36 decisions to be made. The viewpoint represents these 36 decisions qualitatively. Using Table B.5 the qualitative viewpoint is changed to a quantitative value. The qualitative and quantitative values are shown in Table B.6.

Take a look at the first eight decisions in Table B.6. These cover the first set of pairwise comparisons. Payload is a very important attribute; it represents the earning capability of an aircraft. It is more important than all attributes except simplicity and power matching. This, in effect, allows us to rank-order the attributes and the rank ordering is shown in column three. Next, the preference level for each of the decisions shown in column three needs to be established. The preference for simplicity over payload is <u>slight</u>. Power matching is a very important technical attribute. Hence, the preference for it over the payload is <u>strong</u>. Being a commercial endeavor the preference for payload is <u>just about the same</u> - maybe a bit more for payload than engine out safety. Since this is a passenger airplane the volume is important but is probably <u>just slightly less</u> important than payload. Simplicity affects the life-cycle costs. It is a desirable but it should not be achieved at the expense of payload. Hence, simplicity is considered to be <u>slightly</u> less important than payload. Stability for a passenger aircraft is one measure of passenger comfort. Stability of the aircraft, therefore, is important from a marketing standpoint Payload of course is <u>more</u> important than stability and comfort for most passenger airline companies. Since the primary market for the airplane is the US the landing restrictions are not considered to be a problem and hence there is a strong preference for payload over the landing restrictions.

The first three columns of Table B.6 are identical to the first three columns of Table B.3. The underlined words in the preceding paragraph indicate (on an ordinal scale) different levels of preference facilitating entry into Table B.5. These words are shown in the fourth column of Table B.6. The numerical values corresponding to the levels of preference expressed in the preceding viewpoint are picked up from Table B.5 and are entered in the fifth column of Table B.6. The same information is presented in Table B.7 in the form of the decision matrix that was described earlier. In the interest of brevity the rest of the viewpoints are not provided. The maximum eigenvalue of the decision matrix shown in Table B.7 is 9.476 which is close to the number of attributes being considered. Furthermore, the corresponding consistency index C.I. is well below the limit of 0.1 recommended as a measure of inconsistency.

The eigenvector, the maximum eigenvalue and the consistency index for the preceding matrix is computed using an algorithm presented in Shoup [52]. Since the consistency index is less than 0.1 the decision matrix is consistent. In Table B.8 the normalized weightings for the attributes using three different methods is presented. Observe that the relative weights obtained using the three methods are different. Each is correct and appropriate in the context of the amount and quality of information that is available and the importance of the decision being made to the overall success of the project.

| Decision Number | Attributes | Decision | Ordinal Scale | Preference Level |
|---|---|---|---|---|
| 1 | 1,2 | 1>2 | medium | 5 |
| 2 | 1,3 | 3>1 | slight | 1/3 |
| 3 | 1,4 | 4>1 | strong | 1/7 |
| 4 | 1,5 | 1>5 | just slightly less | 2 |
| 5 | 1,6 | 1>6 | strong | 7 |
| 6 | 1,7 | 1>7 | slight | 3 |
| 7 | 1,8 | 1>8 | medium | 5 |
| 8 | 1,9 | 1>9 | about the same | 2 |
| 9 | 2,3 | 3>2 | medium | 1/5 |
| 10 | 2,4 | 4>2 | strong | 1/7 |
| 11 | 2,5 | 5>2 | slight | 1/3 |
| 12 | 2,6 | 2>6 | equal | 1 |
| 13 | 2,7 | 7>2 | slight | 1/3 |
| 14 | 2,8 | 8>2 | just slightly less | 1/2 |
| 15 | 2,9 | 9>2 | slightly more | 1/4 |
| 16 | 3,4 | 4>3 | about the same | 1/2 |
| 17 | 3,5 | 3>5 | medium/more | 3 |
| 18 | 3,6 | 3>6 | strong | 7 |
| 19 | 3,7 | 3>7 | slightly more | 4 |
| 20 | 3,8 | 3>8 | medium/more | 5 |
| 21 | 3,9 | 3>9 | about the same | 2 |
| 22 | 4,5 | 4>5 | slightly more | 4 |
| 23 | 4,6 | 4>6 | about the most | 8 |
| 24 | 4,7 | 4>7 | slight | 3 |
| 25 | 4,8 | 4>8 | less than strong | 6 |
| 26 | 4,9 | 4>9 | slight | 3 |
| 27 | 5,6 | 5>6 | slightly more | 4 |
| 28 | 5,7 | 5>7 | equal | 1 |
| 29 | 5,8 | 5>8 | about the same | 2 |
| 30 | 5,9 | 9>5 | about the same | 1/2 |
| 31 | 6,7 | 7>6 | slight | 1/3 |
| 32 | 6,8 | 8>6 | about the same | 1/2 |
| 33 | 6,9 | 9>6 | medium/more | 1/5 |
| 34 | 7,8 | 7>8 | equal | 1 |
| 35 | 7,9 | 9>7 | about the same | 1/2 |
| 36 | 8,9 | 9>8 | slight | 1/3 |

Notes: The symbol > indicates preference.
The numbers of the attributes correspond to those listed in Table B.2.

**TABLE B.6 -- PREFERENCES FOR THE RECIPROCAL PAIRWISE COMPARISON MATRIX METHOD**

| | PLOD | RNGE | SIMP | PMCH | CACC | LRES | PARK | STAB | ESAF |
|---|---|---|---|---|---|---|---|---|---|
| PLOD | 1 | 5 | 1/3 | 1/7 | 2 | 7 | 3 | 5 | 2 |
| RNGE | 1/5 | 1 | 1/5 | 1/7 | 1/3 | 1 | 1/3 | 1/2 | 1/4 |
| SIMP | 3 | 5 | 1 | 1/2 | 3 | 7 | 4 | 5 | 2 |
| PMCH | 7 | 7 | 2 | 1 | 4 | 8 | 3 | 6 | 3 |
| CACC | 1/2 | 3 | 1/3 | 1/4 | 1 | 4 | 1 | 2 | 1/2 |
| LRES | 1/7 | 1 | 1/7 | 1/8 | 1/4 | 1 | 1/3 | 1/2 | 1/5 |
| PARK | 1/3 | 3 | 1/4 | 1/3 | 1 | 3 | 1 | 1 | 1/2 |
| STAB | 1/5 | 2 | 1/5 | 1/6 | 1/2 | 2 | 1 | 1 | 1/3 |
| ESAF | 1/2 | 4 | 1/2 | 1/3 | 2 | 5 | 2 | 3 | 1 |

$$\lambda_{max} = 9.476$$
$$\text{C.I.} = 0.0411$$

**TABLE B.7 -- DECISION MATRIX FOR THE RECIPROCAL PAIRWISE COMPARISON MATRIX METHOD**

| Attribute | Normalized Relative Importance Method 1 | Method 2 | Method 3 |
|---|---|---|---|
| 1 Payload, or useful load | 0.156 | 0.167 | 0.158 |
| 2 Range | 0.044 | 0.020 | 0.029 |
| 3 Simplicity of design | 0.178 | 0.194 | 0.210 |
| 4 Power matching | 0.200 | 0.222 | 0.275 |
| 5 Cargo accessibility | 0.111 | 0.111 | 0.075 |
| 6 Landing site restrictions | 0.022 | 0.0 | 0.025 |
| 7 Parking area | 0.089 | 0.083 | 0.065 |
| 8 Achieved stability | 0.067 | 0.056 | 0.046 |
| 9 Engine out safety | 0.133 | 0.139 | 0.114 |

Notes: The larger numbers indicate preference.

**TABLE B.8 -- THE RELATIVE IMPORTANCE OF ATTRIBUTES - A COMPARISON**

# APPENDIX C:
## A COMPROMISE DSP TEMPLATE FOR AIRCRAFT DESIGN AND SOME EXPLANATIONS OF THE ANALYSIS ROUTINES

A compromise DSP template consists of data and user provided Fortran code. Input is prepared in accordance with the protocol presented in [32]. In this appendix the user provided Fortran code used for the Boeing 727-200 case study is presented. The subroutines are extensively annotated and an overview of the function of each subroutine is provided. The output from a sample run for Case B Scenario 2 is furnished in Appendix D.

## SUBROUTINE USERIN

This subroutine is used to read information that is user-dependent and is needed for quantifying the system constraints and goals. The information is stored in COMMON /USER/ and made available to other program units. The input to this routine is echo printed on the design run output.

```
C       ****************************************************
C       *   USERIN - Subroutine                            *
C       *                                                  *
C       *   Used to initialize the common block "USER" for *
C       *   storage of information required to evaluate the *
C       *   non-linear system/goal constraints in subroutines *
C       *   to follow.                                     *
C       *                                                  *
C       ****************************************************
C
        SUBROUTINE USERIN
        COMMON /USER/ CKV,L2,R2,SWR,DE,AS,WFI,CLM,SL,MC,AL,
     +                STO,ATO,C,WP,TR,E,U,R,E1,FT,FL,N,M,TC
        REAL L2,MC,N,M
        DATA PI/3.1415926/
C
C       ************************************************
C       *  DEFINITION OF INPUT VARIABLES:              *
C       *                                              *
C       *    CKV = Kinematic viscosity at 35,000 ft.   *
C       *     L2 = Airfoil thickness location parameter *
C       *     R2 = Lifting surface correlation factor. *
C       *    SWR = Wetted area to planform area ratio. *
C       *     DE = Atmospheric density at 35000 ft.    *
C       *     AS = Speed of sound at 35000 ft.         *
C       *    WFI = Weight of fuel estimate.            *
C       *    CLM = Maximum lift coefficient.           *
C       *     SL = Required landing field length.      *
C       *     MC = Landing/Take-off mach number.       *
C       *     AL = Required missed approach climb angle. *
C       *    STO = Required take-off field length.     *
C       *    ATO = Required take-off climb angle.      *
C       *      C = Specific fuel consumption.          *
C       *     WP = Weight of payload.                  *
C       *     TR = Required thrust for cruise.         *
C       *      E = Required endurance or loiter.       *
C       *      U = Useful load fraction.               *
C       *      R = Required cruise range.              *
C       *     E1 = Planform efficiency constant.       *
C       *     FT = Airfoil form factor.                *
C       *     FL = Fuselage form factor.               *
C       *      N = Number of engines.                  *
C       *      M = Cruise Mach Number                  *
C       *     TC = Airfoil thickness ratio             *
C       ************************************************
C
C ====================================
C Read input data and initialize COMMON/USER/
C ====================================
C
```

```
      READ 130, CKV,L2,R2,SWR,DE,AS,WFI,CLM
      READ 130, SL,MC,AL,STO,ATO,C,WP,TR
      READ 130, E,U,R,E1,FT,FL,N,M,TC
C
C ====================
C Echo print input data
C ====================
C
      PRINT 140, CKV,L2,R2,SWR,DE,AS,WFI,CLM,SL,MC,AL,
     +            STO,ATO,C,WP,TR,E,U,R,E1,FT,FL,N,M,TC
      RETURN
 130  FORMAT(8G10.0)
 140  FORMAT(' ',50('*'),//
     + '         AIRCRAFT DESIGN USING THE              '/
     + '      DECISION SUPPORT PROBLEM TECHNIQUE        '//
     + '**************************************************'/
     + ' KINEMATIC VISCOSITY AT 35000 FT           ',F7.6,'  '/
     + ' AIRFOIL THICKNESS LOCATION PARAMETER      ',F3.1,'  '/
     + ' LIFTING SURFACE CORRELATION FACTOR        ',F3.1,'  '/
     + ' WETTED/PLANFORM AREA RATIO OF WING        ',F3.1,'  '/
     + ' ATMOSPHERIC DENSITY AT 35000 FT           ',F8.6,
     + ' SLUGS/CU FT'/
     + ' SPEED OF SOUND AT 35000 FT                ',F5.1,
     + ' FT/SEC'/
     + ' INITIAL WEIGHT OF FUEL (TARGET VALUE)     ',F7.1,' LBS'/
     + ' MAXIMUM LIFT COEFFICIENT                  ',F3.1,'  '/
     + ' LANDING FIELD LENGTH (TARGET VALUE)       ',F6.1,' FT'/
     + ' LANDING/TAKE-OFF MACH NUMBER              ',F5.3,'  '/
     + ' REQ. CLIMB GRADIENT FOR MISSED APPRCH     ',F7.5,
     + ' RADIANS'/
     + ' TAKE-OFF FIELD LENGTH (TARGET VALUE)      ',F6.1,' FT'/
     + ' REQ. CLIMB GRADIENT FOR TAKE-OFF          ',F7.5,
     + ' RADIANS'/
     + ' SPECIFIC FUEL CONSUMPTION (ESTIMATE)      ',F3.1,
     + ' LB/LB HRS'/
     + ' PAYLOAD WEIGHT                            ',F7.1,' LBS'/
     + ' THRUST FOR CRUISE (TARGET VALUE)          ',F7.1,' LBS'/
     + ' ENDURANCE OR LOITER (TARGET VALUE)        ',F4.2,'  '/
     + ' USEFUL LOAD FRACTION (TARGET VALUE)       ',F3.1,'  '/
     + ' AIRCRAFT RANGE (TARGET VALUE)             ',F6.1,' NMI'/
     + ' PLANFORM EFFICIENCY CONSTANT              ',F4.2,'  '/
     + ' WING FORM FACTOR (TARGET VALUE)           ',F6.4,'  '/
     + ' FUSELAGE FORM FACTOR (TARGET VALUE)       ',F6.4,'  '/
     + ' NUMBER OF ENGINES                         ',F3.1,'  '/
     + ' CRUISE MACH NUMBER                        ',F4.2,'  '/
     + ' AIRFOIL THICKNESS RATIO                   ',F4.2,'  ')
      END
```

## <u>SUBROUTINE VALUE</u>

This subroutine is used to determine the value of the achievement function of the compromise DSP template. The achievement function is specified in terms of the deviation variables. The sum of the deviation variables represents the difference between that which is sought and that which is achieved.

```
C
C       **************************************************
C       *   VALUE - Subroutine                           *
```

```
C       *                                                *
C       *   This routine determines the objective function *
C       *   value. For this template, namely, the sum of   *
C       *   the deviation variables.                       *
C       *                                                *
C       **************************************************

        SUBROUTINE VALUE(X,OBJFV)
        DIMENSION X(1)
C
        OBJFV = X(7) + X(8) + X(9) + X(10)
     +         + X(11) + X(12) + X(13) + X(14)
     +         + X(15) + X(16) + X(17) + X(18)
        RETURN
        END
```

## SUBROUTINE SET

This routine is called from within the ALP algorithm. It is used to call routines in which the values of the nonlinear system constraints and goals are evaluated. These values are used to linearize the system constraints and goals. In this template the system constraints and goals are evaluated in three routines, namely, subroutines EVALG1, EVALG2, and EVALG3.

```
C
C       *****************************************************
C       *   SET - Subroutine                                *
C       *                                                   *
C       *   This routine evaluates the non-linear system/goal *
C       *   constraint functions by calling the subroutines *
C       *   EVALG1, EVALG2, AND EVALG3.                     *
C       *                                                   *
C       *****************************************************
C
        SUBROUTINE SET(NGROUP,CVAL,X)
        COMMON /USER/ CKV,L2,R2,SWR,DE,AS,WFI,CLM,SL,MC,AL,
     +                STO,ATO,C,WP,TR,E,U,R,E1,FT,FL,N,M,TC
        REAL LB,L2,MC,M,N
        DATA PI/3.1415926/
        DIMENSION CVAL(1),X(1)
C
C       **************************************************
C       *   DEFINITION OF SYSTEM VARIABLES:              *
C       *                                                *
C       *     S = Wing area, sq. ft.                     *
C       *    TI = Installed engine thrust, lbs.          *
C       *    LB = Fuselage length, ft.                   *
C       *   WTO = Weight at take-off, lbs.               *
C       *     B = Wing span, ft.                         *
C       *     D = Fuselage diameter, ft.                 *
C       *                                                *
C       **************************************************
C
          S = X(1)
         TI = X(2)
         LB = X(3)
        WTO = X(4)
          B = X(5)
```

```
            D = X(6)
C
          GOTO (1,2,3,4,4,4) NGROUP
C
C ==============================================
C Evaluate the non-linear inequality system constraints
C ==============================================
C
    1     CALL EVALG1(CVAL,X)
          RETURN
    2     CALL EVALG2(CVAL,X)
          RETURN
C
C ==============================================
C Evaluate the non-linear equality goal constraints
C ==============================================
C
    3     CALL EVALG3(CVAL,X)
          RETURN
    4        RETURN
          END
```

## SUBROUTINE EVALG1

This routine is called by Subroutine SET. It is used to compute the value of the nonlinear constraints. The form of these constraints is $C(\underline{X}) - D \geq 0.0$. The constraints have been normalized. The abbreviation of the name used in the output for each of the constraints and also the corresponding equation number in the text has been included

```
C
C        **************************************************
C        *   EVALG1 - Subroutine                          *
C        *                                                *
C        *   This routine evaluates non-linear in-equality *
C        *   subsonic aircraft system constraints.         *
C        *                                                *
C        *   NOTE: All constraints are normalized.        *
C        *                                                *
C        **************************************************
C
         SUBROUTINE EVALG1(CVAL,X)
         COMMON /USER/ CKV,L2,R2,SWR,DE,AS,WFI,CLM,SL,MC,AL,
     +               STO,ATO,C,WP,TR,E,U,R,E1,FT,FL,N,M,TC
         REAL LB,L2,MC,M,N
         DATA PI/3.1415926/
         DIMENSION CVAL(1),X(1)
C
           S = X(1)
          TI = X(2)
          LB = X(3)
         WTO = X(4)
           B = X(5)
           D = X(6)
C ============================
C Calculate the dynamic pressure, Q
C ============================
C
```

```
      Q = 0.5*DE*M**2*AS**2
C
C ==================================
C Calculate the lift coefficient, CL
C ==================================
C
      CL = (WTO/(Q*S))
C
C ===========================================
C Calculate the skin friction coefficient, CF
C ===========================================
C
      RE = LB*M*AS/CKV
      CF = 0.455/(ALOG10(RE))**2.58
C
C =========================================
C Calculate the total drag coefficient, CDO
C =========================================
C
      CDO = (CF * (1.0 + L2 *
     +      TC + 100.0 * TC**4) * R2 *SWR+((CF*(1.0+60.0 /
     +      (LB/D)**3+0.0025*(LB/D))*4.0*LB/D)+(0.029/
     +      ((CF*(1.0+60.0/(LB/D)**3)+0.0025*LB/D)*
     +      4.0*LB/D)**0.5))*((PI*(D/B)**2)*0.5774)+.005)
C
C =======================================
C Calculate the wing drag due to lift, EK
C =======================================
C
      EK = (1.0/(PI*(B**2/S)*(E1*(1.0 - (D/B)**2))))
C
C ================================
C Calculate the weight of fuel, WF
C ================================
C
      WF = (1.1*WTO)*(1.0 - (.95)/EXP((1.47)*R*(C/(AS*M))
     +      *(2.13*SQRT(CDO*EK))))
C
C ================================
C CVAL(1) : FUEL WEIGHT CONSTRAINT
C --------------------------------
C DSIDES Designation : FUWT
C Equation [4-46]
C ================================
C
      CVAL(1) = -1.0+(WF/WFI)
C
C ===============================================
C CVAL(2) : REQUIRED THRUST FOR CRUISE CONSTRAINT
C -----------------------------------------------
C DSIDES Designation : THCR
C Equation [4-22]
C ===============================================
C
      CVAL(2) = -1.0+(((CDO*Q*S)+(EK*(WTO**2)/(Q*S)))/TR)
C
C ==================================================
```

```
C  CVAL(3) : SECOND SEGMENT CLIMB GRADIENT CONSTRAINT
C  ------------------------------------------------
C  DSIDES Designation : SSCG
C  Equation [4-12]
C  ================================================
C
         CVAL(3) = -1.0+(((TI/(WTO))*((N-1.0)/N)-
     +              (2.13*(CDO*EK)**.5))/0.027)
C
C  ======================================
C  CVAL(4) : TAKE-OFF FIELD LENGTH CONSTRAINT
C  --------------------------------------
C  DSIDES Designation : TOFL
C  Equation [4-11]
C  ======================================
C
         CVAL(4) = 1.0-(((20.9*((WTO/S)/(CLM*(TI/WTO))))+
     +              (87.0*((WTO/S) * (1.0/CLM))**.5))/STO)
C
C=================================================================
C  CVAL(5) : WING AREA TO FUSELAGE CROSS-SECTION AREA CONSTRAINT
C            LOWER BOUND
C-----------------------------------------------------------------
C  DSIDES Designation : WDRL
C=================================================================
C
         CVAL(5) = -1.0+((4.0*S)/(12.5*PI*(D**2)))
C
C=================================================================
C  CVAL(6) : WING AREA TO FUSELAGE CROSS-SECTION AREA CONSTRAINT
C            UPPER BOUND
C-----------------------------------------------------------------
C  DSIDES Designation : WDRU
C=================================================================
C
         CVAL(6) = 1.0-((4.0*S)/(15.0*PI*(D**2)))
C
C  ======================================
C  CVAL(7) : FUSELAGE FORM FACTOR CONSTRAINT
C             LOWER BOUND NOT PROGRAMMED
C  --------------------------------------
C  DSIDES Designation : FUFF
C  Equation [4-52]
C  ======================================
C
         CVAL(7) = -1.0+((1.0+(60.0/((LB/D)**3))+
     +              0.0025*(LB/D))/1.083)
C
C  ================================================
C  CVAL(8) : WING ASPECT RATIO CONSTRAINT LOWER BOUND
C  ------------------------------------------------
C  DSIDES Designation : ASPL
C  Equation [4-55]
C  ================================================
C
         CVAL(8) = -1.0+(((B**2)/S)/7.2)
C
```

```
C ================================================
C CVAL(9) : WING ASPECT RATIO CONSTRAINT UPPER BOUND
C ------------------------------------------------
C DSIDES Designation : ASPU
C Equation [4-55]
C ================================================
C
         CVAL(9) = 1.0-(((B**2)/S)/10.5)
C
        RETURN
        END
```

## SUBROUTINE EVALG2

In each EVALGi a maximum of ten nonlinear functions can be evaluated. In EVALG1 nine nonlinear constraints are evaluated. The remainder are evaluated in EVALG2.

```
C
C       *****************************************************
C       *   EVALG2 - Subroutine                             *
C       *                                                   *
C       *   This subroutine is a continuation of the EVALG2 *
C       *   routine. Normalized non-linear inequality       *
C       *   constraints are evaluated.                      *
C       *                                                   *
C       *****************************************************
C
        SUBROUTINE EVALG2(CVAL,X)
        COMMON /USER/ CKV,L2,R2,SWR,DE,AS,WFI,CLM,SL,MC,AL,
     +              STO,ATO,C,WP,TR,E,U,R,E1,FT,FL,N,M,TC
        REAL LB,L2,MC,M,N
        DATA PI/3.1415926/
        DIMENSION CVAL(1),X(1)
C
            S = X(1)
           TI = X(2)
           LB = X(3)
          WTO = X(4)
            B = X(5)
            D = X(6)
C
          Q = (.5*DE*(M**2)*(AS**2))
C
         CL = (WTO/(Q*S))
C
         RE = LB*M*AS/CKV
C
         CF = 0.455/(ALOG10(RE))**2.58
C
        CDO = (CF * (1.0 + L2 *
     +       TC+100.0*TC**4)*R2*SWR+((CF* (1.0 + 60.0 /
     +       (LB/D)**3+0.0025*(LB/D)) * 4.0*LB/D)+(0.029/
     +       ((CF*(1.0+60.0/(LB/D)**3)+0.0025*LB/D)*4.0*LB/D)
     +       **0.5))*((PI*(D/B)**2)*0.5774)+.005)
C
        EK = (1.0/(PI*(B**2/S)*(E1*(1.0 - (D/B)**2))))
C
```

```
      WF = (1.1*WTO)*(1.0 - (.95)/EXP((1.47)*R*(C/(AS*M))
     +        *(2.13*SQRT(CDO*EK))))
C
C ==================================================
C CVAL(1) : REQUIRED THRUST FOR CRUISE CLIMB CONSTRAINT
C --------------------------------------------------
C DSIDES Designation : THCC
C Equation [4-34]
C ==================================================
C
       CVAL(1) = 1.0-(((CDO*Q*S)+(EK*(WTO**2)/(Q*S)))/TI)
C
C ================================================
C CVAL(2) : MISSED APPROACH CLIMB GRADIENT CONSTRAINT
C ------------------------------------------------
C DSIDES Designation : MAPC
C Equation [4-6]
C ================================================
C
      CVAL(2) = - 1.0+(((TI/(WTO-WF))*((N-1.0)/N) -
     +            (2.13*(CDO*EK)**.5))/0.024)
C
C ================================
C CVAL(3) : CRUISE RANGE CONSTRAINT
C --------------------------------
C DSIDES Designation : RNGC
C Equation [4-13]
C ================================
C
      CVAL(3) = - 1.0+((((0.5925*(0.943)*AS*M)/
     +            (2.0*C*(CDO*EK)**.5))*(ALOG((1.0 -
     +            (WF/WTO))**-1)))/2000.0)
C
      RETURN
      END
```

## SUBROUTINE EVALG3

This routine is called from SET. The values of the normalized nonlinear goals are evaluated in this routine. These values are used to linearize the system goals. Subroutine SETDEV is called by this routine to calculate the initial values of the deviation variables. Subroutine SETDEV is part of the domain-independent code. The abbreviated names used in the output and the corresponding equation numbers for each of the goals is listed. Three subroutines (DOCOST, AIRCOST, MAINTCT) are used to quantify the return on investment goal equation [4-60]. Subroutine DOCOST is called from EVALG3 and DOCOST calls AIRCOST and MAINTC.

```
C
C       ****************************************************
C       *    EVALG3 - Subroutine                           *
C       *                                                  *
C       *    This subroutine evaluates non-linear equality *
C       *    goal constraints.                             *
C       *                                                  *
C       *    NOTE : EVALG3 calls to routine "SETDEV".      *
C       *                                                  *
```

C-3

```
C       *          SETDEV is called to calculate the     *
C       *          initial values of the deviation       *
C       *          variables.                            *
C       *    COMMON BLOCKS:                              *
C       *          USSIZE - This common block is internal *
C       *           to SLIPML. WHERE;                    *
C       *         KODDEV - is an integer flag.           *
C       *         SETDEV is called when                  *
C       *         KODDEV = 1                             *
C       *         NRVSYS - Number of real system         *
C       *                  variables.                    *
C       *         NDVSYS - Number of deviation           *
C       *                  system variables.             *
C       *                                                *
C       **************************************************
C
        SUBROUTINE EVALG3(CVAL,X)
        COMMON /USER/ CKV,L2,R2,SWR,DE,AS,WFI,CLM,SL,MC,AL,
     +               STO,ATO,C,WP,TR,E,U,R,E1,FT,FL,N,M,TC
        COMMON /USSIZE/ KODDEV,NRVSYS,NDVSYS
         REAL LB,L2,MC,M,N
        DATA PI/3.1415926/
        DIMENSION CVAL(1),X(1),IFORM(8)
C
             S = X(1)
            TI = X(2)
            LB = X(3)
           WTO = X(4)
             B = X(5)
             D = X(6)
C
           Q = (.5*DE*(M**2)*(AS**2))
C
          CL = (WTO/(Q*S))
C
          RE = LB*M*AS/CKV
C
          CF = 0.455/(ALOG10(RE))**2.58
C
        CDO = (CF * (1.0 + L2 *
     +        TC + 100.0 * TC**4)*R2*SWR+((CF * (1.0 + 60.0 /
     +        (LB/D)**3+0.0025*(LB/D))*4.0*LB/D)+(0.029/
     +        ((CF*(1.0+60.0/(LB/D)**3)+0.0025*LB/D)*4.0*LB/D)
     +        **0.5))*((PI*(D/B)**2)*0.5774)+.005)
C
        EK = (1.0/(PI*(B**2/S)*(E1*(1.0 - (D/B)**2))))
C
        WF = (1.1*WTO)*(1.0 - (.95)/EXP((1.47)*R*(C/(AS*M))
     +        *(2.13*SQRT(CDO*EK))))
C
         NP = (0.867*LB*((D/1.83)-1.0)/3.75)
C
        R1=R
        WTO1=WTO
        WF1=WF
        TI1=TI
        S1=S
```

```
        WP1=WP
C  $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C  CALL ECONOMIC SUBROUTINES TO OBTAIN - ROI
C  SET OUTPUT COMMAND TO ZERO - KP =0.
C  KP IS SET EQUAL TO ONE FROM USROUT FOR ECONOMIC OUTPUT
C  $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
          KP=0
          CALL DOCOST(R1,WTO1,WF1,NP,TI1,S1,WP1,KP,ROI)
C  $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
          ROI=ROI*100.
C  =============================================
C  CVAL(1) : LANDING FIELD LENGTH SYSTEM GOAL
C  ---------------------------------------------
C  DSIDES Designation : LDFL
C  Equation [4-3]
C  =============================================
C
        CVAL(1) = ((118.0*(((WTO-WF)/S)/CLM)/SL)
     +            +(400.0/SL))-1.0+X(7)-X(8)
C
C  =======================================================
C  CVAL(2) : MISSED APPROACH CLIMB GRADIENT SYSTEM GOAL
C  =======================================================
C  DSIDES Designation : MACG
C  Equation [4-6]
C  =======================================================
C
        CVAL(2) = (((TI/(WTO-WF))*((N-1.0)/N)-
     +            (2.13*(CDO*EK)**.5))/AL)-1.0+X(9)-X(10)
C
C  ====================================
C  CVAL(3) : CRUISE RANGE SYSTEM GOAL
C  ------------------------------------
C  DSIDES Designation : RNGG
C  Equation [4-13]
C  ====================================
C
        CVAL(3) = ((((0.5925*(0.943)*AS*M)/(2.0*C*(CDO*EK)**.5))
     +            *(ALOG((1.0-(WF/WTO))**-1)))/R)-1.0+X(11)-X(12)
C
C  ==================================
C  CVAL(4) : ENDURANCE SYSTEM GOAL
C  ----------------------------------
C  DSIDES Designation : LOIT
C  Equation [4-42]
C  ==================================
C
        CVAL(4) = ((((1.0/(2.0*SQRT(CDO*EK)))**-1.0)*(1.0/C)*
     +            ALOG((1.0-WF/WTO)**-1.0)/E))-1.0 + X(13) - X(14)
C
C  ============================================
C  CVAL(5) : USEFUL LOAD FRACTION SYSTEM GOAL
C  --------------------------------------------
C  DSIDES Designation : USFL
C  Equation [4-50]
C  ============================================
C
```

```
C ----------------------------------------
C PAYLOAD ALLOWS FOR 200 LBS PER PASSENGER
C ----------------------------------------
         WPP= WP+NP*200.0
C
        CVAL(5) = ((WPP+WF)/WTO)/U-1.0 + X(15) - X(16)
C
C ========================================
C CVAL(6) : WEIGHT MATCHING SYSTEM GOAL
C ----------------------------------------
C DSIDES Designation : WTMA
C Equation [4-49]
C ========================================
C
        CVAL(6) =1.0/(((WTO-WF-WPP)-(1.0377*WTO**0.9362))/
     +          (0.001*1.0377*WTO**0.9362)) -1.0 +X(17)-X(18)
C
C ========================================
C CVAL(7) : FUSELAGE VOLUME SYSTEM GOAL
C ----------------------------------------
C DSIDES Designation : FUSV
C Equation [4-57]
C ========================================
C
        CVAL(7) = ((0.867*LB*((D/1.83)-1.0)/3.75)/190.0)
     +          -1.0+X(19)-X(20)
C
C ============================================
C CVAL(8) : RETURN ON INVESTMENT SYSTEM GOAL
C --------------------------------------------
C DSIDES Designation : ROIG
C Equation [4-60]
C ============================================
C
        CVAL(8) = ROI/15.0 -1.0 + X(21)-X(22)
C
C ============================================
C
C
C ========================================================
C Initial values of the deviation variables are calculated.
C The user provided analysis routine "SETDEV" is called.
C
C  IFORM - Is set equal to 1 as standard formulation is used.
C KOUNTR - Is set equal to 7, as the 7th design variable is a
C         deviation variable.
C ========================================================
C
         DO 111 II=1,8
            IFORM(II)=1
  111      CONTINUE
            KOUNTR=7
            IF(KODDEV .EQ. 1) THEN
         DO 222 K=1,8
C
```

```
C
=============================================================
C  This facilitates automatic generation of deviation variables.
C   The value of CVAL(K) has to be retained. Both deviation
variables
C  corresponding to the goal constraint are calculated in a single
C  pass. Increment KOUNTR by 2.
C
=============================================================
C
              CVALK = CVAL(K)
              IFORMK=IFORM(K)
           CALL SETDEV(X,KOUNTR,CVALK,IFORMK)
              IF(IFORMK .EQ. 1) THEN
              CVAL(K)=CVAL(K)+X(KOUNTR)-X(KOUNTR+1)
              ELSE
              CVAL(K)=CVAL(K)  - X(KOUNTR)  + X(KOUNTR+1)
              ENDIF
              KOUNTR=KOUNTR +2
  222        CONTINUE
              ENDIF
C
C  ================================================
C  CVAL(9)  : DEVIATION VARIABLE EQUALITY CONSTRAINT
C            USED TO FORCE ONE OF THE DEVIATION VARIABLES
C            TO ZERO.  SUPPRESSED BY ALGORITHM WHEN NOT NEEDED.
C  ------------------------------------------------
C  DSIDES Designation : ZCON
C  ================================================
C
            CVAL(9)  = X(7)*X(8)+X(9)*X(10)+X(11)*X(12)
     +                 +X(13)*X(14)+X(15)*X(16)
     +                  +X(17)*X(18)+X(19)*X(20)+X(21)*X(22)
C
        RETURN
        END
```

## SUBROUTINE DOCOST

This routine is used to calculate the aircraft direct operating costs, indirect operating costs and the return on investment. This subroutine is called in EVALG3 and USROUT. If return on investment is not a goal, DOCOST is only called from USROUT

The aircraft direct operating costs (DOC) are based on a method developed by American Airlines [5,55]. The direct operating costs are statistical relationships developed from aircraft industry studies. The total aircraft direct operating costs are the summation of the following costs:

- Depreciation
- Support
- Spares
- Delay
- Insurance
- Fuel expense
- Maintenance
- Landing fee

- Flight crew
- Flight attendant
- Fuel service
- Control fee

The equations for computing the preceding appear in the code that follows.

Contrary to DOC, there are no standard methods for calculating IOC [63]. However, a standard method was developed at Lockheed [62] that was used as a guide in the development of OPDOT and [5]. For the template, the following costs are calculated and summed to determine the total indirect operating cost:

- Maintenance burden
- Food cost
- Movie
- Passenger insurance
- Miscellaneous passenger costs
- Advertising and publicity
- Commission
- Reservation
- Passenger handling
- Baggage handling
- Cargo handling
- Servicing

The equations are listed in the code that follows.

The economic design constants used in the economic analysis of the aircraft DSP template are presented in Table C.1. The constants are not necessarily for the Boeing 727-200, but are constants used within OPDOT [56]. The costs are based on 1979 figures.

| ITEM | VALUE | UNITS |
|---|---|---|
| Fuel cost | 0.75 | dollars per gallon |
| Load factor | 0.55 | |
| Utilization rate | 3200 | hours per year |
| Depreciation period | 14 | years |
| Residual value | 12 | percent |
| Tax rate | 48 | percent |
| Year of study | 1979 | |
| Assumed annual inflation rate | 7 | percent |
| Number of prototype aircraft | 2 | |
| Aircraft fleet size | 250 | |
| Initial production rate | 0.5 | per month |
| Full production rate | 5 | per month |
| Engineering rate (1974) | 19.55 | dollars per hour |
| Tooling rate (1974) | 14.00 | dollars per hour |
| Labor rate (1974) | 10.90 | dollars per hour |
| Engines for test aircraft | 3 | |
| Ratio of manufacturer's airframe weight to take-off weight | 0.75 | |
| Number of pilots | 3 | |
| Number of attendants | 8 | |
| Air conditioning flow rate | 441 | lb./min. |
| Autopilot channels | 5 | |
| Generator capacity | 750 | kV-A |
| Maintenance complexity factor | 1.6 | |
| Hydraulics volume flow rate | 79 | gal./min. |
| Number of inertial platform systems | 1 | |
| Ratio of first class to economy seating | 0.1 | |
| Ratio of first class to economy seating | 0.15 | |

TABLE C.1 -- CONSTANTS USED FOR ECONOMIC ANALYSIS WITHIN THE AIRCRAFT COMPROMISE DSP TEMPLATE

```
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C       BEGINNING OF THE ECONOMIC ANALYSIS: Subroutine DOCOST
C
        SUBROUTINE DOCOST
     $     (R,WTO,WFUEL,NPASS,THRUST,WAREA,WP,KP,ROI)
        CHARACTER*10 YIOC(12),YCOST(7)
        REAL INSUR,PER(12),XIOC(12),CST(7)
C
C
C  ==================================================================
C       DEFINITION OF SOME ECONOMIC PARAMETERS
C       FL, FLIGHT TIME FOR MISSION, (RANGE/AVERAGE SPEED)
C       AVSPD, AVERAGE FLIGHT SPEED = 460.927 KNOTS
C       BLKHR, BLOCKHOUR = FLIGHT TIME PER MISSION + 0.327 (HRS)
C       [OPDOT P.49]
C       UR, AIRPLANE UTILIZATION RATE, HOURS PER YEAR, = 3200
C       FUELCT, FUEL COST, DOLLARS PER GALLON, = 1
C       YEAR, THIS IS YEAR OF STUDY, THE FORMULA BELOW IS FROM
C       OPDOT, 1986.
C*******************************************************************
        UR=3200.
        FUELCT=0.75
        AVSPD=460.927
        YEAR=1979.
        CALL AIRCOST(PRICE,WTO,THRUST,NPASS,KP)
        YRMULT=1.07**(YEAR-1976.)
        PRICE=YRMULT*PRICE
        FL=R/AVSPD
        BLKHR=FL+0.327
C       *************************
C       DIRECT OPERATING COSTS
C       *************************
        DEPRE=0.88*PRICE/(14.0*UR)
        SUPPORT=0.12*PRICE/(14.0*UR)
        SPARES=0.06*PRICE/(14.0*UR)
        DELAY=YRMULT*8.40
        INSUR=0.01*PRICE/UR
        FCOST=WFUEL*FUELCT/6.4
        FCOST=FCOST/BLKHR
        CALL MAINTCT(XMCOST,WTO,WFUEL,NPASS,THRUST,S,KP)
        WTL=(WTO-WF)*0.453592
        FEELAND=YRMULT*1.54*WTL/1000.0
        FEELAND=FEELAND/BLKHR
        ATT=YRMULT*NPASS*(0.691*FL+0.00175*FL*FL)
        ATT=ATT/BLKHR
        CREW=YRMULT*174.*FL+43.5+(0.452*FL+0.11299)*
     $   (WTO*0.453592/1000.)
        CREW=CREW/BLKHR
        SERVICE=YRMULT*63.0
        CONTROL=YRMULT*82.58/BLKHR
        DOC=DEPRE+SUPPORT+SPARES+DELAY+INSUR+FCOST+FEELAND+
     $  SERVICE+ATT+CREW+XMCOST+CONTROL
C
C       *********************************************
C       PERCENT OF TOTAL - DIRECT OPERATING COSTS
C       *********************************************
```

```
      PER(1)=DEPRE/DOC
      PER(2)=SUPPORT/DOC
      PER(3)=SPARES/DOC
      PER(4)=DELAY/DOC
      PER(5)=INSUR/DOC
      PER(6)=FCOST/DOC
      PER(7)=XMCOST/DOC
      PER(8)=FEELAND/DOC
      PER(9)=CREW/DOC
      PER(10)=ATT/DOC
      PER(11)=SERVICE/DOC
      PER(12)=CONTROL/DOC
      DO 30 J=1,12
   30 PER(J)=PER(J)*100.
      TOT=100.00
C
C     *******************************************************
C     INDIRECT OPERATING COSTS PER BLOCK HOUR OF DESIGN FLIGHT
C     *******************************************************
      DATA YIOC/'HMAIN BURDN','FOOD COST','MOVIE','PASS INSUR'
     $ 'MISCE PASS','ADVERTISE','COMMISSION','RESERVATON',
     $ 'PASSE HDLG','BAG HANDLG','CARGO HDLG','SERVICING'/
C     ********************************************************
C     PLF, PASSENGER LOAD FACTOR, 0.55,    REF. OPDOT
C     FARE, FARE ($/SEAT-NAU. MILE)        REF. OPDOT
C     *************************************************
      PLF=0.55
      FARE=0.09
C     *************************************************
      XIOC(1)=XMCOST*1.05
      IFIRS=0.15*NPASS*PLF
      IECON=NPASS*PLF-IFIRS
      XIOC(2)=IFIRS*2.42+IECON*1.05
      XIOC(3)=196./BLKHR
      RPM=NPASS*PLF*R/1000.
      XIOC(4)=0.52*RPM/BLKHR
      XIOC(5)=NPASS*0.18/BLKHR
      REVYR=FARE*NPASS*PLF*UR*R/BLKHR
      REVHR=REVYR/UR
      XIOC(6)=0.023*REVHR
      XIOC(7)=2.35*RPM/BLKHR
      PASSPHR=NPASS*PLF/BLKHR
      XIOC(8)=4.40*PASSPHR
      XIOC(9)=2.87*PASSPHR
      XIOC(10)=1.31*PASSPHR
      TONCAR=WP/2000.
      XIOC(11)=131.08*TONCAR/BLKHR
      XIOC(12)=(0.03*9.5+0.0025)*NPASS/BLKHR
      TOTIOC=0.
      XIOC(1)=XIOC(1)/YRMULT
      XIOC(6)=XIOC(6)/YRMULT
      DO 200 I=1,12
      XIOC(I)=XIOC(I)*YRMULT
      TOTIOC=TOTIOC+XIOC(I)
  200 CONTINUE
C
```

```
C           ************************************
C           RETURN ON INVESTMENT CALCULATIONS
C           ************************************
            XINVEST=0.9*PRICE
            TAXRT=0.48
            COSTHR=DOC+TOTIOC
            PROFIT=(REVHR-COSTHR)*UR
            ROI=(1.-TAXRT)*PROFIT/XINVEST
            FARROI=(0.26*PRICE+COSTHR*UR)*(BLKHR/(NPASS*PLF*UR*R))
C           *****************************************************
C           SET ECONOMIC PARAMETERS FOR PRINTOUT
C           ****************************************************
            CST(1)=DOC
            CST(2)=DOC*BLKHR
            CST(3)=ROI
            CST(4)=FARROI
            CST(5)=R/WFUEL*NPASS
            INCPH=COSTHR+0.15*XINVEST/(UR*(1.-TAXRT))
            INCPF=INCPH*BLKHR
            CST(6)=INCPF
            CST(7)=PRICE
C
            IF(KP.EQ.0) RETURN
C
C           ***************************************************
C           OUTPUT ECONOMIC PERFORMANCE PARAMETERS
C           ***************************************************
            WRITE(6,52)
   52       FORMAT(1X,//,30X,'DIRECT OPERATING COSTS--',
     $      'DOLLARS/FLIGHT  HOUR')
            WRITE(6,54)DEPRE,PER(1),SUPPORT,PER(2),SPARES,PER(3),
     $      DELAY,PER(4),INSUR,PER(5),FCOST,PER(6),XMCOST,PER(7),
     $      FEELAND,PER(8),CREW,PER(9),ATT,PER(10),SERVICE,PER(11),
     $      CONTROL,PER(12)
   54       FORMAT(//10X,'DEPRE',T40,2F10.2,/,10X,'SUPPORT',
     $      T40,2F10.2,/,10X,'SPARES',T40,2F10.2,/,10X,'DELAY',
     $      T40,2F10.2,/,10X,'INSURANCE',
     $      T40,2F10.2,/,10X,'FUEL',T40,2F10.2,/,10X,'MAINTENANCE',
     $      T40,2F10.2,/,10X,'LANDING FEE',T40,2F10.2,/,10X,'CREW',
     $      T40,2F10.2,/,10X,'ATTENDANTS',T40,2F10.2,/,10X,
     $      'FUEL SERVICE',
     $      T40,2F10.2,/,10X,'CONTROL',T40,2F10.2)
            WRITE(6,56) DOC,TOT
   56       FORMAT(/3X,'TOTAL DIRECT OPERATING COSTS'T40,'$',
     $      F9.2,F10.2)
            WRITE(6,150)
  150       FORMAT(///30X,'INDIRECT OPERATING COSTS--',
     $      'DOLLARS/FLIGHT HOUR',///)
            DO 300 I=1,12
            PER(I)=100.*XIOC(I)/TOTIOC
            WRITE(6,152) YIOC(I),XIOC(I),PER(I)
C           WRITE(6,152) XIOC(I),PER(I)
  152       FORMAT(10X,A10,T40,2F10.2)
  300       CONTINUE
            WRITE(6,354) TOTIOC, TOT
  354       FORMAT(/5X,'TOTAL INDIRECT OPERATING COSTS',T40,2F10.2/)
            WRITE(6,550) REVHR,COSTHR,ROI
```

```
550     FORMAT(///30X,'ECONOMIC PERFORMANCE SUMMARY',///
   $    10X,'REVENUE PER BLOCK HOUR'T50,F12.2,/
   $    10X,'TOTAL COST PER BLOCK HOUR'T50,F12.2,/
   $    10X,'RETURN ON INVESTMENT',T50,F12.4///)
        DATA YCOST/'DOC/HOUR','DOC/FLIGHT','ROI','FARE',
   $    'SEAT-MI/GA','FARE','PRICE'/
        DO 570 I=1,7
        WRITE(6,560) I,YCOST(I),CST(I)
560     FORMAT(10X,I5,2X,A10,F12.3)
570     CONTINUE
        RETURN
        END
```

## SUBROUTINE AIRCOST

This routine is used to compute the aircraft development and production costs. It is called from DOCOST.

The aircraft cost estimates are used in calculating the aircraft's DOC. These costs are calculated according to Nicolai [43] and [5]. The development, test and evaluation (DT&E) cost is that cost required to engineer, develop, fabricate and flight test $Q_D$ number of aircraft prior to committing to production. The DT&E aircraft might number as few as two and as many as ten. For the case study presented in Chapter 5 the building of two prototype aircraft is assumed. The cost elements charged to DT&E are as follows:

- Airframe engineering
- Development support
- Flight test aircraft
    - Tooling
    - Manufacturing labor
    - Quality control
    - Manufacturing materials
    - Engine
    - Avionics
    - Active controls system

The cost elements charged to production are as follows:

- Airframe engineering (sustaining)
- Tooling
- Manufacturing labor
- Quality control
- Manufacturing materials
- Engine
- Avionics

The aircraft cost estimates are calculated and tabulated within the aircraft design template. These costs are totaled and divided by the number of aircraft produced to calculate the total cost per aircraft. The aircraft purchase price, $C_{A\$}$, is used to calculate the aircraft's annual return on investment. Information from references [5,43] has been used in this routine. A listing of the routine follows.

```
C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
  SUBROUTINE AIRCOST
C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
```

```
C
      SUBROUTINE AIRCOST(COST,WTO,THRUST,NPASS,KP)
      REAL CD(10),CP(10)
C
C*****************************************************************
C     DEFINE A, AMPR WEIGHT IN LBS. VALUE DETERMINED FROM
C     NICOLAI AND OPDOT
C*****************************************************************
      A=WTO*0.75
C
C*****************************************************************
C     LIST OF PURCHASE PRICE ELEMENTS IN 1974 $.
C     REFERENCE - NICOLAI.
C*****************************************************************
C     ENGINEERING (1)
C     DEVELOPMENT SUPPORT (2)
C     FLIGHT TEST OPERATIONS (3)
C     TOOLING (4)
C     MANUFACTURING LABOR (5)
C     QUALITY CONTROL (6)
C     MATERIALS AND EQUIPMENT (7)
C     ENGINE (8)
C     AVIONICS (9)
C     ACTIVE CONTROL SYSTEM (10)
C*****************************************************************
C     DEFINITION OF CERTAIN AICRAFT COST VARIABLES.  THESE CAN
C     BE CHANGED BY THE USER, BUT FOR TRANSPORT AIRCRAFT THESE
C     ARE REASONABLE ASSUMPTIONS.REFERENCES - OPDOT AND
C     NICOLAI.
C*****************************************************************
C     QD,  NUMBER OF PROTOTYPE AIRCRAFT = 2
C     QP,  NUMBER OF PRODUCTION AIRCRAFT = 250
C     Q,   CUMULATIVE QUANTITY PRODUCED, = QD + QP = 252
C     S,   MAXIMUM SPEED AT BEST ALTITUDE (KNOTS) = 483
C     R,   PRODUCTION RATE,DELIVERIES PER MONTH, = 5
C     E,   NUMBER OF ENGINES, = 3
C     ACS, ACTIVE CONTROL SYSTEM, 1= YES, 0 = NO.
C     ER,  ENGINEERING RATE (1974), DOLLARS PER HOUR, = 19.55
C     TR,  TOOLING RATE (1974), DOLLARS PER HOUR, = 14.00
C     ALR, LABOR RATE (1974), DOLLARS PER HOUR, = 10.90
C     CVG, CONVERTING 1970$ TO 1974$, = 1.3.
C*****************************************************************
      DATA QD,QP,Q,S,R,E,ACS/2.,250.,252.,483.,5.,3.,1./
      DATA ER,TR,ALR,CVG/19.55,14.00,10.90,1.3/
C*****************************************************************
C     AIRFRAME ENGINEERING - DEVELOPMENT AND PRODUCTION
C*****************************************************************
      CD(1)=ER*0.0396*A**0.791*S**1.526*QD**0.183
      CP(1)=ER*0.0396*A**0.791*S**1.526*Q**0.183 - CD(1)
C
C     AIRCRAFT DEVELOPMENT SUPPORT
      CD(2)=0.008325*A**0.873*S**1.890*QD**0.346
      CP(2)=0.
C
C     FLIGHT TEST OPERATIONS
      CD(3)=0.001244*A**1.160*S**1.371*QD**1.281*CVG
      CP(3)=0.
```

```
C
C        TOOLING
         CD(4)=TR*4.0127*A**0.764*S**0.899*QD**0.178*R**0.066
         CP(4)=TR*4.0127*A**0.764*S**0.899*Q**0.178*R**0.066 -
     $   CD(4)
C
C        MANUFACTURING LABOR
         CD(5)=ALR*28.984*A**0.740*S**0.543*QD**0.524
         CP(5)=ALR*28.984*A**0.740*S**0.543*Q**0.524 - CD(5)
C
C        QUALITY CONTROL
         CD(6)=0.13*CD(5)
         CP(6)=0.13*CP(5)
C
C        MANUFACTURING MATERIAL AND EQUIPMENT
         CD(7)=CVG*25.672*A**0.689*S**0.624*QD**0.792
         CP(7)=CVG*25.672*A**0.689*S**0.624*Q**0.792 - CD(7)
C
C        ENGINES
         CD(8)=CVG*QD*(E+1)*109*(THRUST/E)**0.8356
         CP(8)=CVG*QP*E*109*(THRUST/E)**0.8356
C
C        AVIONICS
         CD(9)=QD*300000.
         CP(9)=QP*300000.
C
C        ACTIVE CONTROL SYSTEM
         CD(10)=ACS*206250*QD
         CP(10)=ACS*206250*QP
C
C        $$$$$$$$$$$$$$$$$$$$$$$$$$$
C        CONVERT FROM 1974$ TO 1976$
C        $$$$$$$$$$$$$$$$$$$$$$$$$$$
C
         TOTD=0.
         TOTP=0.
         DO 50 J=1,10
         CD(J)=CD(J)*1.23077
         CP(J)=CP(J)*1.23077
         TOTD=TOTD+CD(J)
         TOTP=TOTP+CP(J)
   50    CONTINUE
C        *****************************************************
C        INCLUDING 10% PROFIT - THIS COULD ALSO ACCOUNT FOR SPARES
C        *****************************************************
         TOTCOST=TOTD*1.1+TOTP*1.1
         COST=TOTCOST/QP
C
C        GO TO OUTPUT OR RETURN
         IF(KP.EQ.0) RETURN
C        *****************************************************
C        OUTPUT SECTION FOR DEVELOPMENT AND PRODUCTION COSTS
C        THIS IS ONLY CALLED FROM SUBROUTINE USEROUT
C        *****************************************************
         WRITE(6,67)
   67    FORMAT(///1X,T20'$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$')
```

```
      WRITE(6,70)
70    FORMAT(1X,//30X,'AIRCRAFT COST ESTIMATES'
 $    //,43X,'DEVELOPMENT',9X,'PRODUCTION'/)
      WRITE(6,72) CD(1),CP(1)
72    FORMAT(10X,'ENGINEERING',T40,F15.2,T60,F15.2)
      WRITE(6,74) CD(2),CP(2)
74    FORMAT(10X,'DEVELOPMENT SUPPORT',T40,F15.2,T60,F15.2)
      WRITE(6,80) CD(3),CP(3)
80    FORMAT(10X,'FLIGHT TEST',T40,F15.2,T60,F15.2)
      WRITE(6,82) CD(4),CP(4)
82    FORMAT(10X,'TOOLING',T40,F15.2,T60,F15.2)
      WRITE(6,84) CD(5),CP(5)
84    FORMAT(10X,'MANUFAC. LABOR',T40,F15.2,T60,F15.2)
      WRITE(6,86) CD(6),CP(6)
86    FORMAT(10X,'QUALITY CONTROL',T40,F15.2,T60,F15.2)
      WRITE(6,88) CD(7),CP(7)
88    FORMAT(10X,'MATERIALS',T40,F15.2,T60,F15.2)
      WRITE(6,90) CD(8),CP(8)
90    FORMAT(10X,'ENGINE',T40,F15.2,T60,F15.2)
      WRITE(6,92) CD(9),CP(9)
92    FORMAT(10X,'AVIONICS',T40,F15.2,T60,F15.2)
      WRITE(6,94) CD(10),CP(10)
94    FORMAT(10X,'ACTIVE CONTROLS SYSTEM',T40,F15.2,T60,F15.2)
      WRITE(6,96) TOTD,TOTP
96    FORMAT(/10X,'TOTAL',T40,F15.2,T60,F15.2)
      WRITE(6,98) COST
98    FORMAT(/5X,'TOTAL COST PER AIRCRAFT = $',F15.2)
      RETURN
      END
```

## SUBROUTINE MAINTCT

This routine is used to compute the aircraft maintenance costs. It is called from DOCOST.

The aircraft maintenance costs were developed from industry statistics [29]. This airframe maintenance model computes labor and material maintenance costs of 26 airframe systems as a function of the characteristics of the maintenance system. Using this model, the relative importance of various systems maintenance can be determined if certain design specifications of the study aircraft are known.

The aircraft maintenance cost equations calculate the material and labor costs for the following systems:

- Inspection and miscellaneous
- Air conditioning
- Auto pilot
- Communications
- Electrical
- Equipment and furnishing
- Fire protection
- Flight controls
- Fuel
- Hydraulic power
- Ice and rain
- Instruments
- Landing gear

- Lighting
- Navigation
- Oxygen
- Pneumatics
- Water/waste
- Airborne auxiliary power
- Structures
- Doors
- Fuselage
- Nacelles/pylons
- Wings
- Stabilizers
- Windows

The maintenance cost analysis also includes the engine system labor and material cost. These are all summed and utilized as the maintenance cost value for the direct operating cost calculation. The maintenance routines were based on the previous studies [5,29]. A listing of the routine follows.

```
C       $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C       THIS SUBROUTINE CALCULATES THE MAINTENANCE COSTS -
C       1976$/HOUR.
C       REF. - ESTIMATING AIRLINE OPERATING COSTS - OPDOT.
C       $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C
        SUBROUTINE MAINTCT(COST,WTO,WFUEL,NPASS,THRUST,WAREA,KP)
        CHARACTER*10 XNM(27)
        REAL MCOST(27),LCOST(27)
        REAL LCST(27),MCST(27), NENG
        DATA XNM/'INSPECTION','AIR CONDIT','AUTO PILOT',
     $  'COMMUNICAT','ELECTRICAL','FURNISHING',
     $  'FIRE PROTE','FLT CONTRL','FUEL',
     $  'HYDR POWER','ICE','INSTRUMENT',
     $  'LANDG GEAR','LIGHTING','NAVIGATION',
     $  'OXYGEN','PNUEMATIC','WATR/WASTE','AIR + APU',
     $  'STRUCTURES','DOORS','FUSELAGE','NACELLES',
     $  'WINGS','STABILZERS','WINDOWS','ENGINES'/
C       *****************************************************
        NENG=3.
        WFUEL=WFUEL*0.453592
        AFW=1.0377*WTO**0.9362*0.453592
        MGW=WTO*0.453592
        THRUST=THRUST*4.448/NENG
        WAREA=WAREA*0.0929053
C       **********************************
        AC=200.
        CHANN=5.
        CF=1.6
        HYD=300.
        NINS=1
        NAPU=1
C       ********************************************
C       MAINTENANCE COST - 1976 DOLLARS/HOUR
C       (1) INSPECTION AND MISCELLANEOUS
C       (2)   AIR CONDITIONING
C       (3)   AUTO PILOT
C       (4)   COMMUNICATIONS
```

```
C          (5)    ELECTRICAL
C          (6)    EQUIPMENT AND FURNISHINGS
C          (7)    FIRE PROTECTION
C          (8)    FLIGHT CONTROLS
C          (9)    FUEL
C          (10)   HYDRAULIC POWER
C          (11)   ICE AND RAIN
C          (12)   INSTRUMENTS
C          (13)   LANDING GEAR
C          (14)   LIGHTING
C          (15)   NAVIGATION
C          (16)   OXYGEN
C          (17)   PNEUMATICS
C          (18)   WATER/WASTE
C          (19)   AIRBORNE AUXILLARY POWER
C          (20)   STRUCTURES
C          (21)   DOORS
C          (22)   FUSELAGE
C          (23)   NACELLES/PYLONS
C          (24)   WINGS
C          (25)   STABILIZERS
C          (26)   WINDOWS
C          ********************************************************
           LCOST(1)=7.66+0.377*AFW/1000.
           MCOST(1)=1.21+0.062*AFW/1000.
           LCOST(2)=2.0386+0.01532*AC
           MCOST(2)=2.32+0.011*AC
           LCOST(3)=2.238*CHANN
           MCOST(3)=0.631+0.398*CHANN
           LCOST(4)=0.0276*NPASS
           MCOST(4)=0.0118*NPASS
           LCOST(5)=4.306
           MCOST(5)=5.748
           LCOST(6)=9.11+0.0531*NPASS*CF
           MCOST(6)=2.38+0.0361*NPASS*CF
           LCOST(7)=0.213+2.2856*(NENG+NAPU)
           MCOST(7)=0.365*(NENG*NAPU)
           LCOST(8)=6.84+0.0035*MGW/1000.
           MCOST(8)=3.876+0.00655*MGW/1000.
           LCOST(9)=1.114+0.0262*WFUEL/1000.
           MCOST(9)=0.595+0.0123*WFUEL/1000.
           LCOST(10)=2.31+0.0034*HYD
           MCOST(10)=1.55+0.0080*HYD
           LCOST(11)=0.5089+0.0013*MGW/1000.
           MCOST(11)=0.0847+0.0037*MGW/1000.
           LCOST(12)=0.509+0.009*AFW/1000.
           MCOST(12)=0.235+0.0031*AFW/1000.
           LCOST(13)=4.58+0.0710*MGW/1000.
           MCOST(13)=4.961+0.1810*MGW/1000.
           LCOST(14)=1.51+0.0072*NPASS*CF
           MCOST(14)=0.047+0.0087*NPASS*CF
           LCOST(15)=2.94+2.1*NINS+3.58*CF
           MCOST(15)=0.086+1.2*NINS+3.675*CF
           LCOST(16)=0.515+0.00265*NPASS
           MCOST(16)=0.00752*NPASS
           LCOST(17)=0.181+0.0003*AC*THRUST/10000.
           MCOST(17)=0.0019*AC*THRUST/10000.
```

```
      LCOST(18)=0.339+0.0023*NPASS*CF
      MCOST(18)=0.00485*NPASS*CF
      LCOST(19)=0.315
      MCOST(19)=0.462
      LCOST(20)=3.+0.0099*AFW/1000.
      MCOST(20)=0.
      LCOST(21)=1.147+0.006*NPASS
      MCOST(21)=0.387+0.00785*NPASS
      LCOST(22)=1.5+0.046*AFW/1000.
      MCOST(22)=0.5833
      NAC=4
      IF(NENG.LT.4) NAC=2
      LCOST(23)=0.3366*NAC
      MCOST(23)=0.1391*NAC
      LCOST(24)=2.9475
      MCOST(24)=0.126+0.00506*WAREA
      LCOST(25)=0.834
      MCOST(25)=0.3737
      LCOST(26)=0.763+0.00043*NPASS
      MCOST(26)=0.0362*NPASS
C     ******************************
C     DIVIDE BY 2.5 HOUR FLIGHT LENGTH
C     ******************************
      DO 50 K=1,26
      LCST(K)=LCOST(K)/2.5
      MCST(K)=MCOST(K)/2.5
   50 CONTINUE
C     *******************************
C     SUMMATION OF MAINTENANCE COSTS
C     *******************************
      TLCOST=0.
      TMCOST=0.
      DO 75 K=1,26
      TLCOST=LCST(K)+TLCOST
      TMCOST=MCST(K)+TMCOST
   75 CONTINUE
C     ****************************************************
C     MAIN ENGINE MAINTENANCE COSTS - REFERENCE OPDOT
C     ****************************************************
      TENG=THRUST/NENG
      LCOST(27)=(NENG/(4.*2.5))*88.5*(TENG/20000.)**0.5
      MCOST(27)=(NENG/(4.*2.5))*109.0*(TENG/20000.)**0.5
C     ****************************************************
C
C     *********************
C     TOTAL MAINTENANCE COSTS
C     *********************
      COST=TLCOST+TMCOST+LCOST(27)+MCOST(27)
C
C     ****************************************************
C     IF THIS IS CALLED FROM SUB USROUT,KP=1,GO TO 80,PRINT
C     STATEMENTS
C     *****************************************************
      IF(KP.EQ.0) RETURN
C     ****************************************************
C     OUTPUT: MAINTENANCE COST - THIS IS ONLY CALLED FROM
C     USEROUT
```

```
C         *****************************************************
          WRITE(6,86)
   86     FORMAT(1X,//30X,'MAINTENANCE OPERATING COSTS',//7X,
     $    ' NO.  SYSTEM',7X,10X,'LABOR',9X,'MATERIAL')
          DO 90 K=1,26
          WRITE(6,88) K,XNM(K),LCOST(K),MCOST(K)
   88     FORMAT(I10,2X,A10,3X,2F15.2)
   90     CONTINUE
          WRITE(6,92)TLCOST,TMCOST,LCOST(27),MCOST(27),COST
   92     FORMAT(//5X,'LABOR COST',T35,F15.2/,5X,
     $    'MATERIAL COST'T35,F15.2//5X,'ENGINE LABOR COST',
     $    T35,F15.2/,5X,'ENGINE MATERIAL COST'T35,F15.2,
     $    ///30X,'MAINTENANCE DOC IN 1976 DOLLARS PER HOUR',F15.2)
C
          RETURN
          END
```

## SUBROUTINE USROUT

This routine is used to provided a formatted output of the final results obtained from exercising the aircraft DSP template .

```
C
C         *************************************************
C         *   USROUT - Subroutine                          *
C         *                                                *
C         *   This subroutine is used to provide a formatted *
C         *   output of the aircraft design optimization    *
C         *   results                                      *
C         *        X - Is the vector containing the final   *
C         *            design variable values which are     *
C         *           used to determine the conceptual     *
C         *            aircraft design parameters.         *
C         *                                                *
C         *************************************************
C
C
C
          SUBROUTINE USROUT(X)
          COMMON /USER/ CKV,L2,R2,SWR,DE,AS,WFI,CLM,SL,MC,AL,STO,
     +                  ATO,C,WP,TR,E,U,R,E1,FT,FL,N,M,TC
          REAL LB,L2,MC,M,N
          DATA PI/3.1415926/
          DIMENSION X(1)
C
            S = X(1)
           TI = X(2)
           LB = X(3)
          WTO = X(4)
            B = X(5)
            D = X(6)
C
             Q = (.5*DE*(M**2)*(AS**2))
C
            CL = (WTO/(Q*S))
C
           RE = LB*M*AS/CKV
```

```
C
        CF = 0.455/(ALOG10(RE))**2.58
C
      CDO = (CF * (1.0 + L2 *
     +      TC+100.0*TC**4)*R2*SWR+((CF * (1.0 + 60.0 /
     +      (LB/D)**3+0.0025*(LB/D))*4.0*LB/D)+(0.029/
     +      ((CF*(1.0+60.0/(LB/D)**3)+0.0025*LB/D)*4.0*LB/D)
     +      **0.5))*((PI*(D/B)**2)*0.5774)+.005)
C
        EK = (1.0/(PI*(B**2/S)*(E1*(1.0 - (D/B)**2))))
C
        WF = (1.1*WTO)*(1.0 - (.95)/EXP((1.47)*R*(C/(AS*M))
     +      *(2.13*SQRT(CDO*EK))))
C
C ==================================
C Calculate the wing aspect ratio, A
C ==================================
C
         A = (B**2/S)
C
C ======================================================
C Print the final aircraft system design variable values
C ======================================================
C
      PRINT 309, S,TC,B,A,D,LB,WTO,WF,WP,N,TI,M
  309 FORMAT(' ',50('*'),//
     + '                AIRCRAFT DESIGN PARAMETERS               '/
     + '                  USING THE DSP TECHNIQUE'//
     + '                        WING AREA = ',F7.1,' SQ FEET'//
     + '              WING THICKNESS RATIO = ',F5.2,' '//
     + '                        WING SPAN = ',F6.1,' FEET'//
     + '                WING ASPECT RATIO = ',F5.2,' '//
     + '                FUSELAGE DIAMETER = ',F6.2,' FEET'//
     + '                  FUSELAGE LENGTH = ',F7.2,' FEET'//
     + '                  TAKE-OFF WEIGHT = ',F9.1,' LBS'//
     + '                      FUEL WEIGHT = ',F8.1,' LBS'//
     + '                   PAYLOAD WEIGHT = ',F8.1,' LBS'//
     + '                NUMBER OF ENGINES = ',F5.2,' '//
     + '                 INSTALLED THRUST = ',F8.1,' LBS'//
     + '               CRUISE MACH NUMBER = ',F5.2,' '/)
C
C ======================================================
C Calculate and print the required thrust for cruise, TR
C ======================================================
C
       TR = (((CDO*Q*S)+(EK*(WTO**2)/(Q*S))))
C
      PRINT 310,TR
  310 FORMAT(' ',
     + '      REQUIRED THRUST FOR CRUISE = ',F8.1,' LBS'/)
C
C ==============================================================
C Calculate and print the available thrust for cruise climb, TIR
C ==============================================================
C
       TIR = (TI/TR)
C
```

```
      PRINT 331,TIR
 331  FORMAT(' ',
     + '                    TI/TR RATIO = ',F5.2,' '/)
C
C ==============================================
C Calculate and print the number of passengers, NP
C ==============================================
C
      NP = (0.867*LB*((D/1.83)-1.0)/3.75)
C
      PRINT 333,NP
 333  FORMAT(' ',
     + '           NUMBER OF PASSENGERS = ',I4,' '/)
C
C ============================================================
C Calculate and print the missed approach gradient parameter, AL
C ============================================================
C
       AL = ((TI/(WTO-WF))*(.667)-(2.13*(CDO*EK)**.5))*100.0
C
      ALA = ((AL/100.0)*(180.0/PI))
C
      PRINT 311,AL,ALA
 311  FORMAT(' ',
     + '       MISSED APPROACH GRADIENT = ',F5.2,' %'/
     + '                                = ',F5.2,' DEGREES'/)
C
C ==========================================================
C Calculate and print the required take-off field length, STO
C ==========================================================
C
       STO = (((20.9*((WTO/S)/(CLM*(TI/WTO))))+(87.0*((WTO/
     +         S) * (1.0/CLM))**.5)))
C
      PRINT 312,STO
 312  FORMAT(' ',
     + '          TAKE-OFF FIELD LENGTH = ',F7.1,' FEET'/)
C
C ========================================================
C Calculate and print the required landing field length, SL
C ========================================================
C
        SL = ((118.0*(((WTO-WF)/S)/CLM))
     +         +(400.0))
C
      PRINT 313,SL
 313  FORMAT(' ',
     + '           LANDING FIELD LENGTH = ',F7.1,' FEET'/)
C
C ==========================================================
C Calculate and print the second segment climb parameter, ATO
C ==========================================================
C
       ATO = (((TI/(WTO))*(.667)-(2.13*(CDO*EK)**.5)))*100.0
C
      ATOA = ((ATO/100.0)*(180.0/PI))
C
```

```
      PRINT 314,ATO,ATOA
 314  FORMAT(' ',
     +  '   SECOND SEGMENT CLIMB GRADIENT = ',F5.2,' %'/
     +  '                                 = ',F5.2,' DEGREES'/)
C
C ==============================================
C Calculate and print the available cruise range, R
C ==============================================
C
        R = ((((0.5925*(0.943)*AS*M)/(2.0*C*(CDO*EK)**.5))
     +      *(ALOG((1.0-(WF/WTO))**-1))))
C
      PRINT 315,R
 315  FORMAT(' ',
     +  '                  CRUISE RANGE = ',F7.1,' NMI'/)
C
C ==============================================
C Calculate and print the aircraft endurance, E
C ==============================================
C
        E = ((((1.0/(2.0*SQRT(CDO*EK)))**-1.0)*(1.0/C)*
     +      ALOG((1.0-WF/WTO)**-1.0)))
C
      PRINT 316,E
 316  FORMAT(' ',
     +  '                        LOITER = ',F5.2,' '/)
C
C ==============================================
C Calculate and print the useful load fraction, U
C ==============================================
C
        WPP = WP+NP*200.
C
        U = ((((WPP+WF)/WTO)))
C
      PRINT 317,U
 317  FORMAT(' ',
     +  '          USEFUL LOAD FRACTION = ',F5.2,' '/)
C
C ==============================================
C Calculate and print the airfoil form factor, FT
C ==============================================
C
        FT = ((1.0+(100.0*(TC)**4)+(L2*(TC))))
C
      PRINT 318,FT
 318  FORMAT(' ',
     +  '             WING FORM FACTOR = ',F7.4,' '/)
C
C ==============================================
C Calculate and print the fuselage form factor, FL
C ==============================================
C
        FL = ((1.0+(60.0/((LB/D)**3))+0.0025*(LB/D)))
C
      PRINT 319,FL
 319  FORMAT(' ',
```

```
     +                 FUSELAGE FORM FACTOR = 'F7.4,' '/)
C
C  ==================================
C  Calculate and print the values of :
C
C                Dynamic pressure, Q
C                Lift coefficient, CL
C        Zero lift drag coefficient, CDO
C      Wing drag due to lift factor, EK
C         Reynolds number at cruise, RE
C          Skin friction coefficient, CF
C  ==================================
C
          PRINT 320,Q,CL,CDO,EK,RE,CF
  320    FORMAT(' ',
     +  '                 DYNAMIC PRESSURE = ',F8.3,'  '//
     +  '                  LIFT COEFFICIENT = ',F7.4,'  '//
     +  '        ZERO LIFT DRAG COEFFICIENT = ',F7.4,'  '//
     +  '      WING DRAG DUE TO LIFT FACTOR = ',F7.4,'  '//
     +  '         REYNOLDS NUMBER AT CRUISE = ',F10.0,' '//
     +  '         SKIN FRICTION COEFFICIENT = ',F7.5,' ')
C
C
=================================================================
C         PRINT ECONOMIC OUTPUT
C         FIRST: CALL AIRCOST FOR DEVELOPMENTAL COSTS OUTPUT
C         SECOND: CALL MAINTCT FOR MAINTENANCE COSTS OUTPUT
C         THIRD: DIRECT OPERATING COSTS
C         FOURTH: INDIRECT OPERATING COSTS
C
=================================================================
C  KP = 1, PRINT ECONOMIC OUTPUT
C  KP = 0, SKIP ECONOMIC OUTPUT
C
=================================================================
          KP=1
          CALL DOCOST(R,WTO,WF,NP,TI,S,WP,KP,ROI)
          RETURN
          END
```

**SUBROUTINE USAN**

This routine has not been used for this template. This routines serves as an interface to other design analysis programs (See Figure 2.10).

```
C         ******************************************************
          SUBROUTINE USAN(X)
C         ****************** DUMMY ROUTINE **********************
C
          DIMENSION X(1)
          RETURN
          END
C
```

# APPENDIX D:
## SAMPLE OUTPUT AND SOME EXPLANATIONS

This appendix contains sample output for Case B, Scenario Two for the Boeing 727-200. The case is described in Chapter 5 and the input is described in Appendix C. For the purpose of explanation the output has been divided into blocks and explained. SLIPML, SLIP2 are older names for the ALP algorithm that has been briefly described in Chapter 2, Section 2.4.3. The algorithm itself is described in detail in [31,36] and its implementation in [32].

## EXPLANATION OF OUTPUT FOR COMPROMISE DSP TEMPLATE

The explanation and output that follows is for a level 3 printout. At the lower levels less information is provided.

**BLOCK 1**
This block contains information pertaining to the version and size limitations of the DSIDES software being used.

```
===================================================================
===================================================================

SLIPML- COMPROMISE DSP JOB RUN ON 29-DEC-86 AT 13:31:56  HOURS

-------------------------------------------------------------------
SLIPML - VERSION 4.6 - MARCH 1985
LAST UPDATE BY F. MISTREE, UNIVERSITY OF HOUSTON, DEPT. OF MECH. ENG.
MAXIMUM NUMBER OF VARIABLES PERMITTED = 50
MAXIMUM NUMBER OF LINEAR CONSTRAINTS PERMITTED = 26
MAXIMUM NUMBER OF NON-LINEAR CONSTRAINTS PERMITTED = 35
UPDATE DONE ON SEPT. 21, 1985
-------------------------------------------------------------------
```

**BLOCK 2**
This block contains the title of the data set, an indication of what information has been provided by a user, whether or not a user provided output routine is to be used, and whether or not some some system provided features are to be used by default, etc.

```
BOEING 727-200:  CASE B, SCENARIO TWO       DEC. 29, 86
*** USER PROVIDED INPUT ROUTINE TO BE USED.
*** USER PROVIDED OUTPUT ROUTINE TO BE USED.
*** NUMBER ANALYSIS/SYNTHESIS CYCLES =    1
*** USER PROVIDED ANALYSIS MODULE TO BE USED
*** AUTOMATIC GENERATION OF DEVIATION VARIABLES
*** TIME STATISTICS PROVIDED
UNITS: FORCE LENGTH MERIT OTHER LBS.        FEET.
-------------------------------------------------------------------
```

**BLOCK 3**
This block contains information pertaining to the size of the DSP template and the grouping of the nonlinear constraint and goal information.

```
    NUMBER OF SYSTEM VARIABLES     6
    NUMBER OF DEVIATION VARIABLES    16
    NUMBER OF CONSTRAINT GROUPS     3
    NUMBER OF NONLINEAR CONSTRAINTS    21
    NUMBER OF CONSTRAINTS IN EACH GROUP     9    3    9
-------------------------------------------------------------------
```

**BLOCK 4**
This block contains the names of the system variables, names of the deviation variables, and names of the system constraints and goals that are specified by the user. FUWT is the name of the first nonlinear system constraint (see Appendix C) and LDFL is the name of

the first system goal in the template. The deviation variables D1- and D1+ are associated with the first system goal LDFL. The priorities for the goals are shown in Block 6

```
NAMES OF SYSTEM VARIABLES
WNGA ITHR FLTH TOWT WGSP FDIA
NAMES OF DEVIATIONAL VARIABLES
D1-  D1+  D2-  D2+  D3-  D3+  D4-  D4+  D5-  D5+  D6-  D6+  D7-  D7+  D8-
D8+
NAMES OF NONLINEAR CONSTRAINTS (SYSTEM AND GOAL)
FUWT THCR SSCG TOFL WDRL WDRU FUFF ASPL ASPU THCC MAPC RNGC LDFL MAGC RNGG
LOIT USFL WTMA FUSV ROIG ZCON
---------------------------------------------------------------------
```

**BLOCK 5**

Subroutine USERIN (see Appendix C) is a user provided utility. This block contains output in the format specified in USERIN. The format is in control of a template developer and it is recommended that part of the output be in a form that is directly usable in a report.

```
************************************************************
  AIRCRAFT DESIGN USING THE COMPROMISE
       DECISION SUPPORT PROBLEM
************************************************************
KINEMATIC VISCOSITY AT 35000 FT            .000406
AIRFOIL THICKNESS LOCATION PARAMETER       1.2
LIFTING SURFACE CORRELATION FACTOR         1.1
WETTED/PLANFORM AREA RATIO OF WING         2.0
ATMOSPHERIC DENSITY AT 35000 FT            0.000737 SLUGS/CU FT
SPEED OF SOUND AT 35000 FT                 973.1 FT/SEC
INITIAL WEIGHT OF FUEL (TARGET VALUE)      40000.0 LBS
MAXIMUM LIFT COEFFICIENT                   2.6
LANDING FIELD LENGTH (TARGET VALUE)        4500.0 FT
LANDING/TAKE-OFF MACH NUMBER               0.197
REQ. CLIMB GRADIENT FOR MISSED APPRCH      0.07200 RADIANS
TAKE-OFF FIELD LENGTH (TARGET VALUE)       6500.0 FT
REQ. CLIMB GRADIENT FOR TAKE-OFF           0.08100 RADIANS
SPECIFIC FUEL CONSUMPTION (ESTIMATE)       0.9 LB/LB HRS
PAYLOAD WEIGHT                              5000.0 LBS
THRUST FOR CRUISE (TARGET VALUE)            9000.0 LBS
ENDURANCE OR LOITER (TARGET VALUE)         0.03
USEFUL LOAD FRACTION (TARGET VALUE)        0.5
AIRCRAFT RANGE (TARGET VALUE)              2400.0 NMI
PLANFORM EFFICIENCY CONSTANT               0.96
WING FORM FACTOR (TARGET VALUE)            1.1560
FUSELAGE FORM FACTOR (TARGET VALUE)        1.0830
NUMBER OF ENGINES                          3.0
CRUISE MACH NUMBER                              0.80
AIRFOIL THICKNESS RATIO                    0.12
-----------------------------------------------------------------
```

**BLOCK 6**

This block contains information about execution, namely, the type of DSP, the stopping criteria (permitted number of iterations and the FRAC values) and the reduced move coefficients. Optimization characteristics of the design run such as number of permitted synthesis cycles, convergence criteria, the reduced move limits and goal priorities specified by the user. Unfortunately, the output format of the goal priorities leaves something to be desired. If N is the number of system variables then the first N pieces of output will be zero (6 in this case). Each goal is associated with two deviation variables. Priorities for each goal are specified as priorities for the deviation variables. For example items 7 and 8 (under GOAL PRIORITIES) indicate the priorities associated with D1- and D1+ of goal LDFL (see Block 4). The priorities associated with the rest of the deviation variables follow.

```
OPTIMIZATION CRITERIA

TYPE OF DSP                GOAL
PERMITTED NO. OF ITERATIONS                      30
FRAC1=  1.00% (OBJ. FUNC. VALUE CHANGE LIMIT(I-1,I))
FRAC2=  1.00% (DESIGN VARIABLE STATIONARY BETWEEN LIMIT(I,I-1) -DEFAULT)
FRAC3= -5.00% (NONLINEAR CONSTRAINT SATISFIED WITHIN LIMIT- DEFAULT)
MOVE =  0.50  (REDUCED MOVE COEFFICIENT)
(I=SYNTHESIS CYCLE NO.)


GOAL PRIORITIES
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00 0.0000000E+00
0.0000000E+00   5.000000       5.000000       6.000000       6.000000
2.000000       2.000000       4.000000       4.000000       7.000000
7.000000       3.000000       3.000000       1.000000       1.000000
8.000000       8.000000
```

## BLOCK 7

Contains the values of the bounds set on the system and deviation variables and linear constraints. For example, for the first system variable WNGA (see Block 4) the lower and upper bounds are 1200 and 2250, respectively. Activity PP is not germaine for this report; for an explanation see [32]. The bounds are called data set 1.

```
DATASET INPUT
.............
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          1   1200.000            1   2200.000
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          2   27750.00            2   55000.00
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          3   105.0000            3   150.0000
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          4   140000.0            4   250000.0
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          5   85.00000            5   140.0000
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          6   10.00000            6   15.00000
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          7  0.0000000E+00        7   2.000000
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          8  0.0000000E+00        8   2.000000
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS          9  0.0000000E+00        9   2.000000
BOUNDS                              ACTIVITY PP
 VAR.NO./GE RHS/LE RHS         10  0.0000000E+00       10   2.000000
```

```
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              11   0.0000000E+00            11    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              12   0.0000000E+00            12    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              13   0.0000000E+00            13    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              14   0.0000000E+00            14    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              15   0.0000000E+00            15    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              16   0.0000000E+00            16    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              17   0.0000000E+00            17    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              18   0.0000000E+00            18    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              19   0.0000000E+00            19    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              20   0.0000000E+00            20    2.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              21   0.0000000E+00            21    1.000000
BOUNDS                                      ACTIVITY PP
 VAR.NO./GE RHS/LE RHS              22   0.0000000E+00            22    1.000000
```

**BLOCK 8**

Information about the specification of linear constraints is provided in this block. The linear constraints are called data set 2. The first constraint is of the form that LHS $\leq$ RHS. The right hand side value for this constraint is zero. The P's after ACTIVITY are position dependent. They indicate which of the six system variables are non-zero. The coefficients of the non-zero coefficients follow. Hence, the first two constraints represent the relationship between the wing area ant the installed thrust (see equation 4-53).

-140*WNGA + TOWT LE 0 and -80*WNGA + TOWT GE 0 that is $80.S \leq W_{TO} \leq 140.S$

Similarly, constraints three and four in the output block represent equation 4-54.

```
NO.  2 CON.NO.     1 LHS LE     0.000 ACTIVITY P..P.................
 LIN.CON.COEF.   -140.0000        1.000000
NO.  2 CON.NO.     2 LHS GE     0.000 ACTIVITY P..P.................
 LIN.CON.COEF.   -80.00000        1.000000
NO.  2 CON.NO.     3 LHS LE     0.000 ACTIVITY .P.P.................
 LIN.CON.COEF.   -4.400000        1.000000
NO.  2 CON.NO.     4 LHS GE     0.000 ACTIVITY .P.P.................
 LIN.CON.COEF.   -2.500000        1.000000
```

**BLOCK 9**

This block provides information on the data sets being used for a particular template. There can be only one set of bounds but there may be many data sets associated with the linear constraints. At any one time a "Standard" data set and up to three others can be used. Information on the level of printout requested by the user is also printed in this block. If a base values has been provided for the objective function this is so indicated.

The starting design follows the entry INI VAR. The zeros correspond to the deviation variables.

The value of OBJFV is determined in S/R VALUE. For a compromise DSP, OBJFV represents the sum of the deviation variables. Since the automatic generation of deviation variables is active, this value at the time of input is zero (the deviation variables have not yet been computed). Hence the numbers shown after TOTALS are zero. The TOTALS are being printed after INI VAR in error.

There are eight goal constraints and therefore sixteen deviation variables. These values correspond to the initial values of the eighteen deviation variables; D1-, D1+, D2-, D2+, etc. Since the automatic generation of deviation variable feature has been activated, their values at this stage are zero.

```
PROBLEM INPUT
.............

            DATASETS      PRINTOUT    DUMP          OBJ.FN.VALUE
           I    II  III  SLIP  EVAL                  BASE    TOTAL
STAND      1     2    0    3     0      0             0.0
   1       1     2    0    3     0      0             0.0      0.0
 INI.VAR.     1250.000       28000.00        108.0000        150000.0
  90.00000    11.00000        0.0             0.0              0.0
  0.0         0.0             0.0             0.0              0.0
  0.0         0.0             0.0             0.0              0.0
  0.0         0.0             0.0
                                              --------------------
                                   TOTALS    0.0               0.0
------------------------------------------------------------------
```

**BLOCK 10**

Contains information on the analysis/synthesis cycle number (see Figure 2.9) and whether the design (in this case the initial design) is feasible. At this stage it is assumed that a designer has ascertained that the starting design does not violate any of the bounds and linear constraints. Hence, the initial design is only checked for feasibility with respect to the nonlinear system constraints.

```
START ANALYSIS/SYNTHESIS CYCLE NUMBER :      1
INITIAL DESIGN (PARTICIPATING CONSTRAINTS ONLY) PROBLEM NO.    1 IS
FEASIBLE
```

**BLOCK 11**

In this block the name, number and value of each of the system variables followed by each of the deviation variables is printed. Note, the values of the deviation variables have been computed.

```
SYNTHESIS CYCLE NO.  1 IN PROBLEM NO.  1       *INPUT*
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
VARIABLE      NAME/NUMBER   WNGA  1      ITHR  2      FLTH  3      TOWT  4
                           1250.0      28000.       108.00       0.15E+06
VARIABLE      NAME/NUMBER   WGSP  5      FDIA  6      D1-   7      D1+   8
                            90.000      11.000    0.22416E-01    0.0
VARIABLE      NAME/NUMBER   D2-   9      D2+  10      D3-  11      D3+  12
```

```
                                 0.00000E+00  0.58702       0.00000E+00  0.19969
VARIABLE       NAME/NUMBER        D4-   13     D4+  14       D5-   15     D5+  16
                                 0.40706      0.00000E+00  0.68607E-01  0.0
VARIABLE       NAME/NUMBER        D6-   17     D6+  18       D7-   19     D7+  20
                                 0.99014      0.00000E+00  0.34147      0.0
VARIABLE       NAME/NUMBER        D8-   21     D8+  22
                                 0.87901      0.00000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

**BLOCK 12**

This block contains information about the objective function. The INITIAL VALUE OF THE OBJECTIVE FUNCTION is the value of OBJFV which is defined in S/R VALUE (see comments for Block 8). The values of the coefficients corresponding to each of the variables of the linear (or linearized) objective function are given in the line identified by OBJ. FN. COEFF.

```
BASE VALUE OF OBJECTIVE FUNCTION =     0.00000E+00
INITIAL VALUE OF OBJECTIVE FUNCTION =  2.2749
VARIABLE NUMBER             1             2               3            4
OBJ.FN.COEFF.             0.0           0.0             0.0          0.0
VARIABLE NUMBER             5             6               7            8
OBJ.FN.COEFF.             0.0           0.0         0.28331E+06    0.0
VARIABLE NUMBER             9            10              11           12
OBJ.FN.COEFF.             0.0          1323.4           0.0  0.36558E+08
VARIABLE NUMBER            13            14              15           16
OBJ.FN.COEFF.        0.18694E+06  0.00000E+00       996.46         0.00
VARIABLE NUMBER            17            18              19           20
OBJ.FN.COEFF.        0.80753E+06  0.00000E+00  0.22062E+09         0.0
VARIABLE NUMBER            21            22
OBJ.FN.COEFF.           9.0375     0.00000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

**BLOCK 13**

This block contains information about the template at the start of a synthesis - it provides information about the linearized form of the compromise DSP template. First, information about the lower and upper bounds is printed out. Internal numbers are used to identify the bounds, linear and nonlinear constraints and the goals in sequential order. These numbers represent the running number of a bound or constraint in the tableau. Another set of numbers called classification numbers are also printed out. Numbers 1 through 99 are reserved for the linear constraints, 101 through 199 for the nonlinear constraints and goals. An asterisk next to a bound or constraint indicates that it is active. Because of the nature of the formulation of the system goals they will always be active.

First the values of the upper and lower bounds on each of the variables is printed. Since there are 22 variables, 44 bounds are printed.

```
NAME/INT.NUM   VALUE           RHS   NAME/INT.NUM   VALUE           RHS
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
WNGA  1    0.125E+04  GE 0.120E+04  WNGA   2 0.125E+04  LE 0.220E+04
ITHR  3    0.280E+05  GE 0.278E+05  ITHR   4 0.280E+05  LE 0.550E+05
FLTH  5     108.      GE  105.      FLTH   6    108.    LE  150.
TOWT  7    0.150E+06  GE 0.140E+06  TOWT   8 0.150E+06  LE 0.250E+06
WGSP  9     90.0      GE  85.0      WGSP 10     90.0      LE  140.
FDIA 11     11.0      GE  10.0      FDIA 12     11.0      LE  15.0
```

```
D1-  13   0.224E-01  GE 0.000E+00 D1-  14   0.224E-01  LE  2.00
D1+  15   0.000E+00  GE 0.000E+00 D1+  16   0.000E+00  LE  2.00
D2-  17   0.000E+00  GE 0.000E+00 D2-  18   0.000E+00  LE  2.00
D2+  19   0.587      GE 0.000E+00 D2+  20   0.587      LE  2.00
D3-  21   0.000E+00  GE 0.000E+00 D3-  22   0.000E+00  LE  2.00
D3+  23   0.200      GE 0.000E+00 D3+  24   0.200      LE  2.00
D4-  25   0.407      GE 0.000E+00 D4-  26   0.407      LE  2.00
D4+  27   0.000E+00  GE 0.000E+00 D4+  28   0.000E+00  LE  2.00
D5-  29   0.686E-01  GE 0.000E+00 D5-  30   0.686E-01  LE  2.00
D5+  31   0.000E+00  GE 0.000E+00 D5+  32   0.000E+00  LE  2.00
D6-  33   0.990      GE 0.000E+00 D6-  34   0.990      LE  2.00
D6+  35   0.000E+00  GE 0.000E+00 D6+  36   0.000E+00  LE  2.00
D7-  37   0.341      GE 0.000E+00 D7-  38   0.341      LE  2.00
D7+  39   0.000E+00  GE 0.000E+00 D7+  40   0.000E+00  LE  2.00
D8-  41   0.879      GE 0.000E+00 D8-  42   0.879      LE  1.00
D8+  43   0.000E+00  GE 0.000E+00 D8+  44   0.000E+00  LE  1.00
```

Next, information on the linear constraints is printed. As per the numbering scheme given earlier, since there are 44 bounds the first linear constraint has an internal number of 45 and a classification number of 101. This constraint has the form LHS $\leq$ 0.0. Twenty two numbers follow the constraint identification line. Each number corresponds to a variable. The order is set in Block 4. The first linear constraint is a function of the first and fourth variables and is

-140*WNGA + TOWT LE 0.0.

This is evident from the printout. At the time of template development, this information should be very carefully checked.

```
NAME//INT                                                   RHS
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
LIN/ 1/ 45                                             LHS LE 0.0
              -140         0.0          0.0         1.0
              0.0          0.0          0.0         0.0
              0.0          0.0          0.0         0.0
              0.0          0.0          0.0         0.0
              0.0          0.0

****   OUTPUT DELETED TO CONSERVE SPACE
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

The first line contains the constraint identification, the nonlinear constraint function value and the sense of the constraint and the right hand side value. All nonlinear constraints and goals are input as

CVAL (n) $\geq$ 0.0.

If there are any constants on the right hand side these must be taken over to the left. The nonlinear constraint function value is the value of CVAL(.). This is the value that is used to check the feasibility of the solution. A negative value indicates infeasibility. This value will always be less than one and ideally should be positive and close to zero. For a system goal this value will always be zero. The rest of the information, in this block, is for the linearized form of the nonlinear constraint. The linearized fuel weight constraint reads:

$-0.283E-03*WNGA + 0.131E-03*FLTH + 0.664E-05*TOWT - 0.103E-01*WGSP + 0.132E-01*FDIA \geq 0.58290$

The information provided here is invaluable for template development. All the linearized coefficients should be of the same order of magnitude and are generally less than one. If any of the coefficients has a large number compared to the others - it spells trouble - something is definitely wrong in the FORTRAN code or the way the constraint is specified or something has not been initialized. The coefficients also give a sense of what goes up when something goes down - this information if used intelligently can save endless ours of debugging.

```
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
NAME//INT      NL CNSTR VALUE  LINEARIZED COEFFICIENTS          RHS
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
FUWT/101/ 49  -0.36376E-02                           LHS GE 0.58290
               0.283E-03   0.0          0.131E-03    0.664E-05
              -0.103E-01   0.132E-01    0.0          0.0
               0.0         0.0          0.0          0.0
               0.0         0.0          0.0          0.0
               0.0         0.0

****    OUTPUT DELETED TO CONSERVE SPACE
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

## BLOCK 14

This block contains the output for a synthesis cycle. In the following, the output of the final synthesis cycle is described. First the values of the system variables (after modification in keeping with the reduced move limit) are printed. In the final cycle (that has converged) the effect of the move limit is minimal. The CURRENT VALUE OF THE OBJECTIVE FUNCTION represents the sum of the deviation variables. This number, at convergence, should be almost the same as for the preceding one or two cycles. It is important that the variables and the sum of deviation variables is checked for the last few cycles. This is particularly important when the template is being developed or significantly modified. Much can be learned by looking at these results closely.

```
---------------------------------------------------------------------------
SYNTHESIS CYCLE NO.   5 IN PROBLEM NO.   1        *OUTPUT*
VARIABLE  NAME/NUMBER    WNGA  1    ITHR   2      FLTH   3        TOWT   4
                        1700.4      46584.        131.63      0.20581E+06
VARIABLE  NAME/NUMBER    WGSP  5    FDIA   6      D1-    7        D1+    8
                        110.62      13.144        0.70049E-03    0.0
VARIABLE  NAME/NUMBER    D2-    9   D2+   10      D3-   11        D3+   12
                         0.0        1.0938        0.0             0.21365
VARIABLE  NAME/NUMBER    D4-   13   D4+   14      D5-   15        D5+   16
                         0.47708    0.0           0.80650E-01    0.0
VARIABLE  NAME/NUMBER    D6-   17   D6+   18      D7-   19       D7+   20
                         0.96941    0.0           0.10671E-01    0.00
VARIABLE  NAME/NUMBER    D8-   21   D8+   22
                         0.51628    0.0
CURRENT VALUE OF OBJECTIVE FUNCTION =      2.8353
```

**BLOCK 15**

The design is checked at the end of every synthesis cycle. First the values of the system and deviation variables together with their bounds are printed out. This is followed by information on the degree of satisfaction of the linear constraints. The number of the linear constraint corresponds to that printed at the time of input (see Block 8). Next, for the linearized system constraints and goals, information about the LHS, the RHS and their relationship is printed. This is followed by a summary of the active constraints. There is a bug in this part of the output and the active constraints should be determined by looking for the asterisks in the preceding output.

The design obtained will always be feasible with respect to the bounds, linear constraints and the linearized nonlinear constraints. This, however, does not mean that the design is feasible from the standpoint of the nonlinear constraints. Hence, the nonlinear constraint function values are checked for feasibility. If this turns out to be true, then, the message DESIGN IS FEASIBLE is printed out. If the change in each of the variables between two iterations is less than FRAC3 (see Block 6) then the message DESIGN VARIABLES BETWEEN ITERATIONS STATIONARY is printed. The solution process is terminated and post-solution information is processed.

```
NAME/INT.NUM A  VAR. VAL        RHS        NAME/INT.NUM A  VAR. VAL.    RHS
---------------------------------------------------------------------------
     WNGA  1     1698.     GE  1200.       WNGA  2     1698.     LE  2200.
     ITHR  3    0.4672E+05 GE 0.2775E+05   ITHR  4    0.4672E+05 LE 0.55E+5
     FLTH  5     132.8     GE  105.0       FLTH  6     132.8     LE  150.0
     TOWT  7    0.2056E+06 GE 0.1400E+06   TOWT  8    0.2056E+6  LE 0.25E+6
     WGSP  9     110.6     GE  85.00       WGSP 10     110.6     LE  140.0
     FDIA 11     13.15     GE  10.00       FDIA 12     13.15     LE  15.00
     D1-  13 * 0.0000E+00 GE 0.0000E+00   D1-  14    0.0000E+00 LE  2.000
     D1+  15    0.0000E+00 GE 0.0000E+00   D1+  16    0.0000E+00 LE  2.000
     D2-  17    0.0000E+00 GE 0.0000E+00   D2-  18    0.0000E+00 LE  2.000
     D2+  19     1.102     GE 0.0000E+00   D2+  20     1.102     LE  2.000
     D3-  21    0.0000E+00 GE 0.0000E+00   D3-  22    0.0000E+00 LE  2.000
     D3+  23    0.2137     GE 0.0000E+00   D3+  24    0.2137     LE  2.000
     D4-  25    0.4738     GE 0.0000E+00   D4-  26    0.4738     LE  2.000
     D4+  27    0.0000E+00 GE 0.0000E+00   D4+  28    0.0000E+00 LE  2.000
     D5-  29    0.7488E-01 GE 0.0000E+00   D5-  30    0.7488E-01 LE  2.000
     D5+  31    0.0000E+00 GE 0.0000E+00   D5+  32    0.0000E+00 LE  2.000
     D6-  33    0.9908     GE 0.0000E+00   D6-  34    0.9908     LE  2.000
     D6+  35    0.0000E+00 GE 0.0000E+00   D6+  36    0.0000E+00 LE  2.000
     D7-  37 * 0.0000E+00 GE 0.0000E+00   D7-  38    0.0000E+00 LE  2.000
     D7+  39    0.0000E+00 GE 0.0000E+00   D7+  40    0.0000E+00 LE  2.000
     D8-  41    0.4937     GE 0.0000E+00   D8-  42    0.4937     LE  1.000
     D8+  43    0.0000E+00 GE 0.0000E+00   D8+  44    0.0000E+00 LE  1.000
---------------------------------------------------------------------------
NAME/INT.NUM A  LHS.LIN.CON        RHS     NAME/INT.NUM A  LHS.LIN.CON RHS
LIN/  1/ 45   -0.3220E+05 LE 0.0000E+00   LIN/  2/ 46    0.6971E+05 GE 0.0
LIN/  3/ 47 * 0.0000E+00 LE 0.0000E+00    LIN/  4/ 48    0.8877E+05 GE 0.0
---------------------------------------------------------------------------

NAME/INT.NUM A LHS.LINZD.CONSTR RHS NAME/INT.NUM A LHS.LINZD.CONSTR RHS
FUWT/101/ 49  0.831  GE       0.527 THCR/102/ 50  0.495  GE        0.385
SSCG/103/ 51  1.81   GE      -0.874 TOFL/104/ 52  0.338  GE     0.867E-01
WDRL/105/ 53 * -1.17  GE     -1.17  WDRU/106/ 54  1.20   GE         1.03
FUFF/107/ 55 *-0.236E-01 GE-0.236E-01 ASPL/108/ 56 * 0.958  GE      0.958
```

```
ASPU/109/ 57  -0.564  GE     -0.878 THCC/110/ 58  0.521  GE        -0.266
MAPC/111/ 59  -0.600  GE     -5.90  RNGC/112/ 60  -0.369E-01 GE    -0.492
LDFL/113/ 61 * 0.857E-01 EQ 0.857E-01 MAGC/114/ 62 * -1.18   EQ    -1.18
RNGG/115/ 63 *-0.996E-01 EQ-0.996E-01 LOIT/116/ 64 *-0.189   EQ    -0.189
USFL/117/ 65 * 0.231     EQ 0.231     WTMA/118/ 66 * 0.869   EQ     0.869
FUSV/119/ 67 *  2.14     EQ 2.14      ROIG/120/ 68 * 3.67    EQ     3.67
-------------------------------------------------------------------------
ACTIVE CONSTRAINTS
------------------
MINIMUM D1-   13  MINIMUM D7-   37
LIN.CON.  3/ 47
WDRL105/ 53     FUFF107/ 55     ASPL108/ 56     LDFL113/ 61     MAGC114/62
0.26037E-02     0.16394E-02    -0.48584E-03     0.63171E-03    -0.36802E-02

LOIT116/ 64     USFL117/ 65     WTMA118/ 66     FUSV119/ 67
0.31302E-02     0.19700E-02    -0.23156E-01     0.87065E-03
-------------------------------------------------------------------------
DESIGN IS FEASIBLE
..................
DESIGN VARIABLES BETWEEN ITERATIONS STATIONARY
..............................................
```

## BLOCK 14

In this block the best feasible design that can be obtained for the given design parameters is presented. In this particular problem the best aircraft design was obtained in the 5th synthesis cycle.

```
BOEING 727-200:   CASE B, SCENARIO TWO        DEC. 29, 86

ANALYSIS SYNTHESIS CYCLE NUMBER :      1
PROBLEM NO.   1 FINAL FEASIBLE DESIGN - SYNTHESIS CYCLE NO.      5
.........................................................
VARIABLE        VALUE                    VARIABLE      VALUE
........        .....                    ........      .....
  WNGA           1700.4                    ITHR         46584.
  FLTH           131.63                    TOWT        0.20581E+06
  WGSP           110.62                    FDIA         13.144
  D1-           0.70049E-03                D1+         0.00000E+00
  D2-           0.00000E+00                D2+          1.0938
  D3-           0.00000E+00                D3+         0.21365
  D4-           0.47708                    D4+         0.00000E+00
  D5-           0.80650E-01                D5+         0.00000E+00
  D6-           0.96941                    D6+         0.00000E+00
  D7-           0.10671E-01                D7+         0.00000E+00
  D8-           0.51628                    D8+         0.00000E+00
VALUE OF OBJECTIVE FUNCTION    2.8353
```

## BLOCK 15

In this block the slacks corresponding to the inactive bounds and constraints and the dual prices (opportunity costs) corresponding to the active bounds and constraints are presented. Note, the slacks and dual prices are computed for the linearized nonlinear constraints and goals. This, is no longer relevant. It is replaced by [20].

```
BOEING 727-200:   CASE B, SCENARIO TWO        DEC. 29, 86
```

```
SENSITIVITY ANALYSIS
....................
CONSTRAINT    SLACK        DUAL         CONSTRAINT    SLACK        DUAL
                           PRICE                                   PRICE
..........    .....        .....        ..........    .....        .....
BOUNDS
 WNGA  1      498.4        0.0000E+00    WNGA  2      501.6        0.0000E+00
 ITHR  3      0.1897E+05   0.0000E+00    ITHR  4      8277.        0.0000E+00
 FLTH  5      27.84        0.0000E+00    FLTH  6      17.16        0.0000E+00
 TOWT  7      0.6558E+05   0.0000E+00    TOWT  8      0.4442E+05   0.0000E+00
 WGSP  9      25.58        0.0000E+00    WGSP 10      29.42        0.0000E+00
 FDIA 11      3.152        0.0000E+00    FDIA 12      1.848        0.0000E+00
 D1-  13      0.0000E+00  -0.3546E+07    D1-  14      2.000        0.0000E+00
 D1+  15      0.0000E+00   0.0000E+00    D1+  16      2.000        0.0000E+00
 D2-  17      0.0000E+00   0.0000E+00    D2-  18      2.000        0.0000E+00
 D2+  19      1.102        0.0000E+00    D2+  20      0.8982       0.0000E+00
 D3-  21      0.0000E+00   0.0000E+00    D3-  22      2.000        0.0000E+00
 D3+  23      0.2137       0.0000E+00    D3+  24      1.786        0.0000E+00
 D4-  25      0.4738       0.0000E+00    D4-  26      1.526        0.0000E+00
 D4+  27      0.0000E+00   0.0000E+00    D4+  28      2.000        0.0000E+00
 D5-  29      0.7488E-01   0.0000E+00    D5-  30      1.925        0.0000E+00
 D5+  31      0.0000E+00   0.0000E+00    D5+  32      2.000        0.0000E+00
 D6-  33      0.9908       0.0000E+00    D6-  34      1.009        0.0000E+00
 D6+  35      0.0000E+00   0.0000E+00    D6+  36      2.000        0.0000E+00
 D7-  37      0.0000E+00  -0.2965E+10    D7-  38      2.000        0.0000E+00
 D7+  39      0.0000E+00   0.0000E+00    D7+  40      2.000        0.0000E+00
 D8-  41      0.4937       0.0000E+00    D8-  42      0.5063       0.0000E+00
 D8+  43      0.0000E+00   0.0000E+00    D8+  44      1.000        0.0000E+00
LINEAR CONSTRAINTS
LIN/ 1/ 45    0.3220E+05   0.0000E+00    LIN/ 2/ 46   0.6971E+05   0.0
LIN/ 3/ 47    0.0000E+00  -0.1014E-01    LIN/ 4/ 48   0.8877E+05   0.0
NON-LINEAR CONSTRAINTS
     /  4     0.8877E+05   0.0000E+00   FUWT/101     0.3036       0.0000E+00
 THCR/102     0.1100       0.0000E+00    SSCG/103     2.685        0.0000E+00
 TOFL/104     0.2511       0.0000E+00    WDRL/105     0.0000E+00  -0.1190E+07
 WDRU/106     0.1669       0.0000E+00    FUFF/107     0.0000E+00  -0.3375E+07
 ASPL/108     0.0000E+00  -0.4863E+07    ASPU/109     0.3138       0.0000E+00
 THCC/110     0.7864       0.0000E+00    MAPC/111     5.301        0.0000E+00
 RNGC/112     0.4549       0.0000E+00    LDFL/113     0.0000E+00  -0.1272E+06
 MAGC/114     0.0000E+00   740.1         RNGG/115     0.0000E+00   0.3432E+08
 LOIT/116     0.0000E+00  -0.1599E+06    USFL/117     0.0000E+00  -802.6
 WTMA/118     0.0000E+00  -0.8415E+06    FUSV/119     0.0000E+00  -0.4350E+06
```

## BLOCK 16

This block contains the time statistics for execution.

```
DSP OPTIMIZATION STATISTICS:
NUMBER OF ITERATIONS          =     5
NUMBER OF PROBLEM VARIABLES   =    22
NUMBER OF CONSTRAINTS         =    48
                        TIME IN PROTAB   =    0.063 SECONDS
                        TIME IN USAN     =    0.012 SECONDS
                        TIME IN DERIV    =    1.391 SECONDS
                        TIME IN NONTAB   =    0.066 SECONDS
                        TIME IN LINOPT   =    1.020 SECONDS
```

```
                  TIME IN CONVER    =    0.016 SECONDS
                  TIME IN PRINT1    =    6.453 SECONDS
                  TIME IN PRINT2    =    2.629 SECONDS
TOTAL TIME TO OPTIMIZE THIS PROBLEM =   11.648 SECONDS

END ANALYSIS/SYNTHESIS CYCLES NUMBER     1
**************************************************
```

**BLOCK 17**

This block contains the formatted output of results. This block is printed by the subroutine USROUT contained in the aircraft DSP template. USROUT is a user specified routine.

```
              AIRCRAFT DESIGN PARAMETERS
               USING THE COMPROMISE DSP

                       WING AREA =  1700.4 SQ FEET

             WING THICKNESS RATIO =  0.12

                       WING SPAN =  110.6 FEET

               WING ASPECT RATIO =  7.20

               FUSELAGE DIAMETER =  13.14 FEET

                 FUSELAGE LENGTH =  131.63 FEET

                 TAKE-OFF WEIGHT =  205808.9 LBS

                     FUEL WEIGHT =  52207.9 LBS

                  PAYLOAD WEIGHT =   5000.0 LBS

               NUMBER OF ENGINES =  3.00

               INSTALLED THRUST =  46584.4 LBS

             CRUISE MACH NUMBER =  0.80

     REQUIRED THRUST FOR CRUISE =   9999.8 LBS

                   TI/TR RATIO =  4.66

           NUMBER OF PASSENGERS =  188

      MISSED APPROACH GRADIENT = 15.06 %
                               =  8.63 DEGREES

          TAKE-OFF FIELD LENGTH =  4892.0 FEET

           LANDING FIELD LENGTH =  4499.7 FEET

   SECOND SEGMENT CLIMB GRADIENT =  9.93 %
                                =  5.69 DEGREES
```

```
                 CRUISE RANGE =  2913.0 NMI
                       LOITER =  0.02
         USEFUL LOAD FRACTION =  0.46
             WING FORM FACTOR =  1.1647
         FUSELAGE FORM FACTOR =  1.0848
             DYNAMIC PRESSURE =  223.322
             LIFT COEFFICIENT =  0.5420
   ZERO LIFT DRAG COEFFICIENT =  0.0126
 WING DRAG DUE TO LIFT FACTOR =  0.0467
   REYNOLDS NUMBER AT CRUISE = 252509584.
   SKIN FRICTION COEFFICIENT = 0.00188
```

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

AIRCRAFT COST ESTIMATES

| | DEVELOPMENT | PRODUCTION |
|---|---|---|
| ENGINEERING | 171369856.00 | 243873040.00 |
| DEVELOPMENT SUPPORT | 52114724.00 | 0.00 |
| FLIGHT TEST | 24151334.00 | 0.00 |
| TOOLING | 207185296.00 | 282847136.00 |
| MANUFAC. LABOR | 110762704.00 | 1285565952.00 |
| QUALITY CONTROL | 14399151.00 | 167123584.00 |
| MATERIALS | 12637840.00 | 569688384.00 |
| ENGINE | 4433392.50 | 415630592.00 |
| AVIONICS | 738462.00 | 92307752.00 |
| ACTIVE CONTROLS SYSTEM | 507692.63 | 63461576.00 |
| TOTAL | 598300480.00 | 3120498176.00 |

TOTAL COST PER AIRCRAFT = $ 16362715.00

MAINTENANCE OPERATING COSTS

| NO. | SYSTEM | LABOR | MATERIAL |
|---|---|---|---|
| 1 | INSPECTION | 24.39 | 3.96 |
| 2 | AIR CONDIT | 5.10 | 4.52 |
| 3 | AUTO PILOT | 11.19 | 2.62 |
| 4 | COMMUNICAT | 5.19 | 2.22 |
| 5 | ELECTRICAL | 4.31 | 5.75 |
| 6 | FURNISHING | 25.08 | 13.24 |

| | | | |
|---|---|---|---|
| 7 | FIRE PROTE | 9.36 | 1.10 |
| 8 | FLT CONTRL | 7.17 | 4.49 |
| 9 | FUEL | 1.73 | 0.89 |
| 10 | HYDR POWER | 3.33 | 3.95 |
| 11 | ICE | 0.63 | 0.43 |
| 12 | INSTRUMENT | 0.91 | 0.37 |
| 13 | LANDG GEAR | 11.21 | 21.86 |
| 14 | LIGHTING | 3.68 | 2.66 |
| 15 | NAVIGATION | 10.77 | 7.17 |
| 16 | OXYGEN | 1.01 | 1.41 |
| 17 | PNUEMATIC | 0.60 | 2.62 |
| 18 | WATR/WASTE | 1.03 | 1.46 |
| 19 | AIR + APU | 0.31 | 0.46 |
| 20 | STRUCTURES | 3.44 | 0.00 |
| 21 | DOORS | 2.28 | 1.86 |
| 22 | FUSELAGE | 3.54 | 0.58 |
| 23 | NACELLES | 0.67 | 0.28 |
| 24 | WINGS | 2.95 | 0.13 |
| 25 | STABILZERS | 0.83 | 0.37 |
| 26 | WINDOWS | 0.84 | 6.81 |

| | |
|---|---|
| LABOR COST | 56.62 |
| MATERIAL COST | 36.48 |
| ENGINE LABOR COST | 28.49 |
| ENGINE MATERIAL COST | 35.08 |

MAINTENANCE DOC IN 1976 DOLLARS PER HOUR 156.67

DIRECT OPERATING COSTS--DOLLARS/FLIGHT HOUR

| | $/Flt.Hr. | PERCENT % |
|---|---|---|
| DEPRE | 393.74 | 18.33 |
| SUPPORT | 53.69 | 2.50 |
| SPARES | 26.85 | 1.25 |
| DELAY | 10.29 | 0.48 |
| INSURANCE | 62.64 | 2.92 |
| FUEL | 920.47 | 42.85 |
| MAINTENANCE | 156.67 | 7.29 |
| LANDING FEE | 26.50 | 1.23 |
| CREW | 250.92 | 11.68 |
| ATTENDANTS | 153.74 | 7.16 |
| FUEL SERVICE | 77.18 | 3.59 |
| CONTROL | 15.22 | 0.71 |
| TOTAL DIRECT OPERATING COSTS | $ 2147.90 | 100.00 |

INDIRECT OPERATING COSTS--DOLLARS/FLIGHT HOUR

| | $/Flt.Hr. | PERCENT % |
|---|---|---|
| MAIN BURD | 164.51 | 19.32 |
| FOOD COST | 157.66 | 18.52 |
| MOVIE | 36.12 | 4.24 |
| PASS INSUR | 28.87 | 3.39 |
| MISCE PASS | 6.24 | 0.73 |
| ADVERTISE | 93.80 | 11.02 |
| COMMISSION | 130.46 | 15.32 |
| RESERVATON | 83.85 | 9.85 |
| PASSE HDLG | 54.69 | 6.42 |
| BAG HANDLG | 24.97 | 2.93 |
| CARGO HDLG | 60.40 | 7.09 |
| SERVICING | 9.96 | 1.17 |
| TOTAL INDIRECT OPERATING COSTS | 851.53 | 100.00 |

ECONOMIC PERFORMANCE SUMMARY

| | |
|---|---|
| REVENUE PER BLOCK HOUR | 4078.36 |
| TOTAL COST PER BLOCK HOUR | 2999.43 |
| RETURN ON INVESTMENT | 0.0995 |

| | | |
|---|---|---|
| 1 | DOC/HOUR | 2147.900 |
| 2 | DOC/FLIGHT | 14276.588 |
| 3 | ROI | 0.100 |
| 4 | FARE | 0.102 |
| 5 | SEAT-MI/GA | 23.125 |
| 6 | FARE | 30741.000 |
| 7 | PRICE | 20045032.000 |

## BLOCK 18

This block contains a continuation of the time statistics of the DSP design run started in Block 16. Time for design evaluation relates to time spent in a design-analysis routine that is independent of DSIDES (see Figure 2.9). In this case no analysis routines were called. The total time in the computer system was 14 .1 seconds on a VAX 780 computer.

```
ANALYSIS SYNTHESIS CYCLE STATISTICS
DESIGN CYCLE NUMBER                  =      1
TIME TO CREATE MODEL                 =      0.867 SECONDS
TIME FOR DESIGN EVALUATION           =      0.000 SECONDS
TIME TO OPTIMIZE                     =     13.051 SECONDS


SLIP2 STATISTICS
NUMBER OF ANALYSIS SYNTHESIS CYCLES  =      1
NUMBER OF DSPS                       =      1
TIME TO CREATE MODEL                 =      0.867 SECONDS
```

```
TIME FOR DESIGN EVALUATION                      =     0.000 SECONDS
TIME TO OPTIMIZE                                =    13.051 SECONDS
TOTAL TIME FOR EXECUTION                        =    12.516 SECONDS
TOTAL TIME IN SYSTEM                            =    14.090 SECONDS


JOB COMPLETED ON:   29-DEC-86 AT:   13:32:11  HOURS
```

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15. Supplementary Notes

Langley Technical Monitor: Jaroslaw Sobieski

16. Abstract

The Decision Support Problem Technique for unified design, manufacturing and maintenance is being developed at the Systems Design Laboratory at the University of Houston. This involves the development of a domain-independent method (and the associated software) that can be used to process domain-dependent information and thereby provide support for human judgment. In a computer-assisted environment, this support is provided in the form of optimal solutions to Decision Support Problems. In this report the DSP Technique is introduced and the principles underlying the formulation and solution of two types of Decision Support Problems explained. Examples from aircraft design are included as illustrations.

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