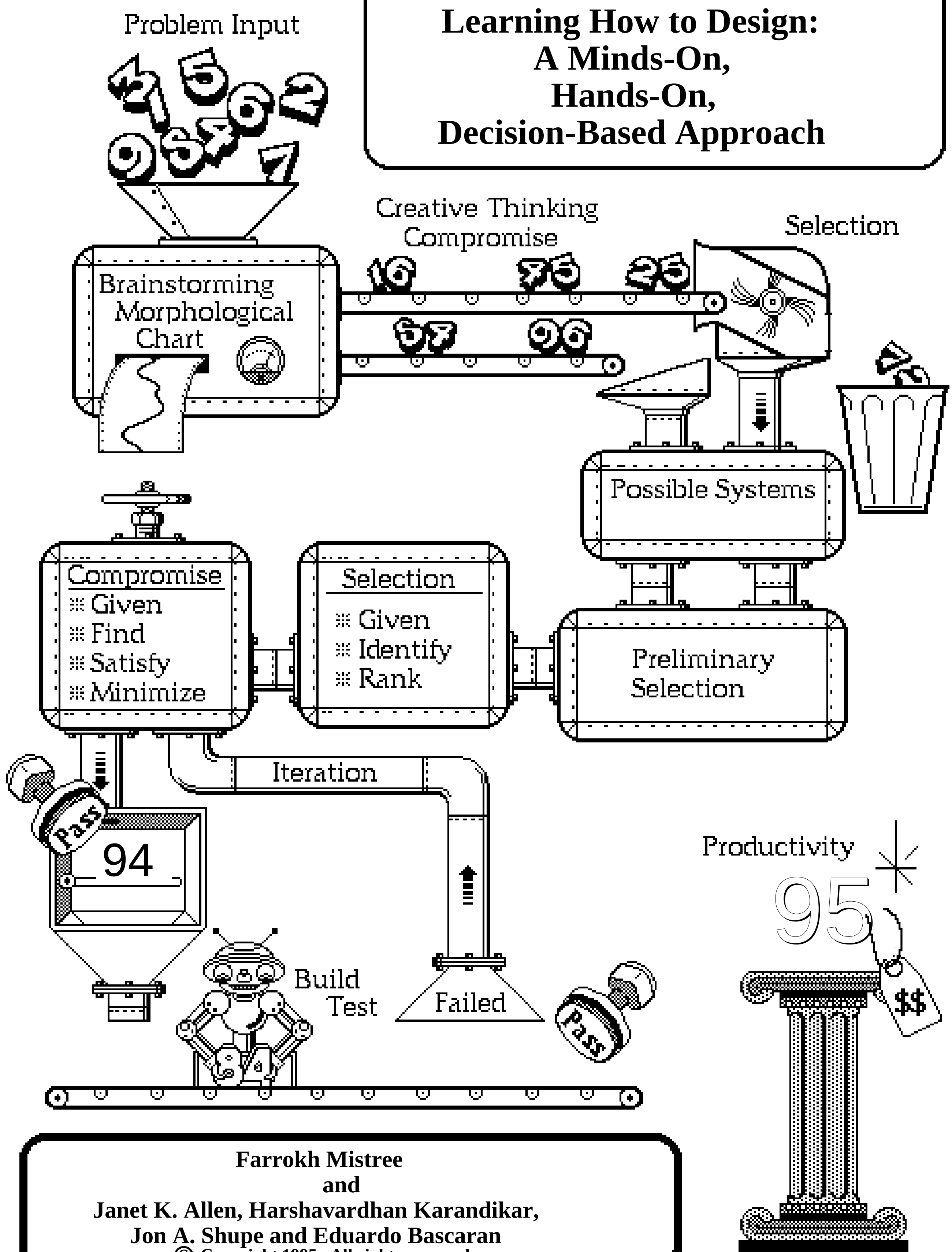
Learning How to Design: A Minds-On, Hands-On, Decision-Based Approach



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WE RECOGNIZE APPLE AS A COMPANY AND MARVEL AT THE REVOLUTION IT HAS WROUGHT. FOR THEIR EQUIPMENT GRANT

T H A N K Y O U

1

On Design and Open Problems

In this chapter we set the stage for our study of design. We define designing as a process of converting information that characterizes the needs and requirements for a product into knowledge about a product. Most real-world design problems cannot be isolated from the environment, usually they are complex. One of the most important aspects of design is identifying what the problem is, see Section 1.3. An introduction to the creative process is presented in Section 1.4.

1.1 What is Design?

Engineering design is in a period of ferment. For more than three centuries, the world view of engineering design has been based on the idea that systems may be designed by reducing them to their components, isolating these components and designing each independently. This is the Newtonian concept of reductionism. However, in the past half century, there has been a virtual revolution. The fundamental reasons for this change are a new emphasis on systems thinking and the pervasive presence of computers.

Systems thinking emphasizes both the system as a single entity and the separate and collective properties of its component subsystems. Further the object being designed is placed in the larger context of the environment in which it will be used.

In the decades since computers became the universal tool of engineers we have observed dramatic changes. We now have computers that can process symbols, words, graphs, and numbers, and they are imbued with the ability to reason. New software and hardware allow us to do things that, even a few years ago, we could contemplate only wishfully.

Designers are on the threshold of being able to use computers not just as tools, but as advisors, critics and, ultimately, as partners in the process of design.

Most futurists agree that we are at the beginning of the Information Age. In this new age, information will be available to designers almost instantly in quantity and quality previously not considered possible. Designers will negotiate the solutions to open problems in conjunction with computers, data-bases and expert systems. They will be involved primarily with the unstructured or partially structured parts of problems, that is, with establishing system goals, partitioning the system in terms of its functional subsystems and planning the design process itself. They will be less involved with the structured part, that is, the design of components, which will be automated.

So what will designers do? Our definition of the term *designing* is as follows:

DESIGNING

Designing is a process of converting information that characterizes the needs and requirements for a product into knowledge about a product.

The term product is used in its most general sense. Not only can specific objects be designed, but processes can also be designed. For example, a designer may design a lawn mower and also design the process by which the design of the lawn mower is to be obtained.

We assert that the principal role of a designer is to make decisions. Decisions help bridge the gap between an idea and reality. The characteristics of design decisions are summarized by the following descriptive sentences:

- Decisions in design are invariably multileveled and multidimensional in nature.
- Decisions involve information that comes from different sources and disciplines.
- Decisions are governed by multiple measures of merit and performance.
- All the information required to arrive at a decision may not be available.

- Some of the information used in arriving at a decision may be hard, that is, based on scientific principles and some information may be soft, that is, based on the designer's judgment and experience.
- The problem for which a decision is being made is invariably loosely defined and open, see Section 1.2. Virtually none of the decisions are characterized by a singular, unique solution. The decisions are less than optimal and are called *satisficing* solutions.

By focusing upon decisions, we have a description of the product development processes written in a common “language” for teams from the various disciplines - a language that can be used in the process of designing. Decisions serve as markers to identify the progression of a design from initiation to implementation to termination. We term this approach Decision-Based Design and our specific implementation of Decision-Based Design is the Decision Support Problem Technique.

1.2 What Is an Open System?

Life-cycle engineering of a system typically covers its realization, its operation, and its maintenance, followed by retirement in an environmentally benign manner. Life-cycle engineering of *open* systems includes the life-cycle of the first generation system, the next generation and so on. Our *working definition* of open engineering systems follows:

> *Open engineering systems are systems of industrial products, services and processes that are capable of indefinite growth and development by both incremental technological advance and major technological change stemming from an existing base.*

An example of an open engineering system is the IBM PC. Several generations of PCs were developed (generations built around the Intel 286, 386 and 486 chips) and variations also occurred within each generation. Other examples of open systems include the Boeing 700 series of airplanes, stereo systems (a juke box is a closed system), and the B52 bomber series.

Engineers have had phenomenal success in solving problems by isolating them from their environments. These artificially isolated systems are called *closed systems*; they are isolated from the real world by a boundary. On the other hand, an *open system* is one in which matter, energy and information may be exchanged with the environment across the boundary. Usually, closed systems - and closed problems - are easier to deal with because they can be defined and completely understood; the unexpected is unusual. Generally closed problems have been tackled using the Newtonian principle of reductionism, that is by breaking them up into smaller and smaller units that may be solved independently and the solution for the entire problem generated from the solutions of the pieces.

An open system - or an open problem - cannot be isolated. Any solution must take into consideration input and output. In general, open problems are more complex than closed ones, in some cases, an answer is not possible. In some cases many answers are possible; it is left to the problem solver to determine which is the “best”. For large scale open problems, it is mathematically impossible to identify an optimum solution. However, it may be possible to identify *satisficing* solutions [2], that is solutions which can be shown to satisfy the requirements specified in the problem statement. Given that the problem solver has a choice of solutions that satisfy the requirements, the problem solver is then left to choose the “best”. For the moment, we merely mention that determining the “best” solution often requires the consideration of many different attributes, e.g., cost, time required, political considerations, etc.

Notice that the solution proposed is very sensitive to the original problem statement. The two questions: How will I pass this course? and How will I get an A? demand different solutions. In some cases, only a partial answer is possible. In other situations, the problem solver may decide to make an experiment of the problem itself or propose a series of steps, for example, I'll do the first three assignments and see what happens, if I don't like the results, then maybe I'll drop the course.

Using a personal computer can enhance your effectiveness in solving open problems for several reasons:

- Most open problems require effective communication - whether among a team of people solving the problem or between a problem solver and people who have posed the problem or those who require a solution. Word processing packages, presentation software, graphics packages, schedulers, etc., enhance effective communication.
- Most open problems require the organization of masses of material - your desk, your office and your mind have finite limits. Schedulers, databases, and on-line libraries can help you organize and prioritize material.
- There are many specific application packages which can help you solve pieces of the problem.

Indeed, we believe that this is an education for the future; computers have made a tremendous change in the way business is done over the last twenty years. Children begin learning about computers sometimes before they start school. It is inevitable that in the future, computation devices will become their partners; and yours, if you are to remain competitive.

1.3 Problem Identification

One of the most important aspects of being able to solve a problem is to understand thoroughly what the problem is, what the constraints are, and what the solution objectives are. It is suggested that when you are presented with a large open problem, you follow a specific sequence of steps.

One such sequence can be implemented in the context of the following building blocks: Story, Technical Brief, Events, Abstracts, Problem Statements, Word Problems, Work Schedule, Mathematical Formulations, Templates, Solution, Validation and Synthesis. A description of each of the terms follows.

> A *Story* is a statement of needs, requirements and specifications, typically defined by a “client”. It may be in lay, rather than technical, terms and may be incomplete and/or may include contradictory statements.
>
> The *Technical Brief* contains information pertaining to the functional requirements, the technical and economic limitations, the technical and economic measures of success and the technical resources available for the entire project. The Technical Brief at the start of the project may be incomplete but it may not include any contradictory statements.
>
> *Events* (for example, feasibility study, conceptual design, etc.) are the entities that are used to model the solution process. Events on a time-line determine the process to be used to achieve the functional (and other) requirements embodied in the Technical Brief.
>
> An *Abstract* contains relevant information from the Technical Brief (for example, the functional and technical requirements) augmented by additional information available at the start of each Event in the design process.
>
> A *Problem Statement* is like an executive summary. A Problem Statement contains information on the type of decisions to be made and a summary of all the information that is needed for making these decisions.
>
> The *Word Problem* is derived from the Problem Statement. It is the link between the problem and a mathematical form that is amenable to a computer solution. The word problem is a “living

document" It has to make connection with both the problem statement and its mathematical form. Remember, a one-to-one correspondence between the word and the math forms is essential.

A *Work Schedule* is developed based on the Word Problem. The schedule is particularly important for engineering problems in which the resources that may be used to solve the problem are limited. For example, is there a hard deadline? Are there enough people available? What about experts? Hardware? Software?

The *Mathematical Formulation* is derived from the Word Problem. It is one of the important links that makes a design problem amenable for numerical solution on a computer. The Problem Statement, Word and Mathematical Formulations are "living documents". They must be consistent and true to the model that is actually being solved.

A *Template* is the implementation of the Mathematical Formulation on a computer.

The *Solution* is the result of implementing the Template on a computer.

Validation is the procedure of checking the Solution by several routes and being sure that a reasonable answer has been obtained. Validation is especially essential for large open problems.

Synthesis involves integrating the solution into a usable package. Post-Solution Sensitivity Analysis may be performed to determine the sensitivity of the solution to changes in the input, constraints or goals.

Do not be concerned if these definitions seem abstract. The rest of this book will guide you in the use of these building blocks.

1.4 An Introduction to the Creative Process

The ability to conceive solutions that never existed is a talent that is unique to the human species. *Creativity* defines the ability to generate an idea or concept. The act of creation may involve the assembly, modification or manipulation of information from experience together with stimuli from human instinct and emotion. The creative part of engineering provides an exhilarating experience. Indeed it is essential through out the design, development, manufacture and delivery of a product or service.

Although a complete understanding of how the human mind functions is not entirely known, there are a number of observations that may provide some understanding of creativity. These are:

- All human beings have the potential to be creative;
- Age and education do not ensure increased creativity;
- Exercise in creative thought does enhance creative ability;
- Barriers to creativity can prevent problem solving;
- Only a few concepts can be maintained in the “active use area” of a human's brain;
- Stress can enhance creative effectiveness.

Each of the preceding is examined in turn.

Studies have shown that a high IQ is not required to think creatively, nor is the creative process the exclusive property of any particular profession, age group, ethnic group, or social class. It is used by engineers, artists, architects, teachers, entertainers, writers and a host of other individuals.

Creative ability is not guaranteed by either increased age or education. Indeed, there is evidence to indicate that education may, in fact, contribute to the formation of barriers to creativity. Some people seem to be capable of more creative output than others because some persons have a larger base of experience upon which to base their problem solving. It is well known that chronological age alone does not guarantee either knowledge or wisdom. Similarly, age does not bestow the ability to create upon an individual. Indeed, some of the most creative activity is carried out by young children at play.

The ability to be creative can be significantly enhanced by practice in much the same way that physical exercise improves muscle tone. Thus, practice with clever thought problems and simple creativity exercises can frequently sharpen creative abilities. Many people who are regarded as highly creative are often found to be persons who enjoy solving puzzles, riddles and abstract problems.

Barriers to creative thought can severely limit effectiveness of designers. The primary reason that children are so creative is that they are uninhibited in their thinking and are not influenced by past experiences that tend to inhibit older people. Fortunately, it has been shown that a better understanding of the nature of these barriers can often help the designer to overcome this limitation to creative thought.

The human mind can store a vast amount of information in its subconscious storage area but only a few concepts, at a particular moment, in the active use area. It is for this reason that conceptual models in the form of equations, pictures, sketches, words, and objects are frequently used to augment and organize the creative process. Some of the techniques presented, provide organizational assistance in the "idea management" portion of the creative process.

It is believed that a modest amount of physiological stress enhances our effectiveness at creativity. Unfortunately, too much stress has a severely negative effect on creative output. Thus it is important, in a work environment, to provide just the right amounts of motivation and challenge for optimum creative effort.

Let us now examine the different types of barriers that inhibit creativity, keeping in mind that a better understanding of these can lead to a greater utilization of our basic ability to be creative.

1.4.1 Limitations and Barriers to Creative Thought

The limitations and barriers that we place on ourselves in creative activity can stifle the basic mental process that is necessary for effective design. These limitations are built through a variety of mechanisms and can be classified as either intellectual barriers, emotional barriers or social and cultural barriers. An excellent text in this regard has been written by Adams [3]. We describe each in turn.

Intellectual Barriers. Intellectual barriers to creative thought stem from either experience directly attributable to the problem at hand or from perceptions that are based on experiences that are not directly related to the problem. Both the practical experiences we have had in life and the knowledge we have learned through our formal education can contribute to intellectual barriers.

The human mind cannot maintain a large number of solution ideas in the active use area at any given time. Thus a single solution sometimes dominates the mind to the extent that no other useful ideas can emerge. One good way to overcome this barrier is to document your initial solution fully (so that it will not be lost to later use) and then force yourself to look for other alternatives. Some designers prefer to leave the problem solving environment and return later when they have had sufficient time to forget the original solution.

Emotional Barriers. Basically the emotional barriers to creative thought come from the fears that are ingrained in our lives to enable us to avoid hurt or disappointment in other domains of our existence. For example we fear having someone laugh at us and our ideas. Thus we are reluctant to expose our creative ideas to the criticism of our peers or our superiors.

We are taught that fantasy and reflection are a waste of time, and yet these are the very tools that creativity depends on for success.

As engineers and professionals we are taught that reason, logic, numbers and utility are good while feeling, intuition, qualitative judgments and pleasure are bad. Yet these human qualities are quite useful in the creative process. In our educational system we are taught that problem solving is serious business and that humor is out of place. Yet a playful, humorous environment is often very conducive to creative thought.

Social and Cultural Barriers. Cultural blocks and taboos are acquired by exposure to a given set of cultural patterns. These rules and norms of behavior help us to live in harmony within our social setting. Unfortunately, cultural blocks and taboos remove entire families of solutions from our consideration. At times we tend to think that such blocks are only present in other peoples lives and not our own.

Often our society rewards conformity. Yet the most creative persons are usually the nonconformists who are willing to make changes from the status quo. If we are to create an environment in which creativity is to thrive, we must provide a situation in which the creators of ideas are not persecuted, ridiculed or laughed at for their efforts.

1.4.2 Methods for Concept Generation

Ideation is the mental process of stimulating one's imagination to produce concepts and ideas to solve the problem at hand. Ideation has been variously termed as “applied imagination” [4], “morphological creativity” [5] and “synectics” [6]. Adams [3] deals with idea generation (conceptual blockbusting) in general. It is excellent and must be read!

Impulse ideation refers to a sudden generation of ideas triggered as a result of a serendipitous happening or one that occurred during the course of daily routines. The most difficult and useful creative activity is demand ideation - generating ideas to solve a particular situation of no previous interest. The technique is the crux of engineering design. Most problems that are posed are not amenable to the demand ideation process because of a lack of knowledge of the problem. Creative persons, however, know how to divide the problem in ways that will stimulate their imagination. This approach can be taught.

In the concept generation phase, the feasibility of concepts generated is of least consequence. The principal aim in using the ideation techniques is to generate as many functional concepts as possible. Then, using the process of *selection* the best alternative for further development is identified.

There are several different demand ideation techniques that are very effective idea stimulators. These methods can be used individually and that is the way they are described in this section.

Brainstorming. Brainstorming is probably the best known of all methods for concept generation. Brainstorming is based on the premise that the more concepts one generates as a solution to a given problem, the more likely it is that one of those concepts will lead to a good solution. Brainstorming is usually done by a group of people but the method can be used, with limited success, by an individual. The basic rules of brainstorming are as follows.

1 A group of persons is assembled for the brainstorming session. These people should be conversant with the field of the problem but should not necessarily be experts. The group can be as large as ten and as few as three. Larger groups tend to be difficult to manage.
2 A person defines the problem and states the goals of the session. Typically, many themes will emerge and the group may follow each one for a brief period. A moderator records the themes that are emerging from the session. The moderator also documents every concept that is offered, no matter how wild or unlikely the solution may seem at first. If the process is getting bogged down, the moderator throws in a theme that had emerged, showed potential but was not fully developed. In this way the moderator provides stimulus and direction to the session. On hearing the theme proposed by the moderator the participants focus on the words briefly and then try to develop the theme further.
3 The session should be conducted in a light, humorous atmosphere with everyone encouraged to offer ideas, with the moderator providing the group with new directions when necessary.
4 No ideas are judged in the idea generation phase. In this way the fear of ridicule is mitigated. This guideline is extremely important, and failure to maintain this environment will severely limit the success of the session. Participants are encouraged to offer as many ideas as they can think of, and may combine or modify the ideas of their fellow group members.
5 The session proceeds until the group begins to tire or until a predetermined stopping time has been reached. This will usually be

about 30 or 40 minutes since longer sessions can be exhausting if the concept generation is at all lively. Next, the group is adjourned for a time to engage in some other, mind clearing activity. This break time may be for only a few minutes or may be as much as several days.

6 Then the group is reconvened for the evaluation phase. Anyone with additional ideas that have been generated during the break time is allowed to add them to the group's list of ideas. Once this step is complete, the group proceeds to structure the information that is available. This involves careful evaluation of each of the ideas on the list. In going back over this list, it may happen that many of the ideas that were originally offered in fun have a great deal of potential whereas others that seemed to have great merit when they were first proposed, are of little worth. The reason for separating the evaluation phase from the idea generation phase is to dilute the feeling of “ownership” of ideas and thus focus criticism on the concept instead of the person who generated the initial concept.

The result of brainstorming is that a large number of concepts are generated. However, there is no way to ensure that all the pertinent facets or characteristics of the problem are considered. Also, there is no particular organization to the concepts generated. Although the group can evaluate the concepts, the best they can be expected to do at this time is to eliminate completely infeasible ideas.

Attribute Listing. The attribute listing technique involves the listing of the characteristics, qualities, or parameters of a material, device or problem area. This technique is used to identify the essential characteristics of the problem or those of the desired solution. The principal objective of attribute listing is to identify and clarify the essential characteristics of the problem and its desired solution. If done comprehensively, the entire scope of the problem is covered and thus one has a good idea of what issues must be dealt with in generating concepts. However, in this method, no concepts are actually generated.

Attribute listing is done by an individual. Different people will interpret a problem differently and will come up with different lists of attributes. Whatever the specific content of the resulting list of attributes, the process through which it is developed helps the mind focus on the basic problem and stimulates creative solutions.

Checklisting. Checklisting involves the use of a check-list of questions designed to jog the thought process about a particular problem solution. Such thought provoking questions often lead the problem solver to look deeper into the implications of the problem and frequently generate new ideas of value to the creation process. For example, the need to design a device to stop a rotating spool on a wire rope manufacturing machine might be satisfied by using an automobile disk brake. This solution is not immediately apparent but could result from considering the second question that has been listed earlier. In this case, the stopping mechanism is essentially an off-the-shelf item thereby reducing the cost.

The effect of checklisting is to make the designer aware of the issues involved in the problem at hand. Like attribute listing, use of checklisting can help ensure that all the aspects of the problem are dealt with. However, no concepts are generated here; one must turn to either brainstorming or morphological charts to generate the actual concepts.

Morphological Chart Method. The morphological chart method is another means of stimulating imagination to generate concepts. It involves the development of a list of independent parameters or characteristics associated with the problem. Each of these parameters is considered independently for possible alternative solutions. All are tabulated in a matrix that can be cross correlated to produce many different combinations as solutions to the problem.

A typical morphological chart is shown in Figure 1.1.

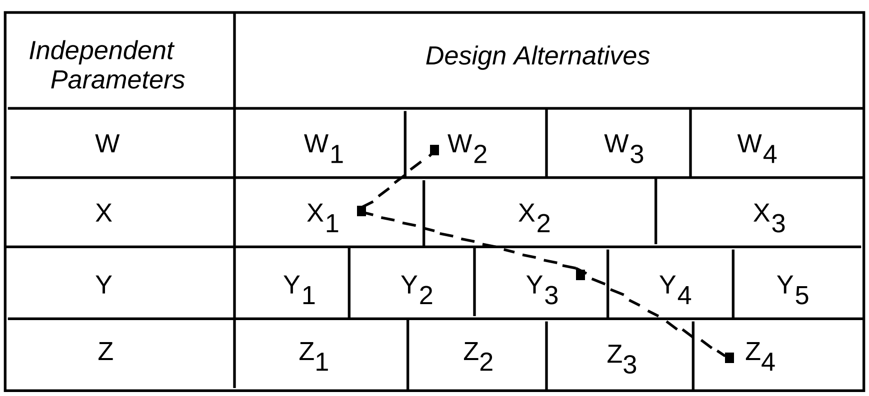


Figure 1.1. A typical morphological chart

Care should be exercised that the alternatives listed represent different concepts that serve the same purpose and are not variations of the same basic concept. In the example that follows "engines" is one of the independent parameters and the concepts associated with it are: piston, gas turbine, turbo fan and tandem fan. Each of the concepts is unique. It would have been inappropriate to list as alternative concepts, e.g., five piston engines of different makes and different thrust ratings, because these would represent variations of one basic concept, namely, piston engines. The chart permits a comparison of different characteristics that might not otherwise be associated. The morphological chart method is a very powerful organizational technique for identifying a large number of solution alternatives in a short time.

Synectics. The method of synectics, also known as Gordon's method, is based on the use of analogies or the comparison of characteristics about a solution idea. For example, consider the similarity between a hedge trimmer and an electric shaver. Such a comparison may provide considerable insight into the design of a new type of hedge trimmer. In this method, an attempt is made to provide different viewpoints into the concept generation environment. Another approach to using synectics is to look for similarities between two objects that are vastly different. For example a comparison between the operation of a family and a computer network bus structure might give considerable insight into information flow and hierarchy concerns for the design of a new type of computer network.

Synectics, like attribute listing and checklisting, is useful in better understanding the problem at hand, and thus better delineating it. It also allows the designer, using analogies, to go beyond his or her sphere of experience and generate truly innovative concepts.

1.4.3 The Thought Process

Another view of the process of creative thought has been developed by DeBono [7, 8] whose view is that:

> *Thinking is an operating skill with which intelligence acts upon experience (for a purpose).*

Consider a car and a driver. The car has a powerful engine, a smooth gear box and a wonderful suspension. The skill of the driver is something different. In no way does the power of the car ensure the skill of the driver. In this analogy the engineering of the car corresponds to innate intelligence and the driving skill of the driver corresponds to the operating skill we call thinking. It is often the case that a more humble car has a better driver. Driving skill can also be learned, practiced and improved.

Processing and Perception:

Excellence in processing does not make up for inadequacies of perception, [9]:

Perception is the way we look at things. *Processing* is what we do with that perception.

Fallacies:

- It does not matter where you start (i.e., your perception) because if your thinking is good enough you will reach the right answer.
- From within the situation, by further processing, you can tell where you ought to have started.
- Traditional perception is enough because it has evolved through trial and error over time.

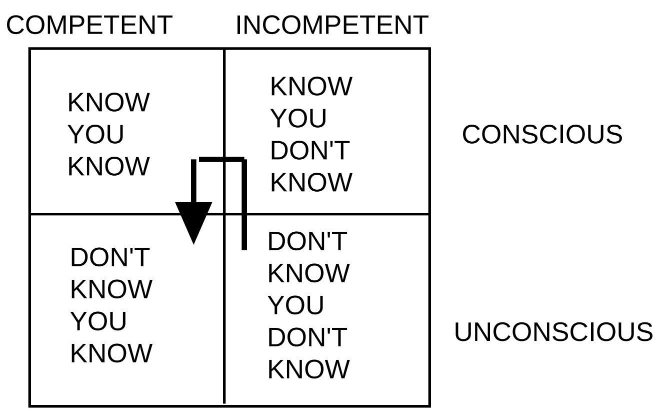


Figure 1.2. From unconscious incompetence in problem solving to unconscious competence [9]

Learning to tie our shoe laces:

Unconscious and incompetent: There is a certain time in our life when we do not know how to tie our shoe laces but are unaware of it.

Conscious and incompetent: We then reach a stage when we become aware that we do not know how to tie them.

Conscious and competent: We then learn how to tie them.

Unconscious and competent: Finally, tying our shoe laces becomes a habit. We know how to tie them but do not need to think about it.

Ramifications of learning: Learning requires that we first move from the lower right corner to the upper right; we become conscious of what we do not know. Moving from the upper right to the upper left and then to the lower left is familiar to us (classes, training, lessons) and fun if we are good at learning. We end up back in highly unconscious territory.

Coping with rapid change in technology: Living with the lower left is rewarding if we are blessed with good problem solving habits. However, to cope with change we must return to the upper right to begin the cycle again. We have to move from habit to an awareness of our ignorance.

Can we move from habit to an awareness of our ignorance? You can tie your shoe laces *unconsciously*. Can you learn a new way to tie them *unconsciously?* Difficult if not impossible. Can you learn a *new* way *consciously?* Ah ha - maybe there is hope.

Question: What are the ramifications of these observations on your approach to problem solving and this course?

Habit and Problem Solving [7]:

- Clasp your hands in front of you and look at them. Notice which thumb is on top. Unclasp them and reclasp them so that your other thumb is on the top. Notice anything?
- Fold you hands across your chest. Notice that one of your wrists is on top. Unfold them and refold them so that the other wrist is on top. What happened?

These are simple physical habits but they do remind us that we are programmed, at least physically in our daily lives. They further show that through conscious effort, a desire to do something differently, and instructions as to what we want to accomplish we can modify our habits. Our first attempts seem awkward, even wrong. However, with reinforcement we can learn new programs.

Habit is not only beneficial but also necessary to life as we know it. If we consider physical habits, our conscious abilities are simply not rapid enough to control our bodies say when we play tennis. Similarly habits allow us to solve intellectual problems much more rapidly than if we had to rely completely on consciousness.

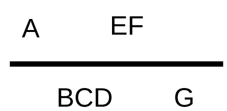
In some situations, habits do not serve us well. They certainly stand in opposition to change and our ability to cope with change. By its very nature, change, whether initiated from within ("I have made it in my field and I am ready to move on.") or from without ("The Japanese are increasing their emphasis on personal computer production.") requires reorientation of habit.

Adaptive Action Learning. Confucius is quoted as having said,

> Tell me and I will forget,
> Show me, and I will remember,
> Let me do it and I will understand.

A Satisficer and an Optimizer. In one of his early works, Herbert Simon characterized a *satisficer* as one who stopped looking through a haystack when he found the needle. An *optimizer*, on the other hand, would take the whole haystack apart looking for all possible needles to be able to pick the sharpest one. Obviously life does not allow us time to disassemble completely all the haystacks we encounter. However, this is pertinent to problem solving. Our natural behavior may often lead us to less than the sharpest needle.

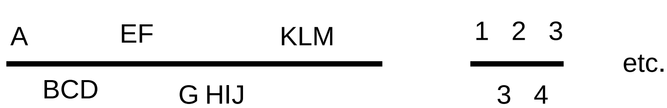
What is your Natural Behavior to Problem Solving? How would you place the remaining letters of the alphabet above and below the line to make some sense to you? Can you identify other ways? What are they?

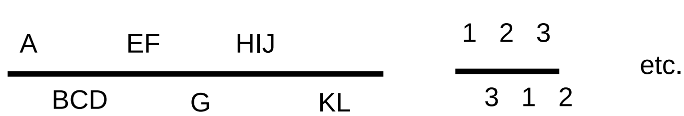


The Human Mind and Satisficing. The mind does not compulsively continue to unearth additional options. It sacrifices concepts to reach a speedy solution. People reach an answer in a short time and then satisfice.

Some examples:

A Group size





B Letter shapes

- Letters with curved lines below; letters without curved lines above.

- Letters with crossbars above; letters without crossbars below.
- Letters below can be formed without lifting a pencil from the paper; letters above cannot.

C Sound

- Top letters are soft; bottom letters are hard.
- Top letters would take the article *an;* bottom letters would take *a*.
- Top letters begin with a vowel sound.

What are your reactions to these? Can you guess why you react the way you do? The answer probably has to do with the fact that you did not think of them. If you satisficed are you now less satisfied?

How did you arrive at the answer(s) you chose? How much of the process was conscious? unconscious? Did your answers "occur" to you? Your mind may have relied upon its familiar mix of conscious and unconscious activity. It acted habitually. By now, you are hopefully convinced that problem solving is influenced by habit - that you are programmed to a considerable degree in your thinking.

Questions: In what ways does Decision-Based Design conflict with your natural predisposition (habit) to problem solving? Why? How do you plan to resolve these differences in the context of this class?

Differences Between Lateral and Vertical Thinking [7]. Lateral thinking and vertical thinking are complementary. One needs skill in both types of thinking.

1. Vertical thinking is SELECTIVE; lateral thinking is GENERATIVE. Rightness matters in vertical thinking. Richness matters in lateral thinking. Generate alternatives for the sake of generating them in lateral thinking. Select the best approach in vertical thinking.
2. Vertical thinking moves ONLY if there is a direction in which to move. Lateral thinking moves in order to generate a direction.
3. Vertical thinking is analytical. Lateral thinking is provocative. To be able to use the provocative qualities of lateral thinking one must also be able to follow up with selective qualities of vertical thinking.
4. Vertical thinking is sequential. Lateral thinking makes jumps.
5. With vertical thinking one has to be correct at every step. With lateral thinking this is not the case.
6. In vertical thinking one uses the negative to block up certain pathways. In lateral thinking there is no negative.

7 In vertical thinking one excludes what is irrelevant. In lateral thinking one welcomes chance intrusions.
8 In vertical thinking categories, classifications and labels are fixed. In lateral thinking they are not. In lateral thinking classification and categories are signposts to help movement rather than fixed pigeon holes to aid identification.
9 Vertical thinking follows the most likely path; lateral thinking explores the least likely.
10 Vertical thinking is a finite process. Lateral thinking is probabilistic. Vertical thinking provides at least a minimum solution. Lateral thinking increases the chance of a maximum solution but makes no promises.
11 In vertical thinking information is used for its own sake to move forward to a solution. In lateral thinking, information is used provocatively to bring about repatterning.

The Basic Nature of Lateral Thinking

1 Lateral thinking is concerned with changing patterns. By pattern we mean the arrangement of information on the memory surface of the mind. A pattern is a repeatable sequence of neural activity.
2 In a self-maximizing system with a memory the arrangement of information must always be less than the best possible arrangement. The rearrangement of information into another pattern is insight restructuring. The purpose of the rearrangement is to find a better and more effective pattern.
3 Lateral thinking is both an attitude and a method for using information.
4 Lateral thinking is never judgment. In lateral thinking information is used not for its own sake but for its effect: one is not interested in the reasons that lead to and justify the use of a piece of information but the effects that might follow such a use. The way of using information is to look forward. In lateral thinking, information is used to alter the structure but not to become part of it.
5 Lateral thinking is directly related to the information handling system of the mind.

1.5 Some Examples of Open Problems

The real world abounds with open problems: How will I pass this course? Get an A? Get a job? What kind of a car should I buy? How can we improve the transit system? Most engineering problems you will be presented with are open problems.

Most design problems start as an ill-defined collection of functional requirements and human needs, e.g., we need a way for cars to go from the university to the city ..., or we need an engineering building ..., or we need a faster computer ..., etc. Successively the problem is identified, resources that are available to help with the solution are identified, the problem is broken up into modules, a solution strategy is chosen and refined.

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SUPPLEMENTARY NOTES 1

DESIGNING FOR SUCCESS IN ME 3110: A CONCEPTUAL EXPOSITION[1]

Farrokh Mistree

My role and this paper I want to foster learning using the paradigms of *adaptive action learning* and *decision-based design.* The design, build and test project is not the end all and be all of this course; learning is. I view my role as that of an orchestrator; one who orchestrates your learning. I believe that I am responsible for providing an opportunity for you *to learn how to learn* - preferably in an atmosphere that is fun for all concerned!

I started development on a course similar to ME3110 at the University of Houston in 1981. Fall 1992, however, was the first time I taught ME 3110 at Georgia Tech. Based on the feedback and my own observations about the course I have decided to put this document together. It is a modified version of a paper titled: *Designing for Concept using Decision Support Problems: A Conceptual Exposition.* I wrote this paper for a short course that I gave at the University of Tennessee and at the Indian Institute of Technology, Delhi in 1988. The references therefore are dated. I have particularized this paper for ME 3110.

Where am I coming from? In the future, information that is useful in designing will be available almost instantly in quantity and quality heretofore not possible. Designers will negotiate solutions to open problems in a computer environment that is characterized by user-friendly desk-top computers networked to much larger machines - machines with the capability to process symbols (words, pictures, numbers, logic) - and extensive data-banks. I assert that the principal role of an engineer in this computer environment is to make decisions associated with the design and manufacture of an artifact.

I believe that design is an *intellectual cognitive decision-based activity.* I also believe that there is no substitute for *human intuition and tinkering* in design. For you, your time is your most precious

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[1] This paper is a modification of a paper titled *Designing for Concept: A Conceptual Exposition* that appeared in the Proceedings of the First International Applied Mechanical Systems Conference (IAMSDC-1) with Tutorial Workshops, Nashville, Tennessee, June 11-14, 1989.

commodity. Once spent you can never retrieve it. I therefore want you to spend it wisely. So? It takes all types to make this world. Some of you will be turned on by the intellectual cognitive approach to design and others by the tinkering approach. There is room in this world for the both categories of designers. However, I believe that to be time-effective one must be comfortable with both approaches and use them at the right time. So? Use this experience to figure out who you are and then go about deliberately experiencing the other.

And finally a few words of advice. Keep coming back to this paper. You will not be able to absorb it all in one sitting. I am not giving you a recipe - but some guidelines. Do not follow these guidelines blindly. Use them wisely, augment them and most importantly think of the consequences before you ignore them. Remember that you still need to read the text!

1. Decision-Based Design and the Decision Support Problem Technique: An Introduction

Decision-Based Design is a new term coined to emphasize a different perspective from which to develop methods for design [1]. In the context of Decision-Based Design we assert that the principal role of an engineer is to make decisions associated with the design of an artifact or product. This seemingly limited role ascribed to engineers is useful to provide a starting point for developing design methods based on paradigms that spring from the perspective of decisions made by designers (who may use computers) as opposed to design that is assisted by the use of computers, optimization methods (computer-aided design optimization) or methods that evolve from specific analysis tools such as finite element analysis.

The implementation of Decision-Based Design can take many forms. A comprehensive approach called the **D**ecision **S**upport **P**roblem (DSP) Technique [2,3,4] is being developed and implemented to provide support for human judgment in designing an artifact that can be manufactured and maintained. 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. In our view, the primary function of the DSP Technique is to catalyze action by a designer and, in the process, to provide a rationale for the thought processes stimulated by the formalism of the Technique's structure. By itself, the Technique does nothing. It has no life of its own; it is not autonomous. It enhances and takes on the intellect of the person using it --- like a chameleon changing color in a new environment. In the context of the DSP Technique design, manufacture and maintenance have a specific meaning, namely,

- **designing -** a process of converting information that characterizes the needs and requirements for a product into knowledge about a prototype of the product,
- **manufacturing** - a process in which the knowledge about a selected prototypical version of the product is converted into replicates of the product, and
- **maintaining -** a process in which information that characterizes the performance of a product in terms of its function and its effects on its environment is monitored and analyzed in order to maximize the performance/cost ratio (thereby enhancing customer satisfaction), and to gain knowledge for design modifications (thereby increasing industrial competitiveness).

Decision Support Problems provide a means for modeling decisions encountered in design, manufacture and maintenance as defined above. Multiple objectives that are quantified using analysis-based "hard" and insight-based "soft" information can be modeled in the DSPs. For real-world, practical systems, all of the information for modeling systems comprehensively and correctly in the early stages of the project, will not be available. Therefore, the solution to the problem, even if it is obtained using optimization techniques, cannot be the optimum with respect to the real world. However, this solution can be used to support a designer's quest for a superior solution. In a computer-assisted environment this support is provided in the form of optimal solutions for Decision Support Problems. 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 among several feasible alternatives [5,6].
- **Compromise -** the improvement of a feasible alternative through modification [6-11].
- **Hierarchical -** decisions that involve interaction between sub-decisions [12,13].
- **Conditional -** decisions in which the risk and uncertainty of the outcome are taken into account [14].

We believe that 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.* Further, it is safe to assume that because of the complexity of the product (an engineering system) the conversion of information into knowledge will have to be accomplished in stages. In the traditional design process names have been given to the stages such as feasibility, conceptual, preliminary and detail. The names and the number of stages, from the standpoint of the information necessary for making decisions in each of the stages, are not important. What is important is that:

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

Our current efforts are focused on understanding what is needed and developing the tools to support human decision making in the early stage of a project. We assert that it is possible based on the ratio of available hard-to-soft information at any time to define the process of design in terms of **events**, for example, designing for concept, designing for manufacture, economic viability, preliminary synthesis, detailed analysis, and the like. We also believe that using this ratio it is possible to categorize computer-based aids for design into categories, for example, tools that provide support for the decision making activities of a human designer and tools that facilitate design automation. These concepts are illustrated in Figure 1.

In designing for concept we seek to cast as wide a net as practicable to generate many concepts and then systematically home-in on a concept that meets the functional specifications and can be produced and maintained. In other words, in designing for concept we are involved in the process of converting information that characterizes the needs and requirements for a product into specific knowledge that can be used in designing for manufacture. In designing for manufacture we attempt to ensure that the product can be manufactured cost-effectively. Of course, we recognize that in practice iteration between events will occur and, for convenience, this has not been shown in Figure 1.

A scenario of the process accomplishing Conceptual Design through Detailed Analysis (see Figure 1) is shown in Figure 2. This is one of many schemes that could be postulated. Let us assume that we are involved in original design and that this process is underway. Let us assume that the economic viability of the project has been established, the go-ahead for the next event (conceptual design) has been received in the form of a problem statement. We are indeed ready to start with the conceptual design of the artifact. The first task in this event is ideation, that is, the generation of alternative ways (concepts) of achieving the objectives embodied in the problem statement. Ideally, a large number of concepts should be generated. Techniques that foster ideation include brainstorming, attribute listing, check listing, synectics, etc. The end-product of ideation will be a number of concepts. At this stage information on these concepts will be limited and most of it will be soft.

How can we identify the best concept? This is a three-step process:

- In the first step we use the available soft information to identify the more promising "most-likely-to-succeed" concepts. This is accomplished by formulating and solving a preliminary selection DSP.
- Next, we establish the functional feasibility of these most-likely-to-succeed concepts and develop them into candidate alternatives. The process of development includes engineering analysis and design; it is aimed at increasing the amount of hard information that can be used to characterize the suitability of the alternative for selection. At the end of this step the ratio R is higher than that at the start of this step.
- In the third step we select candidate alternative for further development. This is accomplished by formulating and solving a selection DSP. The selection DSP has been designed to utilize both the hard and the soft information that is available.

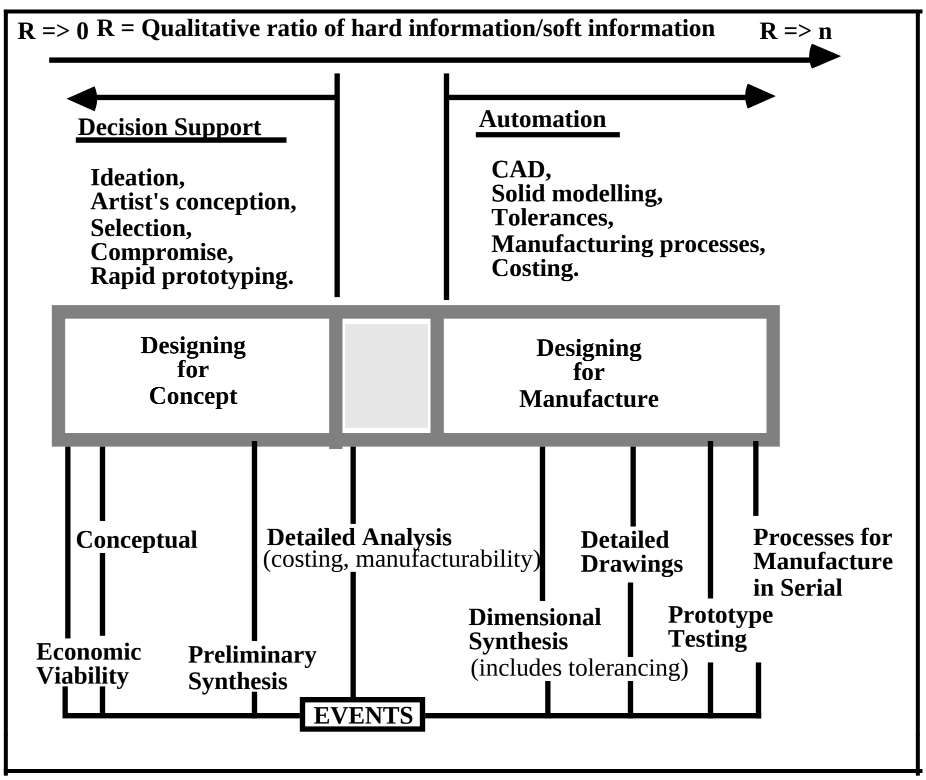

Figure SN1.1. An Example Of Designing For Concept And Designing For Manufacture

Event: Conceptual Design

Ideation (Using ideation techniques generate many concepts.)

Recognize need. Analyze need. Record first impressions.

Decision

Select the *Most-Likely-To-Succeed* concepts.

Formulate and solve a Preliminary Selection DSP.

Critically evaluate the selection.

Engineering

Establish *Functional Feasibility* of the Most-Likely-To Succeed concepts in the context of *Essential Requirements*.. Convert concepts to candidate alternatives.

Decision

Select one candidate alternative for development.

Formulate and solve a Selection DSP.

Critically evaluate the selection.

Engineering

Establish the *Cost-effectiveness and Manufacturability* of the chosen alternative. Critically evaluate the selection.

Event: Preliminary Synthesis

Decision

Improve the *Functional Effectiveness* of selected alternative through modification.

Formulate and solve a Compromise DSP.

Establish and accept a satisficing design.

Event: Detailed Analysis

Engineering

Based on information provided in Preliminary Synthesis test the *Functional Feasibility* of the selected alternative in the context of a *Comprehensive set of Requirements*, and develop information on costs and manufacturing.

Decision

Improve, through modification, the *Functional* and *Cost-effectiveness* of the design.

Refine the Compromise DSP by including information on costs and manufacturability.

Solve the Compromise DSP.

Establish and accept an improved design.

Proceed to the Dimensional Synthesis Event

Figure SN1.2. Designing For Concept: An Idealization

Of course we can repeat any of the preceding steps. Let us assume that we are satisfied with the alternative that we have identified. We develop this alternative further into a feasible alternative (thereby increasing the value of the ratio R). This development results in a feasible alternative, that is, one that satisfies the functional requirements, is probably cost-effective and can be manufactured. We do, at this stage, have a "feel" for the overall dimensions of the artifact but no knowledge of the precise dimensions. Let us assume that we are satisfied with the feasibility of the alternative and are ready to proceed to the next event, namely, Preliminary Synthesis.

In Preliminary Synthesis the alternative is improved through the modification of its dimensions and this is achieved via the formulation and solution of a compromise DSP. The "feel" we had for the dimensions earlier can now be replaced by numbers. We are now ready to undertake the next event, namely, Detailed Analysis. There is sufficient information about the artifact at the start of Detailed Analysis to ensure functional feasibility and estimate cost-effectiveness and the manufacturability of the artifact. Detailed Analysis could include stress analysis using finite element methods, simulation and the like. We are now in a position to ensure the functional feasibility of a design that is cost-effective and manufacturable. This is accomplished by augmenting the formulation of the compromise DSP used for Preliminary Synthesis through the inclusion of economic and manufacturability considerations. The end-product of Preliminary Synthesis is the preliminary design of an artifact. Of course, the value of the ratio R has increased and upon analysis we are ready for the next event, namely, Designing for Manufacture.

Iteration is always a part of designing. Iteration takes time and is therefore costly. We "plan" to avoid unnecessary iteration. We can reduce the cost of iteration by developing the means for rapidly redesigning. In the DSP Technique rapid redesign is facilitated by the DSPs being available for modification and resolution. Costs can also be reduced by having clearly defined points from which the redesign can proceed. In the DSP Technique these points are the clearly defined events. In the process just enunciated the numerical value of the ratio R clearly increases and the definition of the solution matures as the solution matures.

2 *Designing For Success In ME3110*

In Figure 3, we have outlined a possible scheme for you to follow in designing, building and testing your system. It is by no means complete. There are two important items missing, namely, meta-design and the TQM Management and Planning tools. It is of paramount importance for you to learn how to design design processes - plan in other words. This is the theme of Design Report II. During your professional careers you will see many changes in the way design is done. Design has been practiced by human beings for a long time (some say from the time of Hammurabi). It is only in the past decade or so do we see design emerging as a science-based discipline. This will undoubtedly influence the way in which design is practiced. Our work pertains to the conceptual / preliminary decision-based design of engineering systems. Our papers published fall into the following categories:

- Designing processes
- Modeling uncertainty in the early stages of project initiation.
- Developing concepts in original and adaptive design.
- Modeling concurrency in conceptual design.
- Understanding the interaction between design and manufacture in conceptual design.
- Selection in conceptual design.
- Compromise in conceptual / preliminary design
- Design pedagogy.

A comprehensive summary of our work is presented in:

F. Mistree, D. Muster, S Srinivasan and S. Mudali, *Design of Linkages: A Conceptual Exercise in Designing for Concept*, Mechanism and Machine Theory, Special Issue on "Theories of Design - Application to the Design of Machines", Vol. 25 No. 3, 1990.

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Event: Form Team

Event: Write the Technical Brief

Establish the Comprehensive Set of Requirements

- Identify the functions the system as a whole has to perform. Identify constraints on system performance.
- Identify the constraints on system realization.
- Identify how the performance will be evaluated.
- Identify the resources at your disposal.
- Identify what impact these resources have on your design and its realization.

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

Establish the Essential set of Requirements

Identify the rationale you will use to partition the system.

Partition the system into subsystems.

- Clearly describe the function of each subsystem.
- Identify and describe the characteristics of the interfaces between subsystems.
- Identify the constraints on system performance.
- Identify the constraints on system realization.
- Identify how the performance will be evaluated.
- Identify the resources at your disposal.
- Identify what impact these resources have on your design and its realization.
- Identify who is going to do what and who is responsible for what.

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

Event: Conceptual Design

Ideation

For each subsystem

- Using ideation techniques generate many concepts.
  - Recognize need.
  - Analyze need.
  - Record first impressions.
- Perform a PMI on each concept. Are the concepts truly different or just a variation on a theme? Classify concepts and tabulate.
- Revisit interfaces and manufacturability from both a subsystem and system perspective.

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

DESIGN REPORT I.

Decision

For each subsystem

- Select the *Most-Likely-To-Succeed* concepts.
  - Formulate and solve a Preliminary Selection DSP.

Critically evaluate the selection.

Engineering: Convert Concepts into Candidate Alternatives

Establish *Functional Feasibility* of the Most-Likely-To Succeed concepts in the context of *Essential Requirements*.

Revisit interfaces and manufacturability from both a subsystem and system perspective.

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

Decision

For each subsystem

Select a one candidate alternative for development.

Formulate and solve a <u>Selection</u> DSP.

Critically evaluate the selection.

Engineering

For each subsystem

Establish the *Cost-effectiveness and Manufacturability* of the chosen alternative from a subsystem & system perspective.

Critically evaluate the selection.

Revisit interfaces and manufacturability from both a subsystem and system perspective.

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

DESIGN REPORT III

Event: Preliminary Synthesis & Testing

System Configuration

Configure the system using the recommended subsystems.

Does it meet the Essential Requirements? Is it realizable?

What are the modifications needed to make this system work?

Can you substitute another subsystem design?

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

DESIGN REPORT IV

Decision

Improve the *Functional Effectiveness* of selected alternative through modification.

Formulate and solve a <u>Compromise</u> DSP.

Establish and accept a satisficing design.

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

Testing

Improve the *Functional Effectiveness* of selected alternative through testing.

Revisit interfaces and manufacturability from both a subsystem and system perspective.

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

DESIGN REPORT V

Event: Detailed Analysis, Construction & Competition

Detailed Analysis

Based on information provided in Preliminary Synthesis test the *Functional Feasibility* of the system in the context of a *Comprehensive set of Requirements*, and develop information on what is needed, costs and manufacturing.

Plan

Who is going to do what in what time frame and with what resources?

What is the test schedule?

Look downstream. Have you gotten it right for what is to follow? If not, iterate.

Construct and Test System.

- Build and test subsystems.
- Construct system.
- Test system in workshop.
- Test system under competition conditions.

Look downstream. Have you gotten it right for what is to follow? If not, it is probably too late.

Event: Project Turn-in

- Working Project
- Sales Brochure
- Sanitized Log

Event: Learning

- Critical Evaluation: What have I learned?
- Final Exam

Figure SN1.3. Designing For Success: An Idealization

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2

Decision-Based Design and the Decision Support Problem Technique

Assume that the problem has been identified, using the methods discussed in Chapter 1, then we are ready to solve it. We particularize our discussion of general problem solving to design problems and define our approach as Decision-Based Design in which the process of design is characterized by decisions that are made. We describe different types of decisions in terms of the Decision Support Problem (DSP) Technique which incorporates selection, compromise, coupled, conditional and heuristic DSPs. We discuss the implementation of the Decision Support Problem Technique that involves the process of meta-design: "designing the process of design" and design itself. As an aid for meta-design, we propose the DSPT Palette.

2.1 Decision-Based Design

Let us particularize our discussion of problem solving and look at one specific type of problem solving - design in the early stages of project development. First we need to recognize that a designer has at least two problems:

- ❑ What is the best solution to the design problem?
- ❑ What is the best way of obtaining the solution to the problem, that is, what is the best *process of design*?

Our formal definition for the term *design* is given in [1, 2]:

DESIGNING

Designing is a process of converting information that characterizes the needs and requirements for a product into knowledge about a product.

In this definition, we use the term product in its most general sense; it includes processes as well. This definition of design follows from Simon's [3] definition of a designer as anyone who affects or changes the state of things. Three different types of design, namely, original, adaptive and variant [1] have been identified. The distinction is made based on the amount of originality required.

- *Original Design* - an original solution principle is determined for a desired system and used to create the design of a product. The design specification for the system may require the same, similar or a new task altogether.
- *Adaptive Design* - an original design is adapted to different conditions or tasks; thus, the solution principle remains the same but the product will be sufficiently different so that it can meet the changed tasks that have been specified.
- *Variant Design* - the size and/or arrangement of parts or subsystems of the chosen system are varied. The desired tasks and solution principle are not changed.

The design process classification as original, adaptive or variant depends greatly on the perspective chosen. The application of steam power to shipping which occurred during the Industrial Revolution generated original design principles for providing waterborne transportation. Clearly, this represented a step-function in the development of design solutions for naval vessels. Since then, the steam ship concept has been improved vastly by adaptive and variant design.

The major issues facing a designer are different, in original, adaptive and variant design, because the amount and type of design knowledge and information available at the start of the design process is different. In original design, solution principles are of paramount importance, for adaptive design, specified tasks assume major importance, and for variant design, size and/or general arrangement issues must occupy the designer. In adaptive design, the new tasks specified are the major focus, the solution principle remains the same and is therefore of no concern and the size and/or arrangements remain to be determined and are open issues.

Decision-Based Design is a term coined to emphasize a different perspective from which to develop methods for design [1, 4]. This seemingly limited role ascribed to engineers provides a useful starting point for the development of design methods based on paradigms. These paradigms are based on decisions made by designers (who may use computers) rather than design which is assisted by computers, for example, optimization methods (computer-aided design optimization) or methods that have evolved from specific analysis tools, e.g., finite element analysis. While the decisions can be based on many things and may have wide ranging repercussions, it is the decisions themselves that mark the progression of a design from initiation to implementation to termination. They bridge the gap between imagination and service, between an idea and reality. They lock the whole together and they represent the central principles on which the design depends. They are a unit of communication and they have domain dependent and domain independent features.

Some principal observations and beliefs from a Decision-Based Design perspective are as follows:

- The principal role of an engineer or designer is to make decisions.
- 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 by using analysis, visualization and synthesis in complimentary roles. Productivity can also be increased by augmenting the recognized capability of computers in processing numerical information to include the processing of symbols (for example, graphs, pictures, drawings, words) and reasoning (for example, list processing in artificial intelligence).
- Life-cycle considerations that affect design can be modeled in design as information and knowledge.
- Symbols are processed to support human decisions, for example,
  - Analog/signals,
  - Numeric information,
  - Graphic information, and
  - Textual information.
- A technique that supports human decision making, ideally,
  - Must be process-based and discipline-independent,
  - Must be suitable for solving open problems that are characteristic of a uncertain environment, and
  - Must facilitate self-learning.

The characteristics of decisions are governed by the characteristics associated with the design of real-life engineering systems. These characteristics are summarized by the following descriptive sentences:

- Decisions in design are invariably multileveled and multidimensional in nature.
- Decisions involve information that comes from different sources and disciplines.
- Decisions are governed by multiple measures of merit and performance.
- All the information required to arrive at a decision may not be available.
- Some of the information used in arriving at a decision may be hard, that is, based on scientific principles and some information may be soft, that is, based in the designer's judgment and experience.
- The problem for which a decision is being made is invariably loosely defined and open. Virtually none of the decisions are characterized by a singular, unique solution. The decisions are less than optimal and are called satisficing solutions.
- Design is the process of converting information that characterizes the needs and requirements of a system into knowledge about the system itself. In Decision-Based Design it is the making of decisions that causes the transformation of information into knowledge.

By focusing upon decisions, we have a description of the processes written in a common language for teams from the various disciplines - a language that can be used throughout the process of design.

2.2 The Decision Support Problem Technique

The implementation of Decision-Based Design can take different forms. In mechanical engineering, there is an increasing awareness that decisions could be the key element in the development of design methods which facilitate design for the life cycle and foster concurrency in the process, for example, Suh [5], Whitney et al. [6] and Finger et al. [7]. Our approach is called the Decision Support Problem (DSP) Technique [8]. It is being developed and implemented, at Georgia Tech, to provide support for human judgment in designing systems that can be manufactured and maintained. The DSP Technique consists of three principal components: a design philosophy, an approach for identifying and formulating Decision Support Problems (DSPs), and the software.

The DSP Technique is being developed to effect the different types of design previously discussed, namely, original, adaptive and variant. In so doing, the DSP Technique involves the use of a *domain-independent method* to process *domain-dependent information* thereby providing support for human judgment in designing for the life cycle of a product. The DSP Technique and the DSPT Workbook [9] provide the means of partitioning a problem into Decision Support Problems. Partitioning makes it possible to negotiate a satisficing solution and, at the same time, formulate the problem so that its model is a sufficiently adequate approximation of the real world so that the solution yields useful results. The DSP Technique requires that a designer implement two phases, namely, the meta-design phase and computer-based design phase. Meta-design is accomplished through *partitioning* a problem and then devising a *plan* of action. Support for human judgment in a computer-assisted environment is provided in the form of a Partitioner, a Scheduler, a Reporting utility and other utilities by means of which a designer can formulate and solve Decision Support Problems [10].

2.2.1 Decision Support Problems

Decision Support Problems provide a means for modeling decisions encountered in design. Multiple objectives, quantified using analysis-based "hard" and insight-based "soft" information, can be modeled in the DSPs. For real-world, practical systems, in the early stages of design, all the information for modeling systems comprehensively and correctly may not be available. Therefore, the solution to the problem, even if it is obtained using optimization techniques, cannot be optimum with respect to the real world. However, this solution can be used to support a designer's quest for a superior solution. In a computer-assisted environment this support is provided in the form of optimal solutions for Decision Support Problems. 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 among several feasible alternatives [11, 12].
- *Compromise* - the improvement of a feasible alternative through modification [13-16].
- *Coupled or hierarchical* - decisions that are linked together - selection/selection, compromise/compromise and selection/ compomise decisions may be coupled [17-20].
- *Conditional* - decisions in which the risk and uncertainty of the outcome are taken into account [21].

- *Heuristic* - decisions made on the basis of a knowledge base of facts and rules of thumb; DSPs that are solved using reasoning and logic only.

2.2.2 *Events, Designing for Concept and Designing for Manufacture*

In Decision-Based Design the principal role of the design process is to convert information that characterizes the needs and requirements for a product into knowledge about the product itself. For an engineering system this conversion of information into knowledge is invariably accomplished in stages. In the traditional design process names have been given to the stages such as feasibility, conceptual, preliminary and detail.

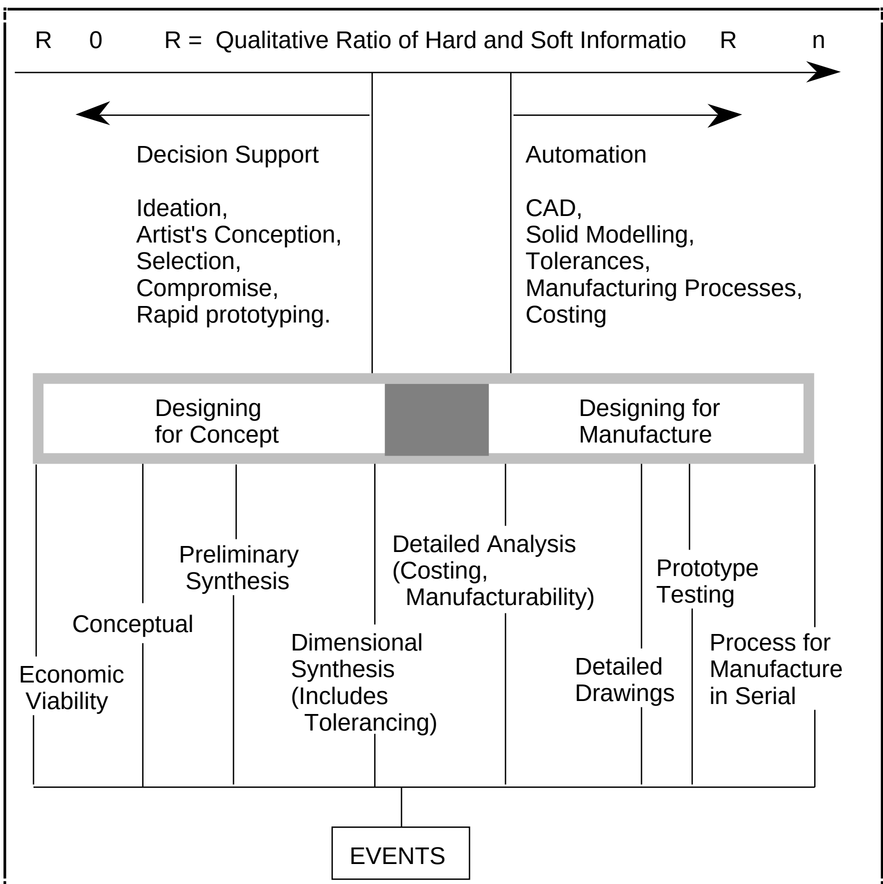

Figure 2.1. An example of designing for concept and designing for manufacture

From the standpoint of the information necessary for making decisions in each of the stages the names and the number of stages are not important. What is important is that:

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

Therefore, in the Decision Support Problem Technique the ratio of hard to soft information at any time in the process is a key factor in determining the nature of the support that a human designer needs to negotiate a solution.

Our current efforts are focused on understanding what is needed and developing the tools to support human decision making in the early stage of a project. We assert that based on the ratio of hard-to-soft information available at any time the process of design may be described in terms of *events*, for example, designing for concept, designing for manufacture, economic viability, preliminary synthesis, detailed analysis, etc. We also believe that using this ratio it is possible to categorize computer-based aids for design into categories, for example, tools that provide support the decision making activities of a human designer and tools that facilitate design automation.

In designing for concept we seek to cast as wide a net as practicable to generate many concepts and then systematically home-in on a concept that meets its functional specifications and can be produced and maintained. In other words, in designing for concept we are involved in the process of converting information that characterizes the needs and requirements for a product into specific knowledge that can be used in designing for manufacture. In designing for manufacture we attempt to ensure that the product can be manufactured cost-effectively. Of course, we recognize that in practice iteration between events will occur and, for convenience, this has not been shown in Figure 2.1.

A scenario of the process accomplishing Conceptual Design through Detailed Analysis (see Figure 2.1) is shown in Figure 2.2. This is one of many schemes that could be postulated.

Let us assume that we are involved in original design and that this process is underway. Let us assume that the economic viability of the project has been established, the go-ahead for the next event (conceptual design) has been received in the form of a problem statement. We are indeed ready to start with the conceptual design of the artifact. The first task in this event is ideation, that is, the generation of alternative ways (concepts) of achieving the objectives embodied in the problem statement. Ideally, a large number of concepts should be generated. Techniques that foster ideation include brainstorming, attribute listing, check listing, synectics, etc. The end-product of ideation will be a number of concepts. At this stage information on these concepts will be limited and most of it will be soft.

Event: Conceptual Design
Ideation
Recognize need.
Analyze need.
Record first impressions.
Using ideation techniques generate many concepts.
Decision
Select "Most-Likely-To-Succeed" concepts.
Formulate and solve a Preliminary Selection DSP.
Critically evaluate the decision.
Engineering
Establish functional feasibility of Most-Likely-To Succeed concepts.
Convert concepts to candidate alternatives.
Decision
Select one candidate alternative for development.
Formulate and solve a *Selection* DSP.
Critically evaluate the decision.
Engineering
Evaluate cost-effectiveness and manufacturability.
Develop one the candidate alternative into a feasible alternative.
Proceed to any of the previous events or to Preliminary Synthesis
Event: Preliminary Synthesis
Decision
Preliminary synthesis.
Improve alternatives through modification.
Formulate and solve a *Compromise* DSP.
Critically evaluate the decision.
Proceed to any of the previous events or to Detailed Analysis
Event: Detailed Analysis
Engineering
Based on information provided in preliminary synthesis check functional feasibility, develop information on costs and manufacturing.
Decision
Refine Compromise DSP; include information on costs and manufacturability into Compromise DSP.
Solve Compromise DSP.
Critically evaluate the decision.
Proceed to any of the previous events or to Designing for Manufacture

Figure 2.2. Designing for concept: an idealization

How can we identify the best concept? This is a three-step process:

- In the first step we use the available soft information to identify the more promising "most-likely-to-succeed" concepts. This is accomplished by formulating and solving a preliminary selection DSP.
- Next, we establish the functional feasibility of these most-likely-to-succeed concepts and develop them into candidate alternatives. The process of development includes engineering analysis and design; it is aimed at increasing the amount of hard information that can be used to characterize the suitability of the alternative for selection. At the end of this step the ratio R is higher than that at the start of this step.
- In the third step we select one (or at most two) candidate alternative for further development. This is accomplished by formulating and solving a selection DSP. The selection DSP has been designed to use both the hard and the soft information that is available.

Of course we can repeat any of the preceding steps. Let us assume that we are satisfied with the alternative that we have identified. We develop this alternative further into a feasible alternative (thereby increasing the value of the ratio R). This development results in a feasible alternative, that is, one that satisfies the functional requirements, is probably cost-effective and can be manufactured. We do, at this stage, have a feel for the overall dimensions of the artifact but no knowledge of the precise dimensions. Let us assume that we are satisfied with the feasibility of the alternative and are ready to proceed to the next event, namely, Preliminary Synthesis.

In Preliminary Synthesis the alternative is improved through the modification of its dimensions and this is achieved through the formulation and solution of a compromise DSP. The feel we had for the dimensions earlier can now be replaced by numbers. We are now ready to undertake the next event, namely, Detailed Analysis.

There is sufficient information about the artifact at the start of Detailed Analysis to ensure functional feasibility and estimate cost-effectiveness and the manufacturability of the artifact. Detailed Analysis could include stress analysis using finite element methods, simulation, etc. We are now able to ensure the functional feasibility of a design that is cost-effective and manufacturable. This is accomplished by augmenting the formulation of the compromise DSP used for Preliminary Synthesis through the inclusion of economic and manufacturability considerations. The end-product of Preliminary Synthesis is the preliminary design of an artifact. Of course, the value of the ratio R has increased and upon analysis we are ready for the next event, namely, Designing for Manufacture.

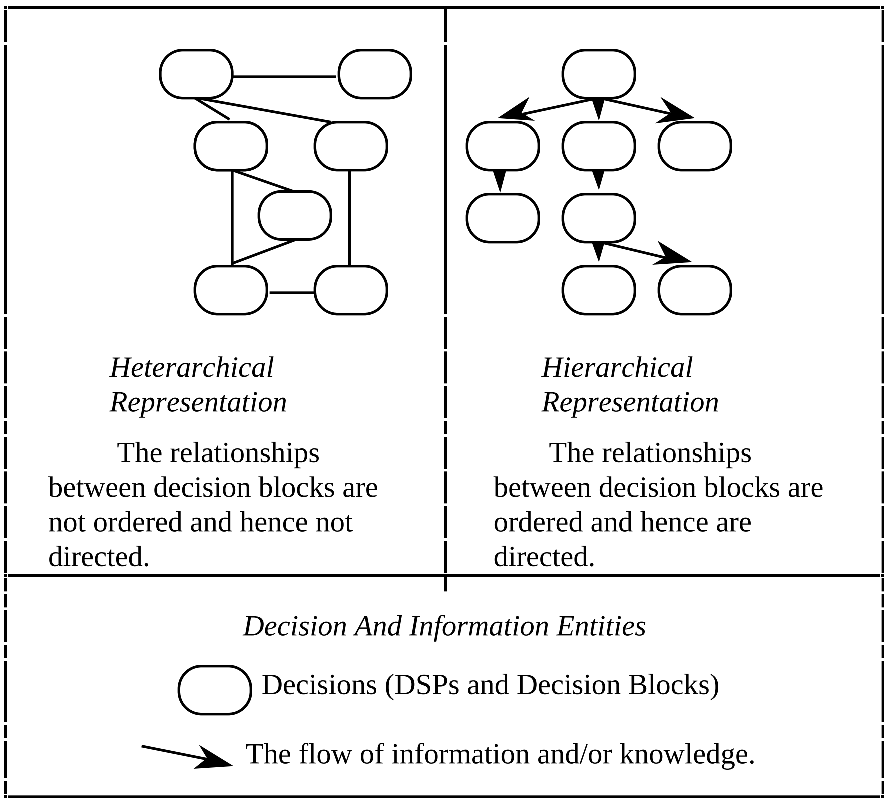

Figure 2.3. Heterarchical and hierarchical representations in Decision-Based Design

Iteration is always a part of designing. Iteration takes time and is therefore costly. We plan to avoid unnecessary iteration. We can reduce the cost of iteration by developing the means for rapidly redesigning. In the DSP Technique rapid redesign is facilitated by the DSPs being available for modification and resolution. Costs can also be reduced by having clearly defined points from which the redesign can proceed. In the DSP Technique these points are the clearly defined events. In the process just enunciated the numerical value of the ratio R clearly increases and the definition of the solution matures as the solution matures.

2.2.3 Heterarchy and Hierarchy in Design: When Do We Start to Design?

Design has as its content a heterarchical set of constructs[1] that embody a designer's perception of the design environment of the real world. The heterarchical constructs associated with a product's life-cycle are the product's market, the product (the design must meet or exceed the criteria related to the product's function, meeting its market, its capability for being manufactured in serial and, when it reaches its market, that it be free of unreasonable dangers), its manufacture (tooling and assembly), its maintenance and its subsequent retirement. A portion of the heterarchical set of constructs for a product's life-cycle is shown in Figure 2.3. In a heterarchical representation, relationships between the constructs are not ordered and therefore are not directed. Decision-Based Design also has as its content a heterarchical set of constructs. A heterarchical set of constructs in this case, however, embodies decisions or sets of decisions that characterize a designer's perception of the decisions involved in effecting a design. A hierarchical set of constructs, on the other hand, characterizes the process or sequence involved in effecting design. Heterarchical and hierarchical representations in Decision-Based Design are drawn using decision and information entities.

When does design start? We assert that design starts when the first step is taken to extract a hierarchy from a heterarchy.

2.2.4 Implementation of the Decision Support Problem Technique

The Decision Support Problem Technique: Two Phases

The Decision Support Problem Technique embraces two types of design, namely, *meta-design* and *computer-based design:*

1 *Meta-design:* Meta-design is composed of two principal parts, partitioning and planning. Partitioning is the process by means of which a designer defines and divides a problem, using a generic discipline-independent modeling technique. Planning is the process by means of which a designer organizes the expertise of individuals and the information and knowledge that resides in computer-available databases.

2 *Computer-based Design:* In computer-based design, discipline-independent processes are used to facilitate the generation of

[1] A construct - a complex idea resulting from a synthesis of simpler ideas.

domain-dependent information and knowledge that are needed to negotiate satisficing solutions to problems.

The organization of the Decision Support Problem Technique is described in the next section.

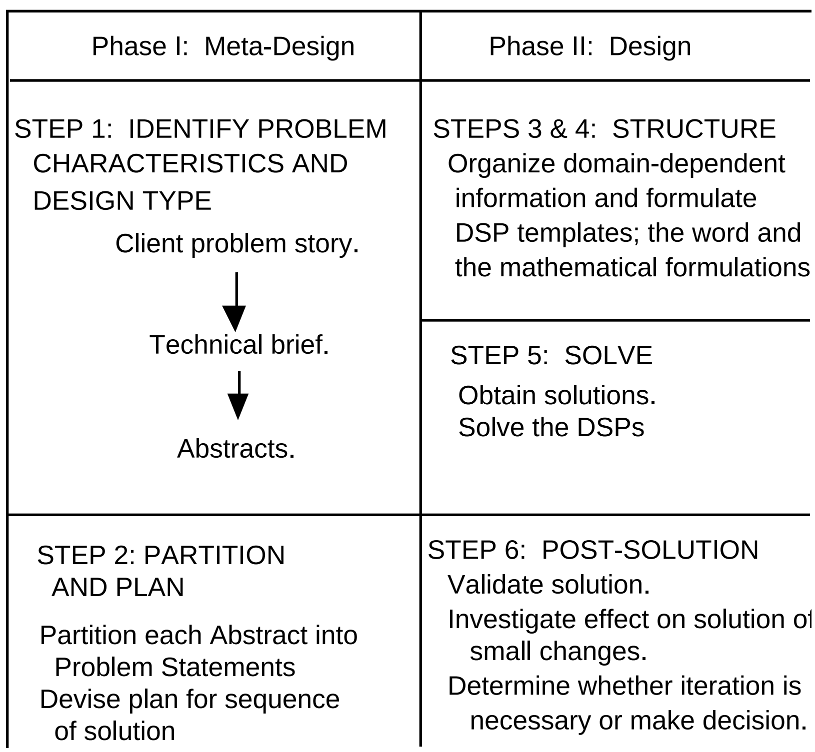

Figure 2.4. The Decision Support Problem Technique

The Decision Support Problem Technique: Organization

The organization of the DSP Technique is shown in Figure 2.4. It consists of two phases which are accomplished consecutively. In the first phase, at the metalevel, the design process itself is designed. The decisions themselves are not made in meta-design; rather, the decisions that need to be made are identified and are then placed in a decision plan. The decisions in the decision plan are needed to convert information that characterizes the needs and requirements for a product into knowledge about a prototype of a product that can be manufactured and maintained. The plan is created with the knowledge of what will be needed in implementing a designer's tasks and on the knowledge gained from meta-design, the design organization and its resources, the time scale and the anticipated costs. In the second phase, at the domain-dependent level of the system being designed, the first-phase process is implemented. The process that results from the first phase is particularized to the requirements of the design process in the second phase and the needs, intuition and skills of the designer who will implement it. In both phases the designer is an interactive partner, not simply an initiator of a sequence of automated processes.

So when does design start? We assert that design starts when the first step is taken to extract a hierarchy from a heterarchy. We assert that design starts when the first step is taken to extract a hierarchical set representative of a Decision-Based Design process to effect the design of a specific engineering artifact (system). In a sense, the hierarchical set of constructs takes on a life directed towards effecting the design of a particular engineering system. The human designer through his/her interactive role in the design process brings dynamism to the chosen set. Design (and problem solving) starts at the same instant.

Decision Support Problem Technique: Steps

The first two steps deal with meta-design whereas the rest deal with design. These steps are valid for any event in the design process and can be implemented at any level within that event. In the following the steps are explained in the context of the design of a mechanical system.

Given: A story.

Step 1: Identify the Problem Characteristics and the Design Type.

- ❑ Identify the components of the heterarchy embodied in a client's problem story. This is done by writing a Technical Brief for the story.
- ❑ Based on the information provided in the Technical Brief identify the Events and graphically display them on a time-line.
- ❑ For each Event write an Abstract.

Step 2: Partition and Plan. The transition from the Abstract to a set of Problem Statements is an unstructured process for which success depends entirely on the judgment exercised by the designer. The principal aim of this step is to characterize the design problem identified in the Abstract in terms of a set of Problem Statements. Two types of partitioning are involved, namely, the partitioning of an artifact into subsystems and the partitioning of the process of design into decisions and organizing them into a Decision Plan.

Step 2a. Partition the artifact into subsystems. Consider, for example, the Event of Conceptual Design. The Abstract for this Event will include a description of the functional requirements and associated tasks, the technical and economic limitations, the technical and economic measures of success and the technical resources (which includes information about similar products). In this case we would proceed as follows:

- ❑ Identify the subsystems. This is accomplished by partitioning the functional requirements (identified in the abstract) for the system into tasks to be performed by each of the subsystems.
- ❑ For each subsystem, establish the type of design involved (that is, original, adaptive, variant). Specifically, determine whether your effort will be directed towards
  - ❑ The design of a device or component that satisfies certain specifications, or
  - ❑ The modification of an existing design in order to satisfy a revised set of specifications, or
  - ❑ The modification of a design to simplify and improve it.

  This analysis should help you identify the type of design involved.
- ❑ Identify the tasks each subsystem has to perform and identify the interactions.
- ❑ On a figure, show the artifact to be designed in terms of its subsystems. On this figure, for each subsystem identify the type of design, the functional requirements and the interactions between the subsystems.

Step 2b. Partition the design process into decisions. Identify the decisions that need to be made so that each subsystem can perform its allocated tasks. Pose questions for these decisions and categorize them as follows:

- ❑ Those that should be answered through analysis,
- ❑ Those that are not technical in character,
- ❑ Those that require experience-based judgment, and
- ❑ Those that involve synthesis and therefore require the formulation and solution of decision support problems.

This constitutes partitioning the design process into decisions.

Step 2c. Write the Problem Statements. Now write the Problem Statements[2] for the questions involving synthesis (selection and compromise in our case). Be sure to include, in your Problem Statements, issues that form the interfaces between Events, between levels within an Event and between Decision Support Problems. When read together, these statements should represent a self-contained, complete, accurate and non-contradictory version of the Abstract. The Abstracts, when read together, should represent a self-contained, complete and accurate version of the Technical Brief.

Step 2d. Develop the Decision Plan. The development of a Decision Plan is an important step. Organize all decisions into a Decision Plan and incorporate this plan into a Work Schedule.

Step 2e. Create a Work Schedule. The Work Schedule differs from the Decision Plan in that the Work Schedule includes all the activities that are associated with the successful implementation of the Decision Plan and completion of the project.

Step 3. Structure the DSPs. Analyze all the Problem Statements. Partition the Problem Statements into three categories that are qualified by the following sentences:

- ❑ A decision can be made using the information provided in the Problem Statement. Proceed to Step 5.
- ❑ Further information is necessary but the decision does not involve synthesis.
- ❑ It is necessary and appropriate for DSPs to be formulated and solved before a decision can be made.

Selection and compromise DSPs are representative of the third category. Structure the Problem Statements associated with these DSPs by rewriting the Problem Statement as a Word Problem. For selection, compromise and coupled DSPs structuring involves the restatement of Problem Statements as Word Problems using key-words:

For Preliminary Selection: Given, Identify, Capture and Rank,

---

2 Writing the Problem Statements is a way of partitioning an Abstract and identifying the technical decisions that need to be made in order to perform the set of tasks identified in the Abstract. Each Problem Statement should be so written that it leads to a formulation of a single DSP. The Problem Statements may overlap each other in some respect. This overlap is normal; it indicates shared variables. The design activity described by the various Problem Statements may not be equally important and may also need to be solved in a sequence.

For Selection: Given, Identify, Rate and Rank, and

For Compromise and Coupled DSPs: Given, Find, Satisfy and Minimize.

By using the keywords in writing the word problem the type and structure for these DSPs is established and the information that is required for solution is highlighted. It may be necessary to modify the Problem Statements in the light of this activity.

Step 4. Mathematical Formulation of the DSPs. Create the Mathematical Formulation of the Word Problem. Ensure that the same keywords are used and ensure that a on-to-one correspondence exists between the Word Problem and its mathematical representation.

It may not be possible to provide a complete and accurate mathematical model using the information that is available. This may occur because of lack of knowledge or resources or both. Therefore, it may be necessary to introduce further assumptions. This increases the role played by the designer and reduces the level of completeness of the numerical solution.

Step 5. Obtain Solutions for the DSPs. Determine the most cost-effective means for obtaining a solution (the computer is not always cost-effective). The mathematical models developed in Step 4 are complete in that they can be solved using any appropriate computational tool. The process of finding a numerical solution is completely structured. At this stage, all the information necessary for solving a DSP is known or can be calculated readily. For relatively small DSPs it may be sufficient to use a graphical technique or one requiring the use of a calculator only. If the solution of a DSP requires the use of a computer, create the DSP template. Determine solutions for the problems embodied in the various Problem Statements by providing solutions to the DSPs.

Step 6. Post-solution Analysis. This step consists of two activities, namely, the validation of the solution and an examination of the sensitivity of the solution to small changes.

Validation is concerned with the designer's answer to the question, "Can I accept the results?" Obviously, a "no" answer must be resolved, perhaps, by an iteration of the entire process, hopefully with few changes. If yes, the designer rationalizes the solution by including factors (the unstructured part of the solution) that are not reflected by the solution of the DSP. Primary conclusions are validated with respect to the Story, the Abstract and the Problem Statement and the degree of completeness of the DSP template that has been solved.

The partially structured nature of the DSP makes the carrying out of post-solution analysis particularly important. An understanding of the sensitivity of the solution to small changes in the design parameters provides the basis for determining the adequacy of the model and for exploring the solution space. The latter is of particular importance because it helps a designer establish the stability of the current solution and to identify some of the better alternatives.

2.3 Breaking up a Problem: The Decision Support Problem

We present a *top-down* approach to problem solving. In the top-down approach, the problem solver is asked to comprehend the problem and develop an approach for negotiating a solution without actually solving the problem. Tasks that are necessary to achieve a solution are identified, a solution procedure need not be specified. In essence, the tasks become a series of black boxes, or modules. The input and the output from the modules can be identified, but at this stage it is not necessary to decide how each performs its function. In a large, complex problem, it is essential to break the tasks into more manageable units so that work may be distributed and organized. The top-down approach for solving problems has several advantages [22]:

- It promotes the efficient use of resources. For example, instead of going out to read everything about the problem available in the library, specific items of information are sought.
- It ensures that some sort of solution will be obtained. In some cases, a bottom-up approach can go on forever; one interesting avenue is followed after another, yet none necessarily leads to the solution.
- A top-down approach leads to the possibility of managing the process itself. A problem solver can decide how to allocate resources to each module. For example, one method of design involves choosing an existing product and modifying it slightly. Then, hypothetically, one of the modules in the solution process for creating a design would be to identify a suitable basis product which is to be modified. In some circumstances, this search for a suitable basis product could be never ending. However, the problem solver, in this case the designer, may decide to allocate a specific amount of time and money to the search and then uses the best basis found in that time.

- A top-down, modular approach to problem solving permits the modification of one module without affecting the rest of the solution process.

The output from each module will be a decision(s); our approach to finding a solution to the problem then becomes a series of decisions.

There are two different approaches to modularizing a problem: it may be divided into subproblems by either *decomposition* or *partitioning.* These terms are not the same. The processes are different. *Decomposition* is the process of dividing the system into its smallest, coherent, self-contained elements. A problem solver using decomposition is guided by the inherent structure of the system being designed. If followed to completion, decomposition always results in the same subsystems, regardless of who performs the decomposition. In decomposition, analysis progresses from the level of parent system to subsystems to subsubsystems and eventually to components. The reverse process, synthesis, progresses from the component to system level. *Partitioning* on the other hand is the process of dividing the functions, processes, and structures that are specified in the problem statement into subsystems, subsubsystems, etc. In partitioning a problem solver is guided by knowledge of the environment, by considerations of the human needs to be satisfied and by the tasks that must be performed by the fully functional system.

Consider the problem of designing a place to live - decomposition would proceed along these lines:

> We need walls and doors and a roof.
> The walls and doors will be made of wood, insulation and nails.
> The roof will be made of shingles.
>
> Notice how the problem is decomposed to produce the smallest physical unit.

Partitioning would proceed along these lines:

> We need a sheltered living area.
> In this living area we must have access to the outside, we must have some climate control, we must have a food preparation area, etc.
> To have access to the outside, we could have a door, a chute, an entrance chamber, etc....
>
> Notice that partitioning leaves a lot more options open to the problem solver early in the process and therefore leaves more room for creativity.

If a problem solver uses decomposition, he / she proceeds by breaking the problem into modules. Usually these modules can be arranged in a logical hierarchy, that is by identifying tasks to be performed, then subtasks and subsubtasks, etc. Each task then becomes a module. These modules may not be entirely independent from each other. Certainly there are interactions between tasks and subtasks, quite often there are also lateral interactions between tasks at the same level. The nature of these interactions has ramifications for the method for solution, but at this stage, the designer is more interested in logically structuring the problem and less interested in the details of solving the problem. Naturally, a hierarchical structure for solving the problem may be modified as you proceed, but it is advisable to have a structure planned. For example, after looking around, you may find some software that can be used directly to solve some of the tasks. Hence the subtasks under that task would have to be rearranged or possibly eliminated.

Once modules have been identified, a problem solver faces the problem of reintegrating them to produce a solution. One approach to solving the problem would be to start at the bottom of the hierarchy of decisions that needs to be made and work upwards until a solution is obtained. Even if this is possible, it is not likely to be the most efficient method of reaching a solution to the problem. (In general it will not be possible.) Not only must the solutions from different modules be integrated, but often a certain amount of iteration between modules is necessary. For example, in designing a car, one module might be to design the engine and another to design the drive shaft / axle / wheel arrangement; one can't truly be designed in isolation from the other. Thus the problem solver must structure or *plan* the problem solving process itself in such a way as to produce a meaningful answer.

This plan could be hierarchical, but it is usually more likely that it will be a heterarchy. Again, a top down approach to planning or structuring the reintegration of modules is preferable to a *bottom up approach*, that is just doing things that you think might be useful for solving the problem.

To facilitate planing the process of design, we introduce the Decision Support Problem Technique Palette. This palette contains symbols or icons (for the entities we introduced earlier) that we use to model a process. The palette consists of a number of icons which are shown in Fig. 2.5.

The Phase icon is identified by a capital “P” and can be used to partition process into smaller more manageable pieces. Events occur within a phase and the Event icon is identified a capital “E”. Tasks and Decisions occur within Events. A task is an activity to be fulfilled. The design process itself is a task for the design team, namely, “convert information into knowledge about the product". The task itself may contain other tasks and decisions - as in the design task. However, simple tasks like "run computer program A" do not involve decisions. In our palette a task is identified by a capital "T".

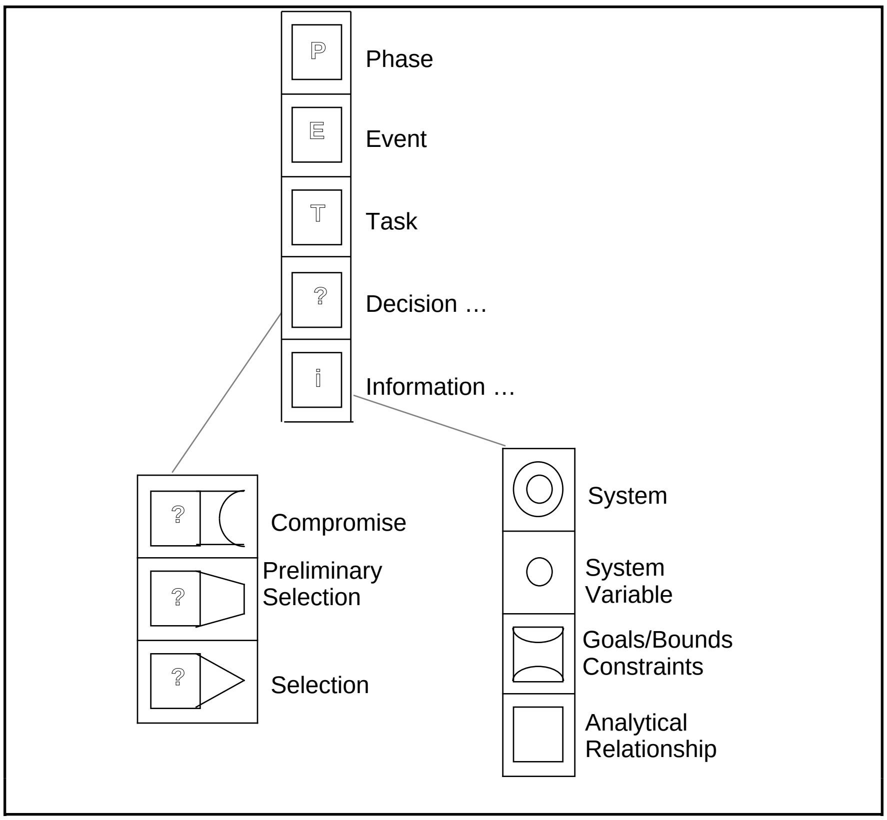

Figure 2.5. DSPT Palette for modeling processes

A Decision icon is defined by a rectangle with a question mark within it. The question mark shows the decision character. Currently we have only included the preliminary selection, selection and compromise decisions in the palette. Selection is a converging activity; the number of alternatives is reduced. The icon for the selection DSPs characterize this in our palette. The sharp point, in the selection DSP icon, is to indicate that on solving a selection DSP a single alternative can be identified for further development. The blunt point, in the preliminary selection icon, is to indicate that on solving a preliminary selection DSP a number of most-likely-to-succeed concepts can be identified for further development. The icon for a compromise DSP ends in a “C”. A compromise represents a trade-off between conflicting goals. When there is no conflict between the goals the solution is represented by the upper and lower extremes of the C in the rectangle. However, when there is a conflict, which invariably is the case, the result emerges from the middle representative of a compromise between two extremes.

Information and Knowledge are required to model any process. All knowledge and information about the process and product are classified as systems. A system is identified by a circle with a smaller circle in the middle. This illustrates the central nature of a system in the process and also the fact that other systems and their associated knowledge and information are embedded in the system. This embodiment is shown by the small circle.

System variables (e.g., total resistance, length, length of an event, number of people involved in a task) are embedded in systems. The icon for a system variable is a small circle showing its atom-like character and that no lower hierarchical level is possible.

Relationships are often considered as black boxes. Hence, we represent analytical relationships as plain rectangles. All icons having a rectangular shape are, in fact, relationships. Phases, Events, Tasks and Decisions are also relationships. Using the rectangular shape emphasizes this observation. A nozzle is embedded within the rectangle for an icon to model goal/constraint/bound type relationship. The nozzle is symbolic of the restrictive nature of these relationships.

All icons as shown embody deterministic/hard knowledge and information. Soft knowledge and information are to be represented using the same icons but with different gray scales. The darker the icon background, the more one is looking in the dark, the softer the knowledge and information. As the icon becomes lighter, the knowledge and information become clearer and harder.

Using the icons in this palette we are able to describe processes. Design information and knowledge flow from left to right through the icons. Meta-knowledge and information are connected to the design information by dotted lines. In a computer environment the meta-information can be stored in a different layer which can be projected onto the layer with the primary design process description. Needless to say the same icons are used to model both meta-design and design knowledge and information.

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3

Selection

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

Early in the decision making process, selection occurs in two major phases, namely:

Phase 1 (Preliminary Selection Decision Support Problem): the identification of potentially superior concepts based primarily on qualitative rather than quantitative information, and

Phase 2 (Selection Decision Support Problem): the identification, using insight-based soft information and science-based "hard" information, of a very limited number of superior alternatives that should be developed further.

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 chapter, we describe the selection DSPs in the context of the selection of horns for an automobile. In this chapter, an idealized view of the process of design in the conceptual phase is presented along with the role and structure of the two types of selection DSPs. In this chapter a practical approach to problem solving, based on the concept of selection is presented. A reader is advised to focus on the process rather than the technical details of the examples.

3.1 The Decision Support Problems

Decision Support Problems provide a means for modeling decisions. Multiple objectives, quantified using analysis-based "hard" and insight-based soft information, can be modeled in the DSPs. For real-world, practical systems, in the early stages of the project, all the information for modeling systems comprehensively and correctly may not be available. Therefore, the solution to the problem, even if it is obtained using optimization techniques, cannot be optimum with respect to the real world. However, this solution can be used to support the quest for a superior solution. In a computer-assisted environment this support is provided in the form of optimal solutions for Decision Support Problems. Formulation and solution of DSPs provides a means for making the following types of decisions:

- *Selection* - the indication of a preference, based on multiple attributes, for one among several feasible alternatives [1].
- *Compromise* - the improvement of a feasible alternative through modification Srinivasan, et al. [2-4]; Mistree, et al. [5]; Marinopoulos [6]; Shupe and Mistree [7]; Smith and Mistree [8]; Nguyen and Mistree [9]; Lyon and Mistree [10]; Jivan and Mistree [11].
- *Coupled or hierarchical* - decisions that are linked - selection/selection, compromise/compromise and selection/compromise decisions may be coupled (Bascaran, et al. [12-13]; Shupe, et al. [7]; Kuppuraju, et al. [14]; Smith [8]).
- *Conditional* - decisions in which the risk and uncertainty of the outcome are taken into account (Zhou [15]).
- *Heuristic* - decisions made on the basis of a knowledge base of facts and rules of thumb; DSPs that are solved using reasoning and logic only.

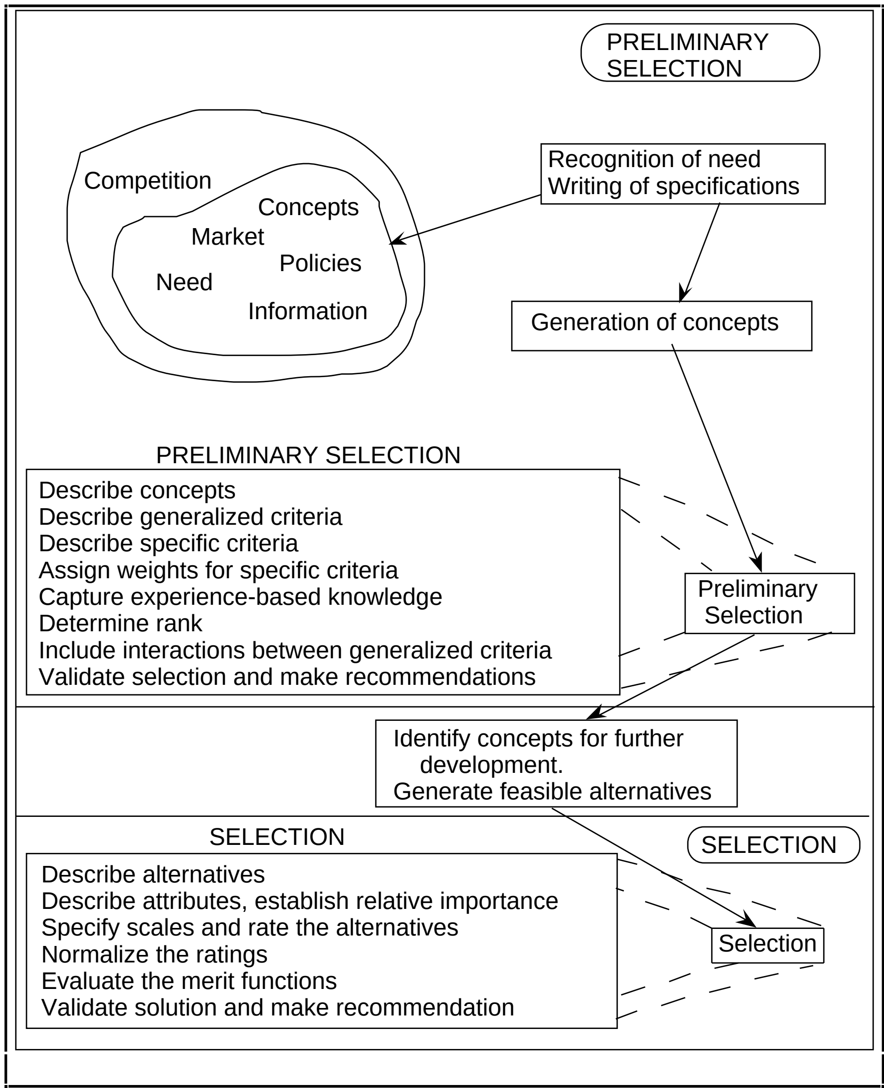

Figure 3.1. The Selection Process

3.2 The Selection Decision Support Problems

Selection occurs in all stages of the solution of a problem. In the early stages there is almost no hard data; most of the data is soft. As the process of resolving an open problem progresses the amount of hard data available increases.

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. *Preliminary selection* involves the selection of the most-likely-to-succeed concepts for further development into feasible alternatives. *Selection* involves the ranking, based on multiple attributes, of the feasible alternatives in order of preference, Figure 3.1.

3.2.1 Preliminary Selection

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 the 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.

Figure 3.2. The Preliminary Selection Decision Support Problem

The method of Pugh [16] forms the basis of the algorithm developed for solving the preliminary selection DSP. In this section, formulation and solution are described. This is followed by an example. *In preliminary selection, some choices are made that narrow the field of contending solution concepts down to a few most-likely-to-succeed concepts.* These choices are made against a set of criteria, as to the preferred performance of the solution.

Let us assume that the competing concepts are known and information about them is available. Let us also assume that

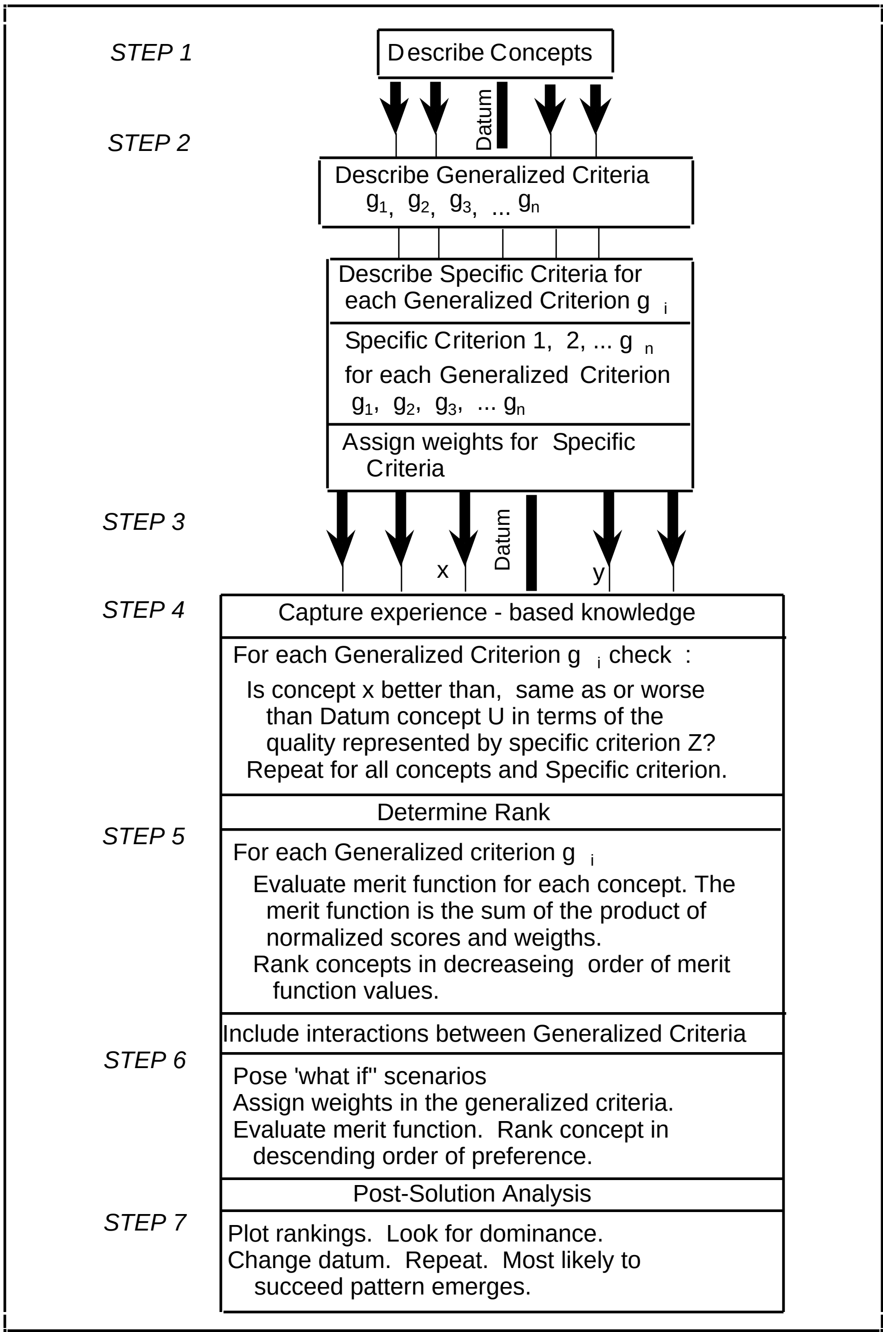

Figure 3.3. Preliminary Selection steps

most of this information is soft, that is based on qualitative, experience-based knowledge. The following steps serve as a set of guidelines to aid the design team identify a set of feasible alternatives. A seven-step procedure to accomplish these tasks is presented.

Step 1 Describe the concepts and provide acronyms. Draw sketches of the embryonic concepts for solution of the problem. If possible, 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, 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 considered in this step will have no effect on the preliminary selection process. The preliminary selection process could thus yield an alternative that 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 desired problem solution. The criteria should be independent of each other and each should measure a single quality of the concepts.

Rank the specific criteria, associated with each generalized criterion, in order of importance. 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 solution 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, or worse than the datum concept y? Enter a score: +1, 0 or -1 for a better than, same as or 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.

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.

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 7 Post-solution analysis: Determine the most-likely-to-succeed 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. Choose another datum. Repeat Steps 4 through 7. Stop when you see a most-likely-to-succeed group of concepts 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.

3.2.2 Selection Decision Support Problems

In this section a summary of the important points and the necessary steps for formulating a selection DSP is presented. 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 Figure 3.4.

Given	A set of *feasible alternatives*.
Identify	The principal *attributes* influencing selection. The *relative importance* of attributes.
Rate	The alternatives with respect to each attribute.
Rank	The feasible alternatives in *order of preference* based on attributes and their relative importance.

Figure 3.4. The Selection Decision Support Problem

The procedure for formulating and solving selection DSPs is:

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, Preliminary Selection, which is described in the preceding section. Assume that the concepts have been developed into alternatives. If possible, 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 its relative importance 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 is not considered in this time. The problem solver should be careful about ignoring a relevant attribute regardless of its relative importance compared to other attributes. An attribute that is not considered in this step will have no effect on the selection process. Thus the selection process could yield an alternative that 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 problem.

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 3A. The method of comparison involves much more effort. Therefore, in the very early stages of the 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. There are four types of scales, namely, ratio, interval, ordinal (Riggs [17]) 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. It is used to model attributes in which the zero is relative, e.g., temperature, efficiency, etc. It is also 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 procedure.

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 problem solver is able to rank-order preference for a particular alternative with respect to a particular attribute. If a problem solver is unable to indicate (even qualitatively) by how much a particular alternative is preferred over another then the ranking method (Appendix 3A) for creating the interval scale is recommended. If a problem solver 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 3A). If a designer is able to articulate clearly a definite and measurable degree of preference, then a scale and associated ratings may be specified. 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 of quantifying the 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. Therefore, 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 ,

$$R_{i,j} = \frac{(A_{i,j} - A^{min}_{i,j})}{(A^{max}_{i,j} - A^{min}_{i,j})} \tag{3.1}$$

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

$$R_{i,j} = 1 - \frac{(A_{i,j} - A^{min}_{i,j})}{(A^{max}_{i,j} - A^{min}_{i,j})} \tag{3.2}$$

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 the attributes using proper weights defined in Step 1. There are several methods for modeling the merit function. The most frequently used model, however, is the linear model:

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

where

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

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, Morris [18].

Model	*Type*	*Comment*
1	Linear Additive $MF_i = \sum_j I_j R_{ij}$	All values are treated similarly.
2	Higher Order Additive (for example) $MF_i = \sum_j I_j \lvert \log(R_{ij}) \rvert$	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 I_j or R_{ij}.

Figure 3.5. Models for the Merit Function

Step 6 Post-solution sensitivity analysis. Post-solution analysis of the selection DSP consists of two types of activities, namely, solution validation and sensitivity analysis. Sensitivity analysis includes both assessing the solution's sensitivity to changes in the attribute weights and the solution's sensitivity to changes in 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 problem solver is able to identify the best and some of the better alternatives. Usually, 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 reexamination 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 for 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 to changes in the attribute ratings.

Sensitivity to changes in 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 reexamining and changing the relative importance of the attributes in or changing the preferences within a comparison and determining the effect of that change on the merit function. The top ranked alternative that 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 attribute weights, a sensitivity analysis of the attribute ratings may be performed 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. Therefore, 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 ± δ 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, the addition or redefinition of attributes may be necessary.

3.2.3 An Example of the Selection Procedure

Preliminary Selection DSP

Problem Statement. An appropriate conceptual design for an automobile horn is required. The automobile is a medium size, medium-price range vehicle suitable for an urban family. 2-door, 4-door and wagon models will be produced. It is anticipated that all will utilize the same type of horn. The manufacturer wants an inexpensive, reliable and easily installed horn. These vehicles are destined for use all over the United States including Alsaka and Hawaii so the concept selected should have tha capability of performing in all weather conditions. The concepts are listed in Figure 3.6.

Preliminary Selection DSP, *Step 1:* Seven concepts which might provide a solution for the design problem were identified during a brainstorming session. These concepts, with acronyms for easy identification, are :

- Concept 1: <Electromagnetic Diaphragm, ED> The diaphragm is attached to a vibrating shaft driven by a rapidly changing magnetic field thereby creating noise.
- Concept 2: <Aeroacoustic Horn, AH> High speed rotary vanes force air out through nozzles producing noise.

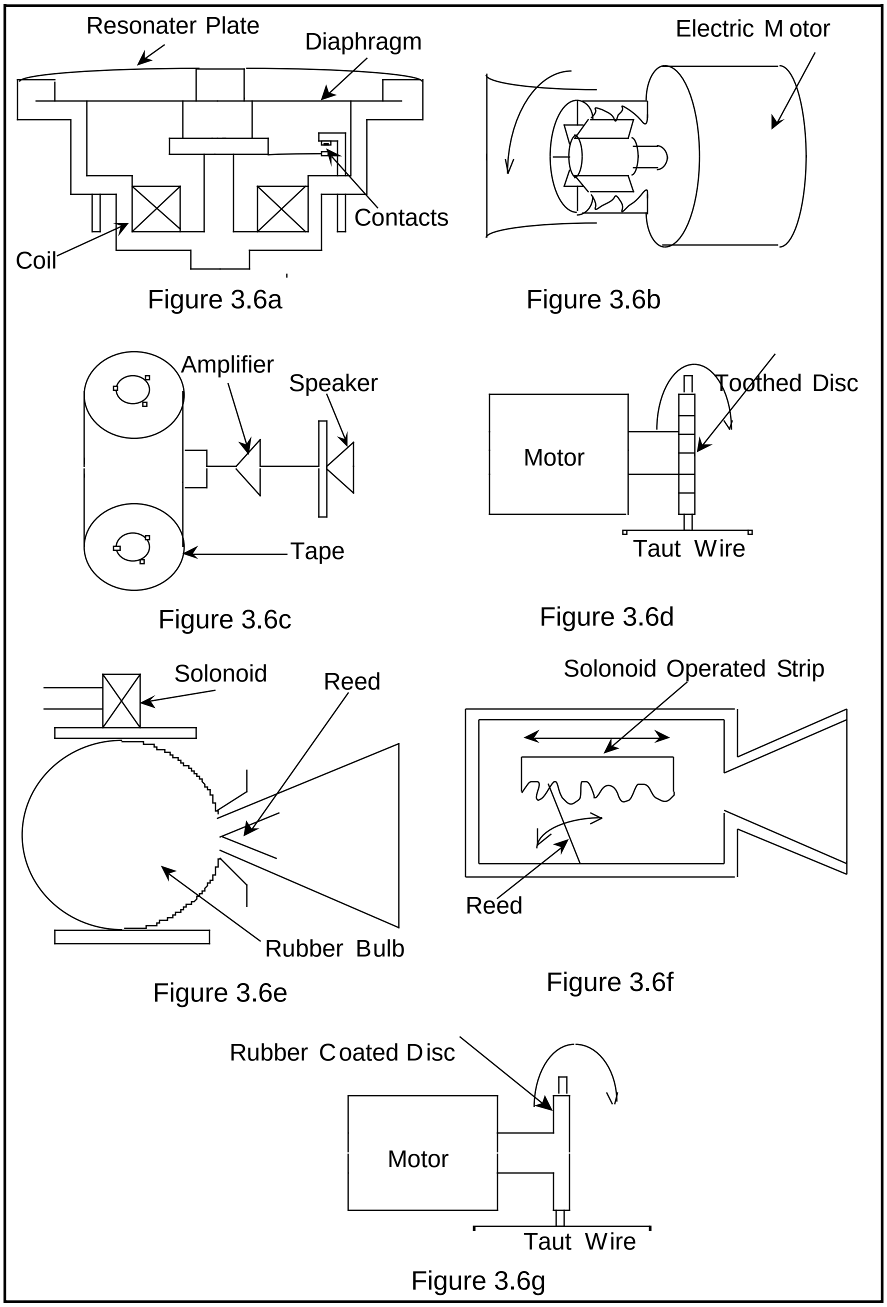

Figure 3.6. Rough Sketches of the Concepts for a Horn. (a) Electromagnetic Diaphragm, (b) Aeroacoustic Horn, (c) Tape Driven Horn, (d) Wire and Toothed Wheel, (e) Rubber Bulb,
(f) Reed, and (g) Wire and Disc.

- Concept 3: <Tape Driven Horn, TDH> Recorded impulses on electromagnetic tape are picked up, amplified and broadcast.
- Concept 4: <Wire and Toothed Wheel, W&TW > Teeth on a wheel pluck a taut wire in rapid succession producing monotonic noise.
- Concept 5: <Rubber Bulb, RB> A solenoid is magnetized and demagnetized alternately. The magnetic core is moved up and down compressing and releasing the bulb to force air through reeds thus producing noise.
- Concept 6: <Reed, R> To and fro motion of the rack plucks the reed to produce noise.
- Concept 7: <Wire and Disc, W&D> Motor-driven rubber-coated disc continuously rubs against a taut wire to produce noise.

Rough sketches of these concepts have been drawn with approximately equal levels of complexity, Figure 3.6.

Preliminary Selection DSP, Step 2: The generalized criteria and acronyms are:

- Criterion 1: <Resistance to Corrosion and Water, Corrosion> Ideally the unit will remain in place for years and be exposed (somewhat) to water and possibly salt from the roads. A unit that can withstand these conditions is desired.
- Criterion 2: <Resistance to Vibration, Shock and Acceleration, VSA>
- Criterion 3: <Resistance to Extremes in Temperature, Temperature> Extremes in temperature may cause variations in clearances. Plastic or rubber may become brittle.
- Criterion 4: <Response Time, Response> To be an effective warning device, rapid response is essential.
- Criterion 5: < Power Consumption, Power> A low power consumption is desirable.
- Criterion 6: <Ease of Maintenance, Maintenance>
- Criterion 7: <Weight, Weight>
- Criterion 8: <Size, Size>
- Criterion 9: <Reliability, Reliability> Concepts with fewer moving parts are more likely to be reliable.
- Criterion 10: <Durability, Durability>
- Criterion 11: <Manufacturing Cost, Cost>
- Criterion 12: <Ease of Installation, Installation>

Preliminary Selection DSP, Step 3: The electromagnetic diaphragm has been chosen as an initial datum since such horns represent the current industry standard design.

Preliminary Selection DSP, Step 4: Capture experience-based knowledge through comparison of concepts, Table 3.1. Assume that each criterion is equally weighted, that is, that the weights are 1/12 or 0.0833.

Table 3.1. Comparison of the concepts for Preliminary Selection to the datum concept, Concept 1, the electromagnetic diaphragm

Criteria		*Concepts*						
		*1‡**	*2**	*3**	*4*	*5**	*6*	*7*
1	Resistance to corrosion	0	-1	0	-1	-1	-1	-1
2	Resistance to vibration, shock and acceleration	0	-1	-1	-1	0	-1	-1
3	Temperature	0	-1	-1	-1	-1	0	-1
4	Response time	0	-1	-1	-1	-1	-1	-1
5	Power consumption	0	-1	+1	-1	-1	-1	-1
6	Ease of maintenance	0	+1	-1	+1	+1	-1	+1
7	Weight	0	-1	-1	-1	-1	-1	-1
8	Size	0	-1	0	-1	-1	0	-1
9	Reliability (fewer parts)	0	0	0	-1	0	-1	-1
10	Durability	0	-1	-1	-1	-1	-1	-1
11	Manufacturing cost	0	0	-1	-1	0	-1	-1
12	Installation	0	0	-1	-1	-1	0	-1
Worse Than Datum		0x-1	6x-1	8x-1	11x-1	8x-1	9x-1	11x-1
Better Than Datum		0x+1	1x+1	1x+1	1x=+1	1x+1	0x+1	1x+1
As Good as Datum		12x0	4x0	3x0	0x0	3x0	3x0	0x0
Raw Score		Datum	-5	3	-10	-7	-9	-10
Normalized Score[1]		.769	.385	1	0	.231	.077	0

*Concepts which have been selected for use in the selection DSP.

‡Datum concept. A "+1" implies better than the datum. A "0" implies it is the same as datum. A "-1" implies it is worse than the datum.

1 Since all of these criteria are weighted equally, the range of raw scores is considered the universe (-10 to +3, or 13 units) and this is adjusted for a 0-1 scale using Equn. 3.1.

Justification for Ratings in Table 3.1:

Criterion 1: Resistance to Corrosion and Water. Concept 1 is a sealed, self-contained unit and has a smaller chance of corroding than all other concepts except Concept 3 which can also be made air- and water-tight. Even if a small amount of corrosion does occur, the functioning is not adversely affected in Concepts 1 and 3 but in others, for instance, the reed-based and wire-based instruments, the quality of noise deteriorates if the parts are corroded. Therefore, a "0" is assigned to Concept 3 and a "-1" to Concepts 2, 4, 5, 6, and 7 in Table 3.1.

Criterion 2: Resistance to Vibration, Shock and Acceleration. Concept 1 scores again over most of the others because it has fewer moving parts. All other concepts except Concept 5 rely on proper clearances which may be altered owing to vibration shock, for instance, the magnetic pickup in Concept 3 or the toothwire clearance in Concept 4.

Criterion 3: Resistance to Extremes in Temperature. Extremes in temperature may cause variations in clearances; for instance, a taut wire becomes slack if its temperature is increased. the rubber bulb in Concept 5 may lose its elasticity or deform owing to extremes in temperature, etc. Concept 6 is at least as good as the datum because it relies on positive reed displacement.

Criterion 4: Response Time. An electromagnetic device has a much smaller response time than electromechanical devices. Concept 3, however, does not compare well with the datum because of possible time delay in tape start-up.

Criterion 5: Power Consumption. Concepts 1 and 3 fare very well against all of the other concepts because the others require more power to activate their prime movers - motor, bellows, rack, etc.

Criterion 6: Ease of Maintenance. Concepts 2, 4, 5 and 7 involve accessible simple parts that can be easily serviced and therefore score over the datum.

Criterion 7: Weight. Concept 1 is lighter than most of the other concepts.

Criterion 8: Size. Concepts 1, 3 and 6 are the most compact.

Criterion 9: Reliability. The fewer moving parts, the greater the reliability. The ratings assigned reflect this fact.

Criterion 10: Durability. Concept 1 is sturdy compared to all the other concepts and hence is deemed the most durable.

Criterion 11: Manufacturing Cost. Components for Concepts 1 and 2 are readily available. Concept 5 is very simple to put together. The other concepts use nonstandard components and are not feasible for immediate use.

Criterion 12: Ease of Installation. Concepts 1, 2 and 6 can function in any given orientation and are compact enough to be located where space is at a premium. The rest of the concepts are either bulky or sensitive to orientation.

Table 3.2. Comparison of the concepts for preliminary selection to the datum concept, concept 5, the rubber bulb

	Criteria	*Concepts*						
		*1**	*2**	*3**	*4*	*5*‡*	*6*	*7*
1	Resistance to corrosion	+1	0	+1	0	0	0	0
2	Resistance to vibration, shock and acceleration	0	-1	-1	-1	0	-1	-1
3	Temperature	+1	0	0	0	0	+1	0
4	Response time	+1	0	0	0	0	0	0
5	Power consumption	+1	0	+1	0	0	0	0
6	Ease of maintenance	-1	0	-1	0	0	-1	0
7	Weight	+1	0	0	0	0	0	0
8	Size	+1	0	+1	0	0	+1	0
9	Reliability (fewer parts)	0	0	0	-1	0	-1	-1
10	Durability	+1	0	0	0	0	0	0
11	Manufacturing cost	0	0	-1	-1	0	-1	-1
12	Installation	+1	+1	0	0	0	0	0
	Worse Than Datum	1x-1	1x-1	3x-1	3x-1	0x-1	4x-1	3x-1
	Better Than Datum	8x+131x+13x+10x+1				0x+13x+1		
	0x+1							
	As Good as Datum	3x031-x0		6x0	9x0	12x0	5x0	9x0
	Raw Score	+7	0	0	-3	Datum	-1	-3
	Normalized Score	1	.364	.364	0	.364	.273	0

*Concepts which have been selected for use in the selection DSP.

‡Datum concept. A "+1" implies better than the datum. A "0" implies it is the same as datum. A "-1" implies it is worse than the datum.

Step 6. Individual concepts scores are assessed, Table 3.1. The datum is by far the best concept (score 0 as compared with negative values for the rest of the concepts) when compared to the others. The top four Concepts are 1, 2, 3 and 5. For most of the twelve criteria, Concepts 1 is overwhelmingly preferred to the rest. The rankings need to be validated by choosing a different datum. Therefore, Concept 5, is chosen as the new datum (this choice being arbitrary) and comparisons are made again, Table 3.2. The top three choices are 1, 5 and 3. Similarly to Table 3.1, the scores are normalized.

When should one stop iterating? It is important to continue with different datums until there is no change in the group that makes up the most-likely-to-succeed concepts. If there are relatively few concepts, say, less than 5 it is imperative that all the concepts be considered as datums.[2]

Can you identify the best concept using preliminary selection? The answer is an emphatic NO. One can only identify a group of concepts that are realtively equivalent. But what if we do want to identify the best concept? Well, to do this you need to solve the selection DSP.

Altering the relative importance of the criteria: Let us assume that the manufacturer hires a consultant to determine the realtive importance of the criteria. The consultant after performing a detailed analysis reports back to the manufacturer that not all criteria should be weighted equally; the criteria "Manufacturing Costs" and "Installation" are five times more important than the other criteria. Then these two criteria are weighted 0.227 (5/22) and the other criteria receive 1/22 weights (0.0455). Thus each row of Table 3.1 is normalized (so scores go from 0 to 1, i.e. values instead of being -1, 0 and +1 become 0, 0.5 and 1). The each row is multiplied by the appropriate scaling factor and the scores are summed. The values obtained are:

	*1**	*2**	*3**	*4*	*5*‡*	*6*	*7*
Normalized Score	.432	.295	+.091	.046	.205	.159	.091

Similarly for the information in Table 3.2 with the criteria "installation" and "Manufacturing Costs" weighted appropriately

	*1**	*2**	*3**	*4*	*5*‡*	*6*	*7*
Normalized Score	.705	.545	.364	.296	.455	.318	.296

After careful consideration of this information, it was decided that further preliminary selection DSPS were not necessary - although for other problems they migh be useful. The concepts: electromagnetic diaphragm, aeroacustic horn, tape driven horn and rubber bulb are identified as suitable for for further investigation (Concepts 1,2,3 and

2 Why?

5). Then these concepts are investigated much more thoroughly "engineering is done" - the information so obtained is presented in Tables 3.6 and 3.7.

The Selection DSP, Step 1: Describe the alternatives and provide acronyms. The alternatives illustrated in Figure 3.7.

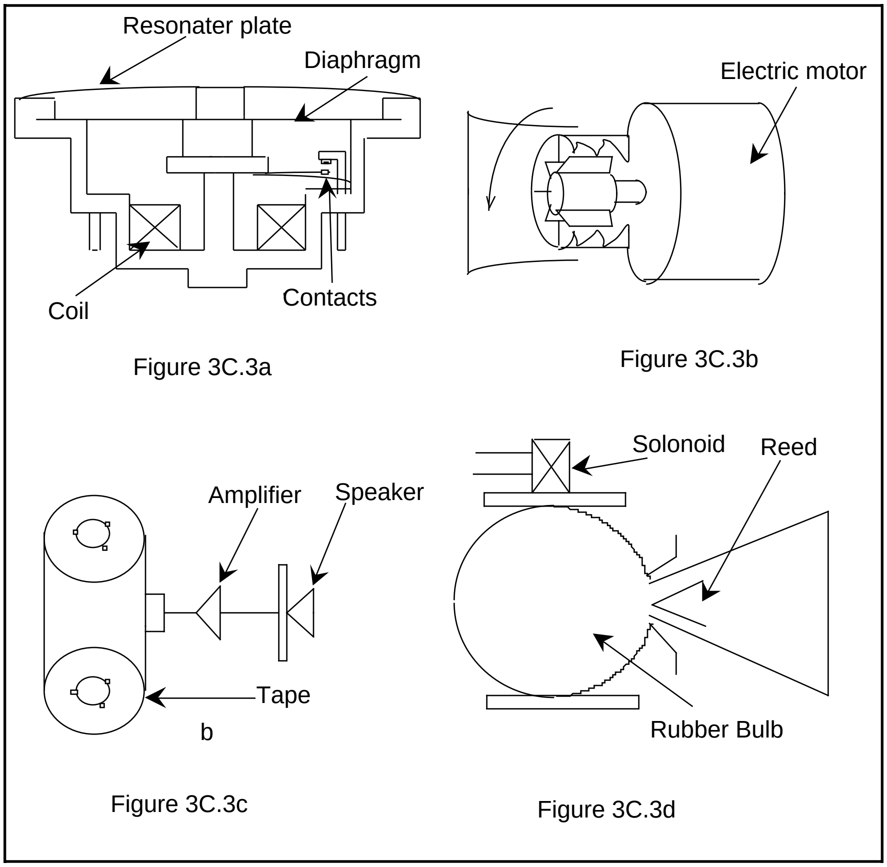

Figure 3.7. Alternatives for horn selection problem
(a) electromagnetic diaphragm, (b) aeroacustic horn, (c) tape driven horn, and (d) rubber bulb.

Alternative 1	Electromagnetic diaphragm, the diaphragm is attached to the vibrating shaft driven by a rapidly changing magnetic field thereby creating noise.
Alternative 2	Aeroacustic horn, high speed rotary vanes force air out through nozzles producing noise.

Alternative 3	Tape driven horn, recorded impulses on electromagnetic tape are picked up, amplified and broadcast.
Alternative 4	Rubber bulb, solenoid is magnetized and demagnetized alternately. Magnetic core moved up and down compressing and releasing the bulb to force air through reeds to produce noise.

Selection DSP, Step 2: Describe the attributes, specify their relative importances. The attributes are:

- < Noise , Attribute 1> The main purpose of the horn is to create noise audible above the background noise in the streets, hence this is the most important attribute.
- < Response Time , Attribute 2> The horn has to respond quickly or it does not serve its purpose.
- < Power Consumption, Attribute 3 > Power consumption is an important factor, but not critical since most horns do not consume much power anyway. The ranking reflects this.
- < Ease of Maintenance, Attribute 4 > Manitainability is the less important criterion because it plays an important role only in the long term and most of the horns have a very long expected life.
- < Size, Attribute 5> The horn has to be small so that it can be installed in the first place.

The relative importance of the attributes are obtained by pairwise comparison, Table 3.3. These comparisons are summarized in Tables 3.4 and 3.5. In this case (which is a small problem), 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. Further information about the use of a Dummy Attribute is presented in 3A.3.2.

Table 3.3. Establishing a viewpoint for the pairwise comparison method of obtaining the relative importance of the attributes for the Selection DSP

Decision Number	*Attributes*	*Decision*	*Viewpoint*
1	1, 2	1>2*	Achieving a noise level above
2	1, 3	1 > 3	background noise is the main purpose of providing
3	1, 4	1 > 4	a horn.
4	1, 5	1 > 5	Hence this attribute is preferred over all others.
5	1, 0	1 > 0	All attributes are preferred to dummy.
6	2, 3	2 > 3	Essential to avoid accidents.
7	2, 4	2 > 4	A larger power source, though undesirable, is not impossible.
8	2, 5	5 > 2	A large horn could cause installation problems.
9	2, 0	2 > 0	All attributes are preferred to dummy.
10	3, 4	3 > 4	Most horns do not require frequent maintenance.
11	3, 5	5 > 3	A large horn could cause installation problems.
12	3, 0	3 > 0	All attributes are preferred to dummy.
13	4, 5	5 > 4	A large horn could not be installed.
14	4, 0	4 > 0	All attributes are preferred to dummy.
15	5, 0	5 > 0	All attributes are preferred to dummy.

Attribute:
1 - Ease of achieving 100-125 dBA.
2 - Low response time.
3 - Low power consumption.
4 - Ease of maintenance.
5 - Small size.
0 - Dummy attribute.

*The symbol > indicates preference.

Table 3.4. Summary of the pairwise comparisons to Obtain the relative importance of the attributes for the Selection DSP

Attribute	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	I_j*
1	1	1	1	1	1											5 (0.333)
2	0					1	1	0	1							3 (0.2)
3		0				0				1	0	1				2 (0.133)
4			0				0			0			0	1		1 (0.066)
5				0				1			1		1		1	4 (0.266)
Dummy					0				0			0		0	0	0 (0)
Total															15	

*I_j is the relative importance. The normalized scores in parentheses are evaluated by normalizing the scores I_j with respect to the total sum of the scores, as is the case here, or with the range of scores or the largest score.

Table 3.5. Summary of the relative importance of the attributes for the Selection DSP

Attribute (j)	*Relative Importance**	*Normalized Relative Importance*
1. Ease of Achieving 100-125 dBA	5	(5/15 =) 0.333
2. Low Response Time	3	(3/15 =) 0.200
3. Low Power Consumption	2	(2/15 =) 0.133
4. Ease of Maintenance	1	(1/15 =) 0.066
5. Small Size	4	(4/15 =) 0.266
Total	15	

*Larger numbers indicate preference.

Selection DSP, Step 3: Specify Scales, Rate the Alternatives with Respect to Each Attribute

Table 3.6. Criteria for the creation of interval scales

Attribute 2 - Low Response Time.		
	Response Time	*Rating*
Avoid accidents with moving traffic on highways.	0-10 ms	10-8
Avoid accidents with moving traffic on streets.	10 ms-1 s	7-5
Avoid accidents with pedestrians.	1-2 s	4-2
Insufficient alert time.	Over 2 s	1

Attribute 4 - Ease of Maintenance.	
Mean time between maintenance	*Rating*
Greater than 5 years.	10-8
3-5 years.	7-6
1-3 years.	5-3
Less than 1 year.	2-1

Attribute 5 - Small Size.	*Rating*
Extremely compact No constraints on location.	10-8
Compact but many moving parts.	7-5
Numerous moving parts .	4-2
Bulky and sensitive to orientation.	1

Step 4. Normalize the Ratings.

Table 3.7. Evaluation of the alternatives

Attribute 1, Noise *Alternative (i)*	*Rating* (A_{i1})*	*Normalized Rating* ($R_{i1}(=A_{i1}/A^{max}_{i1})$)
Electromag. Diaphragm	100	0.666
Aeroacustic Horn	105	1
Tape Driven Horn	95	0.333
Rubber Bulb	90	0

*The sound levels of these concepts are used to determine the normalized rating. Higher values of Attribute 1 are preferred.

Attribute 2, Response *Alternative(i)*	*Rating* (A_{i2})*	*Normalized Rating* ($R_{i2}(=A_{i2}/A^{max}_{i2})$)
Electromag. Diaphragm	9	0.9
Aeroacustic Horn	1	0.1
Tape Driven Horn	1	0.1
Rubber Bulb	3	0.3
		$\Sigma A^{max}_{i2} = 10$

*A larger rating indicates preference (lower response time is preferred).

Attribute 3, Power *Alternative(i)*	*Rating* (A_{i3})*	*Normalized Rating* ($R_{i3}(=A_{i3}/A^{max}_{i3})$)
Electromag. Diaphragm	6	1
Aeroacustic Horn	50	0.312
Tape Driven Horn	10	0.937
Rubber Bulb	70	0

* A lower value of power consumption is preferred.

Attribute 4, Maintenance Alternative(i)	*Rating (A_{i4})**	*Normalized Rating ($R_{i4}(=A_{i4}/A^{max}_{i4})$)*
Electromag. Diaphragm	8	0.8
Aeroacustic Horn	6	0.6
Tape Driven Horn	3	0.3
Rubber Bulb	1	0.1
		$\Sigma A^{max}_{i4} = 10$

* Larger scores indicate preference (less maintenance is preferred).

Attribute 5, Size Alternative(i)	*Rating (A_{i5})**	*Normalized Rating ($R_{i5}(=A_{i5}/A^{max}_{i5})$)*
Electromag. Diaphragm	9	0.9
Aeroacustic Horn	6	0.6
Tape Driven Horn	2	0.2
Rubber Bulb	2	0.2
	$\Sigma A^{max}_{i5} = 10$	

*Larger scores indicate preference (smaller size is preferred).

Step 5. Evaluate the merit function for each alternative. The linear additive model for the merit function is used here.

Table 3.8. Evaluation of the merit function

Alternative	*Merit Function Values*	*Overall Rank*
Electromagnetic Diaphragm	0.827	1
Aeroacustic Horn	0.594	2
Tape Driven Horn	0.329	3
Rubber Bulb	0.120	4

Step 6. Post-solution sensitivity analysis to changes in the attribute ratings. Note that in this problem, the rankings are clear and unique.

This is not always the case, in some situations, it may be advisable to assess for the individual attributes realistic possible levels of variation.

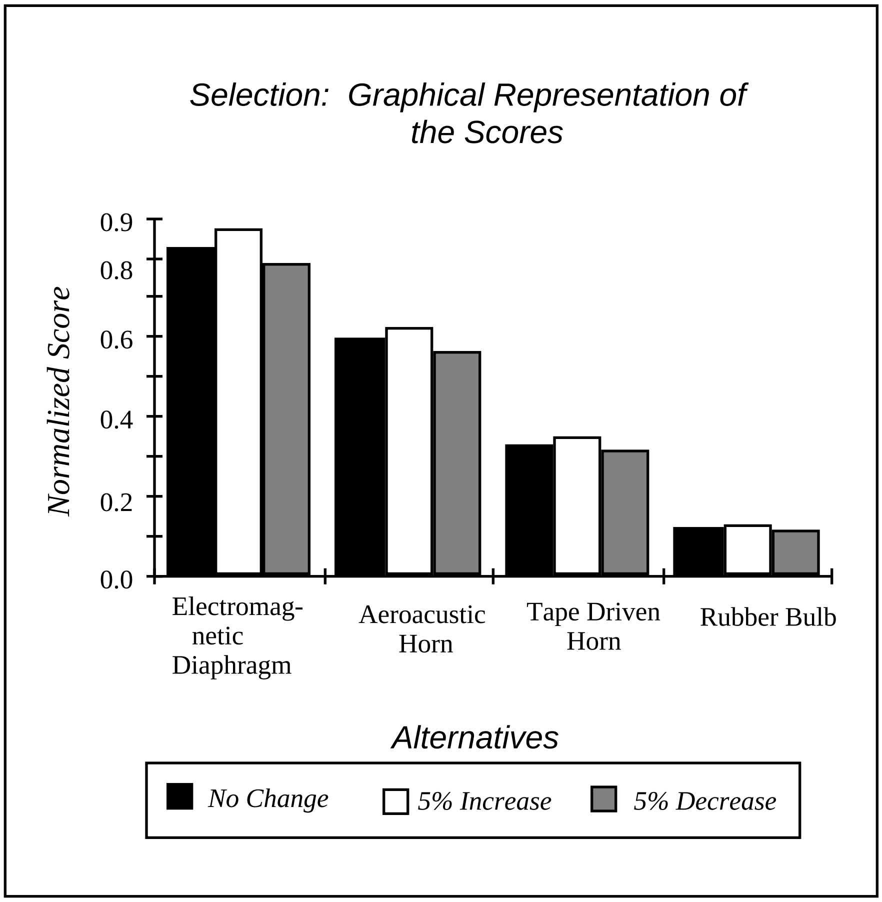

Figure 3.8. Sensitivity of the merit function to changes in attribute ratings.

RECOMMENDATION: The electromagnetic diaphragm concept is recommended.

3.3 On the Use of Selection Decision Support Problems

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 way of replacing human judgment. They do, however, provide an ordered, rational means for making choices 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 problem solver 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 criticized. One remedy is to convert all ratio to interval scales and then to compute the merit function values as has been suggested by Saaty [19]. 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 [20] 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.

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.

Appendix 3A Scales and Weights Using Soft Information

Scales must 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 solution 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.

3A.1 Interval Scales and Their Use in Decision Support Problems

In Preliminary Selection interval scales are used to specify 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 to provide a means for quantifying preferences 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 [17] 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. First, 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 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. If a designer is able to articulate a definite and measurable degree of preference then a scale together with the associated ratings may be specified. It is pointed out 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 what the best alternative is, as well as the worst and everything in between. This will work when a decision can be made based on only one attribute. This is invariably 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 by rank-ordering alternatives, yet the information is necessary for DSPs with multiple attributes. Therefore, 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.

3A.2 The Creation of Interval Scales

Baird [21] presents three methods for developing interval scales:

- Churchman-Ackoff Method
- Standard Gamble Method
- Rating Forms

These are presented as given by Riggs [17] with some modifications to make them useful for decision support problems. Saaty [19] and [20] 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.

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.

3A.2.1The 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 be

X = 1.0	W = 0.4
Z = 0.8	Y = 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). 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 = 1.0 W = 0.2
Z = 0.6 Y = 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.

3A.2.2The 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 is difficult to master, but the scale boundaries for the best and worst outcomes make the ratings comparable for all alternatives.

To describe further 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 0.3 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 we have two schools rated at 0.3 and 0.5, if a third school had a rating of 0.9, this school would be preferred to the other two alternatives by the intervals given by the lotteries (0.6 and 0.4, respectively).

3A.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 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
54 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
21 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

Figure 3A.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 who were previously rated in each category. Each decision maker has a different interpretation of what constitutes perfection, based on personal views and past exposures. *It is not vital* 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. Usually different rating forms will be needed for creating interval scales for different attributes.

3A.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 [17, 19-21]. We present three ways to capture the insight of the problem solver 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. The ranking method and the comparison methods can also be used to create composite scales.

3A.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.

3A.3.2 The Comparison Method

In the comparison method, the preference between each pair of attributes is compared, and a view point 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. 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 totaled. The attribute that gets the highest score is the more important attribute. The scores are then normalized. It is extremely important to present the 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 produce 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 [20] [19] has proposed a check for ascertaining and correcting inconsistencies that should help eliminate the problem of cycling.

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 that 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+1 attributes (n attributes plus one dummy), the number of comparisons is ${}^{n+1}C_2$

$${}^{n+1}C_2 = (n+1)! \,/\, (n-1)!\ 2!$$

where

$$n! = n\,(n-1)(n-2)\ \ldots\ (3)(2)(1).$$

for a large problem where a dummy attribute is not required, the number of comparisons is ${}^{n}C_2$

$${}^{n}C_2 = (n)! \,/\, (n-2)!\ 2!$$

3A.3.3 The Reciprocal Pairwise Comparison Matrix Method

This approach has been proposed by Saaty, [20] [19]. 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. The interval scale in the former varies from 0 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. 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 attribute over another is of the highest possible order.
2, 4, 6, 8	Intermediate values	When compromise is needed between adjacent ratings.

Figure 3A.2. The reciprocal pairwise comparison matrix method: description of the scale for decisions

The decision matrix ***A*** has the following form:

$$\boldsymbol{A} = \begin{vmatrix} 1 & a_{12} & & a_{1n} & \\ 1/a_{12} & 1 & & a_{2n} & \\ & . & . & ... & . \\ . & . & ... & . & \\ 1/a_{1n} & 1/a_{2n} & & 1 & \end{vmatrix} \tag{3A.1}$$

An element a_{ij} is the number corresponding to the preference expressed, for attribute i over attribute j. Therefore, 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 non-zero and positive.

Assume that we have identified a set of *n* garden variety stones and we want, from this set, to select one stone based on its weight. (In this case the stones represent alternatives and the weight an attribute.) Assume that we know the actual weight of the *n* stones, namely, $(w_1,...,w_n)$. Therefore, we can form a matrix, ***A***, of pairwise ratios whose rows give the ratios of the weights of each stone with respect to all others:

$$\boldsymbol{A} = \begin{vmatrix} w_1/w_1 & w_1/w_2 & ... & w_1/w_n \\ w_2/w_1 & w_2/w_2 & ... & w_2/w_n \\ . & . & ... & ... \\ . & . & ... & ... \\ w_n/w_1 & w_n/w_2 & ... & w_n/w_n \end{vmatrix} \qquad (3A.2)$$

Note we have assumed that we know the weights of the stones with certainty in Equation 3A.2. Therefore, if we multiply this matrix by the transpose of the vector of weights, $w^T = (w_1, w_2, \ldots, w_n)$ we obtain the vector n***w***, where n represents the number of stones (attributes) being compared.

The problem can now be expressed as:

$$\boldsymbol{A}\, w = n\, w \qquad (3A.3)$$

This mathematical problem has a nonzero solution only if n is an eigenvalue of the matrix ***A***. Furthermore, ***A*** has unit rank since every row is a constant multiple of the first row. Thus all the eigenvalues λ_i, i = 1, 2, ..,n of ***A*** are zero except one.

It is also known that

$$\sum_{i=1}^{n} \lambda_i = \text{sum of the diagonal elements of } \boldsymbol{A} = n$$

Therefore, only the largest eigenvalue is nonzero:

$$\lambda_{max} = n \quad \text{and} \quad \lambda_i = 0 \text{ for } \lambda_i \neq \lambda_{max}$$

and the original vector of weights is represented by the eigenvector corresponding to the maximum eigenvalue, λ_{max}, of the matrix of decisions ***A***.

In this case, the matrix ***A*** is consistent, it satisfies the property

$$a_{ij}\, a_{jk} = a_{ik}$$

which means that if we are given a row of ***A***, we can reconstruct the whole matrix ***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 ***A*** after normalizing it by the sum of its elements.

Let us return to the decision matrix, ***A***, Equation 3A.1. 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 therefore Equation 3A.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 ***A*** consists of ones ($a_{ii} = 1$) and the variations of the a_{ij} are small, the largest eigenvalue, λ_{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 *w* that satisfies

$$\boldsymbol{A}\, w = \lambda_{max}\, w \qquad (3A.4)$$

To make *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. Therefore, it is unlikely that the decision matrix ***A***, Equation 3A.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 ***A*** is consistent if and only if $\lambda_{max} = n$ and since humans are involved it is more likely 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:

$$C.I. = (\lambda_{max} - n) / (n - 1) \qquad (3A.5)$$

The consistency index of a randomly generated reciprocal matrix based on a scale 1 to 9, with reciprocals forced is called the random index, R.I. The average values for the random indices, R.I., for matrices of order 1 - 15 obtained from a sample size of 500 are listed, as given by Saaty as follows:

RI. Number	*Value*	*R.I. Number*	*Value*
1	0.00	8	1.41
2	0.00	9	1.45
3	0.58	10	1.49
4	0.90	11	1.51
5	1.12	12	1.48
6	1.24	13	1.56
7	1.32	14	1.57
		15	1.59

The ratio of C.I. to the average R.I. for the same order matrix is called consistency ratio, C.R. After performing many experiments Saaty concluded that if C.R. 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 forced mathematically but this is not advised since it might distort the answer to our problem. Improved judgment based on experience is the preferred alternative.

Appendix 3B Summary and Steps for Formulating Selection 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. 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 3.1.

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 summary of these cogent points are presented.

A designer is faced with the task of converting a design problem into a mathematical form that is amenable for solution. Assuming that a design problem has been partitioned the following steps[3] are involved in converting a design problem into a form amenable for computer solution:

Write the problem statement. This provides the basis for identifying and developing all the system descriptors for the selection DSP.

Develop the word formulation of the selection DSP based on the information that is provided in the problem statement. The word problem is structured using key-words.

Structure the information into a manner that is amenable for computer solution.

It should be remembered that iteration between the steps is normal and invariably time-consuming. You will need to budget for this in your schedule.

3B.1The Preliminary Selection DSP

In this section a summary (details in 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.

---

3 Many students ignore this advice and start by attempting to draw the solution space; this is a prescription for disaster. They hope that by so doing they can work their way to the problem statement and afterall since this is a classroom exercise no one will be any the wiser. In our opinion they are wasting the opportunity they are being given to learn through doing and are hence short-changing themselves. Afterall which designer is ever going to be asked to write a problem statement for a design that already exists?

Describe each concept and list the advantages and disadvantages and assign 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 +1, while a worse concept is given a -1 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 "most-likely-to-succeed" 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 most-likely-to-succeed. 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 most-likely-to-succeed concepts.

Valtidate The results through critical examination and convince yourself of their correctness. Document insight.

MAKE YOUR RECOMMENDATION.

3B.2The Selection DSP

In this section a summary (details in 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.

Appendix 3C. The Preliminary Design of A V/STOL Aircraft

It is required to produce a design of a V/STOL aircraft with the following specifications:

- It must be capable of carrying 12 passengers or 3,000 pounds of payload.
- It must be capable of carrying its cargo for at least 800 nautical miles.
- It must have a minimum speed of 400 knots.
- It must be marketable in civilian and military markets.

Eventually, the final design will have to meet safety regulations, economic restrictions and other constraints.

3C.1 Generating Concepts

First, we need to generate a set of *independent parameters* or *categories*. Using attribute listing, we might develop the following list:

- Types of vertical and short take-off and landing configurations,
- Types of wings that can be used,
- Engine types,
- Fuselage configurations,

- ❑ Schemes for balancing the thrust in vertical take-off,
- ❑ Landing gear types,
- ❑ Fuel arrangements, and
- ❑ Cabin layouts,.

There are many attributes we could list, but for this example we will work with the first five attributes that we have listed. So our independent parameters are (see Figure 3C.1): V/STOL configuration, wing configuration, engines, thrust balance and fuselage layout.

The next step is to schedule a brainstorming session with our experts in V/STOL technology, aerodynamics, controls, propulsion and so forth. The goal of the brainstorming session will be to generate *ideas* or *design alternatives* for each independent parameter. To further augment the idea generation of the brainstorming session, we will be employing checklisting and synectics. The leader of the session would be responsible for providing checklist questions to help get the session going or keep it going when slow spots occur. In our airplane problem some of the questions might be:

- ❑ What possible means can a vehicle employ to lift itself off the ground?
- ❑ How can an aircraft be balanced?
- ❑ What elements are common to the civilian and military transportation markets?

Synectics would also be useful in facilitating the brainstorming session. The use of the direct analogy might occur in the analogy between VTOL aircraft and animals that hover, such as dragonflies or hummingbirds. The personal analogy could useful as well, helping the members of the session individually to visualize the needs of the aircraft. Although it might seem strange to think of an aerodynamicist spreading his arms to check the angles for a swing-wing design, for example, it should not. One of the most important things to remember about brainstorming is that there should be no pressure to have a sober, serious discussion. A little levity is useful to help stimulate the imagination, and perhaps the personal analogy stratagem of synectics could be very stimulating.

The morphological chart of a brainstorming session is presented in Figure 3C.1. A number of design alternatives have been generated for each parameter. Now that the morphological chart has been generated and populated, we randomly select a design alternative from each parameter and construct a design concept. This of course leads to some concepts that are ludicrous or impossible - or so we might think at this time. That is why the selection is random, so that we are forced to explore many permutations we would not think of otherwise. After some consideration, the number of concepts is narrowed down to ten. Drawings of the concepts are given in Figure 3C.2.

3C.2 Ideation and Designing for Concept

The application of human creativity is an exciting domain that is one of the most challenging and rewarding activities that the human mind can undertake. A new branch of computer study known as artificial intelligence has recently emerged as a promising area to replace human effort for routine tasks or functions requiring the application of rules developed by experience or practice. While the present capabilities of computers preclude their use for creative thinking, many of the organizational and assistance tasks of the computer can be applied to augment the creative process. For example, the computer can be made to carry out a dialogue with a designer using a check list of standard questions. The computer can also be used to assemble design alternatives using a matrix method. The computer can organize and present information with lightning speed. The computer has no emotional, cultural or social barriers, is never critical, never laughs at the user and never forgets an idea. Thus it is an ideal assistant to the creative designer if applied correctly. Unfortunately, the present day computer does not have intuition, can make only quantitative judgments, and cannot deal with abstract concepts. As the area of artificial intelligence improves, the computer will enrich the creative problem solving environment.

3C.3 An Example to Illustrate the Preliminary Selection of Concepts

The problem, described earlier, has been taken from reference [Team, 1983] and we have developed the problem using information from [Team, 1983 Kuchemann, 1978 Powers, 1981; Thurston, 1978]

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.

CATEGORIES	*IDEAS*				
V/STOL Configuration	Helicopter	Augmentor Wing	Tilt Nacelle	Vector Thrust	Lift Engine
Wing Configuration	Conventional	Canard	Tandem		
Engines	Piston	Gas Turbine	Turbo Fan	Tandem Fan	
Thrust Balance	Thrust on Center Line	Thrust from Opposite Ends	Thrust from One End Only		
Fuselage Layout	Central Fuselage Engine in Fuselage	Center Fuselage Engines in Wings	Fueslage Pod Engines in Twin Booms		

1. *Concept One - Tandem wing, Tandem Engine (TWTE): This concept features tandem fan engines which also provide lift by a type of rector thrust. The wing layout is a pair of tandem wings for a small, easily parked craft.*
2. *Concept Two - Conventional wing, tile nacelle (CWTN): Here, a conventional wing is paired with two cruise turbo jets and two lift/cruise turbo fans.*
3. *Concept Three - Conventional wing, lift engines (CWLE): This concept has four stowable lift turbo fans and two cruise engines.*
4. *Concept Four - Canard augmentor wing (CNAW): Two turbo fans are placed at the rear of a canard wing setup.*
5. *Concept Five - Helicopter (HELI): This concept is a conventional helicopter, with gas turbine engines.*
6. *Concept Six - Tandem wing, lift engine (TWLE): The small overall area of the tandem wins is combines with one lift engine and two tilt nacelles.*
7. *Concept Seven - Twin tail, vector thrust (TTVT): A twin tail with fuselage pod provides very easy cargo access. Two rector thrust engines provide lift and cruise thrust.*
8. *Concept Eight - Conventional augmentor wing (CWAW): A conventional transport layout is provided with augmentor technology for V/STOL.*

NOTES:

1. "Categories" are created using "Attribute Listing".
2. "Ideas" created using "Brainstorming". The output of brainstorming is improved through "Checklisting" and "Synectics".
3. You might be tempted to qualify "Engines" by varying horse power. This would be wrong - the ideas would not be independent of each other.

Figure 3C.1. Creation of concepts for V/STOL problem using a Morphological Chart

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 3C.2a and 3C.2b .

- 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 four 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 conven-tional transport layout is provided with augmentor wing technology for V/STOL capability via two engines mounted on the conventional wing.

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 3C.1. The attribute listing technique (see Chapter 1, Volume 1) 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 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 to be 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 3C.1. It is necessary to record the underlying reasons for the decisions. This is extremely important. In practice, this task requires a lot of information gathering and discussion and involves considerable time and effort. In the summary that follows, to demonstrate the method, more detail is provided for the first generalized criterion than the others. In practice, the level of detail that is provided must be the same for all cases.

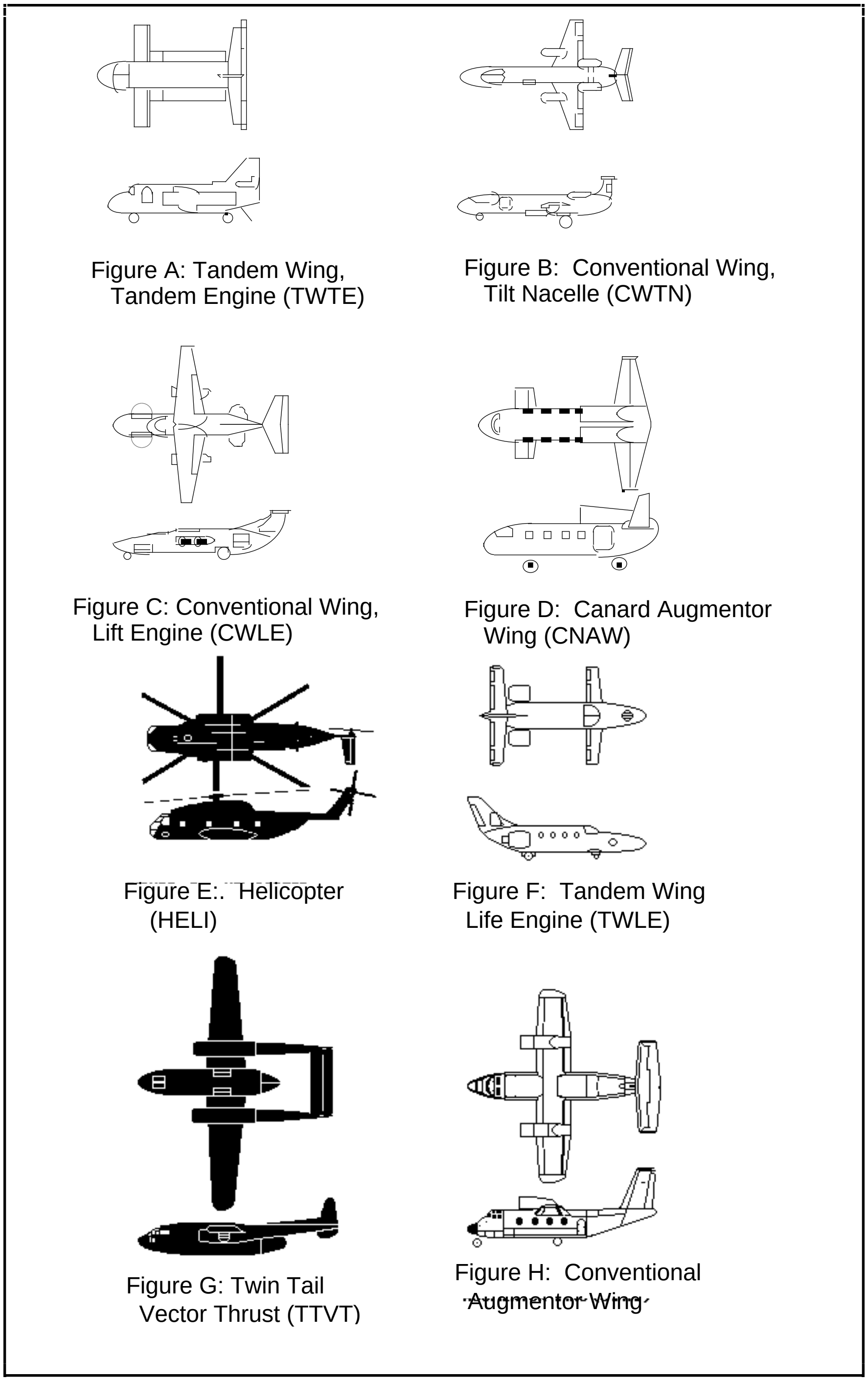

Figure 3C.2. V/STOL aircraft concepts

Generalized Criterion: Safety

- *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 four 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 mechanics? The CNAW, helicopter, the TTVT and the CWAW have the same complexity of mechanics 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.

Generalized Criterion: Performance.

- *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?

Table 3C.1. Preliminary selection: scores and ranks

	CONCEPTS							
	TWTE	CWTN	CWLE	CNAW	HELI	TWLE	TTVT	CWAW
SAFETY								
Engine out/STOL	0	0	0	-1	0	0	0	-1
Engine out/VTOL	0	-1	0	-1	-1	-1	-1	-1
Simplicity	0	-1	-1	0	0	-1	0	0
Reliability	0	-1	-1	1	0	-1	+1	-1
Score	0	-3	-2	-1	-1	-3	0	-3
Normalized score	1	0	0.33	0.67	0.67	0	1	0
PERFORMANCE								
Range vs. Payload	0	0	0	0	-1	0	0	0
Ground effects	0	0	0	0	0	0	0	0
Cruise speed	0	0	0	0	-1	0	0	0
Stability	0	+1	+1	0	-1	0	+1	+1
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	-1	+1	+1	+1	+1	0
Power matching	0	0	+1	+1	+1	0	+1	+1
Technology	0	+1	+1	0	+1	+1	+1	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	-1	-1	-1	0	-1	+1	+1
Passenger comfort	0	-1	-1	0	-1	0	0	0
Landing surface	0	0	0	+1	+1	0	0	+1
Parking space	0	-1	-1	-1	0	0	-1	-1
Noise	0	0	+1	0	-1	0	+1	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	2.5	1.33	1.91	2.59	2.17	1.92	4	2.66
Ranks	4	8	7	3	5	6	1	2

A '-' implies 'worse than the datum' and is represented as a '-1'. A '+' implies 'better than the datum' and is represented as a '+1'. A '0' implies 'same as the datum' and is represented as a '0'. Note: Scores for each generalized criteria are obtained by equal weights of 1.0 (Ij) assumed for every entry. The scores are then normalized. The total scores (overall merit function values) are obtained once again by equal weights of 1.0 (Ij) assumed for the normalized scores of every generalized criteria. It is imperative that viewpoints are provided; they have been omitted from the text in the interest of brevity.

Generalized Criterion: Economics.

- *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?

Generalized Criterion: Market Potential

- *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 the concepts with respect to the four generalized criteria are computed and are shown in Table 3C.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 3C.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 3C.3 are obtained by using the information presented in Table 3C.1. The preliminary selection solution procedure involves the use of multiple datums. In Figure 3C.3, results after using the all of the scenarios are presented.

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 are shown in Table 3C.2. The normalized scores on completion of this first comparison is shown in Table 3C.3a and the final scores (after comparison using five datums) are shown in Table 3C.3b. For example, the overall merit function value for concept TWTE, scenario 1 is calculated using information from Table 3C.1 as follows:

$$0.4\ (1) + 0.2\ (0.75) + 0.2\ (0) + 0.2\ (0.75) = 0.70\ .$$

This score is entered in the appropriate location in Table 3C.3a. The overall values of the merit function are plotted in Figure 3C.3. Note, as is evident by looking at Table 3C.3a, TTVT dominates all the concepts. This is indicative that the formulation of the problem and/or the viewpoints are in error. It is important at this time to review the formulation and the viewpoints. We will, however, continue and the effect of this decision is evident in the results shown in Table 3C.3a.

Step 7 Post-solution analysis: determine the most-likely-to succeed concepts. In Table 3C.3b the top three concepts for each of the scenarios are shown in bold. It is seen that the Twin Tail Vector Thrust (TTVT, Figure 3C.2, Subfigure G) "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 most-likely-to-succeed concepts be identified and the selection DSP is formulated and solved.

It is seen, from Table 3C.3b, 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 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 3C.3b it may appear that TTVT, CWAW and CNAW are the most-likely-to-succeed concepts for Phase 2 of the selection process. From Figure 3C.3, 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 most-likely-to-succeed concepts, namely, TTVT (twin tail, vector thrust), CWAW (conventional augmentor wing), CNAW (canard augmentor wing), TWTE (tandem wing, tandem engine)].

Table 3C.2. Scenarios for the relative importance of generalized criteria

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 3C.3. Preliminary selection: normalized scores

		Scenario				
	Concept	*One*	*Two*	*Three*	*Four*	*Five*
1	*TWTE*	*0.700*	0.650	0.500	*0.650*	*0.650*
2	*CWTN*	0.266	0.466	0.332	0.266	0.366
3	*CWLE*	0.448	0.582	0.448	0.432	0.507
4	*CNAW*	*0.652*	*0.668*	*0.652*	0.618	0.643
5	*HELI*	0.568	0.434	*0.634*	0.534	0.484
6	*TWLE*	0.384	0.534	0.518	0.484	0.509
7	*TTVT*	*1.000*	*1.000*	*1.000*	*1.000*	*1.000*
8	*CWAW*	0.466	*0.666*	0.532	*0.666*	*0.666*

(a) Normalized Scores: First Datum (See Table 3C.1)

	Scenario					
	Concept	*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*
8	*CWAW*	0.621	*0.744*	0.610	*0.744*	*0.744*

(b) Normalized Scores: Solution (Plotted in Figure 3C.3)

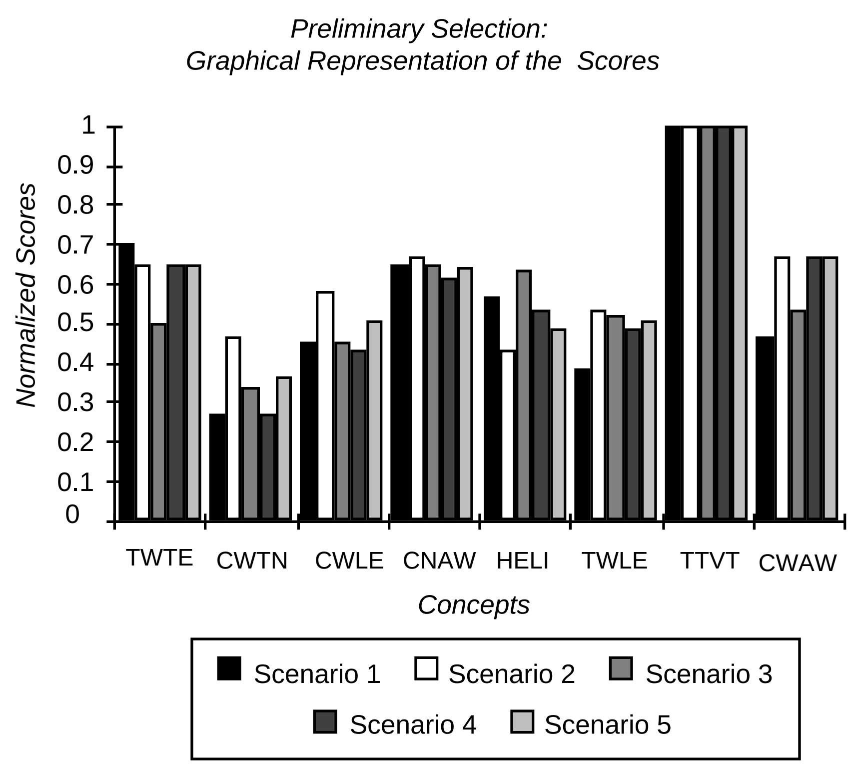

Figure 3C.3. Preliminary selection: graphical representation of the scores

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

3C.4 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 Chapter 3. The steps associated with the selection DSP are explained in Section 3.2.2. An example based on the most-likely-to-succeed concepts identified in Section 3C.3 is presented.

It is assumed that the concepts have been developed into feasible alternatives 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 3A and for the example problem the relative importances using both methods have been computed and presented in Table 3C.4. Note that the relative importances determined, using three methods, are different.

Table 3C.4. The relative importance of attributes - a comparison

		Normalized Relative Importance		
	Attribute	*Method 1*	*Method 2*	*Method 3*
1	Payload, or useful load	0.156	0.167	0.137
2	Range	0.044	0.020	0.027
3	Simplicity of design	0.178	0.194	0.206
4	Power matching	0.200	0.222	0.328
5	Cargo accessibility	0.111	0.111	0.069
6	Landing site restrictions	0.022	0.0	0.023
7	Parking area	0.089	0.083	0.061
8	Achieved stability	0.067	0.056	0.042
9	Engine out safety	0.133	0.139	0.105

Notes: The larger numbers indicate preference.

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 3C.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 3C.6. The comparison method (see Appendix 3A) 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 3C.7. The upper and lower bounds for the scales were specified in Step 3. As indicated earlier the bounds for the ratio scales must be established after very careful consideration.

Table 3C.5. Examples of the creation of interval scales

ATTRIBUTE 3 - SIMPLICITY	
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	
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 3C.6. Example of the creation of composite attribute ratings

POWER MATCHING											
	Decision Number										
	1	2	3	4	5	6	7	8	3C	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	3/10 = 0.3
Dummy				0			0		0	0	0/10 = 0.0

Note: Viewpoint must be included.

Table 3C.7 Attribute Ratings (A_{ij})

	Attributes								
Alternatives	PLOD	RNGE	SIMP	PMCH	CACC	LRES	PARK	STAB	ESAF
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

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 3C.8.

Table 3C.8. Evaluation of normalized relative importance of attributes

	Attribute (j)	Normalized Rank	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.

Step 5 Evaluate the merit function for each alternative. The merit function values are calculated using Equation 3.3, the normalized ratings (Table 3C.9) and the normalized relative weights of the attributes Table 3C.8. The merit function values together with their percentage differences are presented in Table 3C.10. It is clear from Table 3C.10 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, stability and engine out safety. 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.

Table 3C.9. Normalized attribute ratings (R_{ij})

	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 3C.10. Merit function values and final rankings for the alternatives

Alter-natives	*Merit Function Values*	*Percent Difference Between the Best and Others*	*Overall Rank*
*CW*AW	0.504	0.0	1
TTVT	0.493	2.2	2
CNAW	0.430	14.7	3
TWTE	0.413	18.1	4

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 2.8) 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:

$$M'_{CWAW} = 0.493C \text{ and } M'_{TWTE} = 0.427.$$

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:

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

$M'_{CWAW} = 0.500$ 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 i,j 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 3C.4. So also are the corresponding lowest merit function values. The merit function values from Table 3C.10 are labeled “No change” in Figure 3C.4.

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 3C.10. In column two of Table 3C.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 3C.10). 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 coming out on top (compare $M_{TTVT} = 0.439$ with the numbers for CWAW in column two). It is also evident from the numbers shown in Table 3C.11 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.

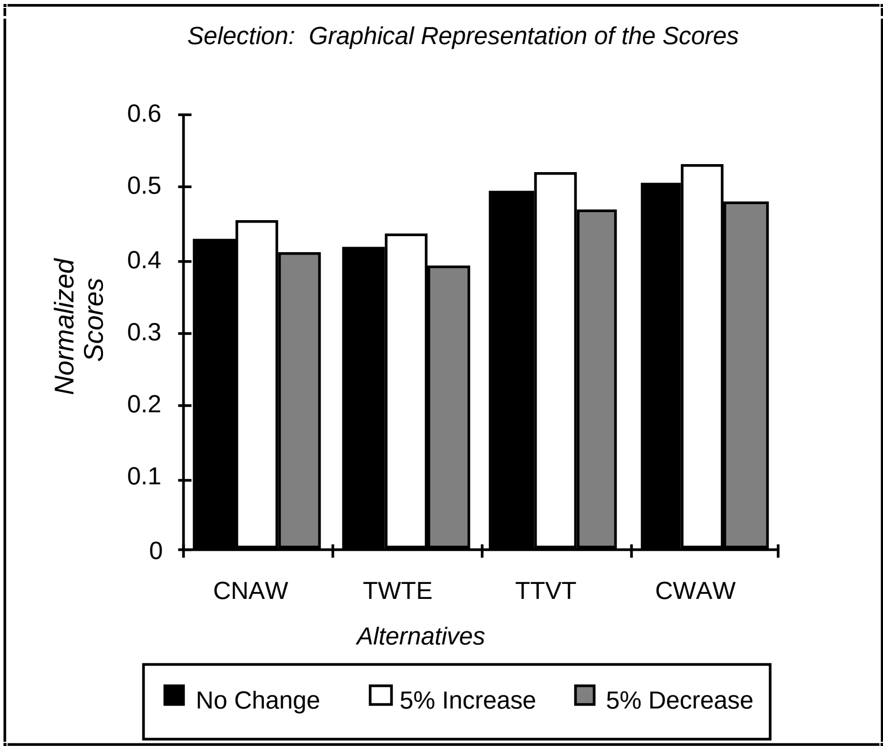

Figure 3C.4. Variations in Merit Function Values

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 3C.11. 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 3C.11 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.

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Appendix 3D Design Through Selection; the Use of QFD in the Attribute Generation Process

This structured selection approach described in this chapter has been successfully applied in a number of academic and industrial environments. Given a problem statement, new users quickly learn to generate concepts and identify the most promising ones based on first impressions-based criteria. A difficulty arises, however, when they are asked to refine these criteria into a more complete set of attributes. In this Appendix, a way to enhance the process of formulating a selection DSP is illustrated. This involves the use of the Quality Function Deployment, QFD, as an auxiliary technique to aid in the identification of attributes.

3D.1The Quality Function Deployment Method

This structured selection approach described in this chapter has been successfully applied in a number of academic and industrial environments. Our experience is that given a problem statement, new users quickly learn to generate concepts and identify the most promising ones based on first impressions-based criteria by solving a preliminary selection DSP. A difficulty sometimes arises, however, when they are asked to refine these criteria into a more complete set of attributes. In this Appendix, we propose to enhance the process of formulating a selection DSP by illustrating the use of the Quality Function Deployment, QFD, method as an auxiliary technique to aid in the identification of attributes. This is illustrated in Figure 3D.1. QFD provides us with a proven technique to generate these attributes based on the perceptions of the final recipient of the artifact of design, i.e. the customer of the design process. This customer might refer to a combination of members from the manufacturing team, the company itself and the final user of the artifact.

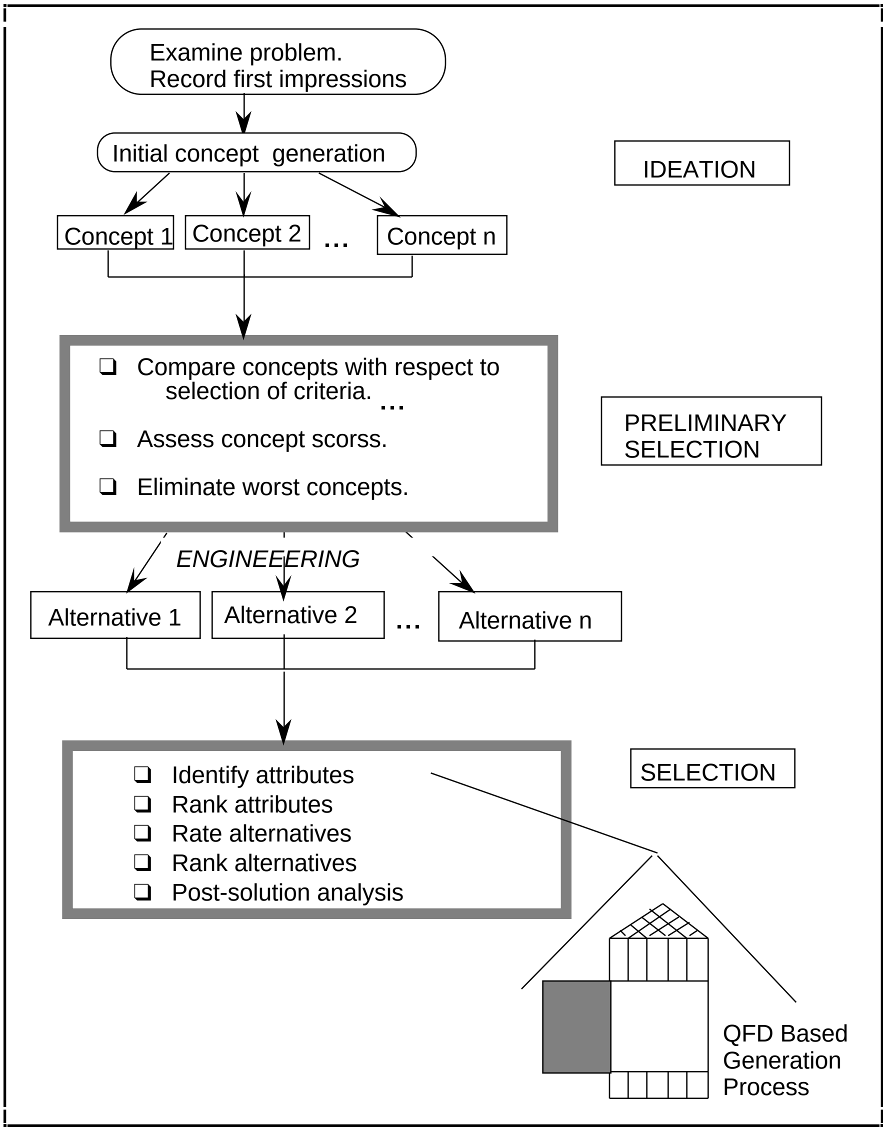

Figure 3D.1. Schematic of the Selection Process

Quality Function Deployment has been introduced as a system for translating customer requirements into appropriate company requirements at each stage of the product development process [22] and [23]. With QFD, broad product-development objectives are broken down into specific, actionable assignments with a comprehensive team effort. The process begins with the identification of customer requirements, usually expressed as qualitative characteristics. This is similar to the criteria employed in the preliminary selection described in the preceding section. These initial requirements are translated by way of QFD into “design requirements”, generally global product characteristics that will satisfy customer requirements if properly executed. This notion is very similar to the definition of attributes in the selection DSP. Based on these ideas it seems to us that QFD represents a natural bridge to develop selection attributes from initial customer defined criteria.

Implementation of QFD is based on graphical representation tools. In the basic matrix representation form or “house of quality”, initial customer requirements are represented as “what” items, Figure 3D.2. One example would be the criterion of resistance for a product. To provide further definition, each “what” item is broken into one or more “how” items. These items represent technical requirements (selection attributes in our case). The process of transforming each “what” item into one or more “how” items is similar to the process of refining marketing specifications into system level engineering specifications. The process is continued until every item on the list is actionable. It is important to note that some of the “what” items affect more than one “how” item. These relationships between “what” and “how” items are traced via a relationship matrix, as illustrated in Figure 3D.2. Unique symbols are used to depict weak, medium or strong relationships. Running parallel with the “how” axis on the bottom edge of the relationship matrix is a third element, the “how much” axis. These items represent measurements for the “how” items and provide an indication of the magnitude of the measurements or the type of scale to be used in assigning quantitative values to these items. In our case, the “how much” element provides a link to the creation of attribute scales.

The triangular “correlation matrix” is located parallel to and above the “how" axis”. This matrix describes the correlation between each “how” item (selection attributes) via unique symbols that represent positive or negative ratings and the strength of each relationship. By charting conflicting relationships the matrix facilitates timely resolution of trade-off issues. The correlation matrix can be used to identify which

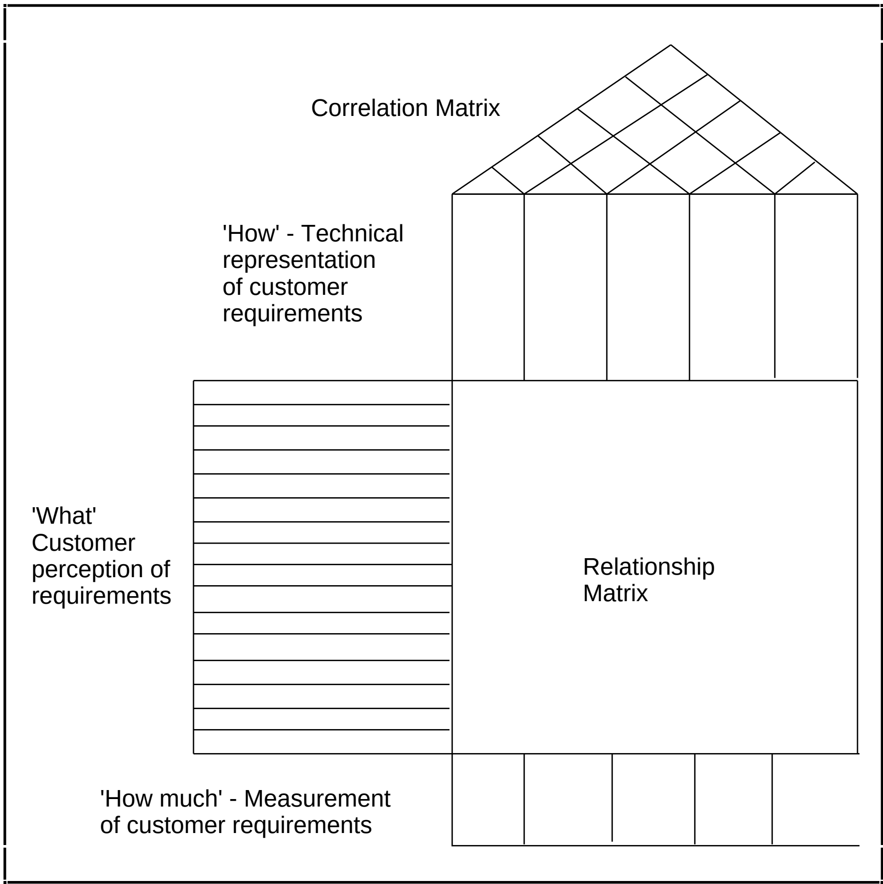

Figure 3D.2 . QFD matrix representation

"how" items support one another and which ones are in conflict. In positive correlations, one "how" item supports another "how" item. In negative correlations the two "how" items are in conflict, indicating the need to consider trade-offs among the items. In the context of a selection problem, these conflicts indicate attributes for which high alternative ratings are associated with low ratings with respect to the conflicting attribute. This information plays an important role in the post-solution analysis of the selection process. This is illustrated in Step 7 as illustrated in the case study presented in the following section.

An important feature of the QFD matrix representation is that it can be built in many shapes and forms to meet almost any need; one of its greatest strengths is the possibility of tailoring it to the application.

The what/how/how much process forms the basis for almost all QFD charts. In addition to this basic structure relating criteria and attributes in the selection process discussed in this paper, our QFD representation is enhanced through the use of the correlation matrix to detect conflicts among attributes and a process of weighting and rating to reduce the number of attributes under consideration. This is illustrated in the following section. The use of additional QFD related structures such as the competitive assessment vectors [22] are not considered in our model.

3D.2An Example to Illustrate the Process

The example presented to illustrate the process was originally proposed by Pugh [16] and later adapted in [1] to illustrate the structure of the selection DSP. In the problem statement we are required to come up with an appropriate conceptual design for an audible means of warning of approach for an automobile (car horn). The solution to the problem is presented following the selection DSP formulation steps described in Section 3.2.2. We concentrate on the steps involved in attribute identification.

- *Step 1. Identification of alternatives.* Assume that a number of concepts have been developed into alternatives through engineering and refinement. Describe each alternative in words (or figures), and set forth the advantages and disadvantages of each.

The alternatives illustrated in Figure 3D.3 are described as follows:

Alternative 1	Electromagnetic diaphragm, the diaphragm is attached to the vibrating shaft driven by a rapidly changing magnetic field thereby creating noise.
Alternative 2	Aeroacustic horn, high speed rotary vanes force air out through nozzles producing noise.

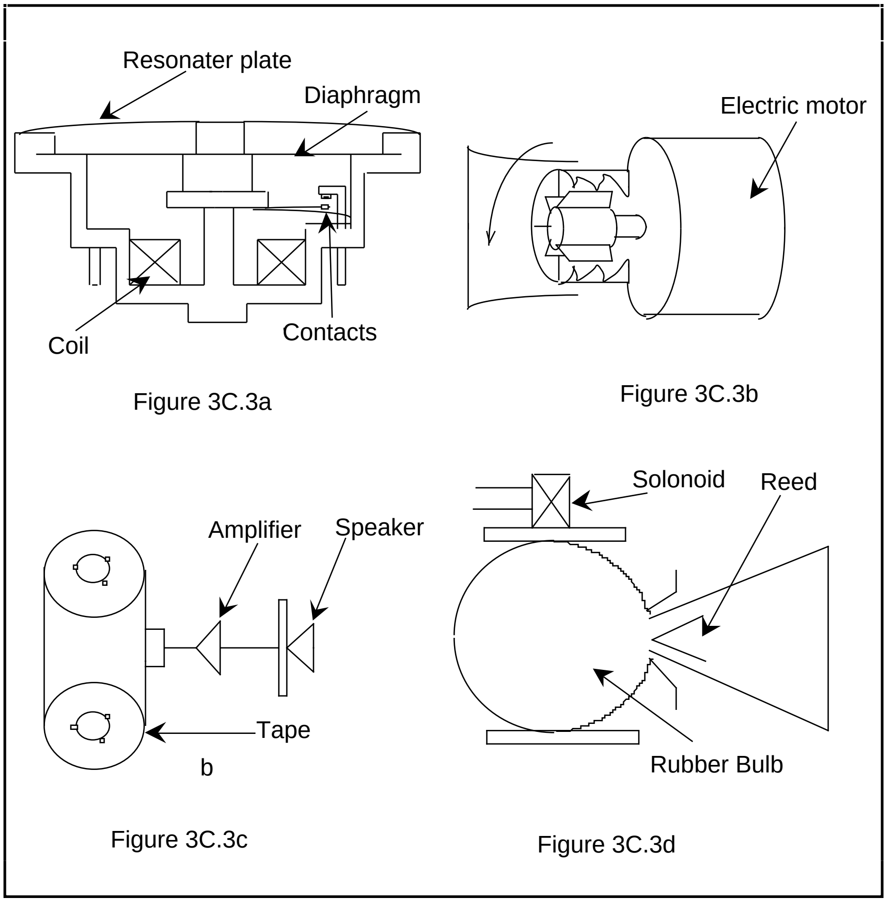

Figure 3D.3. Alternatives for horn selection problem (a) electromagnetic diaphragm, (b) aeroacustic horn, (c) tape driven horn, and (d) rubber bulb.

Alternative 3	Tape driven horn, recorded impulses on electromagnetic tape are picked up, amplified and broadcast.
Alternative 4	Rubber bulb, solenoid is magnetized and demagnetized alternately. Magnetic core moved up and down compressing and releasing the bulb to force air through reeds to produce noise.

- *Step 2. Identification of attributes and relative importances.* After the alternatives have been determined, the next step is the identification of attributes by which the alternatives are to be judged. An attribute represents a quality of the desired solution and this quality must be quantifiable.

The auxiliary procedure proposed in this work involves the transformation of customer specified criteria into more complete and "actionable" attributes through the use of QFD. The following additional steps are proposed:

- *Step 2.1. Identification of user requirements.* As a result of the needs identified in the problem statement, a vector of "how" items or user requirements is formed. If a preliminary selection process has been performed, the associated criteria can in most cases be used in this step.

  This vector is illustrated at the left of the QFD relationship matrix illustrated in Figure 3D.4. A desirable horn as identified by the user is one that presents the following characteristics: loud noise, quick response, resistant, easy to repair, easy to install, small, requiring minimum maintenance and low cost.

- *Step 2.2. Identification of technical requirements.* Initial customer requirements (criteria) are transformed into technical or design requirements by decomposing them into concrete or actionable items. This "what" vector is composed of a number of candidate attributes.

  This vector is illustrated at the top of the QFD relationship matrix illustrated in Figure 3D.4. For example, the user requirement "resistance" is transformed into "resistance to vibration and temperature and resistance to water and moisture". In the same manner, the following candidate attributes are identified: sound level, response time, number of parts, complexity, number of stages, ease of installation, ease of maintenance, size, power consumption and manufacturing cost (note that this problem is slightly different than the one presented earlier.)

  Associated with these candidate attributes is the information presented in the "how much" row illustrated at the bottom of Figure 3D.4. Each attribute is

User Requirements "What"		Sound level (Dba)	Response time	Resistance to vibration, temperature	Resistance to moisture water	Number of parts	Complexity, number of stages	Ease of installation	Ease of maintenance	Size	Power consumption	Manufacturing cost
		Technical Requirements "How"										
Loud noise	5	◎									△	○
Quick response	5		◎				△					
Resistant	3			◎	◎	△	○					
Easy to repair	2				△	○			◎			
Easy to install	2							◎				
Small	2					△				◎	△	
Minimum maintenance	3			○	○	◎	○			○		
Cheap	4			△	△	△	△			△		◎
"How much"		100 - 125 db	Less than 2 sec.	Expert judgement	Expert judgement	Expert judgement	Expert judgement	Expert judgement	Time interval	Less than 150 mm	Less than 200 W	Less than $30
Importance ratings		45	45	40	40	42	24	18	18	28	7	45

◎ Strong (9) ○ Medium (3) △ Weak (1)

Figure 3D.4. Relationship matrix and ranking of "how" items associated with a range of values or an indication for the need of expert judgment that can be later used to identify scales in Step 3 of the selection DSP structure.

- *Step 2.3. Relationship Matrix.* After the candidate alternatives have been identified, the next step involves the documentation of interactions between the original customer requirements and candidate alternatives. Commonly used symbols are a triangle for weak relationships, a circle for medium relationships and a double circle for strong relationships, Figure 3D.4. Numerical values of 1,3 and 9 are respectively associated with these relationships. If no relationship exists, the matrix space is left blank. As an example consider the initial requirement "easy to repair". This requirement presents a strong relationship with the candidate attribute "ease of maintenance", it is also related to the number of parts and the complexity of the design artifact. Finally a weak relation is depicted with the attribute "resistance to water and moisture", since it is usually associated with hermetic, hard to open cases.

- *Step 2.4. Ranking of Technical Requirements and Identification of Attributes.* In traditional QFD theory, the "what" items are rated based on a one to five scale. A numerical value is placed to the right of each "what" item to reflect the relative importance of this item to the customer. The values assigned in this example are illustrated in Figure 3D.4 to the right of the customer defined criteria. Loud noise and quick response are considered to be the most important ones with a rating of five. These ratings are then multiplied by the weights assigned to each matrix symbol (weak, medium, strong) to obtain a final score that can be used to rank the attributes and identify the ones that are critical for a correct selection.

  Based on the decisions illustrated in Figure 3D.4, the following attributes are identified for this problem: sound level, response time, resistance to vibration and temperature, resistance to water and moisture, number of parts, size and manufacturing estimated costs. It is important to note that the final choice as to which attributes to eliminate depends solely on the designers judgment and experience.

Table 3D.1. Relative importance of attributes

0 Sound level	0.439
Response time	0.201
Resistance to vibration and temperature	0.047
Moisture and water resistance	0.044
Number of parts	0.0256
Size	0.087
Cost	0.155

After the attributes have been identified, the Reciprocal Matrix Comparison method described in Appendix 3A is used in our example to determine the relative importance of the attributes considered. The results obtained are presented in Table 3D.1. The values reflect a strong importance associated with the sound level attribute, followed by response time and cost.

- ❑ *Steps 3 and 4. Specify scales, rate the alternatives with respect to each attribute. Normalize the ratings.* Four types of scales are described in Section 3.2.2, namely, ratio, interval, ordinal and composite. The choice of a particular type of scale to model an attribute depends on the nature of available information as presented in the "how much" row of the QFD relationship matrix. Once the scales are established, the rating of alternatives with respect to the resulting attributes is recorded. The justification of each rating is extremely important as described in Section 3.2. Finally, the ratings are normalized using Equations 3.1 and 3.2.

- ❑ *Step 5. Evaluate the merit function for each alternative.* A merit function combines all the individual ratings of attributes together using proper weights defined earlier. The linear model described in Figure 3.5 is recommended in most cases.

❑*Step 6. Post-solution sensitivity analysis.* Post-solution analysis of the selection DSP consists of two types of activities as described in Section 3.2.2. These activities contemplate the 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. In this Appendix we investigate an additional post-solution study that can be performed by using the information obtained by constructing the correlation matrix on the QFD attribute generation process illustrated in Figure 3D.2.

This matrix describes the correlation between each “how” item (selection attributes) via unique symbols that represent positive or negative ratings and the strength of each relationship. Commonly used symbols are a circle to indicate a positive relationship and a cross to indicate a negative relationship, Figure 3D.5. In the context of a selection problem, negative relations or conflicts indicate attributes for which high alternative ratings are associated with low ratings with respect to the conflicting attribute. The addition of a correlation matrix to the QFD relationship matrix is illustrated in Figure 3D.4. It is observed that some trade-offs occur specially between the cost attribute and performance related attributes like resistance, sound level and response time. In general, enhanced performance will result in additional manufacturing expenses. This insight can be used to create additional scenarios where the relative importance of attributes is artificially varied to observe the results of the selection problem if more importance is given to each of the conflicting sets of attributes. Two scenarios corresponding to these extreme cases are presented in Table 3D.2, associated with the resulting alternative merit function values.

The first scenario presented in Table 3D.2 illustrates a strong preference for the performance attributes identified as conflicting with the cost related attribute. In the second scenario a strong preference is placed on the cost attribute, which might result on a different alternative as being the preferred one. By knowing the outcome of these extreme cases we are able to estimate the stability of our solution and perform more detailed trade-off studies by modifying the attribute relative importance vector

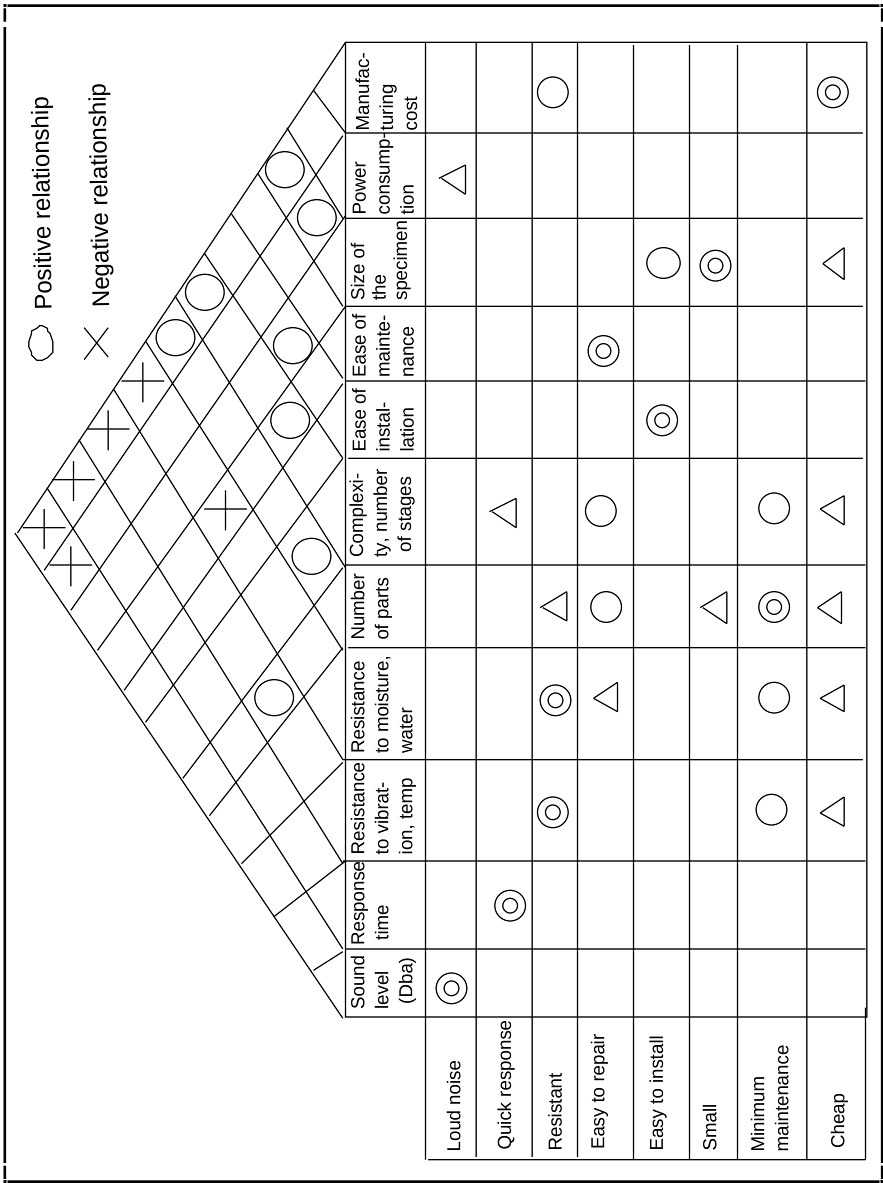

Figure 3D.5. Correlation matrix

Table 3D.2. Relative importance scenarios

Attribute	*Scenario 1*	*Scenario 2*
Sound level	0.2	0.04
Response time	0.2	0.04
Resistance to vibration and temperature	0.2	0.04
Water and moisture resistance	0.2	0.04
Number of parts	0.067	0.04
Size	0.067	0.04
Cost	0.067	0.76
Alternative	*Merit Function*	*Merit Function*
Electromagnetic	0.725	0.675
Bulb & Reed	0.665	0.826
Aeroacoustic	0.555	0.377
Recorded noise	0.437	0.280

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SUPPLEMENTARY NOTES 4

MECHANISMS

David Rosen

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<u>Types</u>

- Linkages
- Gear Trains
- Cams
- Drives - belt, CV, block-and-tackle, etc.

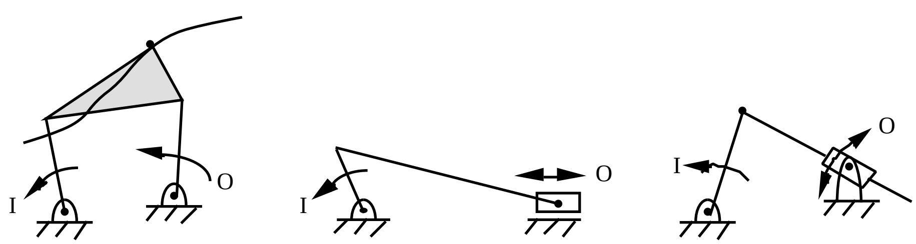
<u>Classify by Function</u>

- Vary rotational energy
- Convert rotation to translation
- Convert translation to rotation
- Channel energy => Transmit torque or force

<u>Classify by Motion Characteristics</u>

LINKAGES

Set of rigid bars joined by revolute (pin) or slider joints.
Simplest is 4-bar linkage
Non-linear input/output relationship: Position, velocity, acceleration, force



Driver
Coupler
Follower

Could drive by air cylinder
or hydraulic cylinder

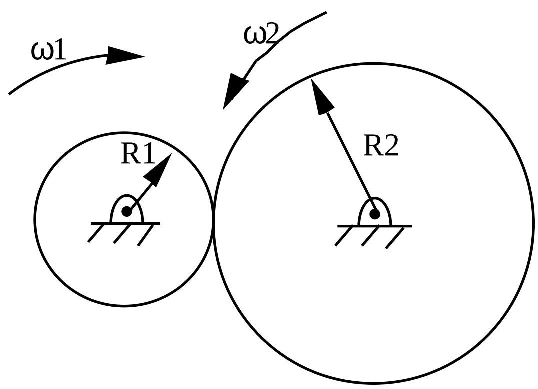
GEAR TRAINS

Characteristics:

- Linear position relationship between input and output.
- Constant velocity ratio.

Spur Gears

- Linear offset between in/out axes
- Parallel axes



$$\omega 1 R1 = \omega 2 R2$$

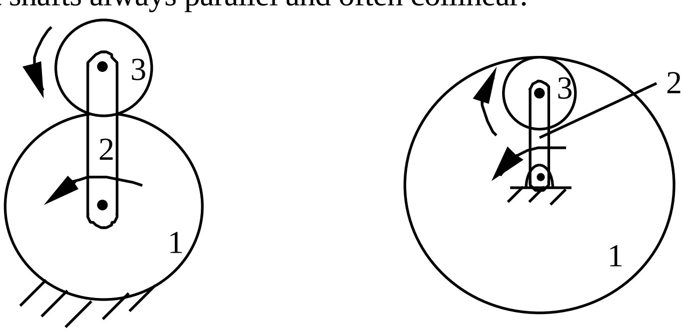
$$\frac{\omega 1}{\omega 2} = -\frac{R2}{R1} = -\frac{N2}{N1}$$

N = number of teeth

w2 = (R1/R2) w1
If R1 < R2, R2 spins more slowly
If R1 > R2, R2 spins more quickly

EPICYCLIC DRIVES (PLANETARY)

Inversion of regular gear trains
Input / Output shafts always parallel and often collinear.



(a) (b)

Applications: More compact than conventional gear trains

- Automatic transmissions in cars
- Helicopter transmissions
- Propeller airplane transmissions

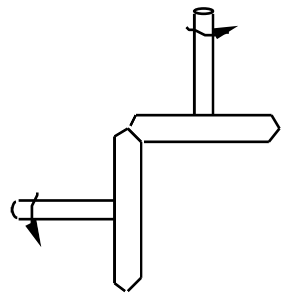
Rules of Thumb (for all types of gear trains)

Restrict mating gear ratios to be 8:1 or less

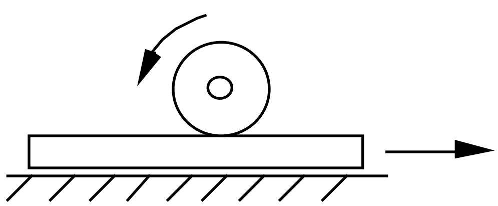
Each gear should have at least 12 teeth

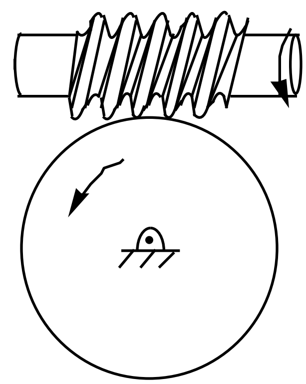
OTHER TYPES OF GEARS

Bevel: Non-parallel, intersecting shafts; (90 degrees); Change speed and direction



Rack and Pinion Rotation -> Translation

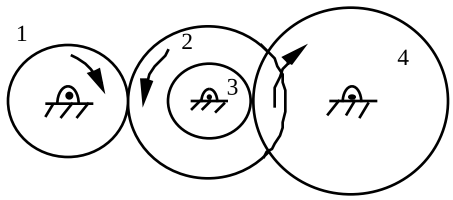




Worm: Axis change of 90 degrees; Non-parallel, non-intersecting shafts.
Self-locking - the Worm drives the pinion, but not the other way around.

GEAR TRAIN ANALYSIS

Velocity analysis of compound gear train. In cases where the needed gear reduction is too large for just one gear pair, pairs can be chained together.



$$\frac{\omega_2}{\omega_1} = -\frac{N_1}{N_2} \qquad \frac{\omega_2}{\omega_1}\left(\frac{\omega_3}{\omega_2}\right)\left(\frac{\omega_4}{\omega_3}\right) = \left(-\frac{N_1}{N_2}\right)\left(-\frac{N_3}{N_4}\right)$$

$$\frac{\omega_3}{\omega_2} = 1 \qquad \frac{\omega_4}{\omega_1} = \frac{N_1\,N_3}{N_2\,N_4}$$

$$\frac{\omega_4}{\omega_3} = -\frac{N_3}{N_4} \qquad \frac{\text{driven}}{\text{driver}} = (-1)^{I}\,\frac{\text{Product of driving gears}}{\text{Product of driven gears}}$$

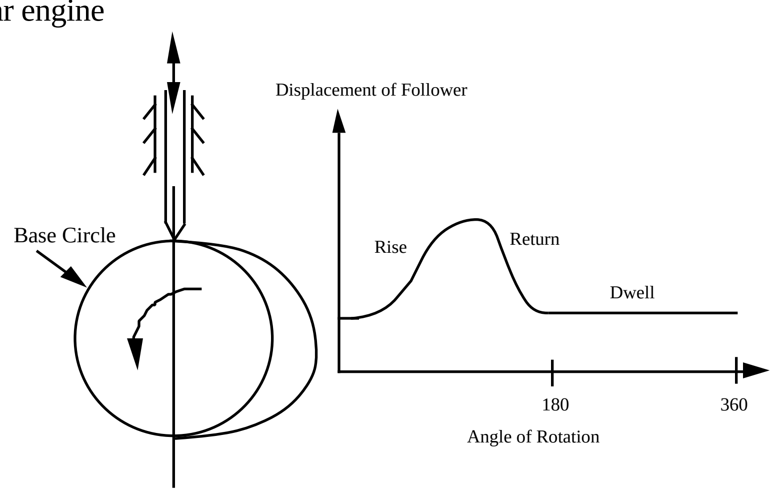
CAMS

Virtually any type of output motion from a rotational input. Rolling and Sliding joint

Can also connect linkages to followers to transfer and modify output motion.

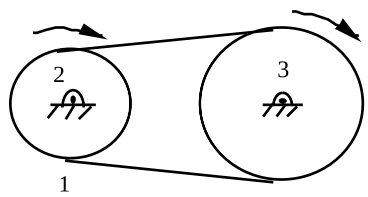
<u>Applications of Cams</u>

- Cams are prevalent in production/automatic equipment
- Rolling/sliding joints are very common
- Car engine



OTHER DRIVES

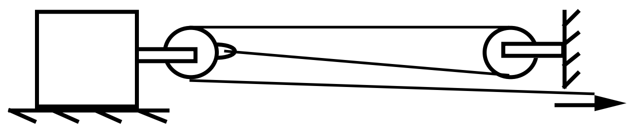
Belt and Chain drives.



$\omega 1 R1 = \omega 2 R2$

$$\frac{\omega 1}{\omega 2} = \frac{R2}{R1}$$

Parallel shafts. Constant velocity ratio



Block and Tackle **Force reduction of 3:1**

DEGREES OF FREEDOM (DOF)

Measure number of inputs necessary to determine position of every link in mechanism

DOF = 0 Structure

> 0 Mechanism

Link floating in the plane has 3 DOF:

translation along X and Y axes, plus rotation about Z axis.

Need to consider the numbers of DOFs removed by different joint types.

Joint Types	DOF	Removes DOF
Revolute	1	2
Slider	1	2
Gear	2	1
Rolling & Sliding	2	1
Screw (couples rotation and translation)	1	2

GRUEBLER'S EQUATION

Planar mechanisms

$$DOF = 3(L - 1) \cdot \sum_{i=1}^{J} f_i$$

$3(L - 1)$ = number DOF of $(L - 1)$ disconnected links (1 link is ground)

$\sum_{i=1}^{J} f_i$ = number DOF removed by all joints

Pair of links connected by revolute joint. One link is ground.

$L = 2$ $\qquad DOF = 3(2-1) - 2$

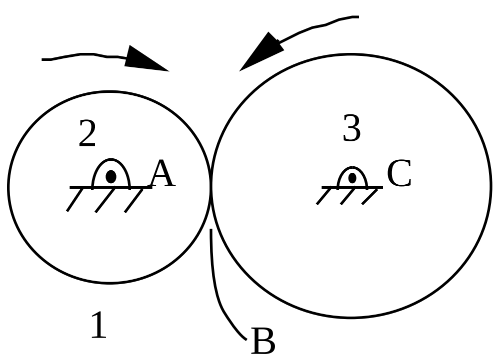
$J = 1$ $\qquad = +1$

4-bar

$L = 4$
$J = 4$
$f_i = 2, i = 1, \ldots, 4$

$$DOF = 3(4 - 1) \cdot \sum_{i=1}^{J} f_i$$
$$= 9 - (2 + 2 + 2 + 2)$$
$$= +1$$

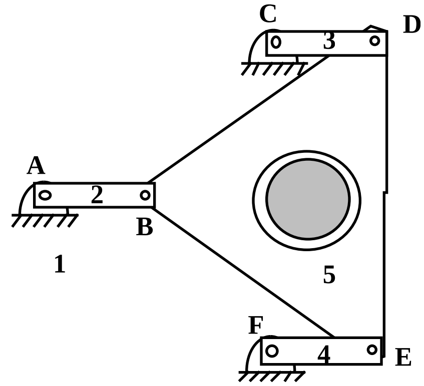
Simple Gear Train



$$DOF = 3(3 - 1) - (2 + 1 + 2)$$
$$= +1$$

PAINT MIXER

Patented design.
Unfortunately, the designers did not realize that they designed a moving structure

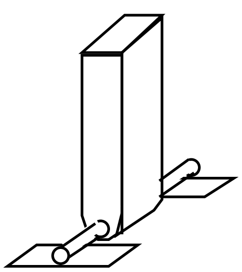


DOF: 5 Links, 6 Revolute Joints => 0 DOF

$$DOF = 3(L-1) - \sum_{i=1}^{J} f_i \quad \begin{aligned} &= 3(5-1) - (2+2+2+2+2+2) \\ &= 12 - 12 \\ &= 0 \end{aligned}$$

Solution: Expensive bearings to compensate for tolerances in the revolute joints.

MECHANISM JOINTS

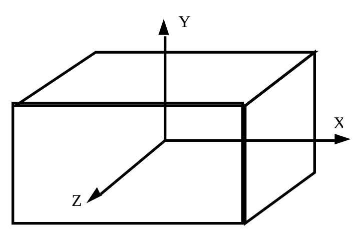


Revolute Joints

- Pin and hole
- Washers
- Cotter Pins
- Retaining Rings
- Bearings
- Hinges

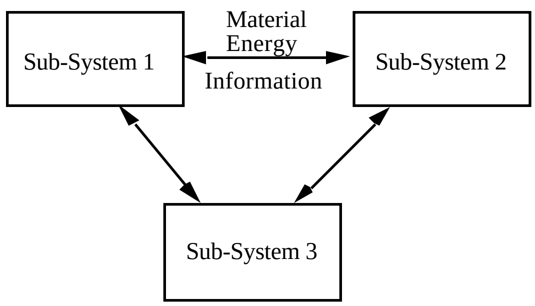
Sliding Joint

- Block and Slide
- Piston-Cylinder
- Shaft sliding thru Block
- Block sliding on Rail
- T-Slide
- Channel-shaped Slide
- Gravity



Care must be taken when constructing real mechanisms from 2D sketches. Objects in 3D have 6 Degrees-of-Freedom. 1 DOF Joints must eliminate 5 Degrees-of-Freedom.

SUB-SYSTEM INTERFACES

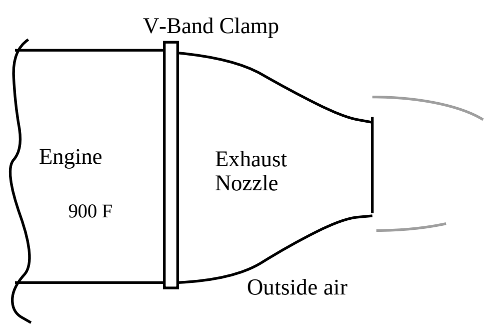


Material - Eggs, mechanisms, objects being transported or conveye

Energy - moving objects (kinetic energy), forces, moments, torques, vibration; electrical energy, magnetic fields, etc.

Information - signals: start-stop, reset, repeat doesn't have to be electrical.

C-130 Engine Exhaust System



Material Compatibility

4

Compromise

In this chapter, the compromise Decision Support Problem, DSP, is presented. In engineering the compromise DSP is used to determine values of design variables that satisfy a set of constraints and at the same time achieve, as well as possible, a trade-off between a set of conflicting goals.

4.1 The Role of Optimization

Let us assume that an initial feasible solution is known for the open problem. We therefore have some knowledge of both the performance requirements (demand) and the extent to which the artifact as designed will satisfy the requirements (capability). An existing solution can be improved in two ways, namely, by repeated modification and by solving an "optimization" problem. The scenario for the two cases follows.

A By repeated modification,

- *find* the value of the design variables *sequentially*,
- *check* whether the design satisfies the requirements,
- *modify* until an adequate design has been obtained, *or*

B By formulating and solving an "optimization" problem,

- *find* the value of the design variables *simultaneously* which
- *satisfy* the requirements and
- *optimize* a set of objectives.

The first scenario (A), typifies a spiral, heuristic, or judgment-based "trial and error" approach. A problem solver obtains and reviews numerical and/or graphical information about the solution to the problem and then changes it. The decision about what should be changed and by how much, rests on experience-based insight. Typically, this model involves extrapolation, interpolation and improvement through repeated modification; the values of the variables are changed or made firm *sequentially*. In this scenario it is difficult to provide systematic decision support to the designer. The second scenario (B), represents an optimization problem and its solution, if the model reflects reality, an optimum solution. In this case, the variables are determined *simultaneously* and iteration is necessary only if the formulation and/or the input data are altered. However, in our opinion it is easier to provide support for systematic decision making in scenario B than for scenario A.

What then is the role of optimization in the Decision Support Problem Technique? To obtain an answer consider the following questions: What is an optimum solution? The terms *optimize* and *optimum* entered the English language in the middle of the nineteenth century. When used by the English-speaking laity, the definitions of both terms carry with them the connotation of ideal, perfect and best, all of which convey a sense of the superlative nature of the condition they are attempting to characterize. In keeping with the pragmatic nature of engineering an engineer has to partition a problem into subproblems and accept a solution that is less-than-superlative and less-than-optimal. Thus, designers can use optimization techniques only to find the solutions of subproblems that can be modeled adequately but not completely. In the Decision Support Problem Technique, solutions to these subproblems are sought to support the human decision of accepting a satisficing, but less-than-superlative, solution of the overall problem. This last is a superior - not superlative - solution among the set of feasible alternatives that satisfy the system constraints.

The phrase “optimum solution” implies the end of a process. One might well ask, once the solution to an optimization problem is obtained: The optimum has been found - why bother doing anything more? In engineering this cannot be further from the truth. In our case the solution of a problem, albeit using optimization techniques, represents at best a good trade-off between conflicting goals. This solution does not represent the end of the process - rather it provides a good starting point. Therefore, the function of optimization is to provide *support for human judgment* and its solution is NOT an optimum or optimal solution.

We use a mathematical construct in problem solving, for example, multiobjective optimization to understand more about the problem domain. We achieve this by formulating and "solving" a quantitative representation (i.e., a mathematical model) of the problem. For real-world systems, however, the information for modeling a problem comprehensively and correctly will not be available. Therefore we ask ourselves: How can optimization be used as a tool if it is impossible to model the problem exactly?

We believe that before any attempt is made to construct a mathematical description of the problem under consideration it is important to gain as much appreciation about the problem as possible. This is generally done by observing (if possible) the problem situation, spending time with those familiar with the problem, and simply spending time thinking about its different aspects.

Finally, it is important to remember that all numbers obtained as a result of solving the mathematical construct are simply solutions to a model that approximates the real world. The more complete the model the smaller the discrepancies between the solution to the mathematical representation and the real world. We believe, that the knowledge about the completeness of the mathematical model is as important as the solution obtained.

The *Compromise DSP* - involves improvement of an alternative through modification. It is stated in words as follows:

Given

An alternative that is to be improved through modification.
Assumptions used to model the domain of interest.
The system parameters.
The goals for the design.

Find

The values of the independent *system variables* (they describe the attributes of an artifact).
The values of the *deviation variables* (they indicate the extent to which the goals are achieved).

Satisfy

The *system constraints* that must be satisfied for the solution to be feasible.
The *system goals* that must achieve a specified target value as much as possible.

Bounds

The lower and upper bounds on the system variables.

Minimize

The *deviation function* which is a measure of the deviation of the system performance from that implied by the set of goals and their associated priority levels or relative weights.

The preceding formulation of a compromise DSP is a hybrid formulation in that it incorporates concepts from both traditional mathematical programming and goal programming (GP), and makes use of some new ones. It is similar to goal programming in that the multiple objectives are transformed into system goals (involving both system and deviation variables) and the deviation function is solely a function of the goal deviation variables. (This is in contrast to traditional mathematical programming where multiple objectives are modeled as a weighted function of the system variables only.) The concept of system constraints, however, is retained from the traditional constrained optimization formulation. Special emphasis is placed on the bounds on the system variables unlike in traditional mathematical programming and goal programming. In effect the traditional formulation is a subset of the compromise DSP - an indication of the generality of the compromise formulation.

4.2 Descriptors of the Compromise DSP Formulation

System descriptors are used to define a compromise DSP.

Parameters - are used to complete the modeling of the compromise DSP. For example, in the case of the design of a structure, the material properties are invariably treated as parameters, that is, their values are needed to enable solution but they are not affected by the solution process itself. Parameters are sometimes called “fixed variables”.

Variables

- ❑ System variables.
- ❑ Deviation variables.

System constraints

(Equivalent to rigid goals in the GP formulation).

System goals

(Equivalent to soft goals in the GP formulation).

Bounds

- ❑ On system variables (formulated as rigid goals in the GP formulation).

Deviation function

In this section, the system descriptors for a compromise DSP are described. The descriptors are illustrated in Figure 4.1 for a two dimensional compromise DSP.

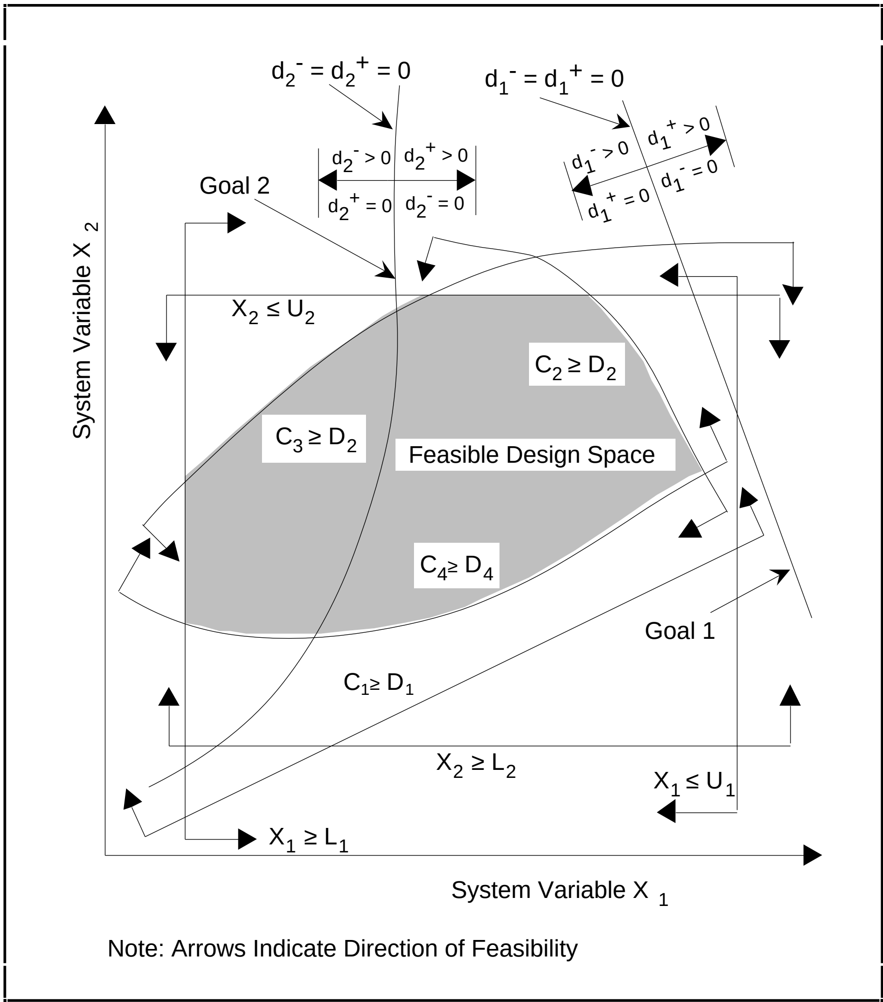


Figure 4.1. Typical design space for a two variable compromise DSP

4.2.1 System Variables and System Constraints

System Variables

$$X = (X_1, X_2, ..., X_n),\ \ X_i \geq 0.$$

System Constraints

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

Compromise DSPs have a minimum of two system variables. Consider a set of 'n' design variables represented by *X*. The vector of variables includes continuous variables and boolean variables (1 if

TRUE, 0 if FALSE). 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 that define the physical attributes of an artifact are always nonzero and positive. In Figure 4.1 the system variables X_1 and X_2, being independent, are represented by the abscissa and ordinate, respectively. Each member of the set *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(X)* to the capability of the system *C(X)* to meet the demand. The region of feasibility defined by the system constraints is called the *feasible design space.*

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 requiring equality constraints may arise. All system constraints shown in Figure 4.1 are inequalities.

4.2.2 Deviation Variables and System Goals

A set of system goals is used to model the aspiration a designer has for the design. It relates the goal (aspiration level), G_i, of the designer to the actual attainment, $A_i(X)$, of the goal. Three conditions need to be considered:

1. $A_i(X) \leq G_i$; we wish to achieve a value of $A_i(X)$ that is equal to or less than G_i.
2. $A_i(X) \geq G_i$; we wish to achieve a value of $A_i(X)$ that is equal to or greater than G_i.
3. $A_i(X) = G_i$; we would like the value of $A_i(X)$ to equal G_i.

We will now introduce the concept of a deviation variable. Consider the third condition, namely, we would like the value of $A_i(X)$ to equal G_i. The deviation variable is defined as:

$$d = G_i - A_i(X)$$

The deviation variable d can be negative or positive. Considerable simplification of the solution algorithm is effected if one can assert that all the variables in the problem being solved are positive. Therefore, the deviation variable d is replaced by two variables:

$$d = d_i^- - d_i^+$$

where

$$d_i^- \cdot d_i^+ = 0$$

and

$$d_i^- , d_i^+ \geq 0 \ .$$

The preceding ensures that the deviation variables never take on negative values.

The system goal becomes:

$$A_i(X) + d_i^- - d_i^+ = G_i \ ; \qquad i = 1, 2, ..., m \qquad (4.1)$$

where

$$d_i^- ,\ d_i^+ \geq 0 \quad \text{and} \quad d_i^- \cdot d_i^+ = 0$$

The product condition ensures that one of the deviation variables will always be zero. If the problem is solved using an algorithm that provides a vertex solution as a matter of course then the condition is automatically satisfied, making its inclusion in the formulation redundant. Since, the solution scheme described in this book and the software that is available for solution makes use of an algorithm that provides a vertex solution we will assume that this condition is satisfied. For completeness we include this condition as a constraint in the mathematical forms of the compromise DSP given later in this chapter and for brevity will omit this constraint from all subsequent formulations.

Note that a system goal is always expressed as an equality. 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. 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. When considering Equation 4.1, the following will be true

IF $A_i \leq G_i$ (underachievement) THEN $d_i^- > 0$ and $d_i^+ = 0$.

IF $A_i \geq G_i$ (overachievement) THEN $d_i^- = 0$ and $d_i^+ > 0$,

and

IF $A_i = G_i$ (exact achievement) THEN $d_i^- = 0$ and $d_i^+ = 0$

How do we model the three conditions listed earlier using Equation 4.1?

1 To satisfy $A_i(X) \leq G_i$, we must ensure that the positive deviation d_i^+ is zero. The negative deviation d_i^- will measure how far is the performance of the actual design from the goal.

2 To satisfy $A_i(X) \geq G_i$, the negative deviation d_i^- must be made equal to zero. In this case, the degree of overachievement is indicated by the positive deviation d_i^+.

3 To satisfy $A_i(X) = G_i$, both deviations, d_i^- and d_i^+ must be zero.

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 originates on the surface of the system goal. This is illustrated in Figure 4.2. The value of the i^{th} deviation variable is determined by the degree to which the i^{th} goal is achieved. It depends upon the value of $A_i(X)$ alone (since G_i is fixed by the designer). $A_i(X)$ in turn is dependent upon the system variables X. 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.

The system goal represents an equation for a family of either parallel linear or nonlinear functions. In Figure 4.2, goal i (represented by line A) is the target goal 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, as follows,

1. In terms of system variables.
2. In terms of the system variables and the nonzero deviation variable.
3. In terms of the system variables and both the deviation variables.

In 1 (see Figure 4.2) 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, the underachievement d_1^- is nonzero and the overachievement d_1^+ is zero. For C it is the other way around.

Since only one deviation variable, by definition, can be nonzero we are able to write the equation for the family of system goals B through C. This is analogous to Equation 4.1.

4.2.3 Range of Values for Deviation Variables

The objective of a traditional single objective optimization problem requires the maximization or minimization of a certain function. This function is in terms of the system variables. In a compromise DSP formulation each of the objectives is converted into a goal (using Equation 4.1) with its corresponding deviation variables. The resulting formulation is similar to a single objective optimization problem but with the following differences:

- The objective is always to minimize a function.
- The objective function is expressed using deviation variables only.

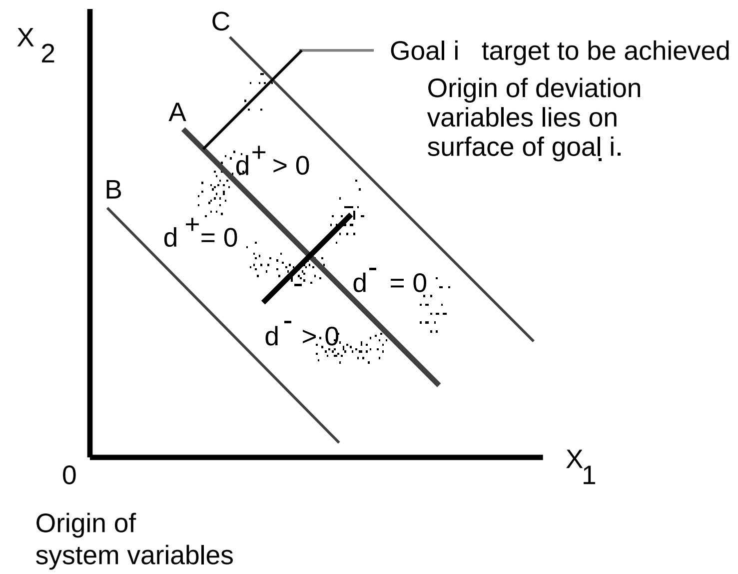
System Variables: X_1, X_2, ... Form the axes of the design space.

Deviation Variables:

d^- Represents underachievement of the goal.

d^+ Representsoverachievement of the goal.

Note: Goals are represented by the parallel lines A, B and C.



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. $a_1X_1 + a_2X_2 + d_1^- - d_1^+ = b_1$	$8X_1 + 7X_2 + d_1^- - d_1^+ = 13$
with $d_1^- > 0$, $d_1^+ = 0$	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. $a_1X_1 + a_2X_2 + d_1^- - d_1^+ = b_1$	$8X_1 + 7X_2 + d_1^- - d_1^+ = 13$
with $d_1^- = 0$, $d_1^+ > 0$	with $d_1^- = 0$, $d_1^+ = 2$
Equation for a Family of Goals B Through C	
3. $a_1X_1 + a_2X_2 + d_1^- - d_1^+ = b_1$	$8X_1 + 7X_2 + d_1^- - d_1^+ = 13$
with d_1^- , $d_1^+ \geq 0$	with d_1^- , $d_1^+ \geq 0$

Figure 4.2. The system goal

The objective in the compromise DSP formulation is called the deviation function. As indicated earlier, the deviation variables are associated with system goals and therefore their ranges of values depend on the goal itself. Goals are not equally important to a designer. Therefore to solve the problem, given a designer's preferences, the goals are rank-ordered into priority levels. Within a priority level it is imperative that the deviation variables are of the same order of magnitude. This is achieved by normalizing the goals. If this is not done the deviation variable with the larger numeric value will dominate the solution process without regard to the designer-established preference for the set of goals.

A solution to the order of magnitude problem is to normalize the achievement $A_i(X)$ with respect to the target value G_i before the deviation variables are introduced. The following rules are used to formulate the system goals in a way that ensures that all the deviation variables will range within the same values (0 and 1 in this case).

a. To maximize the achievement, $A_i(X)$, choose a target value G_i greater or equal to the maximum expected value of $A_i(X)$, so that the ratio $A_i(X)/G_i$ is always less or equal than 1. For example, if $A_i(X)$ is the reference stress then G_i could be the yield stress. Consider the following:

$$A_i(X) \leq G_i \qquad\qquad A_i(X)/G_i \leq 1$$

Transform the expression into a system goal by adding and subtracting the corresponding deviation variables (which in this case will range between zero and one).

$$A_i\,(X) \,/\, G_i + d_i^- - d_i^+ = 1 \tag{4.2}$$

In this case, the overachievement variable, d_i^+, will always be zero, as indicated in Section 4.2.2. Then minimize the underachievement deviation, d_i^-, to ensure that the performance of the design will be as close as possible to the desired goal.

b. To minimize the achievement, $A_i(X)$, the following steps are in order:

i. Choose a target value, G_i, less than or equal to the minimum expected value of $A_i(X)$. In this case, the ratio $G_i \,/\, A_i(X)$ will be less than or equal to one.

$$A_i(X) \geq G_i \qquad\qquad G_i \,/\, A_i(X) \leq 1$$

Transform the expression into a system goal (note the inversion of G and A) and flip the signs of the deviation variables (to account for the inversion). The deviation variables will vary between 0 and 1.

$$G_i / A_i(X) - d_i^- + d_i^+ = 1 \tag{4.3}$$

The underachievement deviation, d_i^-, will be zero as indicated in Section 4.2.2. Minimizing the overachievement deviation, d_i^+, will ensure that the performance of the design is as close as possible to the desired goal.

ii. If the target value, G_i, is taken as zero, get an estimate of the maximum value that the achievement, $A_i(X)$, can obtain within the bounds set for the system variables, $A_i^{max}(X)$. Then divide the inequality by this maximum value and convert into a system goal with the following result:

$$A_i(X) / A_i^{max}(X). + d_i^- - d_i^+ = 0 \tag{4.4}$$

The deviation variables will now vary between 0 and 1. Note that the signs of the deviation variables remain as in the original Equation 4.1. In this case, the underachievement deviation d_i^- will always be zero. Minimize then the overachievement deviation d_i^+ to ensure that the performance of the design will be as close as possible to the desired value of zero.

c. If it is desired that $A_i(X) = G_i$, and

i. If the target value G_i is approached from below by $A_i(X)$, use Equation 4.2 and minimize the sum $(d_i^- + d_i^+)$.

ii. If the target value G_i is approached from above by $A_i(X)$, use Equation 4.3 and minimize the sum $(d_i^- + d_i^+)$.

iii. If the target value G_i is equal to zero, use Equation 4.4 and minimize the sum $(d_i^- + d_i^+)$.

4.2.4 Bounds on System and Deviation Variables

Bounds are specific limits placed on the magnitude of each of the variables. Each variable has associated with it a lower and an upper bound. Bounds are important for modeling real-world problems because they provide a means to include the experience-based judgment of a designer in the mathematical formulation. Unfortunately, in most engineering design text-books that encourage the notion of using optimization techniques in design there has been a tendency to ignore bounds. Bounds on the system variables take the form

$$L \leq X \leq U$$

where L and U represent the set of lower and upper bounds respectively. The bounds on the system variables demarcate the region in which a search is to be made for a feasible solution. In engineering design, the lower bounds are always nonzero and positive, reflecting physical limitations.

Deviation variables are by definition nonnegative (see Section 4.2.2) and therefore a lower bound of zero is always associated with them.

4.2.5 The Deviation Function

In the compromise DSP formulation the aim is to minimize the difference between that which is desired and that which can be achieved. This is done by minimizing the deviation function, $Z(d^-, d^+)$, which is always written in terms of the deviation variables.

A designer sets an aspiration level for each of the goals. It may be impossible to obtain a design that satisfies all the levels of aspiration. Therefore, a compromise solution must be accepted by the designer. It is desirable, however, to obtain a design whose performance matches the aspiration levels 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, $Z(d^-, d^+)$. This deviation function provides 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 most general form of the deviation function for m goals in the Archimedean formulation is

$$Z(d^-, d^+) = \sum (W_i^- d_i^- + W_i^+ d_i^+) \qquad i=1,..., m$$

where the weights, $W_1, W_2, ..., W_m$, reflect the level of desire to achieve each of the goals. In this formulation, the weights, W_i, satisfy the following conditions:

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

The relationships between the goals (aspiration level), G_i, of the designer and the actual achievement, $A_i(X)$, of the goals are summarized in Table 4.1.

Table 4.1. System Goal Formulation for Archemedean Case

Condition	*Deviation Variables*	*Minimize*	*Weights*
$A_i \leq G_i$	$d_i^- > 0, d_i^+ = 0.$	d_i^+	$W_i^- = 0, W_i^+ = W_i$
$A_i \geq G_i$	$d_i^- = 0, d_i^+ > 0$	d_i^-	$W_i^- = W_i, W_i^+ = 0$
$A_i = G_i$	$d_i^- = 0, d_i^+ = 0$	$d_i^- + d_i^+$	$W_i^- = W_i^+ = W_i$

It may be difficult to come up with truly credible weights. A systematic approach for determining reasonable weights is to use the schemes presented in [1-3]. In most of these methods the decision maker is asked to compare the goals in pairs and state his/her preference. Specially recommended is the reciprocal pairwise comparison matrix method proposed by Saaty. The details of this method are presented in 3A.3.

In the Preemptive approach, the difficulty of assigning weights is circumvented by rank ordering the goals. This is probably easier in an industrial environment or in the earlier stages of design. The measure of achievement is obtained in terms of the lexicographic minimization of an ordered set of goal deviations, wherein within each set of goals at a particular rank, weights may be used. Goals are ranked lexicographically and an attempt is made to achieve a more important goal before considering other goals.

The mathematical definition of lexicographic minimum follows, see [4-5]:

LEXICOGRAPHIC MINIMUM Given an ordered array **f** of nonnegative elements, f_k's, the solution, given by $f^{(1)}$, is preferred to $f^{(2)}$ if

$$f_k^{(1)} < f_k^{(2)}$$

and all higher-order elements (i.e., $f_1, \ldots, f_{k-1}$) are equal. If no other solution is preferred to **f**, then **f** is the lexicographic minimum.

As an example, consider two solutions, $\mathbf{f}^{(r)}$ and $\mathbf{f}^{(s)}$, where

$$\mathbf{f}^{(r)} = (0, 10, 400, 56)$$

$$\mathbf{f}^{(s)} = (0, 11, 12, 20)$$

In this example, note that $\mathbf{f}^{(r)}$ is preferred to $\mathbf{f}^{(s)}$. The value 10 corresponding to $\mathbf{f_2}^{(r)}$ is smaller that the value 11 corresponding to $\mathbf{f_2}^{(s)}$. Once a preference is established then all higher order elements are assumed to be equivalent. Hence, the deviation function for the Preemptive formulation is written as

$$Z = [\ f_1(d_i^-,d_i^+), ..., f_k(d_i^-,d_i^+)\ ]\ .$$

For a four goal problem, the deviation function may look like

$$Z(d^-, d^+) = [\ (d_1^- + d_2^-), (d_3^-), (d_4^+)\ ]$$

In this case, three priority levels are considered. The deviation variables, d_1^- and d_2^-, have to be minimized preemptively before variable d_3^- is considered and so on. These priorities represent rank, that is, the preference of one goal over 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 to the Archimedean approach in which the numerical evaluation of the deviation function is required even for the simplest case.

The numerical solution of a Preemptive formulation requires the use of a special optimization algorithm developed to solve these types of problems. One such algorithm has been developed by Ignizio [6]. It is also possible to solve the Preemptive formulation by reformulating the deviation function into a pseudo-preemptive form as suggested by Schniederjans [7]. Schniederjans notion is to force the deviation function to satisfy the priorities by multiplying each priority level by a quantity P_i, whose numerical value is much larger than the corresponding one associated with the next priority level. The deviation function for the example problem presented earlier expressed in a pseudo-preemptive fashion looks like

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

where $P_1 >> P_2 >> P_3$, .

In the preceding the >> implies preference and the P_i's represent rank-ordered priorities that are modeled numerically. Lexicographic preference is modeled numerically on a computer only if the numerical values between the priorities are substantial. For example let us try to model the following numerically:

$$P_1 >> P_2 >> P_3.$$

Consider the following series of numbers:

$$3 >> 2 >> 1$$

$$300 >> 200 >> 100$$

$$10^{37} >> 10^{20} >> 10^{10} .$$

Which of the three series models the preference the best? The correct answer is the third set of numbers.

The following example is presented to illustrate the difference in the solution obtained by using the Preemptive and the Archimedean formulations. The design space for the example problem is shown in Figure 4.3.

The algorithms that have been developed to solve the compromise DSPs provide vertex solutions[1]. Therefore we will restrict our discussion to vertex solutions only. Further, we are seeking a solution that achieves all three goals completely.

Find

System Variables

$$X_1, X_2$$

Deviation Variables

$$d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+$$

Satisfy

System Constraints

$$2X_1 + 3X_2 \leq 30 \quad [c1]$$

$$6X_1 + 4X_2 \leq 60 \quad [c2]$$

---

1 Aside: How can this be justified in the case of practical engineering problems? Hint: Answer the following question first - Under what conditions is a vertex optimum almost the same as a field optimum?

System Goals (Dimensionless, Normalized)

$$X_1/10 + X_2/10 + d_1^- - d_1^+ = 1 \quad [g1]$$

$$X_2/7 + d_2^- - d_2^+ = 1 \quad [g2]$$

$$X_1/8 + d_3^- - d_3^+ = 1 \quad [g3]$$

Bounds omitted for brevity.

Minimize

Case a: Using the Preemptive approach (lexicographic minimum).

$$Z = [(d_1^- + d_1^+), (d_2^- + d_2^+), (d_3^- + d_3^+)]$$

All deviation variables are considered due to equality goals.

Case b: Using the Archimedean approach.

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

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

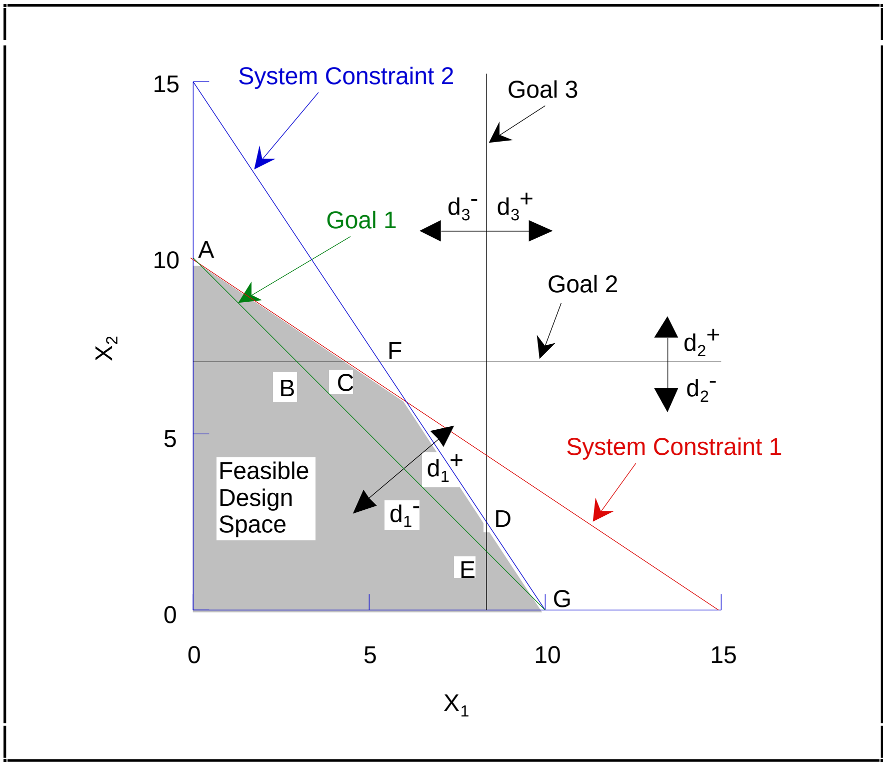


Figure 4.3. Design space for example problem

The solution to the preceding compromise DSP using both the Preemptive and Archimedean approaches follows:

Case A Preemptive

- The goal with the highest priority is considered first (Goal 1). This goal lies completely within the feasible design space and consequently any point satisfying the goal is considered to be a solution, namely, vertices A, B, E and G.
- We next move to priority level 2, which requires the minimization of d_2^- and d_2^+. Notice that in Figure 4.3, these deviations may be set to zero at point B without reducing the value of the solution obtained for priority 1. That is, d_2^- and d_2^+ may be set to zero without any increase in either d_1^- or d_1^+. Therefore vertex A is the second preferred solution, with the first priority still being satisfied (d_1^-, d_1^+ = 0) and a minimum value for the overachievement of the second goal d_2^+.

- Moving to priority level 3, we attempt to minimize d_3^- and d_3^+ without degrading the solution for the other priority levels. In this case, the solution point that comes closer is once again point B, with d_1^-, d_1^+, d_2^-, d_2^+ and $d_3^+ = 0$ and a minimum value of the third goal underachievement d_3^-.
- If the priorities were changed to goals 1, 3 and 2 in that order, the preferred solution would be at point E. We suggest that you solve this as an exercise.

Case B Archimedean

In Table 4.2 the values of the deviation variables and the deviation function at different vertices are summarized. It follows from the table that the best solution is at 'C' where Z is a minimum (Z=0.196).

The solutions obtained in the two cases are different. The Preemptive approach is suitable when less is known about the design and consequently a designer is only able to rank-order the preferences for the goals. Using the Archimedean approach is warranted when it is possible to determine the relative importance of the goals using a pairwise comparison method, Appendix 3A[2].

Should *all* the deviation variables be included in the formulation of the deviation function? If one is only interested in obtaining a solution to the DSP then we know *à priori*, see Section 4.2.3, which deviation variables will be zero and consequently we can exclude them from the deviation function. If one is interested in varying the target values to study the sensitivity of the solution it is necessary to include *all* the deviation variables in the deviation function.

Table 4.2. Deviation function values for Archemedean solution

Vertices (coord.)	*Acceptable Value of Normalized Dev. Var.* d_1^-	d_1^+	d_2^-	d_2^+	d_3^-	d_3^+	*Sum* $\Sigma(d_i^- + d_i^+)$	*Solution Func.* Z
A = (0, 10)	0	0	0	0.429	1	0	1.429	0.476
B = (3, 7)	0	0	0	0	0.625	0	0.625	0.208
C = (4.5, 7)	0	0.150	0	0	0.438	0	0.588	***0.196***
D = (8, 3)	0	0.100	0.571	0	0	0	0.671	0.224

2 If you were solving a compromise DSP without a computer being available, under what conditions would each of the approaches be the method of choice? We leave this as an exercise for you to answer.

E = (8, 2)	0	0	0.714	0	0	0	0.714	0.238	
F = (6, 6)	0	0.200	0.143	0	0.250	0	0.593	0.198	
G = (10, 0)	0	0	1	0	0	0.250	1.250	0.417	

4.3 The Two Coal Problem

Recent revisions of pollution control laws have had a direct influence on the running of a power station. These revisions have reduced the allowable emission of pollutants into the atmosphere from the plant's exhaust gases. To comply with these new regulations expeditiously and eliminate downtime it is desired, now, to control the emission rates by the appropriate use of coal.

Historically, coal has been bought from two sources, say A and B. Both types of coal are transported to the plant and stored in separate stockpiles. From there they are fed by a mechanical conveyer into a pulverizer, crushed into fine particles, mixed at a specified rate and burnt in a combustion chamber.

Coal from source A, Coal A, is relatively hard, clean-burning, has a low sulfur content and is more expensive than Coal B which is soft, smoky when burnt, and has a high sulfur content. The thermal value, in terms of steam produced, is 24,000 lbs/ton for Coal A and 20,000 lbs/ton for Coal B. Since Coal A is hard, the pulverizer can handle 16 tons/hr of it. Since Coal B is soft, the pulverizer can handle 24 tons/hr of it. The capacity of the conveyer is 20 tons/hr for both types of coal. There is a limit to the amount of coal that can be stockpiled. This limit translates to a maximum of 25 tons/hr for any type of coal that can be burnt.

The new pollution regulations limit sulfur oxide emissions to 3,000 parts per million and the particulate emissions (smoke) to 12 kg/hr. The characteristics of the two types of coal are summarized in Table 4.3.

Case A: A Linear Single Objective Optimization Problem.

Problem Statement: Determine the most efficient combination of the two types of coal to be burnt that satisfies the constraints and bounds and maximizes the rate of production of electricity. No information is given in the story about the lower bounds on the rates of consumption of the two types of coal. It is reasonable to assume, initially, that the lower bounds are zero. The implication of this assumption is that a solution that requires the burning of a single type of coal, in our case coal from a single vendor, is acceptable.

Table 4.3. Coal and material handling characteristics

PROPERTIES	*Coal A*	*Coal B*	*Units*
Thermal value	24,000	20,000	lbs steam / ton
Sulfur oxides emission	1,800	3,800	ppm
Particulate emission	0.5	1.0	kg / ton
Pulverizer coal handling capacity	16	24	tons / hour
Conveyer coal handling capacity	20	20	tons / hour

Case B: The Linear Single Objective Optimization Problem - Revisited.

Problem Statement: The power company does not want to rely on a single source for its supply of coal. The purchasing department has determined that there is a minimum order quantity for the coal. This minimum order quantity translates to a lower bound of 5 tons of each type of coal per hour. Determine the most efficient combination of the two types of coal to be burnt that satisfies the constraints and bounds and maximizes the rate of production of electricity.

This problem is used to illustrate the algorithm for solving the most general linear single objective optimization problem. The preceding requires the introduction of two nonzero lower bounds on the system variables and the introduction of artificial variables to get an initial solution by inspection. Unlike Case A, in this case it is inappropriate to drop the lower bounds at the very outset.

Case C: A Linear Single Goal Compromise Decision Support Problem.

Problem Statement: The demand for steam is likely to increase to 432,000 lbs/hr during the summer months. Can this be achieved without violating any of the constraints and bounds?

This problem is formulated as a single goal compromise DSP, and the solution compared to that of the single objective optimization problem, Case A.

Case D: A Linear, Multigoal Compromise Decision Support Problem.

Problem Statement: The demand for steam is going to increase to at least 432,000 lbs/hr during the summer months. Management is prepared to violate some of the pollution constraints and pay a fine, if necessary, to get this amount of steam from the plant. Company executives have identified one viable scenario as putting out as much sulfur oxides and smoke as is permissible and maximizing the amount of steam produced.

This problem is used to illustrate the solution of a multigoal compromise DSP.

Case E: A Nonlinear, Multigoal Compromise Decision Support Problem.

Problem Statement: The plant is being modified and access to the warehouse is limited. For a short period the management would like to hold the stockpiling down so as not to exceed 10 tons/hr of Coal A and 5 tons/hour of Coal B. The cost for stockpiling per ton is assessed proportionally to the excess capacity, over the desired capacities, and is equal to $3/(excess ton of Coal A) and $4/(excess ton of Coal B). The prices reflect the difficulties in stockpiling the softer Coal B. An incentive is provided in stockpiling less coal than available capacity and is equal to $3/(surplus ton of Coal A) and $4/(surplus ton of Coal B). It is desirable to limit the total stockpiling costs to $30/hr.

4.4 Linear Single Objective Optimization: Formulation and Graphical Solution

4.4.1 Case A: The Word Problem

Given

- The properties of Coal A and Coal B.
- The capacity of the conveyer unit.
- The capacity of the pulverizer unit.
- Emission limit on sulfur oxides.
- Emission limit on particulates.
- Upper limits on the amount of coal that is stockpiled.

Assumptions

- Uninterrupted supply of coal is available.
- The combustion chamber can handle any amount of coal supplied from the pulverizer.
- The maximization of the rate of electricity produced is equivalent to the maximization of the rate of steam generated.
- The coal prices are stable.

Find

Independent System Variables

The rate of consumption of Coal A: X_1 [tons/hr]
The rate of consumption of Coal B: X_2 [tons/hr]

Satisfy

System Constraints

1. The conveyer capacity is 20 tons/hr for any type of coal.
2. The pulverizer can process 16 tons of Coal A and 24 tons of Coal B per hour.
3. The emission of sulfur oxides is limited to 3,000 parts per million.
4. The emission of particulates (smoke) is limited to 12 kg/hr.

Bounds on the System Variables

5. The system variables should be nonnegative.

6. The maximum of any one type of coal that can be burnt is 25 tons/hr.

Maximize

7. The rate of steam generated and therefore, the electricity produced.

4.4.2 *Case A: Derivation of the Constraints and the Objective Function*

The system variables. In the short run the plant's facilities are fixed. It is quite appropriate that management has decided to affect the output of electricity by using the best combination of the two types of coal. Therefore, let X_1 be the number of tons of Coal A burnt per hour, and X_2 be the number of tons of Coal B burnt per hour. These variables have two characteristics. One, they are physical quantities and are therefore nonnegative. Two, these variables are continuous, that is, any value that is feasible is acceptable from a mathematical standpoint.

The system constraints and bounds. The system constraints are written in terms of the system variables. In engineering, system constraints are invariably inequalities. The system constraints and bounds must be satisfied for feasibility. System constraints generally model the physics of the problem. The bounds, on the other hand, are the product of experience-based insight. They represent what is acceptable to the designer without regard to the physics of the problem. A constraint invariably has two or more system variables. A bound contains only one system variable and is always parallel (geometrically) to the axis represented by the system variable. Rarely is a constraint specified in terms of a single system variable. In this case the constraint plays the same role as a bound in the design space even though it may represent the physics of the problem.

1 *The constraint on conveyer capacity*

The conveyer has a capacity of 20 tons/hour. This capacity is independent of the type of coal that is placed on the conveyer. Therefore, the constraint is written as:

$$X_1 + X_2 \leq 20 \qquad \text{[tons/hr]}$$

The constraint is shown in Figure 4.4.

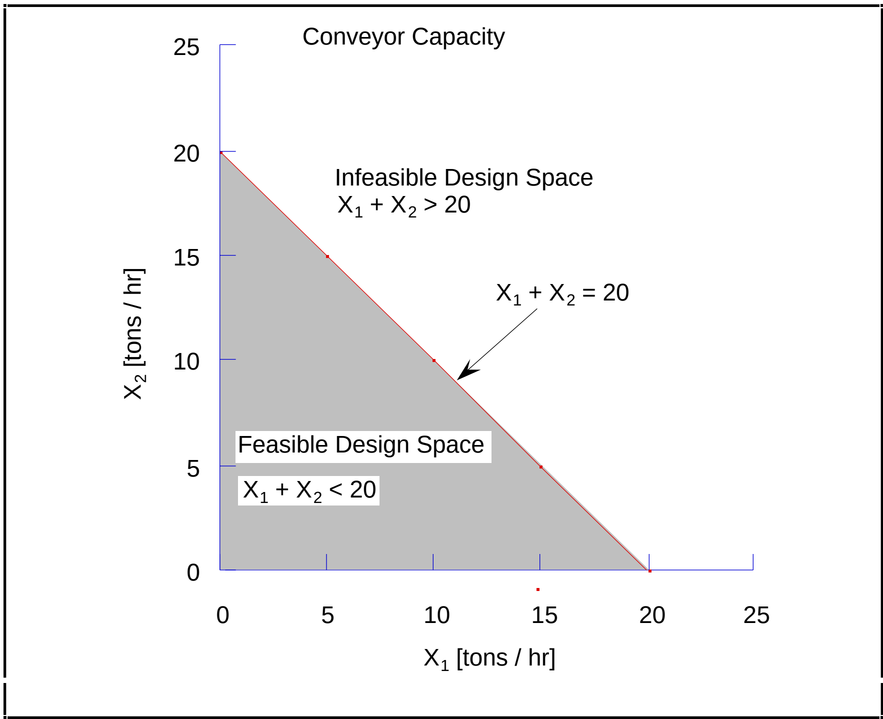


Figure 4.4. Conveyor capactiy

2 *The constraint on pulverizer capacity*

The pulverizer capacity constraint is shown in Figure 4.5. The maximum capacity of the unit is 16 tons of Coal A or 24 tons of Coal B per hour or any corresponding combination of the two. The right hand side for this constraint has not been specifically given in the problem statement. It has to be figured out. In this case, consider the amount that can be pulverized in one hour: it takes 1/16 of an hour to pulverize a ton of Coal A and 1/24 of an hour to pulverize a ton of Coal B.

Therefore, the constraint is written as:

$$X_1/16 \; + \; X_2/24 \; \leq \; 1 \qquad [-]$$

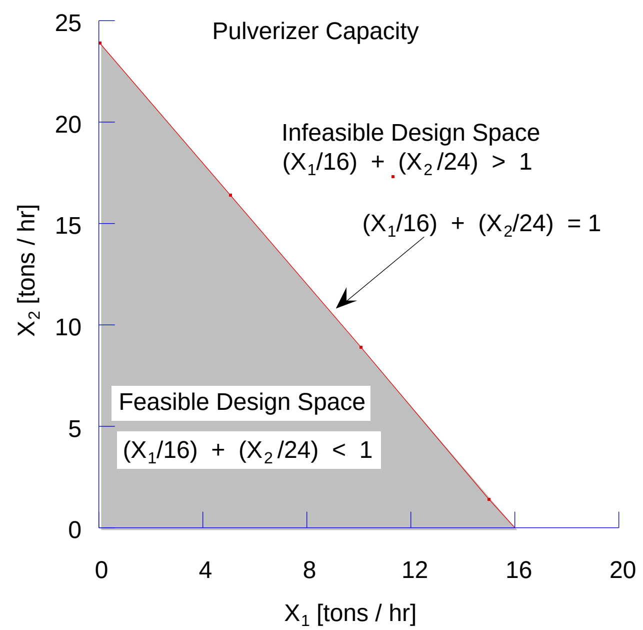


Figure 4.5. Pulverizer capacity

Therefore, the pulverizer capacity for one 24 hour day is (multiplying through by 24 [hrs/day]):

$$1.5X_1 + X_2 \leq 24 \qquad [\text{day}]$$

Notice the units. Normally, multiplying through does not result in meaningful units. In this case, because there are 24 hours in a day, the second form of the constraint has meaningful units.

3 *The limit on sulfur oxides emission*

The maximum emission of sulfur oxides is limited to 3,000 ppm. This constraint is shown in Figure 4.6. There may be an urge to specify the constraint as:

$$1{,}800X_1 + 3{,}800X_2 \leq 3{,}000.$$

What is wrong with the constraint? The units on the left hand side and the right hand side of the equation do not match. What is to be done? The units of 1,800, 3,800 and 3,000 are parts per million. If only the X_1 and X_2 were dimensionless the preceding constraint would be acceptable. The way around this problem is to normalize X_1

and X_2 and make them dimensionless. How? Given that the two coals are burnt simultaneously, assume that a combination of X_1 tons/hr of Coal A and X_2 tons/hr of Coal B is fed into the combustion chamber as a homogeneous mixture.

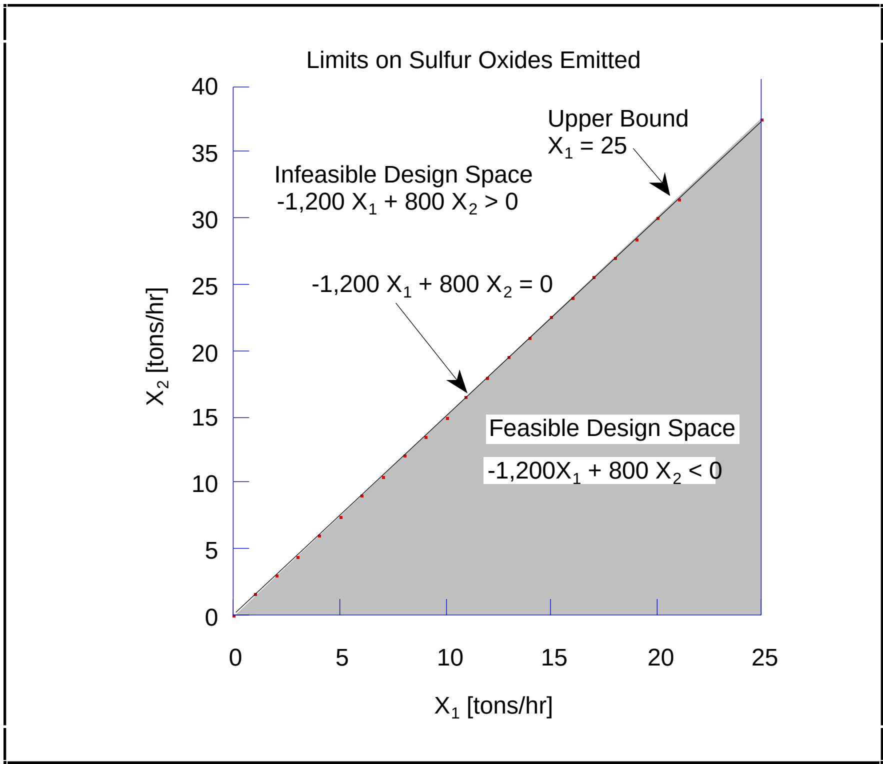


Figure 4.6. Limit on sulfur oxides

Then,

The proportion of Coal A in the total mixture is

$$X_1/(X_1 + X_2), \text{ and}$$

The proportion of Coal B in the total mixture is

$$X_2/(X_1 + X_2).$$

Now the constraint on the sulfur oxides emission level is equal to the weighted average of the individual levels, i.e.,

$$1{,}800X_1/(X_1 + X_2) + 3{,}800X_2/(X_1 + X_2) \leq 3{,}000 \qquad \text{[ppm]}$$

The preceding can be rewritten as:

$$-1{,}200X_1 + 800X_2 \leq 0 \qquad \text{[NMU]}$$

The second form of the constraint though algebraically simpler than the first has no meaningful units (NMU). The second form is more convenient to use from a computational standpoint. Since the second form has no meaningful units associated with it, it will not be possible to gain much meaningful insight through post-solution analysis. Since the first form has meaningful units, it is preferred over the second form for the post-solution analysis.

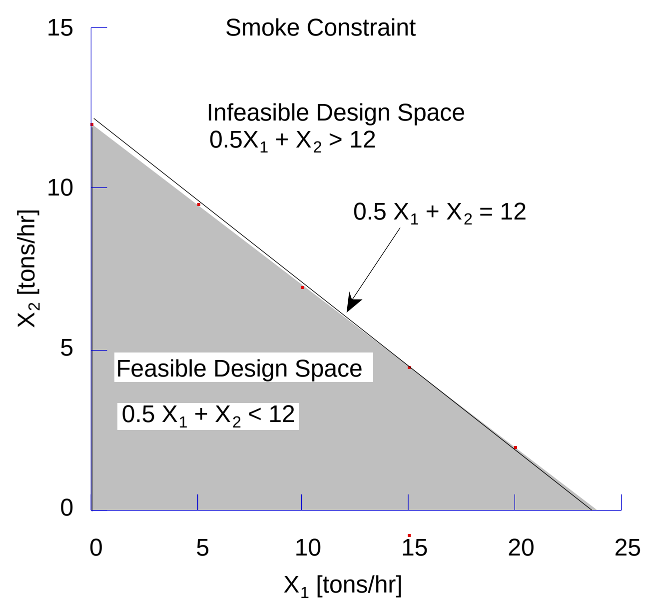


Figure 4.7. Smoke constraint

4 *The limit on particulate (smoke) emission*

According to the information given, each ton of Coal A produces 0.5 kg of smoke and each ton of Coal B, 1 kg of smoke. The amount of smoke that can be emitted per hour is limited to 12 kg. Therefore, this constraint is stated as:

$$0.5X_1 + X_2 \leq 12 \qquad \text{[kg/hr]}$$

This constraint is shown in Figure 4.7

5 *The lower bounds on the system variables*

Nothing is mentioned explicitly in the problem statement about lower bounds. Since this problem deals with physical quantities and they are always nonnegative, the lower bounds on the system variables are stated as follows:

$X_1 \geq 0$ [tons/hr]

$X_2 \geq 0$ [tons/hr]

6 *The upper bounds on the system variables*

The upper bounds on the system variables are explicitly stated in the problem statement and these are as follows:

$X_1 \leq 25$ [tons/hr]

$X_2 \leq 25$ [tons/hr]

The objective (deviation) function. The objective (see Figure 4.8) is to maximize the electricity produced at the plant. Since electricity is produced by using steam to drive the turbines, there is a direct relationship between the amount of electricity that is produced and the amount of steam that is produced in a specified length of time. What is the amount of steam produced for any arbitrary combination of coal used in any hour?

Coal	Steam (lbs/ton)	Fuel used (tons/hr)	Steam (lbs/hr)
A	24,000	X_1	$24{,}000X_1$
B	20,000	X_2	$20{,}000X_2$

The total amount of steam (lbs/hr) = $24{,}000X_1 + 20{,}000X_2$. The objective function therefore is,

$Z = 24{,}000X_1 + 20{,}000X_2$ [lbs/hr]

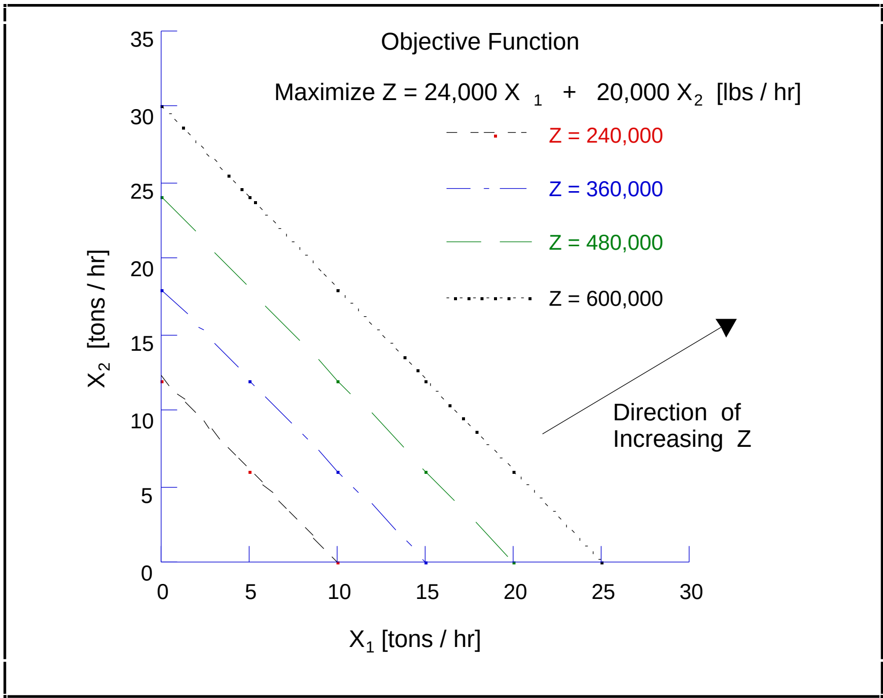


Figure 4.8. The objective function

4.4.3 *Case A: The Mathematical Form of the Word Problem*

Given

As stated in the word problem.

Find

System variables

X_1 - the rate of consumption of Coal A [tons/hr]
X_2 - the rate of consumption of Coal B [tons/hr]

Satisfy

System Constraints

1. Conveyer capacity

$X_1 + X_2 \leq 20$ [tons/hr]

2. Pulverizer capacity

$X_1/16 + X_2/24 \leq 1$ [tons/hr]

or

$1.5X_1 + X_2 \leq 24$ [tons/day]

3. Sulfur oxides emission

$1{,}800X_1/(X_1 + X_2) + 3{,}800X_2/(X_1 + X_2) \leq 3{,}000$ [ppm]

or

$-1{,}200X_1 + 800X_2 \leq 0$ [NMU]

4. Smoke emission

$0.5X_1 + X_2 \leq 12$ [kg/hr]

Bounds on system variables

5. Lower bounds on system variables

$X_1 \geq 0$ [tons/hr]

$X_2 \geq 0$ [tons/hr]

6. Upper bounds on system variables

$X_1 \leq 25$ [tons/hr]

$X_2 \leq 25$ [tons/hr]

Maximize

7. The rate of steam produced

$Z = 24{,}000X_1 + 20{,}000X_2$ [lbs/hr]

$= 24\ X_1 + 20\ X_2$ [1000 lbs/hr]

4.4.4 Case A: The Graphical Solution

The set of all combinations of the system variables that satisfy all constraints and bounds simultaneously is called the set of feasible solutions and the space consisting of the feasible solutions is called the feasible design space. This is shown in Figure 4.9. A solution that results in the violation of any of the constraints or bounds is called an infeasible solution. A constraint or bound that does not border the feasible design space is called a redundant constraint or bound. In this example, the upper bounds and the conveyer constraint are redundant.

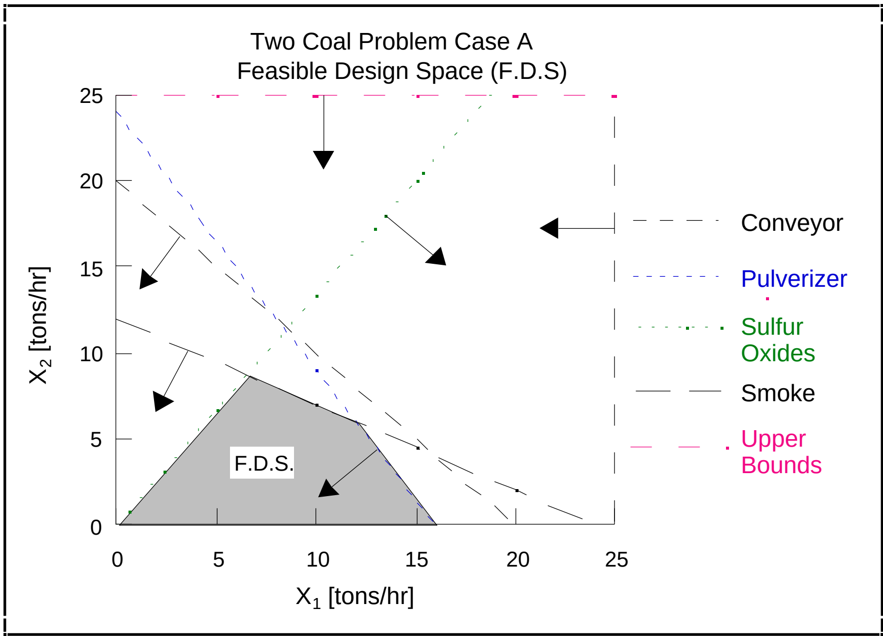


Figure 4.9. Case A feasible design space

The graphical solution is shown in Figure 4.10. Pay particular attention to the following:

- ❑ The independent system variables are the axes of the design space.
- ❑ The system constraints and bounds form the feasible design space.
- ❑ The direction of feasibility is indicated, with arrows, on each constraint and bound. Experience has shown that many errors are avoided if students do not omit this simple step.
- ❑ The constraints and bounds are labelled in a way that makes it easy to refer back to the word problem and its mathematical form. A one-to-one correspondence should exist between the word problem, its mathematical form and the graphical solution. Experience has shown that the errors made by students are fewer if this is checked as a matter of course.
- ❑ The best solution for the model, at which the objective has the highest value (when maximizing), is at a vertex of the feasible design space.
- ❑ The solution to the problem consists of not just the values of the system variables and the objective function but also the active

and inactive constraints, etc. The solution is shown on the graph and a recommendation is made, as required, to management.

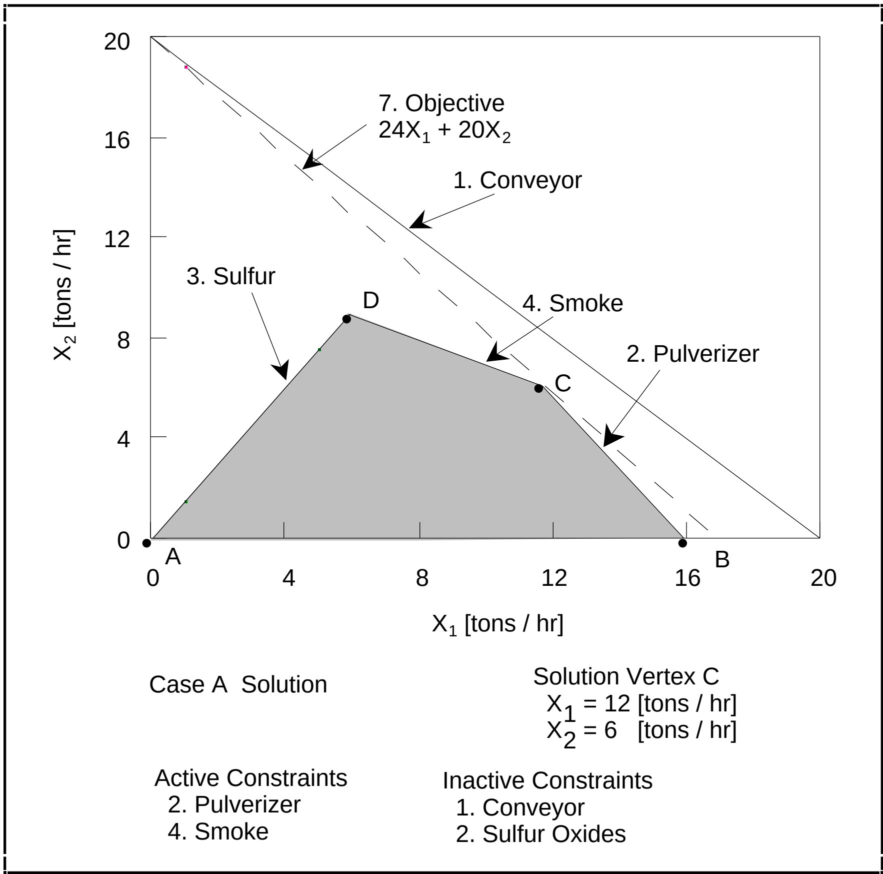


Figure 4.10. Case A solution

4.4.5 Case A: Recommendation[3]

If 12 tons of Coal A and 6 tons of Coal B are burnt per hour, 408,000 lbs of steam will be generated per hour. This will result in the maximum amount of electricity being produced with all the constraints and bounds being satisfied.

The best solution for the model occurs at vertex C in Figure 4.10. At vertex C the smoke constraint, constraint 4, and the pulverizer

---

3 Be sure to put recommendation in context of assumptions.

constraint, constraint 2, are active. The maximum amount of particulates that can be emitted into the air are being emitted and there is no reserve capacity for the pulverizer.

4.4.6 Case A: Post-solution Analysis

Post-solution analysis deals with the "What is the impact on ... if ..." questions. For example,

- What happens if there is a change in the coefficient of a variable in the objective function?
- What happens if there is a change in the right hand side of a constraint?
- What is the impact on the solution of adding a variable, i.e., another type of coal?
- What happens if one of the coefficients on the left hand side of a constraint changes?

The first three will be answered in this section.

Slack and surplus variables. For any feasible solution, the difference between the left hand side and the right hand side of the constraint is called the amount of slack (for ≤ inequalities) or surplus (for ≥ inequalities). In system constraints, this difference is represented by the inclusion of *slack* or *surplus* variables. For Case A, after the introduction of the slack and surplus variables, the mathematical form is as follows (note the form used for constraint 3):

Find

$X_1, X_2, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8$

Satisfy

1. $X_1 + X_2 + S_1 = 20$ [tons/hr]
2. $1.5\,X_1 + X_2 + S_2 = 24$ [hours]
3. $1{,}800\,X_1/(X_1+X_2) + 3{,}800X_2/(X_1 + X_2) + S_3 = 3{,}000$ [ppm]
4. $0.5\,X_1 + X_2 + S_4 = 12$ [kg/hr]
5. $X_1 - S_5 = 0$ [tons/hr]
6. $X_2 - S_6 = 0$ [tons/hr]
7. $X_1 + S_7 = 25$ [tons/hr]

8. $X_2 + S_8 = 25$ [tons/hr]

Maximize

$Z = 24 X_1 + 20 X_2$ [1,000 lbs/hr]

Slack and surplus variables represent unused resource or capacity. If either the slack or surplus variable is zero for a particular constraint, then that constraint is *active.* If the slack or surplus variable for a constraint is nonzero, then the corresponding constraint is *inactive.* For Case A, with $X_1 = 12$ and $X_2 = 6$ tons/hour the slacks and surplus variables are[4]:

Conveyer	$S_1 = 2$	[tons/hr]	Inactive
Pulverizer	$S_2 = 0$	[hours]	Active
Sulfur	$S_3 = 533.33$	[ppm]	Inactive
Smoke	$S_4 = 0$	[tons/hr]	Active

The nonzero slacks indicate the amount of reserve capacity or resources. For Case A, the amount of reserve conveyer capacity is 2 tons per hour and the additional amount of sulfur oxides that can be emitted into the atmosphere without penalty is 533 parts per million.

Change in the slope of the objective function. What happens if the values of the coefficients of the objective function change? Assume that the thermal value of Coal A is 32,000 pounds of steam per ton. The objective function changes to

$$Z = 32 X_1 + 20 X_2 \quad [1000 \text{ lbs/hr}].$$

4 Aside: Be sure that you know how to obtain these numbers.

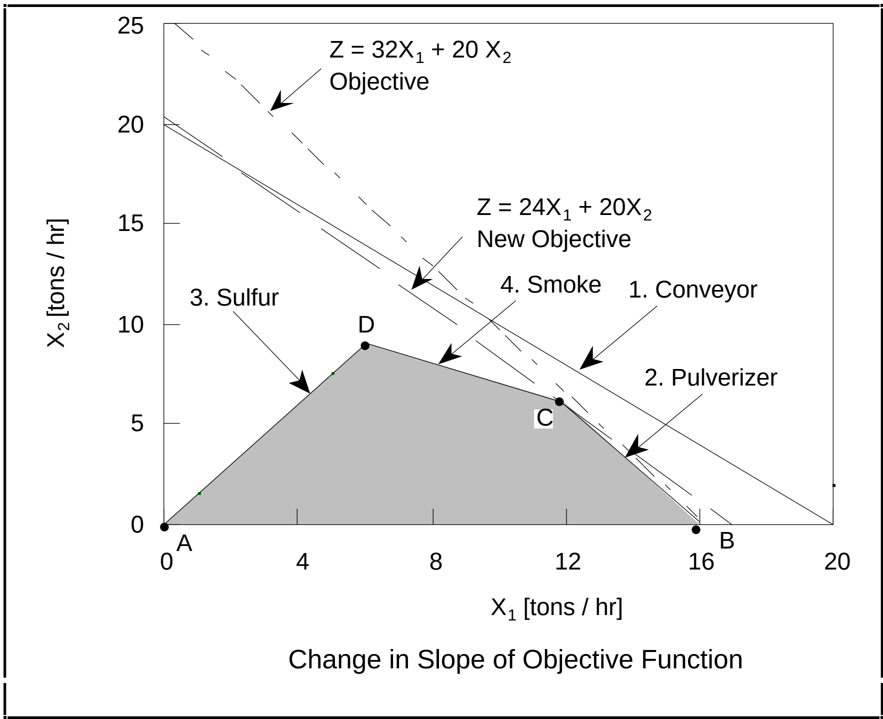


Figure 4.11. Change in slope of objective function

The change in the coefficient changes the slope of the objective function and if this slope is sufficiently large the solution will move to another vertex, Figure 4.11. This will alter the values of the system variables, the objective function and the slack and surplus variables. In Case A, the solution moves to vertex B. *Ranging* or *parametric analysis* of the objective function is the answer to the following question: By how much can we change the coefficient of the objective function and still keep the same solution? Ranging involves identifying the range of change of a coefficient for which the solution remains the same. For example, if C_1 is the coefficient of X_1, then the solution will be at vertex C or include vertex C as long as C_1 satisfies the following[5]

$$10 \leq C_1 \leq 30.$$

---

5 Aside: You should verify this graphically and determine the range of variation of C_2, the coefficient of X_2, for which the solution involves vertex C. In engineering it is preferable that the new solution point is close to the old one. Why?

Change in the right hand side value of a constraint. Suppose, the management is contemplating the installation of emission control equipment that would reduce smoke emission from the smoke stack by 25 percent. This would allow legal emission standards to be met by "uncontrolled" emission of smoke at the furnace of up to 15 kg/hr. How much would this be worth per hour in terms of steam output?

Assume, for the present, that the limit on particulate emission is raised by 1 kg/hr. In this case the right hand side of the smoke constraint goes from 12 to 13 and the smoke constraint becomes:

$$0.5X_1 + X_2 \leq 13.$$

As seen from Figure 4.12, the solution moves from vertex C to vertex C'. The net change in the amount of steam produced is calculated as follows:

Old Solution Point C	*New Solution Point C'*	*Difference*	*Change in Z*
$X_1 = 12$	$X_1 = 11$	-1	(-1) 24
$X_2 = 6$	$X_2 = 7.5$	+1.5	(1.5) 20
		Net change in Z	6

The new value of the objective function is (408 + 6), i.e., 414. So, 414,000 lbs of steam is generated per hour. This change in value of the objective for a unit change in the value of the right hand side is called *imputed value, opportunity cost, shadow price, dual price or dual variable*[6].

6 Warning: The first four quantities are equivalent. There is, however, a subtle difference between dual prices and dual variables.

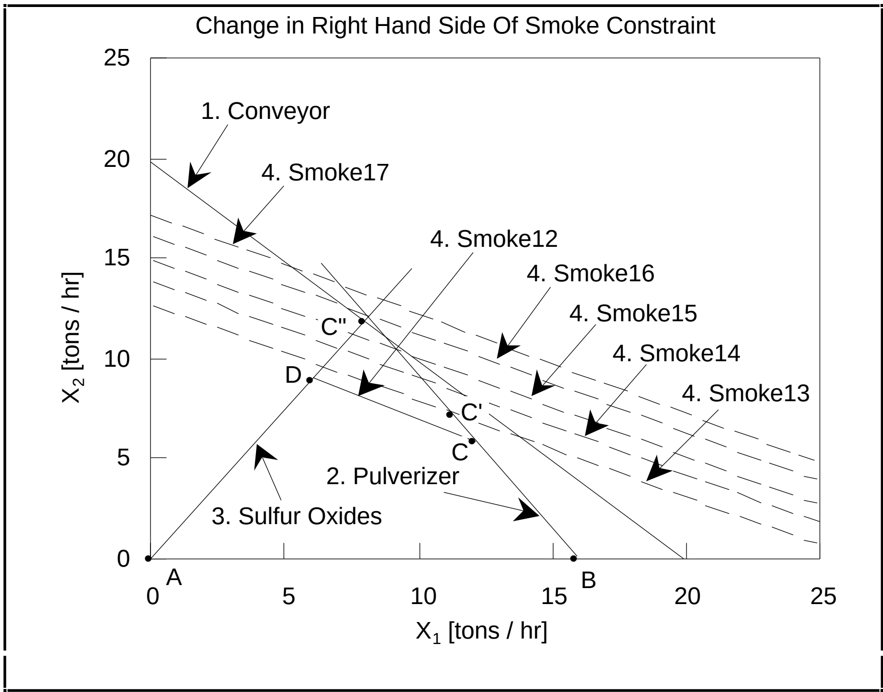


Figure 4.12. Change in right hand side coefficient

As the right hand side of the smoke constraint is further relaxed to 14, 15, etc., the value of the objective function continues to increase until a maximum steam production of 432,000 lbs. of steam per hour is reached at a right hand side value of 16. Further increase in the right hand side coefficient of the constraint has no impact on the value of the objective function since smoke constraint becomes inactive and the conveyer and sulfur constraints become active. The pulverizer constraint continues to remain active. At C", the imputed value for relaxing the smoke constraint goes to zero. The imputed value for tightening the smoke constraint is -6.

Slacks, imputed values and insight. The imputed value for an active constraint is nonzero. For an inactive constraint it is zero and therefore the impact of the constraint on the objective, after a change in its right hand side, will remain zero. Therefore, it is adequate to compute the imputed values for the active constraints. These values provide insight into the stability of the solution from the standpoint of the active constraints. The slack or surplus variable is zero for an active constraint and nonzero for an inactive constraint. The nonzero slacks provide insight into the stability of the solution from the standpoint of the inactive constraints. For Case A, the information used to understand the stability of the solution is as follows:

Constraint	*Slack/Surplus*	*Imputed Value*	*Constraint Status*
Conveyer	2	0	Inactive
Pulverizer	0	14	Active[7]
Sulfur	533.33	0	Inactive
Smoke	0	6	Active

A constraint is said to be tightened if by changing the right hand side value of the constraint, the feasible design space is reduced. A constraint is said to be relaxed if changing the right hand side value increases the size of the feasible design space. With this by way of definition, what if it becomes necessary to reduce the design space (say because of maintenance of equipment), which constraint should be tightened? If on the other hand it is possible to increase the size of the feasible design space by investing in some equipment, which constraint should be relaxed?

The addition of another system variable.

Problem Statement: Plant management is evaluating the possible use of a third type of coal, Coal C. This coal has the following properties:

Pulverizer	1/20 hour pulverizer time/ton
Sulfur oxide emission rate	2,000 ppm
Smoke emission rate	0.8 kg/ton
Equivalent thermal value	21,000 lbs/ton.

The questions are:

- ❑ Should this coal be used? If no,
- ❑ What should be the properties of a coal that is likely to be selected?

The mathematical form for the Three Coal Problem follows.

Find

System Variables

X_1 - the rate of consumption of Coal A [tons/hr]

X_2 - the rate of consumption of Coal B [tons/hr]

X_3 - the rate of consumption of Coal C [tons/hr]

---

7 Aside: Can you compute this value?

Satisfy

System Constraints

1. Conveyer capacity

$$X_1 + X_2 + X_3 \leq 20 \quad \text{[tons/hr]}$$

2. Pulverizer capacity

$$1.5\,X_1 + X_2 + 1.2\,X_3 \leq 24 \quad \text{[hours]}$$

3. Sulfur oxides emission

$$-1{,}200\,X_1 + 800\,X_2 - 1000\,X_3 \leq 0 \quad \text{[NMU]}$$

4. Smoke emission

$$0.5\,X_1 + X_2 + 0.8\,X_3 \leq 12 \quad \text{[kg/hr]}$$

Bounds on System Variables

5. Lower bounds on system variables

$$X_1 \geq 0 \quad \text{[tons/hr]}$$
$$X_2 \geq 0 \quad \text{[tons/hr]}$$
$$X_3 \geq 0 \quad \text{[tons/hr]}$$

6. Upper bounds on system variables

$$X_1 \leq 25 \quad \text{[tons/hr]}$$
$$X_2 \leq 25 \quad \text{[tons/hr]}$$
$$X_3 \leq 25 \quad \text{[tons/hr]}$$

Maximize

7. The rate of steam produced

$$Z = 24\,X_1 + 20\,X_2 + 21\,X_3 \quad \text{[1000 lbs/hr]}$$

The preceding can be solved by starting afresh or by using the imputed values from the Two Coal Problem solution, Case A.

Let us assume (arbitrarily) that 1 ton of Coal C is burnt per hour. This has the same effect of reducing the right hand sides of the system constraints as follows:

1. Conveyer capacity

$$X_1 + X_2 \leq 20 - 1 \quad \text{[tons/hr]}$$

2. Pulverizer capacity

$$1.5\,X_1 + X_2 \leq 24 - 1.2 \qquad \text{[hours]}$$

3. Sulfur oxides emission

$$-1{,}200\,X_1 + 800\,X_2 \leq 0 + 1000 \qquad \text{[NMU]}$$

4. Smoke emission

$$0.5\,X_1 + X_2 \leq 12 - 0.8 \qquad \text{[kg/hr]}$$

The change in the value of the objective function on using 1 unit of Coal C is computed as follows:

Constraint	*Imputed value*	*Change in RHS*	*Change in Z*
1. Conveyer	0	-1	0
2. Pulverizer	14	-1.2	-16.8
3. Sulfur	0	1,000	0
4. Smoke	6	-0.8	- 4.8
Total change in steam output			-21.6
Steam produced by 1 unit of Coal C			21.0
Net change in steam output [1000 lbs/hr]-0.6			

Since the steam output decreases, Coal C is not competitive and should not be used. For Coal C to be competitive its thermal value should be greater than 21,600 lbs/hr.[8]

4.4.7 Case B: Formulation and Graphical Solution

The mathematical form of Case B is identical to that of Case A. In Case B, however, the lower bounds on the system variables are nonzero:

$X_1 \geq 5$ [tons/hr]

$X_2 \geq 5$ [tons/hr]

The solution space, for Case B, is shown in Figure 4.13. Because of the nonzero lower bounds in Case B, the feasible design space in Figure 4.13 is smaller than the feasible design space for Case A in Figure 4.11. The best solution occurs at vertex C and is the same as that for Case A. The active constraints are also the same in both cases. Why then are the two cases being presented?

The reason is principally pedagogical. Case A is used to illustrate the method of *formulating* a linear single objective optimization problem so that the *pivoting* operations required for solving the problem using the pre-multiplication technique are possible. For Case B, it is assumed that a person knows how to pivot, the formulation is extended so that the pre-multiplication technique can be used to solve any linear single objective optimization problem.

[8] Aside: Can you identify two other conditions under which coal C would be competitive?

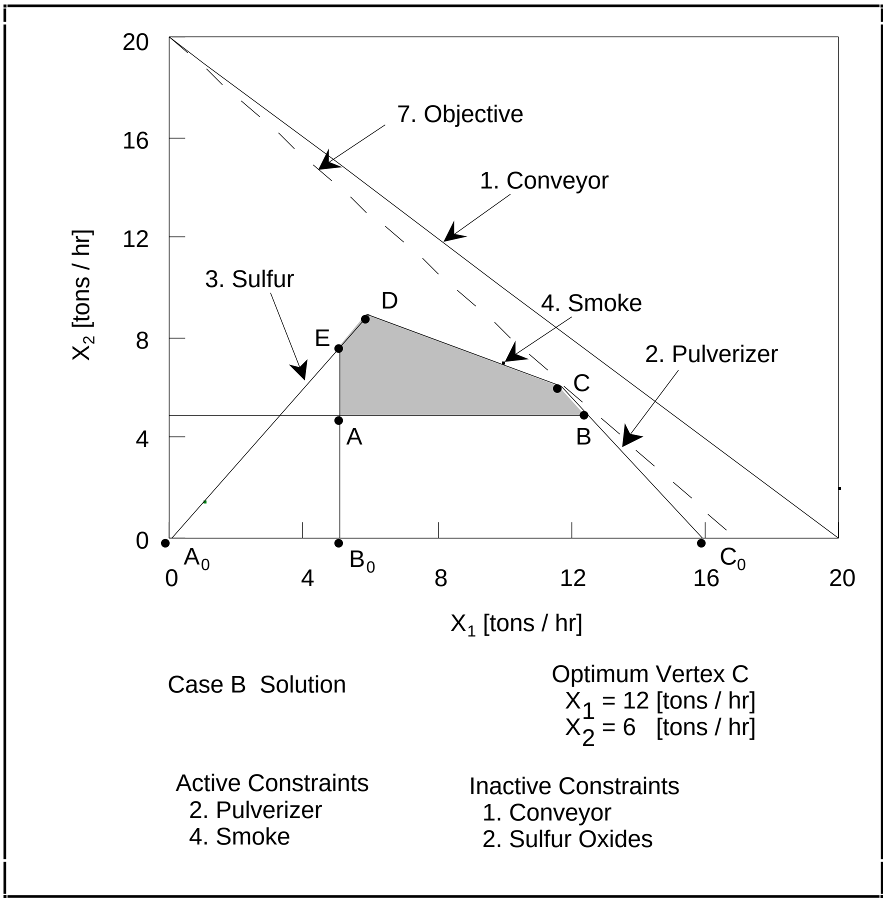


Figure 4.13. Case B solution

4.5 The Single Goal Compromise Decision Support Problem

In this section, the single objective optimization problem is reformulated and solved as a single goal compromise DSP. It will be shown that single objective optimization problems that call for the minimization or the maximization of an objective can be reformulated and solved as single goal compromise DSP.

4.5.1 General Formulation

The linear optimization problem can be rewritten as a single goal compromise DSP. A target value is first assigned to the objective which can then be written as a goal. Then depending on the objective the appropriate deviation variable is included in the minimizing deviation function.

Find

The Independent System Variables

X_1, X_2

The Deviation Variables

$d^-, \; d^+$

Satisfy

System Constraints

$$a_{11}X_1 + a_{12}X_2 \leq b_1$$
$$a_{21}X_1 + a_{22}X_2 \leq b_2$$
$$a_{31}X_1 + a_{32}X_2 \geq b_3$$

System Goal (Normalized)

$$(c_1/T)X_1 - (c_2/T)X_2 + d^- - d^+ = 1$$

(T = Target value)

Bounds on System Variables

$$X_1 \geq X_1^{min}$$
$$X_2 \geq X_2^{min}$$
$$X_1 \leq X_1^{max}$$
$$X_2 \leq X_2^{max}$$

Minimize

The Deviation Function

$$Z = d^- + d^+ \quad \text{or} \quad d^- \quad \text{or} \quad d^+.$$

The formulation here is different from the single objective case in that it includes deviation variables and a system goal. Also the “objective” here is in terms of the deviation variables only. The target value T has to be set to an appropriate value.

4.5.2 Case C: The Word Problem

Given

Same as in Section for Case A.

Target value, T, of steam to be produced [lbs/hr]

Assumption

The maximization of the rate of electricity produced is equivalent to the maximization of the rate of steam generated.

Find

Independent System Variables

The rate of consumption of Coal A: X_1 [tons/hr]
The rate of consumption of Coal B: X_2 [tons/hr]

Deviations from the target amount of steam to be produced

d^- underachievement of the rate of steam production [-]

d^+ overachievement of the rate of steam production [-]

Satisfy

System Constraints

1. The capacity constraint on the conveyer unit.
2. The capacity constraint on the pulverizer unit.
3. The emission of sulfur oxides is limited.
4. The emission of particulates (smoke) is limited.

System Goal

5. It is desirable to achieve the target value of steam, T, to be produced.

Bounds on the System Variables

6. The system variables should not be less than a specified value.
7. The system variables should not exceed a specified upper limit.

Minimize

Underachievement of the steam production target, d^-.

4.5.3 *Case C: The Mathematical Form of the Word Problem*

Given

As stated in the word problem.

T = 432,000 lbs/hr

Find

System Variables

X_1 -	the rate of consumption of Coal A	[tons/hr]
X_2 -	the rate of consumption of Coal B	[tons/hr]

Deviations from the Target Amount of Steam to be Produced

d^-	underachievement of the rate of steam production	[-]
d^+	overachievement of the rate of steam production	[-]

Satisfy

System Constraints

1 Conveyer capacity

$$X_1 + X_2 \leq 20 \quad \text{[tons/hr]}$$

2 Pulverizer capacity

$$1.5X_1 + X_2 \leq 24 \quad \text{[hours]}$$

3 Sulfur oxides emission

$$-1200X_1 + 800X_2 \leq 0 \quad \text{[NMU]}$$

4 Smoke emission

$$0.5X_1 + X_2 \leq 12 \quad \text{[kg/hr]}$$

System Goal

5 Steam generation

$$(24{,}000/T)\ X_1 \ + \ (20{,}000/T)\ X_2 \ + d^- - d^+ = 1 \qquad [-]$$

Bounds on System Variables

6 $X_1 \geq 0, \ X_2 \geq 0$ [tons/hr]

7 $X_1 \leq 25, \ X_2 \leq 25$ [tons/hr]

Minimize

8 The deviation from the target rate of steam production, T.

$$Z = d^- \qquad [-]$$

4.5.4 Case C: Graphical Solution

The solution space is shown in Figure 4.14. The following points are pertinent to the solution:

- The compromise solution is at point C in the figure.
- The rate of consumption of Coal A (X_1) is 12 tons/hour.
- The rate of consumption of Coal B (X_2) is 6 tons/hour.
- The pulverizer constraint, constraint 2, and the particulate emission constraint, constraint 4, are active.
- The slack capacity of the conveyer constraint (S_1) is 2 tons/hour.
- The slack in the sulfur oxides emission limit is (S_3) 533.33 ppm.
- The target amount of steam cannot be generated without violating at least one of the other constraints. The shortfall of steam generated, d^-, is 24,000 lbs/hour. Therefore, only 408,000 lbs of steam can be generated without violating any of the constraints.

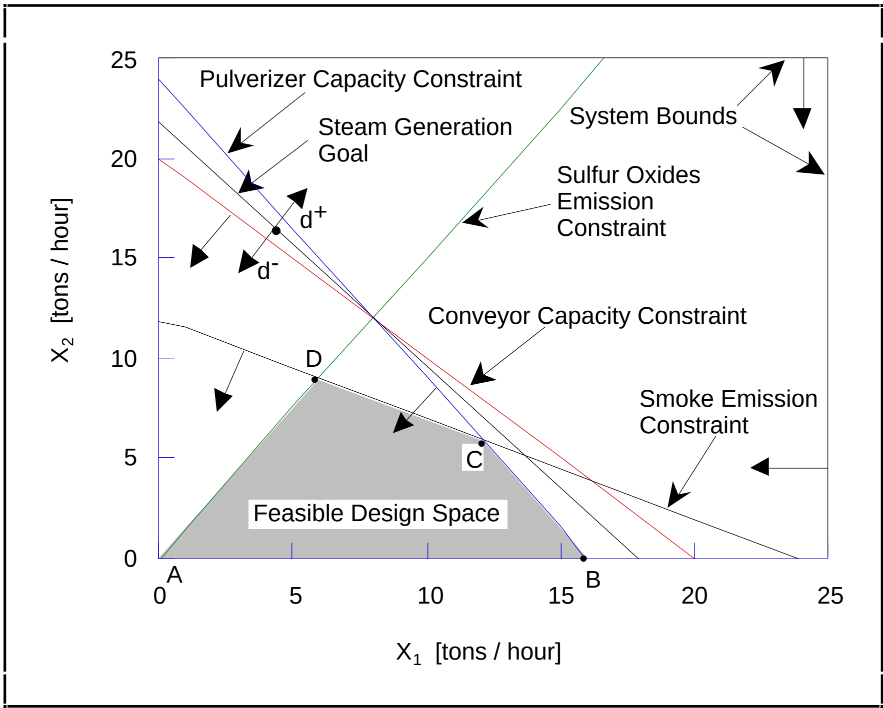


Figure 4.14. Case C design space

4.6 The Linear, Multigoal Compromise Decision Support Problem

4.6.1 General Formulation of the Linear, Multigoal Compromise DSP

Given

Same as in Section 4.5.1

Assumption

The maximization of the rate of electricity produced is equivalent to the maximization of the rate of steam generated.

Find

Independent System Variables

The rate of consumption of Coal A: X_1 [tons/hr]
The rate of consumption of Coal B: X_2 [tons/hr]

Deviations from the rate of sulfur oxides emission

d_1^- surplus capacity to emit sulfur oxides without penalty [-]

d_1^+ sulfur oxides emitted over specified limit [-]

Deviations from rate of smoke emission

d_2^- surplus capacity to emit smoke without penalty [-]

d_2^+ smoke emitted over limit [-]

Deviations from the target amount of steam to be produced

d_3^- underachievement of the rate of steam production [-]

d_3^+ overachievement of the rate of steam production [-]

Satisfy

System Constraints

1. The capacity constraint on the conveyer unit.
2. The capacity constraint on the pulverizer unit.

System Goals

3. The emission of sulfur oxides is limited.
4. The emission of particulates (smoke) is limited.
5. It is desirable to achieve the target value of steam, T, to be produced.

Bounds on the System Variables

6. The system variables should be greater than the specified lower limit.
7. The system variables should not exceed a specified upper limit.

Minimize

8. A function of the deviation variables. All goals have the same importance.

4.6.2 Case D: The Mathematical Form of the Word Problem

The derivation of all the constraints and the goals in the mathematical formulation has been covered in Section 4.5. Of special interest is the adjustment of the coefficients of constraint 3 to ensure that the deviation variables of all goals vary within the same range. The constraint was divided by 10 to make the coefficients on its left hand side of the same order as in the other system goals.

Find

System Variables

X_1 - the rate of consumption of Coal A [tons/hour]

X_2 - the rate of consumption of Coal B [tons/hour]

Deviations from the Target Rate of Sulfur Oxides Emission (normalized)

d_1^- surplus capacity to emit sulfur oxides without penalty [-]

d_1^+ sulfur oxides emitted above limit [-]

Deviations from the Target Rate of Smoke Emission (normalized)

d_2^- surplus capacity to emit smoke without penalty [-]

d_2^+ smoke emitted above limit [-]

Deviations from the Target amount of steam to be generated (normalized)

d_3^- underachievement of the rate of steam production [-]

d_3^+ overachievement of the rate of steam production [-]

Satisfy

System Constraints

1. Conveyer capacity

$$X_1 + X_2 \leq 20$$ [tons/hour]

2. Pulverizer capacity

$$1.5X_1 + X_2 \leq 24$$ [hours]

System Goals

3. Sulfur oxides emission

$$-0.1X_1 + 0.0667X_2 + d_1^- - d_1^+ = 0$$ [-]

4. Smoke emission

$$(0.5/12)X_1 + (1/12)X_2 + d_2^- - d_2^+ = 1$$ [-]

or

$$0.0417X_1 + 0.0833X_2 + d_2^- - d_2^+ = 1$$

5. Steam generation (Target value, T = 432,000)

$$(24{,}000/T)\, X_1 + (20{,}000/T)\, X_2 + d_3^- - d_3^+ = 1$$ [-]

or

$$0.0556X_1 + 0.0463X_2 + d_3^- - d_3^+ = 1$$

Bounds on System Variables

6. $X_1 \geq 0, \; X_2 \geq 0$ [tons/hour]
7. $X_1 \leq 25, \; X_2 \leq 25$ [tons/hour]

Minimize

8. The deviation function

$$Z = W_1 d_1^+ + W_2 d_2^+ + W_3 d_3^-$$ [-]

where $W_1 + W_2 + W_3 = 1$ and $W_1 = W_2 = W_3 = W$.

The value of W = 0.33 is used in this case.

4.6.3 Case D: Graphical Solution

The design space for Case D is shown in Figure 4.15. The feasible design space has been identified. In this case the solution lies at point P on the boundary of the feasible design space. The solution is the same as the one obtained in Cases A, B and D. The smoke emission goal is exactly satisfied at this point. The sulfur oxide emission and steam generation target values are underachieved. Note that because of fewer system constraints the feasible design space is larger.

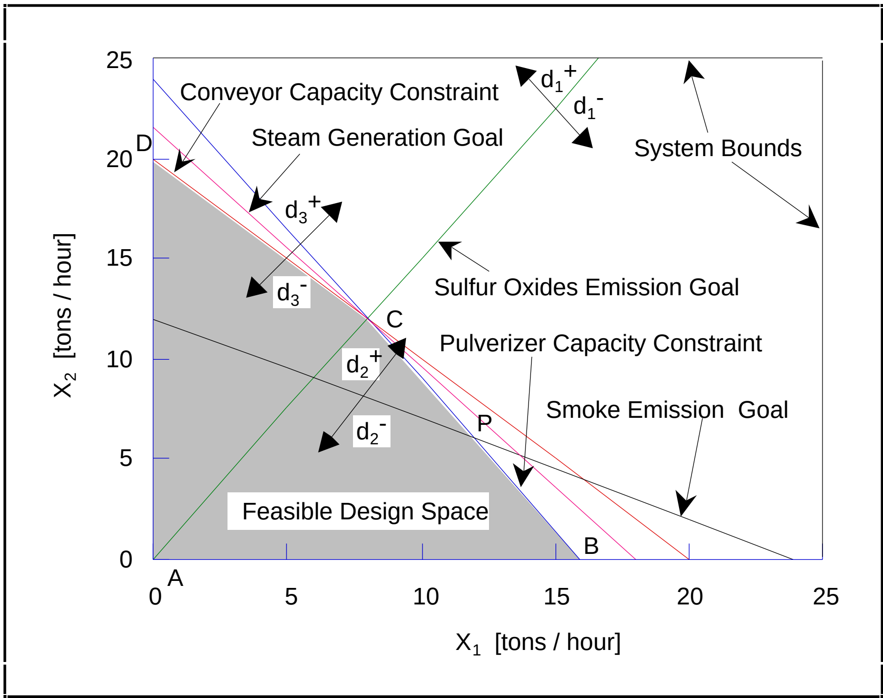


Figure 4.15. Case D solution space

4.7 The Nonlinear, Multigoal Compromise Decision Support Problem

4.7.1 Case E: Mathematical Formulation

The modification to the story introduces a new, nonlinear, constraint in the original formulation. The constraint deals with the upper limit on the stockpiling costs.
It reads:

$$3X_1(X_1 - 10) + 4X_2(X_2 - 5) \leq 30 \quad (\$/\text{hour})$$

The mathematical formulation for the nonlinear problem is given next. An additional system constraint is added and the lower bounds on the system variables are taken as zero.

Given

Same as for Cases A and B.

The penalties (gains) from stockpiling coal above (below) the desired limits. A maximum stockpiling cost of $30/hour.

Assumption

The maximization of the rate of electricity produced is equivalent to the maximization of the rate of steam generated.

Find

System Variables

X_1	The rate of consumption of Coal A	[tons/hour]
X_2	The rate of consumption of Coal B	[tons/hour]

Deviations from the target rate of sulfur oxides emission (normalized)

d_1^-	Surplus capacity to emit sulfur oxides without penalty	[-]
d_1^+	Sulfur oxides emitted above limit	[-]

Deviations from the target rate of smoke emission (normalized)

d_2^-	Surplus capacity to emit smoke without penalty	[-]

d_2^+ Smoke emitted above limit [-]

Deviations from the target amount of steam to be generated (normalized)

d_3^- underachievement of the rate of steam production [-]

d_3^+ overachievement of the rate of steam production [-]

Satisfy

System Constraints

1. Conveyor capacity

$$X_1 + X_2 \leq 20 \quad \text{[tons/hour]}$$

2. Pulverizer capacity

$$1.5\,X_1 + X_2 \leq 24 \quad \text{[hours]}$$

3. Stockpiling cost

$$3\,X_1\,(X_1 - 10) + 4\,X_2\,(X_2 - 5) \leq 30 \quad \text{[\$/hour]}$$

System Goals

4. Sulfur oxides emission

$$-0.1X_1 + 0.0667X_2 + d_1^- - d_1^+ = 0 \quad [-]$$

5 Smoke emission

$$0.0417X_1 + 0.0833X_2 + d_2^- - d_2^+ = 1 \quad [-]$$

6. Steam generation

$$0.0556X_1 + 0.0463X_2 + d_3^- - d_3^+ = 1 \quad [-]$$

Bounds on system variables

7. $X_1 \geq 0, \quad X_2 \geq 0$ [tons/hour]

8. $X_1 \leq 25, \quad X_2 \leq 25$ [tons/hour]

Minimize

The deviation function

$$Z = W_1\,d_1^+ + W_2\,d_2^+ + W_3\,d_3^- \quad [-]$$

$W_1 + W_2 + W_3 = 1$ and $W_1 = W_2 = W_3 = W\ (= 0.33)$

4.7.2 Case E: Graphical Solution

The design space for this problem is shown in Figure 4.16. The feasible design space is shown by hatched lines. The new constraint, constraint 3, is also shown. The graphical solution is obtained by linearizing constraint 3. The method for linearizing equations is described in greater detail in Volume 2.

Step 1

Rewrite constraint as $f(X) \geq 0$

$$f(X) = 30 - 3X_1(X_1 - 10) - 4X_2(X_2 - 5) \geq 0$$

Step 2

Choose an initial starting point, X^o

$$X^o = \{ X_1^o = 0, X_2^o = 0 \}$$

Step 3

Evaluate the following coefficients at X^o

$A = f(X) = 30$

$B_1 = \partial f(X)/\partial X_1 \big|_{\underline{x}^0} = 30$ $\quad B_2 = \partial f(\underline{X})/\partial X_2 \big|_{\underline{x}^0} = 20$

$C_1 = \partial^2 f(X)/\partial X_1^2 \big|_{\underline{x}^0} = -6$ $\quad C_2 = \partial f(X)/\partial X_2^2 \big|_{\underline{x}^0} = -8$

Step 4

Evaluate secant plane derivatives

$a_1 = (AC_1/B_1)/(1 - (1\text{-}2AC_1/B_1^2)^{0.5}) = 32.748$

$a_2 = (AC_2/B_2)/(1 - (1\text{-}2AC_2/B_2^2)^{0.5}) = 24.832$

Step 5.

This step is skipped because the roots are real.

Step 6.

Evaluate the right hand side of the linearized constraint.

$$b = a_1X_1^o + a_2X_2^o - A = -30$$

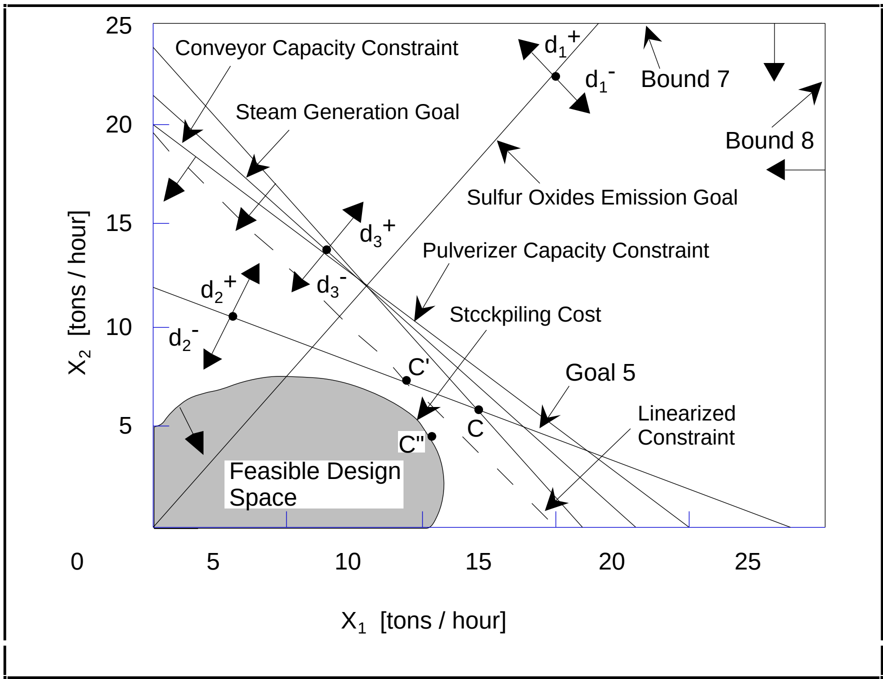


Figure 4.16. Case E design space

Step 7

Establish the linearized constraint

$$a_1X_1 + a_2X_2 \geq b$$

i.e.,

$$32.748\ X_1 + 24.832\ X_2 \geq -30$$

This constraint when plotted in the design space makes the entire first quadrant of the design space feasible and therefore is redundant.

Step 2

Choose C, Figure 4.16, as the next initial point.

$$X^o = \{\ X_1 = 12,\ X_2 = 6\ \}$$

Step 3

Evaluate the following coefficients.

$$A = -66$$

$$B_1 = -42 \qquad B_2 = -28$$

$$C_1 = -6 \qquad C_2 = -8$$

Step 4

Evaluate the secant plane derivatives.

$$a_1 = -36.588$$

$$a_2 = -18.857/(1- (-0.3469)^{0.5})$$

Step 5

Are a_1 and a_2 real?

$$a_2 \text{ is imaginary}$$

$$\text{Set } a_2 = B_2 = -28$$

Step 6

Evaluate the right hand side of the linearized constraint. Hence,

$$b = -541.06$$

Step 7

Establish the linearized constraint, viz.,

$$-36.588\ X_1 - 28\ X_2 \geq -541.06 \quad \text{or}$$

$$36.588\ X_1 + 28\ X_2 \leq 541.06$$

This constraint is plotted, line 3', in Figure 4.16. As determined by the set of linearized constraints, the optimum is found to be at C' = $\{X_1 = 9.08, X_2 = 7.46\}$. However, this solution is approximate. It is in the vicinity of the optimum. To obtain a more accurate solution, a new starting point needs to be chosen and steps 1 through 8 repeated to obtain solutions close to the actual optimal. Point C" $\{X_1 = 10, X_2 = 5.75\}$ is determined to be the true optimum. The algorithm is cumbersome when calculations are done by hand.

5

Vayun Capers

In this chapter, projects are presented that are suitable for use together with the text. These projects include stories or fairy tales taking place on an imaginary planet named Vayu. The fairy tales require students to design, build, and test, under competition conditions, mechanisms that (for the students) represent original design. This allows them to be creative and to innovate in a manner that results in a working mechanism. We have found these projects to be of immense value in providing students the opportunity to learn through doing, and in the process gain confidence in their ability to negotiate solutions to open problems.

5.1 Grading Scheme and Mindset

The chapters of this book have been concerned with the development of a theory of decision making in design. The purpose of this chapter is to introduce a complete set of design, build and test projects suitable for use in a design course that uses the Decision Support Problem Technique. These projects have all been used in the first mechanical design course, in the fourth semester of a sixteen semester program at the University of Houston. Each class is divided into groups of three to four students. (The students were allowed to pick their own groups. It is felt by the authors that this often teaches the object lesson, "Your best friend is not necessarily your best choice as a partner.") The student groups are then placed in the role of design consultants or other design professionals, and set loose to realize a design for the specification they have been given.

The academic organization of the class is based on the need to teach design synthesis alongside analysis in design. The grading scheme is as follows:

Synthesis	60%	
Project		60%
Quality of construction (group)		20%
Creativity of design (group)		20%
Performance (group)		50%
Critical Evaluation (individual)		10%
Take-home Exams	40%	
Selection (individual)		20%
Compromise (individual)		20%

Analysis 40%

- Homework
- Mid-term exam or mini-project
- Final exam

At the University of Houston, design analysis issues from strength of materials are taught. However, for programs at other institutions, different analysis-oriented material may be appropriate. e.g., kinematics, fluid dynamics, control. The engineering analysis required for these projects is sometimes more advanced than what a sophomore engineer knows; however, it has been found that this gives the student a greater appreciation of the disciplines they encounter down the road.

The projects in this chapter have been included to provide a potential instructor with ready-made problems that have been used in the past with the DSP Technique as the principal design method. As importantly, the projects are here to give the student a sense of what other students have been able to achieve with the DSP Technique. In addition to examples presented previously, the projects demonstrate the types of system design problems that have been attacked and solved by other students.

Our mindset in creating projects has been to encourage, where possible, a design consultant role-playing activity. The design groups report weekly to a project coordinator, who is

Figure 5.1. Map of Vayu, circa 550 S.E.

responsible for oversight of the project. However, the coordinator keeps a loose rein on the design groups, only stepping in when there is danger of the group falling completely apart. The creation of a new design project is done every semester. In this way, the design groups are always put in the role of having to deal with new designs. (This is also why no pictures of the projects designed by our students have been included in this chapter. Anyone involved in these designs will thus be working from a clean slate.) Other stipulations are: that there should be a minimum of control over what the student groups create; and that there is a minimum of work necessary to set up a test course for the project so that the students can work and test anywhere. The projects should also have a certain amount of drama involved, so that the local media are interested in the proceedings. This further reinforces the design consultant role in terms of dealing with the public and press.

The projects in this chapter have been presented in historical order, following the history presented in Section 5.2. However, the projects also follow other groupings base on the major analysis and synthesis issues involved. For instance, projects OLDTEK, Section 5.3.4, and ARM, Section 5.3.8, emphasize the need for a close study of ergonomics, since there is an important man-machine interface involved. Projects RAT, Section 5.3.3, and BUG, Section 5.3.5, emphasize kinematics. POP, Section 5.3.2, and WindBAG, Section 5.3.10, both require considerable thought in terms of systems. RSVP, Section 5.3.7, and SHARK, Section 5.3 11, both require some analysis of the control issues involved.

5.2 A Breif History of Vayu

The planet Vayu is a fictional construct upon which the stories for the projects have been based. Fictional stories are made use of to provide a setting, a need and peripheral information that may or may not have a bearing on the project. This setting challenges the student groups more, since they encounter an open problem, a problem whose solution requires new ideas and new techniques. This fairy tale approach helps to simulate design problems the student will face in the future, where it may be as important to know the background of the specifications, as it is to know the design specification itself. Without further ado, the planet Vayu, its people and its history are presented.

The planet Vayu is an Earth-type planet, the third planet orbiting Chara, a yellow star about 30 light years from the Earth's sun. Vayu has a 60% hydrograph, Earth-like gravity, atmosphere and temperature and is blessed with extremely rich resources. The planet consists of two major continents, one in the northern hemisphere and one in the southern. The northern hemisphere contains large virgin forests and considerable amounts of arable land. Most of the mineral resources, including iron, aluminum, titanium and radioactives, are found in the southern continent. Vayu also has three moons, two of which are also resource rich. A map of Vayu, in its technological heyday, is depicted in Figure 5.1. A timeline, with some of the more important events is shown in Figure 5.2.

The planet was colonized by Earthers, in the second wave of expansion of the Galactic Confederation of Planets, in the year 426 S.E.

(S.E. denotes Space Expansion, and represents the number of years from the date the first colony ship left Earth.) Vayu was chosen for colonization because of its Earth-like characteristics and its extremely rich resources, which would allow it to become self-sustaining, rapidly. Because of the arable lands in the north, the colony was able to feed itself, with very few imports. The existence of mineral resources meant that the colony would be able to pay for its startup costs, quickly. At the time of colonization, technology was very advanced and this, along with the existence of cash resources for heavy industry, meant that society on Vayu was based on and glorified technology. There were artists and farmers among the colonists, but they were among the minority. The colony was able to pay its way early on, with mining and heavy industry, and soon earned a spot among the more advanced worlds in the galaxy.

As Vayu emerged as a technological focal point for its end of the galaxy, the planetary government evolved into a technocracy and leaders of industry and science made the laws. Agricultural fed the people, but did not bring in hard cash, and so the farmers were left to themselves on the northern continent, while the technocrats exploited the southern continent. During this time, arts suffered greatly. The society became very aggressive, with talk of expansion and even world conquest for more resources and breathing room. The powerful companies grew from mining claims and industrial complexes into feudal corporate clans, as shown in the map in Figure 5.1. Healthy economic competition began to turn ugly. During this time, individuals that desired personal freedom were only able to find it in the north. Many artists, individualists, iconoclasts and others, huddled together in communes, growing their own food and shunning the south and the ‘Hi-te’ way of life.

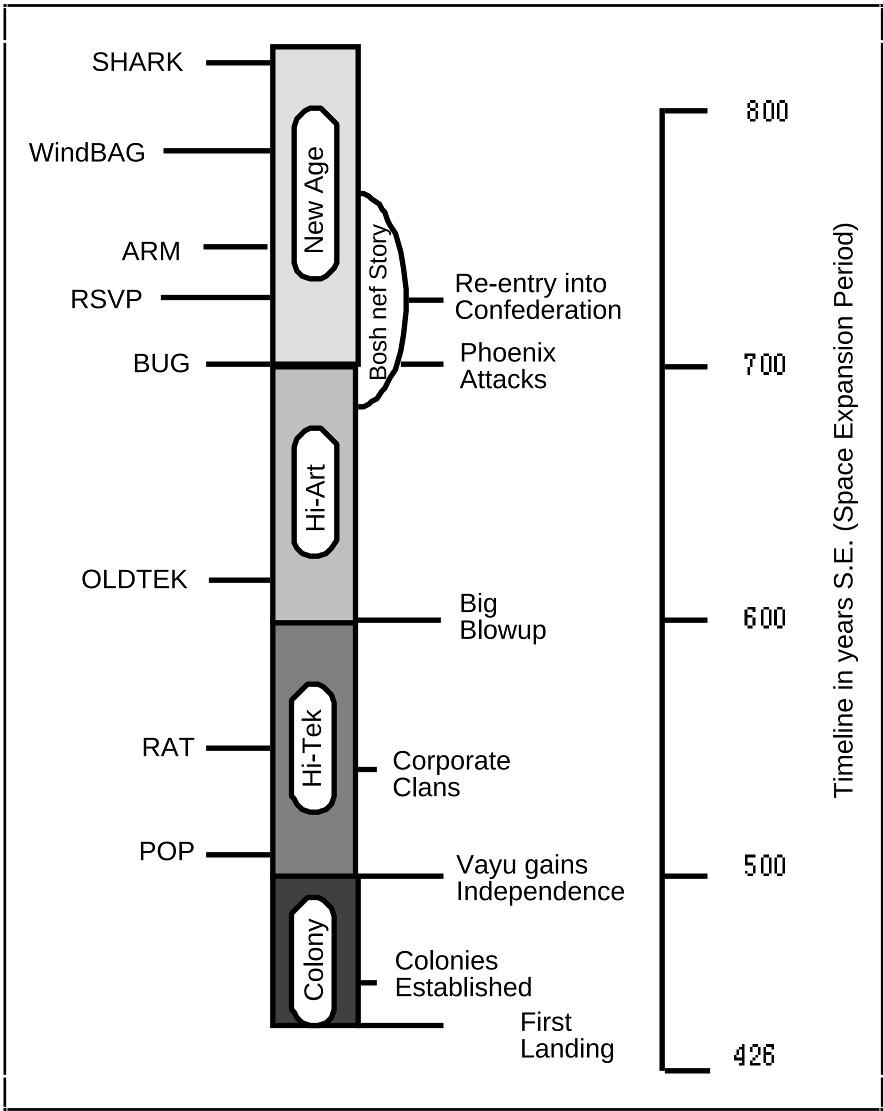


Figure 5.2. Timeline for Vayu from discovery onward

During the waning years of the sixth century S.E., the corporate clans ceased looking off-world and fell to bickering among themselves. Each clan wanted to take the leadership role, not only on Vayu, but in that arm of the galaxy. The bickering gave way to vendettas and assassinations, and finally to total war, each clan fielding its own army. Eventually, the entire southern continent was devastated by the total war of the corporate clans and their civilization was reduced to near barbarism. The only civilized settlements existed in the farming regions and art communes of the north. The farmers, artists, and individualists slowly began to pick up the pieces and thus were able to lead Vayu back from the brink of total barbarism. However, this occurred at the expense of Vayu's industrial might since there was a heavy backlash from the survivors against anything Hi-tek. The planet Vayu withdrew from its position of power within the galactic community, and became another quiet, backwater planet.

A new society grew up on Vayu, the basis of which were gentlemen farmers. There was also a vast increase in patronage of the arts. Almost everyone practiced one art or the other, and if rich enough, supported one or more artists choice. Due to the abundant farm land untouched by the Corporate Clan Wars, Vayu could support itself on its own agricultural produce. Some artists even gained interplanetary renown for their works, and some of the spices and the wines produced from the best vineyards were much sought after, around the galaxy. Vayu still had some cash crops capable of balancing trade.

The new rulers of the mostly agrarian Vayu were the strongest proponents of the pastoral way of life. They were also pragmatists, and allowed some of the old technologies to be maintained, particularly transportation and communication. Remnants of the technocracy were called wrenches, and they and their children were placed in servitude to the farmers. However, new inventions or developments were viewed with distrust and discouraged, or even outlawed in some areas.

Another crisis point for Vayu occurred when the evil creature Phoenix threatened the world, Section 5.3.5 The farmers were unable to deal with Phoenix. They had imagination, but no technical skills. The wrenches were unable to deal with the Phoenix, since imagination had been discouraged among them for years. The savior of Vayu is Bosh nef Storey - a farmer who saw the potential benefits of new and innovative technology, as well as the kind of thinking that led to innovation and creativity. He rallied the leaders and the people by helping them to synthesize their ideas into a concept capable of defeating the Phoenix.

A new age arose with Bosh nef Storey leading the way. Technology was no longer despised nor was it revered. A University was established to produce more people like Bosh. Innovative and efficient students rose to take places of power in planetary leadership. After a time, the Confederation contacted Vayu to reestablish relations. Vayu reestablished trade with the galaxy, selling among other things, radically different agricultural products. To the surprise and delight of the Confederation, Vayu had become a cornucopia of basic and exotic foodstuffs. This was fortuitous for the Confederation, since many planets could not provide enough food for their people, and food riots began to break out. Vayu thus became a focal point again, this time as a breadbasket. Further, being impressed with the way Vayu turned itself around, the Confederation began to send students to the University of Vayu. Vayu became a major learning center, patron of arts and focal point of trade.

5.3 The Vayun Design Project Stories

The following projects are approximately in chrnological order in Vayun history. Each project stresses the problems of dealing with systems, creativity and innovation, and basic aspects of engineering analysis, mechanics, aerodynamics, hydrostatics, etc. Further, in every project the student group is presented with conflicting objectives. The authors feel this is one of the most important aspects of creating a design project.

Each project is presented in story form first with the task, followed by restrictions, conditions and performance rules. The projects are presented in the chronology presented in Figure 5.2. The aim of these design projects is to give the student the opportunity of taking a design beyond the drawing board stage to see how the ideas work out in practice. Also, in the preliminary stages of testing the mechanism, the student groups are able to modify and develop the design to improve its performance. These are extremely important stages in the learning process of the designer as they help him or her to develop a feeling of what will or will not work in practice. In addition to creativity and quality of construction, the mechanism will be assessed on how well it will perform. The students are expected to make every effort to come up with a working and competitive mechanism.

All mechanisms should be submitted for assessment of design creativity and quality of construction at a time set by the instructor. At the same time a group log ("sanitized" progress reports) with a suitable introduction that highlights aspects of the design and the method of design must be submitted. The introduction must be no more than two typewritten or three legible hand-written pages. In addition, a critical evaluation of the design and the method of design must be submitted by each student designer, 2 sheets maximum. The critical evaluation should highlight what a student designer has learned about design process and the insight he/she is able to provide as a result of this experience. A penalty is levied for incomplete or late submissions. At this time the student group will be expected to give a sales/technical presentation of their design. To accompany the presentation, the students should prepare a sales brochure, and a specification sheet, to allow display of their design There are general and project-specific restrictions and conditions placed on all projects. The project-specific restrictions are given with each project. The general restrictions and conditions follow.

Restrictions.

1. The mechanism may be constructed of any type of material.
2. The mechanism must be constructed using materials and "off-the-shelf" items found in average suburban hardware stores and shopping malls. The use of any type or form of construction kit is not allowed.
3. All construction work must be done by the students.
4. The total cost of the mechanism should not exceed $100.

Conditions.

1. Students should work in groups of four. Each student in the group is expected to receive the same grade for the design, construction and performance of the mechanism.
2. The mechanism must be completely self contained; unless specified otherwise, and no form of remote control is allowed.
3. All groups shall submit the final concept of their proposed system on the prescribed form for approval by a panel of judges. This panel is composed of the instructors and project coordinators for the course. The concepts will be examined by the judges to ensure that the proposed system satisfies the restrictions and conditions of the project. The judges must be informed *in writing* of any subsequent changes in the concept (not in the detailed design) of the system.

5.3.1 Project SOG: Planetary Expeditions Are All Wet

LOG OF THE GCS SALIENT
(PIONEERING AND EXPLORATION)
ENTRY 3297
RE: EXPLORATION OF CHARA 4, "VAYU"

THE DESERT EXPLORATION TEAM HAS ENCOUNTERED DIFFICULTIES IN THEIR SURVEY OF PROSPECTIVE MINING SITES IN THE DESERTS OF VAYU, THE FOURTH PLANET OF THE STAR CHARA. IT SEEMS THAT THE TEAM HAS BEEN HAVING PROBLEMS WITH ONE OF THE INDIGENOUS CREATURES, WHICH THE TEAM HAS NICKNAMED GRONKS,

AFTER THE SOUND THE ANIMALS MAKE. THE GRONKS ARE REPORTED TO BE FEROCIOUS, TERRITORIAL CREATURES, WHICH ATTACK ANYTHING OR ANYONE THAT COMES WITHIN 5 METERS OF THEM. THE GRONK'S NATURAL WEAPONS INCLUDE BLURRING SPEED, RAZOR SHARP TEETH AND CLAWS CAPABLE OF RIPPING THOUGH THE EXPLORER'S ENVIRONMENTAL SUITS, AND A POISON THAT PARALYZES THE VICTIM WITHIN SECONDS. FURTHER, THEIR SKIN ACTS AS ARMOR AGAINST OUR STUN WEAPONS. THEY CAN BE KILLED WITH PROJECTILE WEAPONS OR EXPLOSIVES, BUT WE WISH TO AVOID THIS, IN ACCORDANCE WITH THE DIRECTIVE PRESERVING ENVIRONMENTS OF NEWLY DISCOVERED PLANETS UNDERGOING EXPLORATION. AT THE PRESENT THE OTHER SURVEY TEAMS ARE EXPLORING THEIR AREAS SUCCESSFULLY, BUT THE DESERT TEAM IS STYMIED...

“Captain, I have an incoming message from Ensign Montgomery with the DesEx team.”

“Yes, please put her through, Lieutenant.”

“Captain Witherspear, Ensign Montgomery reporting, sir. We have been unable to do any significant exploration due to the gronks, as I have reported previously. We have had two more attacks on crew members, fortunately, their envee suits were not breached by the creatures. However, we have discovered something significant, sir.”

“Yes, yes, go on ....”

“Well sir, Zimmerman was throwing out the waste water, which we have been unable to recycle since the recycling unit was destroyed in the sandstorm. Anyway, he happened to stumble on a gronk behind the mess tent and reflexively, threw the bucket of water at the gronk. The bucket bounced off the creature's thick hide, but after being drenched with water, it fell down stunned. We watched it carefully, and about thirty minutes later, the little bugger managed to crawl off, still dazed a little. Cray, the xeno-biologist, surmises since gronks are desert creatures, a sudden exposure to a quantity of water overburdens their system and puts them right out. Cray says four liters of water should do the trick every time as long as it is applied quickly. I've issued pails of waste water to every member of the team that goes out of camp. We also leave the waste water in strategic places inside the camp, in case anymore gronks get curious and wander into camp. If we could be issued a larger ration of water, we might even be able to finish the survey in this area.”

“Good work, Ensign. I'll go you one better, and make sure you have the proper tools for the job. Lieutenant, send the following spacex to

Research Command, along with transcripts of discussions and the log which pertain to the gronk problem."

SPACEX 1459/894/#18
TO: RESEARCH COMMAND
FROM: CAPTAIN JEAN MARC WITHERSPEAR
GALACTIC CONFEDERATION SHIP SALIENT
IN ORBIT, CHARA 4 "VAYU"
RE: A WATER DELIVERY AND SUBDUAL SYSTEM

1. AS YOU CAN SEE FROM THE PRECEDING TRANSCRIPTS, WE ARE HAVING A PROBLEM WITH INDIGENOUS CREATURES HOLDING UP OUR EXPLORATION EFFORTS.
2. WE SEEM TO HAVE SERENDIPITOUSLY DISCOVERED A WAY OF SUBDUING THE GRONKS BY SIMPLY DOUSING THEM WITH WATER.
3. WE NEED A BETTER WAY OF DOUSING THE GRONKS THAN WITH A PAIL IN EACH HAND.
4. WE NEED A DEVICE THAT IS CAPABLE OF HITTING A SMALL AREA OVER 5 METERS AWAY, DELIVERING, AS QUICKLY AND ACCURATELY AS POSSIBLE, ABOUT FOUR LITERS OF WATER.
5. THE DEVICE SHOULD HAVE AN EASILY RENEWED POWER SUPPLY, THAT DOES NOT REQUIRE ENERGY FROM THE EXPLORATION TEAM'S OWN POWER SUPPLIES.
6. WE NEED THE DEVICE WITHIN 4 EARTH MONTHS, SO THAT WE WILL BE ABLE TO COMPLETE OUR MISSION ON SCHEDULE.
7. I'M SURE WE CAN COUNT ON YOU PEOPLE TO COME THROUGH.
8. KNOWING THE PENCHANT OF GOVERNMENT TYPES FOR ACRONYMS, MIGHT I SUGGEST SOG - SUBDUE OUR GRONKS.
9. END.

Task. Design, build and test a SOG system capable of delivering as much water as possible at a point 5 meters away from the SOG. The SOG will be given four (4) liters of water and will be expected to deliver a high percentage of that water on target, according to the rules below. In addition, the water should be delivered as quickly as possible. The design and construction of the SOG are subject to the following restrictions and conditions.

Restrictions.

1. The total system weight (dry) should not exceed two thousand (2,000) grams.
2. The system at rest should fit in an imaginary globe one (1) meter in diameter.
3. Electric batteries, as a power source, are strictly prohibited.

Performance tests. The performance of SOG will be tested in two areas:

i. Delivery speed - this test will measure the speed of the SOG in delivering a quantity of water over a distance of five (5) meters. The course begins at a starting line five (5) meters away from a model of a gronk. Timing begins when the system begins emitting the water and ends when the system has used up its initial allotment of 4 liters of water.
ii. Delivery efficiency - This is a measure of how efficient the system is in delivering four (4) liters of water. The model gronk will be placed in a bowl capable of holding four liters of water. The efficiency will be measured based on how much of the allotted water winds up in the bowl.

Each group will be allowed to put their SOG through the test twice. Groups will be allowed two (2) minutes to set up for a test and one (1) minute to remove their device from the testing area.

i. Points for Delivery Speed

$$P_{speed} = \left[1 - \left(\frac{Time - Time_{min}}{Time_{max} - Time_{min}} \right) \right] \times 25$$

where
Time is elapsed time delivering the water,
$Time_{min}$ is the minimum elapsed time any group's SOG requires to deliver the four (4) liters of water, and
$Time_{max}$ is the maximum elapsed time any group's SOG requires to deliver the four liters of water.

ii. Points for Delivery Efficiency

$$P_{efficiency} = \left[1 - \left(\frac{\eta - \eta_{min}}{\eta_{max} - \eta_{min}} \right) \right] \times 25$$

where

η is the delivery efficiency for the SOG,

η_{min} is an efficiency of 10%, and

η_{max} is a perfect efficiency of 100%.

iii Total points

The total points for a test will be the sum of the above points minus deductions due to penalties, i.e.

$$Points_{total} = P_{speed} + P_{efficiency} - Penalties$$

The final score for a group will be the highest from the two tests. The group with the most points will be judged as winners of the competition.

5.3.2 Project POP: You Can't Get What You Want Until You Find It

The sun was sliding from the sky over the desolate region known as the Eastern Wastes on the planet called Vayu. The nocturnal animals were beginning to stir, looking for food, or trying to avoid becoming food for another. The diurnal animals were scurrying for their dens and nests, some more successful than others at the game of survival.

Striding across the wasteland towards the safety of his camp, came a tall silvery creature. He too had been involved in the game of survival, but not in the search for food. His search was for the elastic pockets of gas that lay just below the surface. If one knew how and where to look, these gas pockets could be found, tapped and processed to provide energy for the needs of an advancing civilization.

The creature was a robot, programmed and trained to prospect for the gas pockets. However, at the moment he seemed to be agitated, for when he reached the camp he waved his arms at the two men at the campfire and said, [ERGMIN SATURSTY GRONKIN STUMIN VONT!!!!!]

“Garu 5, clean the sand out of your voice box and just calm down,” commanded his friend and partner, Josa. “After this prospecting tour, we have to get you a new voice box, maybe one of those with the empathy module. Then you might even sound human!”

[URK!! ... AH-AH ... JUST A MO ... *aaahh ... That's much better. And why would I want to sound human. I'm very proud of being a robot. What I lack in aesthetics is more than compensated by my endurance, strength, analytical capabilities and ...*]

“Ah, you know Josa didn't mean it as an insult,” Kimicha, the third member of the unlikely trio, broke in. “It's just that sometimes your voice can get on our nerves, especially on these long prospecting trips. Look, if all goes well, we can get you fixed up and you won't even lack in the aesthetics department. Okay?”

[*Well, I suppose. It might be nice to have a voice change. Something to look forward to,*] buzzed the robot, as he finished cleaning his parts.

“Anyway, what was it that you were trying to tell us a minute ago, Garu?” queried Josa.

“Did you find anything good?” added Kimicha.

[*I think I found a likely spot on the south ridge, but I can't be certain. Even with my sophisticated circuitry, we still need exploratory drilling to be done before we are certain.*]

“Well, call it in and register it with the rest of the claims,” said Kimicha. After the robot had gone inside the tent to use the radio, Kimicha turned to Josa and said, "This whole system is much to slow. It takes forever to register the claim, contact the drillers, test the site and all the rest of the garbage. There ought to be a better way. They have all that great technology in the cities, but out here in the Eastern Wastes, all we have is our hands on that walking computer!”

“Do you want to go back to the cities and try to make a living?” countered Josa. “Or maybe you could work on a farm on the northern continent.”

“No, no, that's not what I meant. You know I grew up on a farm, and left. It's so boring. And the cities are no better. They're so crowded. I like it out here. This is where a man - sorry, Garu - a sentient being can really live.”

“Well, what are you grousing about then?”

“I just wish we had better tools, that's all.”

“What's your point?” said Josa.

“Okay, so now we're having an energy crisis. Imported energy is much too expensive and new energy technologies haven't had enough lead time to be properly developed.”

“So? Everybody knows that. That's why we and hundreds of other wildcat teams are prospecting out here in the desert. There are lots of untapped sources of energy out here - or so the geologists say.”

“Right you are,” replied Kimicha, “but the time from a registered claim to final production is much too long. We are not producing enough domestic energy. Our planet-wide economy is unstable because we have to depend too much on the imported energy. We have to shorten the time it takes to exploit a new discovery.”

“I'm in total agreement with you there, buddy. If nothing else it would increase my profits. Or decrease the amount of work I have to do. So what is this new technological marvel you have in mind.”

[*You're going to replace me, aren't you?*] rasped Garu, who had finished registering the days claims. [*You want a new robot. O woe, woe.*]

“Just knock it off, will you?” snapped Kimicha. “I was thinking in terms of a new kind of vehicle. One that could handle all the things we have to deal in our explorations. It would drive over rough terrain like a goat and have all the comforts of home.”

[*It could contain a complete computer and telecommunications center*,] said Garu, dreamily.

“Why not just have it turn itself into a drilling rig after you make a find?” added Josa, sarcastically. “That would really save time.”

“Perfect. That's absolutely beautiful Josa.” exclaimed Kimicha.

“What?”

“That's exactly what we need. An all terrain vehicle that can transform itself into a drilling rig.”

“Aw, you're dreaming.”

[*I hate to agree with Josa, but even assuming this miracle on wheels is feasible how would we get it built?*]

“We'll propose it to the government. Anything that would provide independence for Vayu from the other worlds would bring lots of money and researchers. Well, this ought to challenge them sure enough. But I hope they hurry. It's prospect or perish here in the Eastern Wastes.”

Task. Design, build and test a mechanism capable of traversing and maneuvering through a given obstacle course (see Figure 5.3) and then transforming itself into a piercing mechanism that can pierce through a surface layer made of styrofoam balls and then pop a balloon lying underneath this surface, subject to the restrictions and conditions.

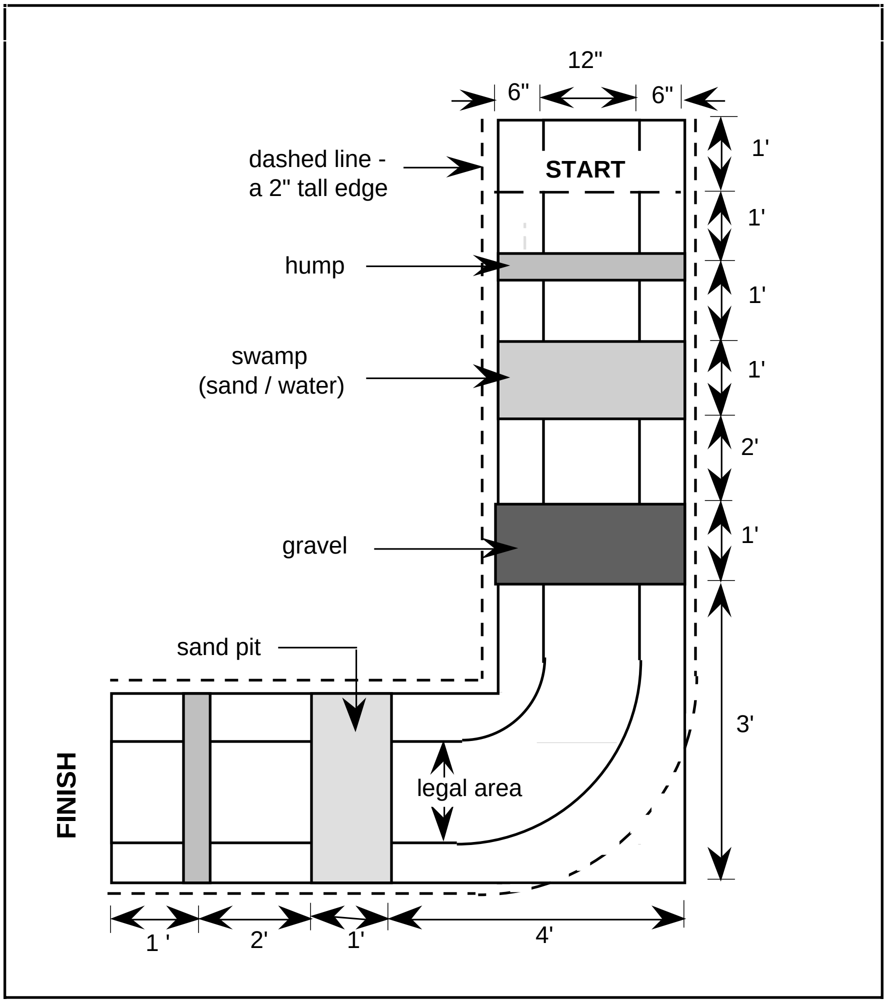


Figure 5.3. Course for Project POP

Restriction:

The weight of the mechanism including the power source should not exceed two (2) pounds.

Conditions:

1. No guide wires of any kind will be allowed. The obstacle course shown will have borders on both sides of the track.
2. After the mechanism has traversed the track, it will have to pierce through a surface layer made of styrofoam balls and pop a balloon

lying underneath this surface. More details are given in the next section.

3. The maneuverability of the mechanism will also be tested, details of which are given in the next section.

Performance test: The performance test will consist of three parts. These are:

i. Prospecting the obstacle course.
ii. Piercing
iii. Maneuverability

The details of each of the above parts are given below:

i. Prospecting the obstacle course.

   This part tests the ability of the mechanism to traverse any kind of terrain. The amount of time taken by the mechanism to traverse the track from start to finish will be used in the calculation of points for this portion of the performance test. Once the mechanism has crossed the start line it shall not be aided in any way to complete traversing the obstacle course.

ii. Piercing

   This part tests the versatility of the mechanism. After the mechanism has crossed the finish line it will have to pierce through a surface layer made up of styrofoam balls and pop a balloon lying underneath this surface. The minimum thickness of the styrofoam layer must be one inch. This test can be conducted in two ways. In the first option, the mechanism automatically starts piercing after it has crossed the finish line. The time clock will be started as soon as the mechanism crosses the finish line and stops when it has completed piercing through the balloon. This time will be used in the calculation of points for this portion of the test.

   In the second option, the group will be allowed to transform the mechanism from a moving vehicle into a stationary piercing machine after the mechanism has crossed the finish line. The time clock in this case will start as soon as human hands touch the mechanism for the transformation process and stop when the balloon is pierced. A group can choose either option.

   The versatility of the mechanism will be rated highly in the creativity portion of the grade. The versatility of the mechanism in the context of this project is defined as having the least number of total components to do the maximum number of tasks. The components of the mechanism used while traversing the course should also be put to use in the drilling process. Thus the emphasis in this project is to minimize the redundancy of the various mechanism components.

iii. Maneuverability

This portion tests the maneuverability of the mechanism. This will be measured in terms of the turning radius and the length of the wheel base. This will be measured in the following manner:

A nail will be fixed on a wooden board. A freely rotating reel that will have a string wound around it will be placed over this nail. The trailing end of the string will be tied to a hook. This hook will be attached to the mechanism at the midpoint line of the wheel base. Each group will be responsible of having some kind of arrangement on the mechanism whereby the hook can be attached to it. With the mechanism in the mobile mode, the group will be allowed to set up their mechanism such that it will have the smallest turning radius. Then the mechanism will be turned on and allowed to complete one revolution. The amount of string unwound during this one revolution will be measured and the length of the wheel base will also be measured. These values will be used in the calculation of points for this portion of the test.

Each mechanism will be required to go through each of the performance tests twice. Students will be allowed 2 minutes to set up their mechanism before each run on the obstacle course, while there will be a 1 minute set up time before the maneuverability test. The mechanism must be removed from the competition area within 1 minute. Penalties will be levied if the set up and removal times are exceeded. The weight of the mechanism will be measured before undergoing any of the performance test.

The points for each part of the performance test will be calculated as follows:

i. Points for prospecting the obstacle course.

$$P_1 = 100 - \left[\frac{\text{Time}_1 \text{ x Weight}}{\text{15 sec. x 32 oz.}} \text{ x } 100 \right]$$

where

Time_1 is the time taken by the mechanism to traverse the course.

It is assumed that the maximum time taken to traverse the course is 15 seconds.

ii. Points for piercing

$$P_2 = 50 - \left[\frac{Time_2}{5 \text{ sec.}} \times 50 \right]$$

where
$Time_2$ is the time taken to complete the piercing process.

It is assumed that the time taken to complete the piercing process is 5 seconds. Bonus points will be awarded to those groups that do not require any human aid in transforming the mechanism from a prospecting to piercing mode. The number of points awarded will be calculated as follows:

$$\text{Bonus Points} = 0.25 \times P_2$$

iii. Points for maneuverability

$$P_3 = 50 - \left[\frac{L_w \quad L_s}{6 \text{ in.} \times 6 \text{ in.}} \times 50 \right]$$

where
L_w is the length of the wheel base
L_s is the length of the string unwound

It is assumed that the ideal length of the wheel base is 6 inches and the ideal turning radius is also 6 inches. The original points for each performance will be the sum of the above points after deductions due to any penalties, i.e.

Original Points =
$$P_1 + P_2 + P_3 + \text{Bonus Points} - (\text{Penalties})$$

The sum of the original points from both runs of the performance test will be the group points. The group with the most points will be judged as winners of the competition.

5.3.3 Project RAT: It Takes a Rat to Catch a Thief?

Joe Black and Midnight Blue, Joe's longtime partner and love-of-his-life, were trying to make it out of the headquarters before being detected. They had successfully passed through several checkpoints and bypassed innumerable patrols in the darkened hallways. They had only one obstacle left - but it has a hulking obstacle, rather colloquially named Lenny the Atomic Tank. His pumpkin shaped head might contain a brain or it might not. Joe and Blue didn't plan on hanging around long enough to find out. Their nerves tensed as they begin their final run to freedom.

“Hey, you!” bellowed the guard, as the pair darted furtively past, “Get over here, now!”

“Sorry, Blue, I guess we didn't quite make it.”

“Don’t worry Joe, we may be able to make the weekend in the country, yet,” said Blue, comforting her man. “We’ve worked hard, and we deserve to leave the city and spend a while on the farm.”

“Okay, youse guys,” rumbled Lenny, “Da bossman wants to see ya. He sez he's gotta little ‘diversion’ for the two of ya!”

“Oh no!” wailed Blue, “The last time The Director had a diversion for us, we had to steal a triphibious battlecruiser - complete with crew and space marines!”

With that last comment, the pair were escorted in silence back through the corridors, past the craftily evaded checkpoints, around the now alert security patrols, and into the inner sanctum that was The Director's office. Disgruntled and slightly worried, Joe Black and Midnight Blue, his wife, were seated before their boss and began discussing the ‘diversion’.

“Look here, Director, this had better be a creampuff of a job. We've been pretty badly shook up the last few missions and we deserve a rest!”

“And a mighty fine rest you will have, my boy. Just as soon as you and Blue re-procure historical material 0001-*AZ1 from those godless heathens, in whose worthless, slimy hands it rests. E’en as we speak, the barbarians could be subjecting the precious artifact to unspeakable sacrilege!”

“Joe, The Director wants us to steal the Moon rock back from the Rusericans,” whispered Blue.

“The what?”

“Joe, don’t be such a dummy! This Moon rock is the one the colonizers brought from earth with them when they settled Vayu It was a symbol of Man's first landing on another planetary body.”

“So you want us to swipe a rock, eh, Boss?”

“Not just a rock, Joe,” intoned The Director, “a priceless heirloom of the Amessian people. It represents everything dear to us, from our first faltering steps into space, to the level of technical excellence we enjoy today. And those godless barbarians removed it from its shrine in the Amessian capital in a brazen attempt to provoke another world war. We must get it back, or the people of Amessia will demand satisfaction by blood from Ruserica.”

“Okay, okay, enough with the Civilization-as-we-know-it-will-come-to-an-end-if-you-don’t-help speeches. We’ll bring back the rock, won’t we Blue? Now, what’s the plan?”

“I thought you would never ask,” chuckled The Director.

Several hours, 5 liters of coffee, and two dozen doughnuts later, Joe lifted his head from the map he was poring over and spoke, “O.K. let me get this straight. Blue and I parachute into the capital of Ruserica and head to the museum where they are storing the rock. Disarming the outer alarms with our normal elan, we then proceed to the room where the rock is kept. Now the problems begin. How do we get the rock out of the room? The floor and the walls have sensors that set off an alarm if anything heavier than a small rodent, such as a rat,moves across their surface. The rock sits on a pedestal in the center of the room. If the pedestal is touched, a plane of energy at about knee height is projected into the room, cutting anyone over a half meter tall into two portable pieces.”

“Well can’t we just storm the control room and deactivate all the sensors?” asked Blue.

“Too many guards, even for the two of you, and besides Headquarters wants a quiet operation,” corrected The Director.

“Oh. Hm.” Blue thought a moment and, “All right, if the floor detects anything bigger than a rat, then let's use a rat to get the rock!”

“Blue, I don’t think we can train a rat to walk to the pedestal, get the rock down, and carry it off.”

“No, we use a mechanical rat. As the rat walks past the pedestal, it touches it, thus setting off the plane of energy which passes over the rat's back. After that burst of energy, the floor sensors will be deactivated for a short time ...”

“Just long enough for us to race across the floor unnoticed and scoop up the rat and the rock, leaving a fake and no clues behind!” exclaimed Joe. “Blue, we're geniuses!”

“Er, thanks, Joe.”

“As well as modest,” interrupted The Director. “It sounds like an excellent plan to me. You two proceed to the Engineering Directorate and tell them what you need. I'll arrange for authorization. We need a code name for this project.”

“How about Recovery of Amessian Treasure, RAT?” suggested Joe.

“Of course, that will do nicely. Now, off you go and give my regards to the other side.”

Task. Design, build and test a mechanism that can move under its own power to a given destination as quickly as possible. The mechanism must also be very accurate about reaching the point at which it is aimed. The mechanism must also be light and compact, for easy portability.

Restrictions

1. The total system weight (dry) should not exceed two thousand, five hundred (2500) grams.
2. The system at rest should fit in an imaginary globe one-half (1/2) meter in diameter.
3. The locus of a contact point between the mechanism and the ground cannot complete a full continuous arc. (Note: this should rule out wheels, belts, treads, etc.)
4. The entire weight of the mechanism must be supported by the ground.

Performance tests. The performance of RAT will be tested in two areas:

i. Speed - The speed test will be a time trial over a distance of 5 meters. A single guide wire will be permitted for the speed trial only. The fastest time for a maximum of two runs will the official time for the group.
ii. Accuracy - The mechanism will be required to proceed along a straight line for a distance of three (3) meters. The accuracy is defined as the ratio between the perpendicular distance away from a target line that runs from the start to the target and the distance traveled along the target line towards the target. The accuracy trial consists of a single run only.

Groups will be allowed two (2) minutes to set up for a test and one (1) minute to remove their device from the testing area.

i. Points for speed

$$P_{speed} = \left[\left(1 - \frac{Time - Time_{min}}{Time_{max} - Time_{min}}\right) x\ 20\right] + 5$$

where
Time is elapsed time over the five (5) meter course,
$Time_{min}$ is the minimum elapsed time (best) any group's RAT requires to cover the course, and
$Time_{max}$ is the maximum elapsed time (worst) any group's RAT requires to cover the course.

ii. Points for accuracy

$$P_{accuracy} = \left[\left(1 - \frac{Ratio - Ratio_{min}}{Ratio_{max} - Ratio_{min}}\right) x\ 20\right] + 5$$

where
Ratio is the accuracy ration for the RAT,
$Ratio_{min}$ is the lowest accuracy ratio (best) achieved by any group, and
$Ratio_{max}$ is the highest accuracy ratio (worst) achieved by any group.

iii. Total points

The total points for a test will be the sum of the above points minus deductions due to penalties, i.e.

$$Points_{total} = P_{speed} + P_{accuracy} - Penalties$$

The final score for a group will be the highest from the two tests. The group with the most points will be judged as winners of the competition.

5.3.4 Project OLDTEK: Everything Old is Technological Again

Dr. Josephus Witherspear, Professor of Systems Synthesis and Computer Based Creativity, stared at a blank page. Silly of it, being blank like that. It should have been full of specifications about the next design, build and test project for his second year design class. Why couldn't the paper generate an idea for a design project by itself? But that is what the Northern Agrarian and Mechanical University of Vayu paid him to do, so he, not the paper, was responsible for ideas. “Someone needs to invent intelligent paper,” he muttered, “but that kind of hi-tech was outlawed after the last world war. Yes indeed, looks like all low-tech for some time now. We wouldn't want another war.”

Since the technocrats had blasted themselves out of power and off the southern continent, the farmers and artists of the northern continent had come to power. With a typical knee-jerk reaction, work in new technologies was halted. Any technological breakthroughs would be strictly related to agriculture or perhaps something to support the arts. Yet, this was not enough for Josephus. Josephus had to find a project that dealt with something unfamiliar to his students - something that would force them to use design methods the school taught so they could learn to deal with open-ended problems requiring new solutions. At the same time it had to be simple enough to manufacture in one semester.

Sighing, Josephus pushed back from his desk and stood up, stretching. His mind was as blank as the paper. He simply could not think a minute longer. If he did not get home to his wife, she would nail him to the wall. Quickly, he packed up his briefcase and, casting a last, disparaging look at the offensive blank page, turned out the lights and left his office.

The next day, Josephus tried to get back to the project but something else came up. Some janitors had found some boxes of papers in the basement. The Dean wanted the contents sorted and filed, and since they were marked ‘Design I: Dr. Ertsim’, logically, the task fell to Josephus. Josephus did not agree with this line of reasoning but he was in no position to disagree.

After several hours of sorting, Josephus had decided that there couldn't possibly be anything of worth in these boxes. All that these people seemed to have been interested in were projects about vermin, like bugs and rats. He was almost ready to pitch it all when a photo caught his eye. It was from about 75 years before, and it bore the legend ‘Dr.Ertsim's Design Project’. It depicted two students in what appeared to be a wooden human powered vehicle. The students were maneuvering the vehicle around obstacles in an outdoor race course.

Josephus knew instantly that this was the project for which he was looking. His students had probably worked with wood before, but always in a static capacity, such as fence posts, furniture, or sculpture. This project will give the students the opportunity to deal with an old material in a new way (for them at least). The students would have a project based on old technology, so to speak, and thus learn to deal with the unfamiliar and become flexible enough to deal with problems given to them in the future.

Now Josephus was happy that the boxes had been discovered. They were a veritable treasure trove. Chuckling, he turned back to his desk. At the top of the once blank page, he quickly wrote the title ‘Old Limb Driven Technology Emanates Knowledge’. The blank sheet of paper began to fill.

Task. Design, build and test a vehicle capable of carrying two students over a course with specified obstacles, subject to the following restrictions and conditions:

Restrictions

1. The system must be constructed entirely of animal and/or vegetable materials. Synthetic materials (e.g., plastics) and metals are expressly excluded. Timber in any form may be used,

including hardboard, particle board, plywood and similar products.

2. The total system weight should not exceed ten (10) kilograms.
3. The students should be able to ride the fully assembled vehicle through a standard size door. The vehicle should be capable of passing through all obstacles on the designated course.
4. Metal fasteners (nails, screws, bolts and pins) are not allowed, but glues, adhesives and lubricants can be used on joints.

Conditions

1 The students in the vehicle can only touch the ground for control or propulsion purposes, but at all times their weight should be carried by the vehicle from start to finish.

2 The vehicle must be powered by the students in the vehicle. There shall be no assistance in any way from any other person or from any external power source.

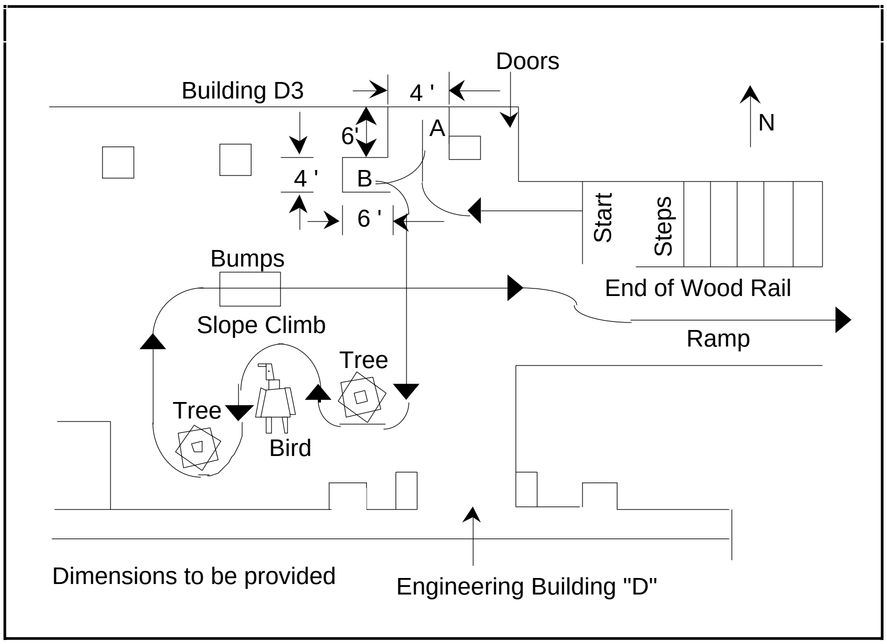


Figure 5.4. The Oldtek Track

Performance tests. The performance of OLDTEK will be tested in two areas:

i. Speed - The speed test will be a time trial over a defined by the instructors. The course will include a cul-de-sac to test backing and low speed maneuverability, a speed bump and several other turns.

ii. Weight - The vehicle is to be no more than 10 kilograms. However the points formula emphasizes a low weight vehicle, so minimum weight is preferred.

Each vehicle shall be required to make two runs of the course. Each student in the group must take part in propelling the vehicle through one run. Groups will be allowed two (2) minutes to set up for a test and one (1) minute to remove their device from the testing area.

Points for each run will be computed using the following formula:

$$P_{run} = 25 - \left[\frac{\text{Time x Weight}}{\text{Time}_{max} \text{ x } 10 \text{ Kg}} \text{ x } 20 \right]$$

where

Time is elapsed time over the course and

Time_{max} is the maximum elapsed time (worst) any group's OLDTEK requires to cover the course.

The penalties for each run will be levied as follows:

Problem	Penalty
Failure to move out of the cul-de-sac	Loss of 0.1 x Original Points
Failure to stay within course boundary	Loss of 0.1 x Original Points
Vehicle comes into contact with obstacle on course	Loss of 0.2 x Original Points
Exceeding the set up and removal times	Loss of 0.1 x Original Points per minute

The sum of the points from the two runs after deductions due to penalties will be the group points. The group with the most points will be judged as the winners of the competition.

5.3.5 Project BUG: Villain Driven Buggy Before Bugging Out

The planet Vayu, a full member of the Confederation of Worlds and largest supplier of foodstuffs in the Confederation, was a peaceful planet that only asked to be allowed to grow food. Every available patch of ground was cultivated and those held in the highest esteem were the farmers with the highest yield per acre rather than the number of acres owned.

Agriculture was the soul of the people of Vayu, and they kept their lives simple and untainted by modern conveniences. There were machines, of course, to harvest the crops, but these were kept out of sight when they were not used. The farmers of Vayu also avoided contact with the machines that were designed and built by engineers and mechanics. These people were called wrenches by the Vayun farmers. They were treated well enough, but they were at the bottom of the social order because they worked with machines.

Vayu might have continued being peaceful and simple, but a creature called the Phoenix changed all that. This Phoenix was capable of not just self-immolation but of immolation of his surroundings as well. He appeared to be bent on gaining control of the Confederation and Vayu was first on his list of conquests.

The Phoenix came to Vayu in a huge black ovoid spaceship. To deny access to the ship by outsiders, he hung a mesh from the sides of his ship. He was somehow able to start a fire between the net and the ship so that the whole affair took on the appearance of a burning egg encircled by a fiery net. This fire, which was created by the Phoenix, only consumed animate matter, else his mesh and ship arrangement would have been consumed.

The Phoenix announced to the world of Vayu that it was his, to do with as he pleased. Any move by the confederation to retake the planet would lead to its certain destruction. Not only would Vayu's farmers die, but many people in the federation would starve. In return for Vayu's food, the Phoenix wanted no less than control of the Confederation. Anything less and Vayu would quickly become a smoking ember.

The Vayuns were desperate. They had to save their world. But how could they get past the blaze? They all recognized that the blaze would have to be extinguished before any action could be taken against the

Phoenix. They could not however, devise a plan to do this. In their despair, the farmers called a meeting with the wrenches, hoping they would be able to solve the problem.

The meeting was chaotic. Many plans were put forth by both the farmers and the wrenches, but no plan received support. The farmers had grand conceptions of how to defeat the Phoenix and the wrenches had all kinds of ideas for mechanisms that could climb nets or put out fires. But neither side could produce a workable scheme for doing both things.

Finally, a man that had been silent during the meeting spoke. The man - Bosh nef Storey - was an anomaly on Vayu. He owned a small farm in the northern hemisphere and produced mainly fruits. He was an anomaly since he not only raised fruits, but he also took care of his own machines. He was half farmer and half wrench, and he was as much hated and feared as he was respected, because he did both jobs well.

When Bosh spoke, the rest quieted down to listen to what he had to say. His idea was to design a lightweight, quiet machine that could climb the Phoenix’s fiery mesh and extinguish the madman's fire and ambitions. This would allow the Vayuns to board the ship to incapacitate the Phoenix himself and turn him over to the Confederation Police.

The Vayuns were ecstatic that a plan had been made. They put Bosh in charge of the project, which they called Bosh's Ultimate Gambit. To give Bosh enough authority, he was proclaimed Chief Engineer of Vayu. The machine was built under Bosh's direction and the evil Phoenix was captured and sent to the ice planet of Griswold.

Bosh was acclaimed a hero and children thereafter were directed towards him as a role model. To this day, one of the high honors bestowed on a person is the Order of the Engineers of Vayu.

Task. Design, build and test a mechanism capable of climbing a plastic mesh track and releasing powder when it reaches the top of its climb.

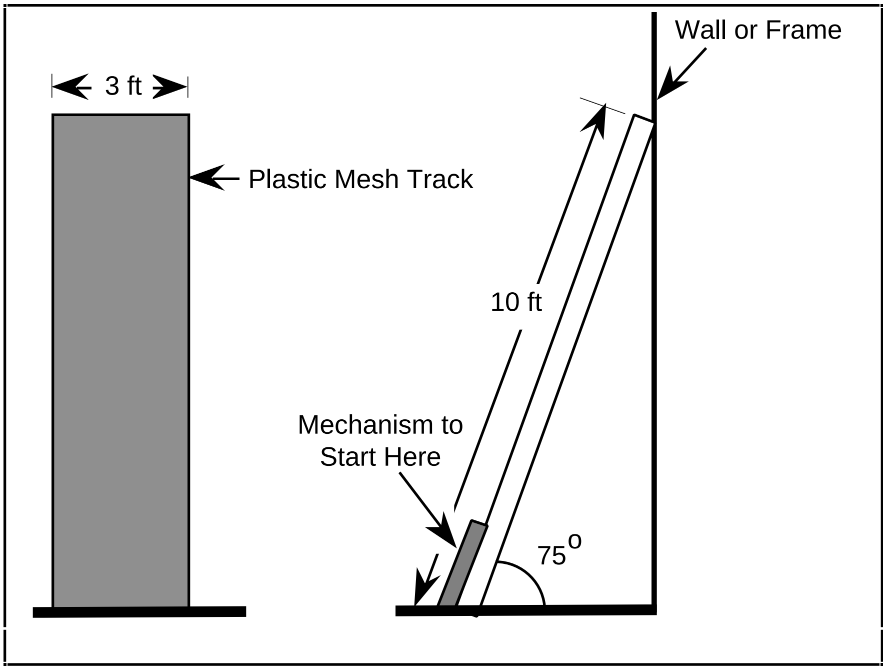


Figure 5.5. The Bug Track

Restrictions

1. The mechanism must be completely self-contained. No guide-wires will be allowed.
2. The maximum dimensions of the mechanism at its most extended points are specified as:

Height	1/2 meter
Width	2/3 meter
Length	2/3 meter

   The mechanisms weight is not to exceed 2.5 kilograms
3. The mechanism must be designed to climb the maximum distance on the inclined mesh track (as far as possible) and to achieve a maximum speed to weight ratio.
4. The mechanism is required to release twenty five (25) grams of powder after it has finally come to a stop.

Performance Tests. The test track is made of metal mesh fencing material [approximately one-half (1/2) inch grid size] mounted on a wooden frame. The mesh track will be approximately three (3) feet wide and ten (10) feet long. An additional area of three (3) feet by five (5) feet will be flat on the ground to be used as a starting area for the track. The amount of space above the mesh within which the mechanism can move has a maximum height of two and one-half (2.5) feet. The mesh track area can be inclined at the angles of 30° and 60°. At each inclination the mechanism (which is required to start under its own power) will have to climb the mesh track and release its powder payload when the mechanism has come to a stop on the track. The distance from the ground to the top of the mechanism at its final resting point on the track will be measured along a straight line on the inclined track. If the mechanism is resting on the inclined track, the distance will be measured from the nose of the mechanism in the initial position to its tail in the final position. As in the first case, the distance will be measured along a straight line on the inclined track. The time taken by the mechanism to travel from the start to finish will also be measured. This also includes the time taken for the release of the powder. Speed will be calculated as the ratio of distance measured on the inclined track to the total time of travel. Points for the performance at each inclination will be awarded as follows:

$$\text{Points} = 35\left[\frac{\text{Distance measured on inclined track}}{\text{10 feet}}\right] + 15\left[\frac{\text{Speed}}{\text{Weight}} \times \frac{\text{30 sec x 5 lb}}{\text{10 feet}}\right]$$

It is assumed that the maximum time of travel will be 30 seconds. Each group will be allowed a maximum of two runs on each incline. The best run for each incline will determine the points for the group. The sum of the points from the two runs after deductions due to penalties will be the group points. The group with the most points will be judged as the winners of the competition.

5.3.6 *Project HUEVO: You Can't Make an Omelet Without the Right Eggs*

For many years after the Phoenix incident, peace had reigned on the planet Vayu. Under the leadership and counsel of a series of Vayun Engineers, Vayu had firmly established itself as the leading agricultural center of the galaxy. In addition, Boshome, the planetary capital, had become an educational center. Students came from throughout the galaxy to learn to be effective and efficient professionals in their chosen fields. Their education was guided by the basic principle of the Vayun engineers; "A fully capable brain is a fully utilized brain."

Many students came to the University of Vayu, but only those who were able to take full advantage of the training available at the University of Vayu were graduated with full honors. These top students were highly sought after and almost all brought honor to Vayu. Almost all, except one who would use his talents for evil. His name was Jink pur Dilig and he was a seeker of power, beginning with Vayu. This is the story of how his evil plans were thwarted.

Through diligent research and creative application, the Engineers of Vayu had been able to produce some quite remarkable eggs. These eggs contained a catalyst which was activated when the egg's shell was cracked open. The catalyst caused the eggs to cook automatically without out any outside sources of heat. They went from the carton to the table in five seconds flat (six for hard boiled). Naturally, these eggs were in great demand, and became a major export for Vayu. Over the years, production and distribution of the eggs began to influence planetary policy heavily. Much time and effort were spent to ensure that the production of Vayu Eggs would remain uninterrupted. Jink pur Dilig knew that this would be the starting point of his rise to power. By controlling the production of the eggs, he would gain economic leverage against the rest of the planet.

His plan, which had not been seen in this part of the galaxy in some time, was based on the old protection racket. Jink gathered a gang of thugs and thieves to do his dirty work. His thugs were sent out to offer "protection" to the egg producers. For a reasonable fee, Jink guaranteed that the eggs would be fetched by his organization and delivered safely to shipping sites for export to offworld markets. Those who did not pay the protection money were warned that, "Accidents are bound to happen!"

The egg producers refused to be bullied. After all, their ancestors had faced greater problems than this and overcome them. Why should the egg producers pay any attention to a common thief like Jink?]

Much to their chagrin, the egg producers soon found that Jink was no common thief, nor was he bluffing. The trucks that normally fetched the eggs were being detoured or hijacked. The few that managed to get through to the egg farms were destroyed when they tried to leave. Deliveries and sales of Vayu Eggs had ground to a halt.

A Planetary Council meeting was held with Master Amanou Ki Ba, chief Engineer to Vayu, presiding. The council agreed that Jink pur Dilig must be stopped. There had to be a way to send the eggs to shipping points without interference from Jink and his gang. The council discussed many different schemes for ridding the planet of this menace. After all, ideas had been rejected as being unworkable, Master Amanou decided that the university students would have the freshest approach to the problem, since they had no preconceptions about the possible and impossible. Thus the following statement was issued at the University of Vayu.

TO ALL STUDENTS:
VAYU NEEDS YOU

It is well known that the individual Jink pur Dilig is a menace to the economy of the planet Vayu. To defeat him, Vayu Eggs must be transferred to shipping points for export. All students are hereby required to devote their time to generate a prototype of a vehicle that will safely transport Vayu Eggs. The vehicle should be capable of fetching the eggs quickly and easily without requiring any being's supervision and must be self contained. The prototype should also be fast and capable of self defense.

The planet is in a state of emergency and the students are expected to pitch in to help. However, the students must maintain their other classes as well. Life and academics go on. The project will be known as HUEVO: Hiding Unprotected Eggs from Vicious Outlaws.

GOOD LUCK TO YOU ALL!

Task. Design, build and test a mechanism capable of safely loading six eggs at random pickup points and unloading them without breakage at a depot at the end of a track to be specified, subject to restrictions and conditions.

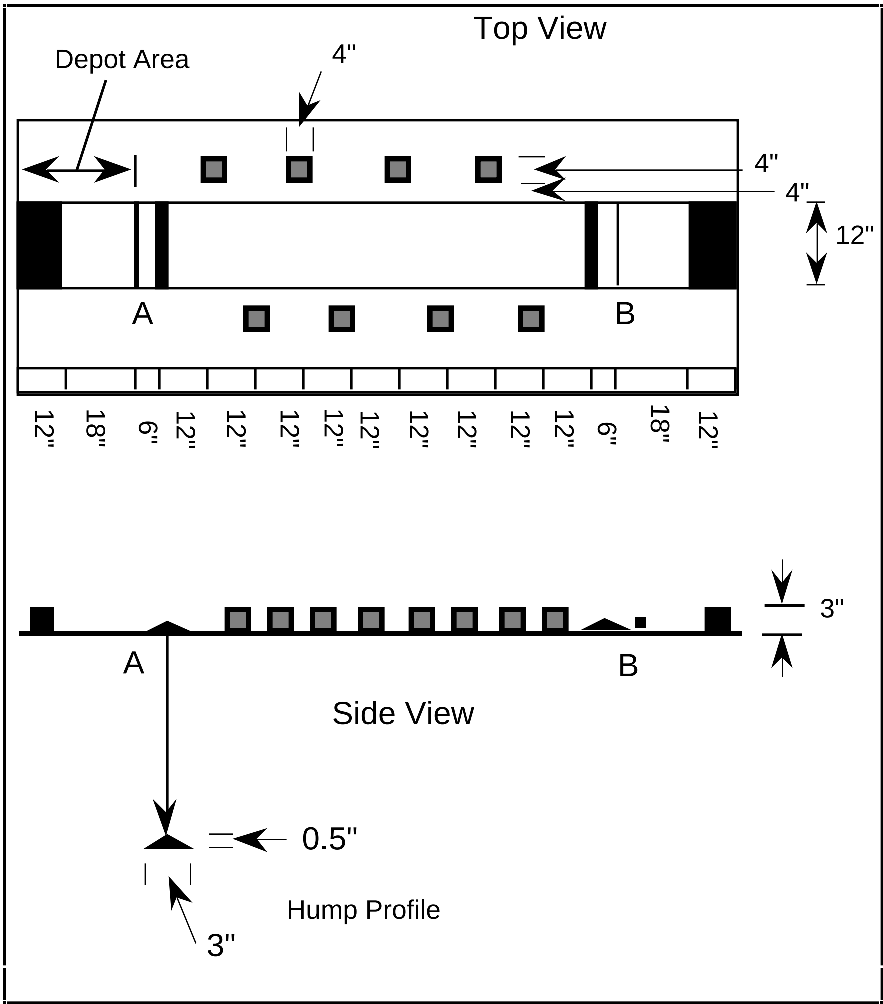


Figure 5.5. The Huevo Track (diagram not to scale)

Restrictions

1. The weight of the mechanism should not exceed one thousand (1,000) kilograms.
2. While traversing the track, the HUEVO mechanism is required to load one egg from a container placed on each of six pickup points or pedestals.
3. The eggs are to be supplied by the groups. The size of the eggs to be used is GRADE AA Medium. Boiled or cooked eggs will not be allowed.

4. There is no size condition on the container except that they should fit on their respective pedestals. It is the group's responsibility that the egg container does not topple over from the pedestal when the test run is being made.
5. No remote control on the egg containers is allowable.
6. A wire or rope running the length of the track will be provided.

Performance Tests. The track the mechanisms will run on will be made out of wood to specifications to be supplied for the individual class. The track will have eight pedestals, four on each side of the track, evenly spaced. One egg container (supplied by each group) will be placed on each of six randomly chosen pedestals. The choice of the pedestals for each group will be done by ballot, with a group member drawing six numbers from a set of eight. One egg will be placed in each egg container.

The HUEVO mechanism will be placed behind the starting point at one end of the track. The time clock is started as soon as the nose of the mechanism crosses the starting line and will be stopped when the nose of the mechanism crosses the finish line at the other end. This time will be used in the calculation of points for the test run.

While traversing the track, the mechanism will be required to load eggs safely from the pick-up containers placed as previously mentioned. As soon as the mechanism has crossed the finish line, it will have 15 seconds to unload the eggs without breakage on the designated unloading area of the track. Eggs unloaded after the 15 second time limit will be considered as failures.

Each mechanism shall be required to make two runs on the track. Students will be allowed two (2) minutes to set up their mechanism before each test run. The mechanism must be removed from the track within one (1) minute. Penalties will be levied if the set up and removal times are exceeded. It will be the group's responsibility to clean any mess created during the test runs. The time taken by the mechanism to travel from start to finish will be measured. The weight of the mechanism will be measured before making the runs. The points for each run will be calculated using the following formula:

$$P = 100 - \left[\frac{\text{Time x Weight}}{\text{(30 sec) x (1,000 Kg)}} \text{ x } 100 \right]$$

It is assumed that the maximum time taken to traverse the track is no more than thirty (30) seconds. Penalties for each run will be assessed as follows.

Criterion	*Penalty*
Failure to load and carry eggs to the depot	Loss of $n_1/12$ x P
Failure to unload eggs at the depot	Loss of $n_2/12$ x P
Exceeding the set up and removal times	Loss of 0.05/60 x P for every second exceeded

n_1 = 6 - number of non-leaking eggs delivered
n_2 = 6 - number of non-leaking eggs unloaded

The sum of the points from the two test runs after deductions due to penalties will be the group points. The group with the most points will be judged as the winners of the competition.

5.3.7 Project RSVP: Please Tell Us If You Can Attend the Disaster

It is the first day of the new term at the University of Vayu. There are students everywhere, scrambling to find their classes, telling about their vacations, and discussing their classes.

"Boring, boring, boring!" exclaims a sandy haired student. "This is going to be a boring class. I bet the project will be absolutely worthless, a paper exercise or some other make-work."

"Yunics, you know nothing of the sort," says the teaching assistant for the class, a serious young woman named Ms. Doss. "Why, there have been several crises that the people of Vayu have depended on students from this very class to solve. There was the Phoenix, then there was Jink pur Dilig and the eggs, there were several energy crises, not to mention the problems in the ocean cities and the orbital platforms. All of these were solved by students like you."

"But those things happened in the Transition Time, while Vayu moved from an agrarian society into the balanced culture we have today.

Everything is stable now, there is nothing left for us to do, Ms. Doss. This class will be just a study of all those projects.”

“Ah, but that is where you are wrong, young sir.”

All eyes turn to the door of the classroom, where a man of indeterminate age stands. His face is lined and creased with age, as is his hands. Yet his eyes shine with a fierce fire, and he stands poised, as if embarking on a new journey. He walks slowly but strongly to the podium and opens his lecture notes, which are more wrinkled than he. After holding the students' curiosity at bay for as long as he dares, he speaks.

“I know many of you expected a young professor for your first course, but many have left the University, attracted by lucrative offers on other worlds. I have been called up out of retirement to take this class, since there is a shortage of instructors. Some of the Powers That Be think that I am a dinosaur. Some of you may believe that also.”

“Some others think that I may be able to inject some life into a weak program. If I did not agree with that, I would not be here. I hope to prevent the boredom one of your peers has decried.”

The new professor begins passing out packets of material. “So. This is it, then. We have a project of great utility this term. It is to be a new agricultural vehicle . . .”

A chorus of moans and groans erupt from the class. There wouldn’t be any adventure this term!

Rapping on the podium, the professor regains control and continues. “This is a proposal for an important and vital design project you have before you. It may be the most important project you ever work on. It certainly will be while you are at the University.”

“Excuse me, sir,” says Yunics, “this important project you are talking about is nothing more than a planter. My dad had something like that on his tractor, back on the farm. There’s no mystery here.”

“Ah, but the machine won’t be planting just any seeds. You see, the agricultural department has developed a . . . um, a putty that contains the seeds and is rich in nutrients. This combination will make plants grow very fast.”

“So what? It's still just a planter. The agriculture department will have all the thunder.”

“No, no!” replies the professor, his voice hushed, yet gaining in intensity. “The machine must displace the seed putty away from the machine, since the seeds grow fast - as soon as they hit the ground they begin. In addition, this machine will be used for planting a very special plant. It will not be used on the farms. It will be used for planting flowers . . .”

“Flowers!”

“This is crazy!”

“He's no dinosaur, he's fossilized.”

“I travel across the galaxy to listen to this?”

These are a few of the milder comments heard in the classroom. Things are getting worse from the students’ view.

“Students, students. Would professional engineers treat a prospective client this way? Of course not. Listen to the rest of the proposal before you complain.”

“The flowers to be planted are very important. The flowers are the very rare Moonbeams. As you may know, these flowers are considered more beautiful and precious than diamonds. However, they bloom only once, and then only for an hour.”

“The importance of the flower is magnified by the upcoming visit by the Galactic Emperor’s daughter, Princess Amiga Lorraine, who is scheduled to visit Vayu - a few days before the end of this term. The visit is actually a fact-finding tour to determine if the Empire should absorb Vayu (one of the few remaining autonomous worlds) and turn it into a military base, since it lies on some important space shipping lanes. What the Vayun Council has discovered is that Princess Amiga Lorraine is absolutely awed by the Moonbeams. If she were to see them growing along both sides of the road wherever she goes, it is felt that she would be more likely to ask that Vayu be preserved as a park world rather than a military base.”

“So. This is it, then. The result of this project could be either the ruination of our world or its preservation as an independent planet. This is our RSVP to their ‘invitation’ to join the empire. Our **R**apid **S**eeder for **V**ayun **P**reservation, that is. Any further questions?” asks the Professor, as he begins packing his notes.

“Just one sir,” says Yunics. “Could you tell us who you are?”

“Oh, dear me. I had forgotten. I am Bosh nef Storey. I founded the University of Vayu.”

Task. Design, build and test a mechanism capable of traversing a given course while placing a nutrient enriched seed putty in designated zones on both sides of the course (see Figure 5.4), subject to certain restrictions and conditions.

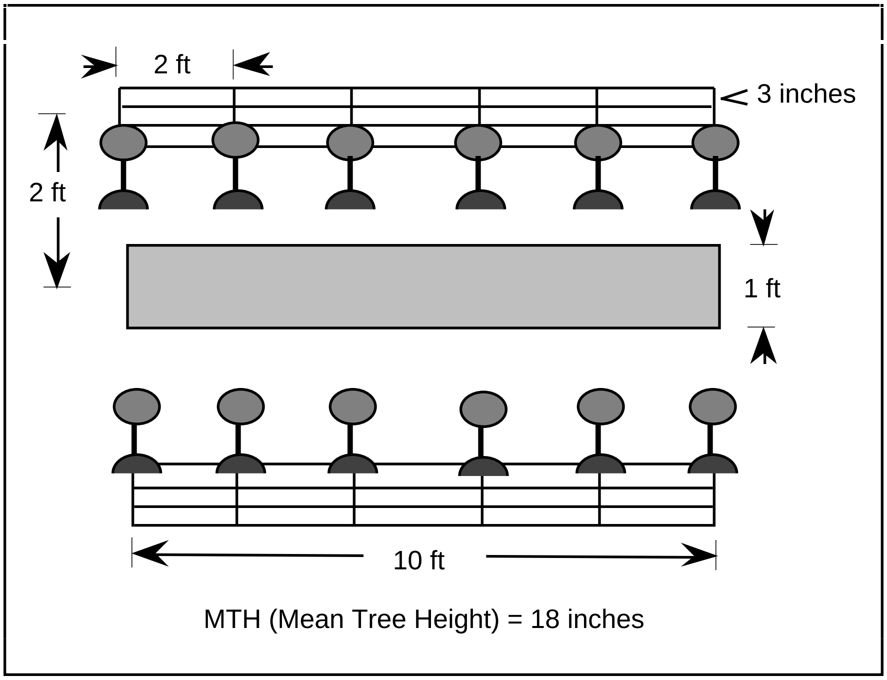


Figure 5.6. The RSVP Track

Conditions

1. The mechanism will be required to traverse the course shown in Figure 5.4 with continuous forward motion of the vehicle (i.e., no stops).
2. No guide wires of any kind will be allowed.
3. While the mechanism traverses the track, it will have to place a small amount of seed putty in each of the zones indicated in Figure 5.4. More details are given in the next section.
4. The weight of the mechanism including the power source should not exceed two (2) lbs.
5. The width of the body of the vehicle shall not exceed the width of the road on the track.
6. The height of the mechanism shall at no time exceed the Mean Tree Height.
7. Students shall be responsible for selecting a putty substance as a carrier for the seeds. A sample of the putty is to be submitted along with the final concept for approval.

8. Poppy seeds will be used to simulate the seeds of the Moonbeam flower. On the day of testing the students will be given a number of poppy seeds to mix with their selected putty.

Performance Tests

The performance test will consist of two parts. These are:

i. Speed through the course.
ii. Accuracy of seed putty placement.

The details of are given in the sections that follow.

Speed through the course. This part tests the ability of the mechanism to traverse speedily a typical Vayun road, to plant the seeds in advance of Princess Amiga's caravan. The mechanism will be required to traverse the given course shown in Figure 5.4. The amount of time taken by the mechanism to traverse the track from start to finish will be used in the calculation of points for this portion of the performance test. Once the mechanism has crossed the start line it shall not be aided in any way to complete traversing the course.

Note: a high possible speed is desirable, so that the vehicle can keep pace with Princess, should she desire to travel at high speeds. However, a variable speed is desired, of course, so that the vehicle can stay one hour ahead of the Princess, whatever the speed of her caravan.

Points for traversing the course will be computed using the following formula:

$$P_1 = 100 - \left[\frac{\text{Time x Weight x 100}}{\text{15 sec}} \right]$$

where Time is the time taken by the mechanism to traverse the course and Weight equals 1 if project is under the weight limit. Otherwise, Weight is the ratio of the over-limit weight to the weight limit of 32 ounces. It is assumed that the maximum time taken to traverse the course is fifteen (15) seconds.

Accuracy of seed putty placement. This part tests the accuracy of the mechanism. The mechanism must place at least one seed putty pellet in each of ten target zones. The means for placing the pellet is up to the designers, as long as it falls within the rules listed herein. If the pellet falls short or long of the target zone, but still lands within three inches of the zone, half the points are scored. Outside this range, no points are scored. The score is determined by the resting place of the pellet; it is not determined by the initial impact point. Interference by trees, rolling of the pellet, etc., matter not, the pellet must **stop** inside the target zone for full points to be awarded.

Note: the Princess will not be impressed by Moonbeams growing hither and thither. Thus, it is desirable for the seed putty pellets to stop in the target zone.

On the day of testing, the teams of designers will be given poppy seeds to simulate the Moonbeams. The designers will have up to four minutes to mix the seeds with their chosen putty and to load and set-up their vehicle. If the set-up time expires, that team will be penalized (see above). Points for accuracy will be computed using the following formula:

$$P_2 = \sum_{i=1}^{10} \frac{S_i}{N_i}$$

where:

$$S_i = \sum_{k=1}^{N_i} p_k \text{ , the sum of points scored from target zone i}$$

N_i = number of attempts taken for target zone i.

p_k = points for a single attempt k taken placing putty in a zone.

For each attempt:

10 points are scored for placing the putty inside the target zone.

5 points are scored for placing the putty in the long or short zones.

The maximum score possible for one zone is ten (10). For the entire course, the maximum possible score is 100 (ten target zones times ten points per zone). The total points for the competition will be the sum of the above points after deductions due to penalties, i.e.

Original Points (OP) = $P_1 + P_2$ - (Penalties)

The sum of the total points from both runs of the performance test will be the group points. The group with the most points will be judged as winners of the competition.

5.3.8 Project ARM: Reach Out and Touch Someone

"Grampa, Grampa, tell us a story."

“Yes, Grampa, please, please, please, please tell us a story . . . we’re not sleepy yet!”

How can one refuse a plea like this from two beautiful children, like Johanna and Sebastian? Especially when they belong to the nef Storey clan. Besides, I am not against spinning a tale or two, especially during the holidays. I have been accounted as somewhat of a raconteur by my peers, so certainly I can entertain two small children.

“Children, you leave your Grampa Bosh alone, it is past his bedtime as well as yours.” That's my lovely, but over concerned wife, Arelda. She has a warped sense of time, especially bedtimes.

“Now, Arelda dear, don’t you think that we could all stay up just a little longer. I don’t get to see the grandchildren very often, and I have to go back to the University tomorrow. One story won't take long.”

Now one must choose carefully the story to tell at times like this. It must have just the right blend of adventure, high moral tone, heroism and just a little romance - yet it cannot be too high spirited or horrible. Otherwise, the children will never go to sleep. That is why I chose to tell Sebastian and Johanna the story of Josiah Witherspear and his wonderful arm.

“Once upon a time, there lived a dwarf among dwarves named Josiah Witherspear. Josiah was famous for miles around. He wasn't a mighty fighter, nor was he a magician. He could not sing nor could he tell jokes - he always forgot the punch line.”

“Well what could he do, Grampa?” pipes up Sebastian.

“I'm getting there ... Josiah was an incredibly gifted builder. If you wanted something built, you merely had to describe it to Josiah and he would build it for you in a wink of an eye. He had built incredibly beautiful carriages for the King of the dwarves, a clever water pump for the village and many other fine useful artifacts. Josiah was very happy, living in his little village, building and creating, and the village was very happy to have such a dwarf in residence.

“One day, the peace of the village was shattered when a horrible, vicious, slimy, smelly dragon landed on the outskirts of the village. It was quite obvious that the dragon did not want to make friends with the dwarves. In fact, the blood and the bones of its latest victims were still dripping from its mouth ....

“Ooh, I'm scared!” squeals Johanna.

“Right, well you have the general idea about the dragon. Not only did the dragon not want to be friends, but he demanded that the dwarves in the village give up their daughters to him or he would destroy the village and all that lived in it.

“Now these dwarves were made of stern stuff. They had lived through orc raids and many were veterans of the Wars of the Tapestry. (That's a story for another time Sebastian, be still and listen to this one) The dwarves were not going to give up their daughters without a fight. So the village elders gathered up the best and most valiant fighters in the village. This band of stalwarts were then sent forth amidst trumpet calls and war cries and cheers to defeat the nasty dragon.

“Those who remained behind in the village watched as the fighters sallied forth in a mighty charge against the dragon. For a long time the battle raged. A pillar of dust rose against the sky. Many were the screams of dwarves and horses and many were the bellows of the fierce monster. Finally, as the sun sank into a blood red sunset, the fighters returned to the village. Some returned with their shields, but all too many returned on their shields, never to fight again. But the calamity of calamities was that the dragon yet lived. As the fighters retreated, this despicable creature showered them with debris and derision.

“The elders shook their heads as the once proud warriors retreated to their huts to have their wounds dressed. They spoke with the leader, a veteran of many campaigns. What went wrong, they demanded. Did the dwarves not fight hard enough, strong enough, smart enough? No, the answer came back, we are not tall enough to defeat the dragon. We cannot reach his vital parts. His limbs are too long and we can't fight past them.

“The village was in shock. It looked like they would have to give up their daughters to the dragon. Then Josiah stepped forward. He said he would build them an arm long enough to reach inside the dragon's defenses to kill it. And since all the warriors were injured or dead, Josiah would use his ARM to kill the dragon. The villagers cheered, but tentatively, because although Josiah was well known for his prowess as a builder, his fighting skills were unknown. Still, he was their only hope.

“Through the night Josiah worked on the arm. The sounds of the work reverberated throughout the village. No one could sleep. Finally, after the sun had started its journey through the sky and the cock had finished crowing, Josiah emerged from his workshop. The villagers gasped as the arm, which was strapped to Josiah’s torso, gleamed in the early morning sun. None doubted the skill and care that had gone into its creation. The question on the lips of all was, would it slay the dragon?

“After receiving the best wishes and advice from all, Josiah strode forth, taking some practice swings with the arm. For a weapon, the arm held a blade which belonged to Josiah’s grandfather. All was in readiness, Josiah had merely to challenge the dragon.

“The dragon could barely contain himself when he saw Josiah coming. They send one dwarf, to do what a score could not, he thought. ‘This should provide some light entertainment before I get on with destroying the village,’ the dragon bellowed to Josiah, ‘Lets get on with it.’ ‘Have at ye,’ cried Josiah. With that they fell together with a mighty crash. Again, the dust of battle filled the air, but this time the outcome was not long in coming. With a mighty thrust, Josiah’s arm zipped past the dragon’s clawed arms and struck him through to the heart. The creature fell to the ground and died with a final spasm.

“And so ended the dragon threat. As for Josiah, he was wined and dined throughout the land. He married the prettiest girl in the village and his business never lacked for customers. As for the arm, it disappeared after the battle and no one has seen it since. That is the end of the story and it is also the end of tonight’s entertainment. I think your Gramma Arelda wants to take you to bed now children.”

“Aw, c’mon Grampa, tell us another,” says Sebastian, clinging to my leg for dear life. I pick him up and pass him over to Arelda. Fortunately, Johanna is no problem since she has already fallen asleep. I carry her, and we get the children to their bedroom without incident.

After Arelda and I tuck the children in, Sebastian asks, “Grampa, what happened to Josiah's arm? It didn't really disappear, did it?”

“I'm afraid so, Sebastian. Why do you ask?”

“Well, it would be really swell to have something like that around now. I could use it to get books and toys off the shelf where I can’t reach and help kittens out of trees and lots of stuff.”

“Yes, I suppose you could get into a lot of stuff. Like Gramma's cookie jar, no doubt.”

“Oh no, Grampa, I’d be good.”

“Still it could be useful to have an extension ARM at times, an **a**rticulated **r**eaching **m**echanism, as it were. I must put my class at the university on to this at once. Goodnight Sebastian.”

“Goodnight, Grampa Bosh.”

Task. Design, build and test a system capable of converting wind energy into some more useful form of energy and then store this energy in some compact, transportable module. The wind source will be represented by a household electric fan. The energy modules must be used to propel a vehicle, carrying as large a payload as possible, over as long a distance as possible, subject to the restrictions and conditions.

Performance Tests. The system that is to be tested shall consist of a conversion/storage device, energy modules and a vehicle. In the first part of the test, each group will be given 5 minutes to convert and store as much energy as their design allows. The energy modules shall then be integrated with the group's vehicle, the payload added and two runs shall be made.

The performance run will be scored by two measurements. These are:

i. The useful load carried by the vehicle (payload).
ii. The distance traveled by the vehicle.

The measurement of the useful load carried by the vehicle (payload) is an indicator of the useful work down by the vehicle and energy module.

The distance traveled by the vehicle will be used in the calculation ofpoints for this portion of the performance test. Once the vehicle has crossed the start line it shall not be aided in any way to complete traversing the course.

Each mechanism will be required to go through the performance test twice. Students will be allowed 2 minutes to set up their system before each run on the course, which includes installation of modules and payload. The system must be removed from the competition area within 1 minute after completion of the test. Penalties will be levied if the set up and removal times are exceeded.

The points for each part of the performance test will be calculated as follows:

The points for the payload will be determined using the following formula:

$$P_1 = \left[\frac{\text{Weight - Weight}_{min}}{\text{Weight}_{max}\text{ - Weight}_{min}} \text{ x } 50 \right]$$

where
Weight is the payload,
Weight_{max} is the maximum payload any group's vehicle is carries, and
Weight_{min} will be determined later.

The points for distance travelled will be determined using the following formula:

$$P_2 = \left[\frac{\text{Distance - 3 meters}}{\text{Distance}_{max}\text{ - 3 meters}} \text{ x } 50 \right]$$

where
Distance is the number of feet traveled by the vehicle in a straight line, and
Distance_{max} is the maximum distance traveled by all the vehicles.

The original points for each performance will be the sum of the above points after deductions due to penalties, i.e.,

$$\text{Original Points (OP)} = P_1 + P_2 - \text{(Penalties)}$$

The sum of the original points from both runs of the performance test will be the group points. The group with the most points will be judged as winners of the competition.

5.3.9 Project TALL: The Harder They Are, The Taller They Will Build

Seen from the mono-railway, the Outer Congolia Private Helifield and Airstrip seems to be just that - a private airfield for the use of commercial companies that offer charter flights, aero-sightseeing tours of remote regions, flight training, crop-dusting and other small, commercial aviation ventures. It does appear to be rather large for a private airfield, but perhaps it is just more profitable for other airfields. It has a very prosperous appearance, in any case. The main building is built of the most modern building materials, Alumarubber and Flexiferroglass, resulting in a transparent, reconformable terminal building - when new rooms are needed, the building stretches to accommodate.

If one flies over the Outer Congolia Private Helifield and Airstrip, one notices something very peculiar. (There are no aircraft landing or taking off. No aircraft are even taxiing. Exactly nothing appears to be going on except for some pilots converging on one of the hangars.

At the top of the hangar, across the front, in large neo-neon letters is the name of the company that owns the hangar and its contents. “Jagues LaMano’s Flying Wolverines”, proclaims the sign, “We Fly Anybody, Anywhere, Anytime”. On this day, all the airplanes have been pulled out of the hangar, and in their place is a large, angry mob. One senses that the aviation business may be facing an economic downturn.

A large man, with matching fiery hair and temper, and complimenting accessories (lantern jaw, red nose, barrel chest, fists the size of hams, etc.) is pounding with a wrench on a temporary podium made of oil drums. The meeting eventually comes to order.

“You all know me, I’m Jagues LaMano,” the man at the podium states. “We're here for same reason, so let’s not fight amongst ourselves. Besides, if it comes to a fight, you all know I can whip you all. The aviation industry is in bad shape, boys, and there are several facts we gotta face. Fact one - we're in a fuel crunch and it has forced our prices sky high. Fact two - since the government has decided to subsidize those dang dirigibles, they’ve been able to reduce the prices on those windbags. Fact three - the Vayun government has placed so many restrictions on us ‘cause of noise pollution and air pollution that we have to build our fields way outside any of the cities. Then nobody wants to do business ‘cause we’re out in the boonies. Geez, Outer Congolia...! Fact four - well, fact is, this whole situation stinks and we better do something or we'll all be sweeping the streets.”

At this, the equilibrium the mob seemed to have previously falls to pieces as everyone begins talking or yelling with their own ideas.

“I'm a flyboy, I can’t do anything else!”

“Let’s bomb the Vayun Hall of Government.”

“No, let’s shoot them dirigibles out of the sky!”

“Hey, maybe we can get subsidies from the government.”

“That’s fine for you buddy, but I ain’t no freeloader.”

“Yeah, well how about that twenty you’ve owed me for a year!”

“Why you lousy ...”

The large mob begins to break into smaller mobs, each with its own ideas and suggestions, each less constructive and more violent than the last. Finally, a man and a woman, one as old as the other is young, make their way to the oil drum podium. Jagues steps aside and gives the old man the floor. The old man, who looks like he could be the father of all fliers, raises his hand for silence and immediately gets it.

As the mob waits, the young girl steps up and speaks first. “Sebastian nef Storey here, or Grandpa, as you all call him, has been running Sobo Sailplanes for years. My name is Sonya nef Storey, Sebastian’s granddaughter. I recently graduated form the University of Vayu with a degree in small business management, and I recently got my pilot’s certificate. We think - rather, Grandpa thinks he has a solution to the problem and he wants me to tell you about it.”

“I think we realize that the days of powered, heavier-than-air craft are numbered, for the reason mentioned by Jagues. In the future, the only powered aircraft will be space shuttles and dirigibles. As a matter of fact the space shuttles may not be around to long either. Many of you have heard of the “beanstalks” that the Vayun government are building; they are compliant structures that dangle from space stations that have been placed in geosynchronous orbit. The beanstalks will be used to place people and materials into orbit, using device much like huge elevators. All the energy required to operate the beanstalks will come from solar collectors on the space station. So they are not particularly worried about fluctuating fuel prices.

“So what has this got to do with our situation?” asked Sonya, beating several in the crowd to the punch, “Just this - we design an elevator for the beanstalk that will carry a sail-plane or glider to high altitudes and then release it.”

“Sail-planes and gliders they're giving us,” moans someone in the back of the crowd.

“True, some types of aviation won’t find this scheme immediately beneficial. The charter and sightseeing flights have been mostly taken over by dirigibles. But the small jobs, aerial photography, crop dusting, police reconnaissance and others can benefit and compete in this scheme. More importantly, it keeps fixed wing aviation alive!”

“But what about helicopters?” a dark, stout pilot yelled.

“Have you ever heard of autogyros? Besides, we can put smaller engines in the aircraft for cruising, since we don’t need all the power required for a take-off.”

Heads nod, murmurs of agreement are murmured and the idea is accepted. On the spot, TALL, Total Aero Lift, Ltd. is formed and plans are made to recruit some bright, young engineers from the university of Vayu to make up the design team. To close the meeting, Grandpa Sebastian has this to say, “Let us not fool ourselves - this project is going to be a TALL order indeed, so let's get right to work.”

Task. Design, build and test a mechanism capable of traversing a "beanstalk" to the height of five (5) meters and is capable of releasing a paper aircraft upon reaching that height, subject to certain restrictions and conditions. In addition to the mechanism, the beanstalk and aircraft must also be designed and built. The beanstalk must reach from the first floor to a support provided by the instructors, five meters from the ground. The aircraft should be capable of extended duration.

Conditions

1. The weight of the mechanism including power source should not exceed one thousand (1000) grams.
2. No dimension of the mechanism shall exceed one meter.
3. Students shall be responsible for selecting a material for use as a beanstalk. A sample of the beanstalk is to be submitted along with the final concept for approval.
4. Students shall be responsible for selecting a material and design for use in constructing the aircraft. An example of the aircraft is to be submitted along with the final concept for approval.

Performance Tests

The performance run will be scored by two measurements. These are:

i. Speed of lifting up the beanstalk.
ii. Time aloft of released paper aircraft.

Speed up the beanstalk. This run tests the ability of the mechanism to lift itself speedily up the beanstalk in order to release the aircraft. The mechanism will be required to traverse the beanstalk. The amount of time taken by the mechanism to traverse the beanstalk from start to finish will be used in the calculation of points for this portion of the performance test. Once the mechanism has been placed on the beanstalk it shall not be aided in any way to complete the traversal of the beanstalk.
Time aloft of the paper aircraft: This portion tests the flight duration of the aircraft released by the lift mechanism at the top of the beanstalk. The means for releasing the aircraft is up to the designers, as long as it follows the rules specified here.

Each system will be required to go through the performance test twice. Students will be allowed 2 minutes to set up their system before each run on the course, which includes installation of beanstalk, lift mechanism and the aircraft payload. The system must be removed from the competition area within 1 minute after completion of the test. Penalties will be levied if the set up and removal times are exceeded.

The points for each part of the performance test will be calculated as follows:

i. Points for traversing the beanstalk

$$P_1 = 100 - \left[\frac{\text{Time}}{\text{Best Time}} \times \text{Weight} \times 100 \right]$$

where
Time is the time taken by the mechanism to traverse the beanstalk,
Best Time is the shortest time any mechanism takes to traverse the beanstalk and weight equals one (1) if the project is under the weight limit. Otherwise, Weight is the ratio of the over-limit weight to the weight limit of 1000 grams.

ii. Points for time aloft

$$P_2 = \left[\frac{\text{Time Aloft}}{\text{Best Time}} \right] \times 100$$

where
Time Aloft is the time from point of release until the aircraft touches the ground, and
Best Time is the longest time aloft of any of the aircraft.

The original points for each performance will be the sum of the above points after deductions due to penalties, i.e.

Original Points (OP) = $P_1 + P_2$ - (Penalties)

The sum of the original points from both runs of the performance test will be the group points. The group with the most points will be judged to be winners of the competition.

5.3.10 Project WindBAG: Whither the Wind Goes, I Store.

Professor Joachin Witherspear is moderately displeased. Although he had originally been excited about being invited to teach at the University of Vayu, (he had been awarded the coveted Bosh nef Storey Fellowship, named after the founder of the University, a man responsible for many innovations on the planet of Vayu) he is rather upset with the arrangements. He has been given a nice office and a brand new compustation, but the keys for the office and the building will take a week and a half. The Galactic Express people have been very nice in extending him credit, but he is not sure that it will be enough. And then there are all the numbers and forms and who knows what else that he had to apply for just to get the power and tele-vid turned on at his rental house. Still the house is clean and the people are friendly enough. He is determined, as would be anyone from his planet of Gleesong, to do the best job he can while at the University of Vayu.

"It is a good thing that I am still single or this move to Vayu would have been extremely difficult," Joachin thinks to himself as he walks to the conference room for his appointment with a Mr. Vindebagg. "I wonder why the chair-person wants me to meet with this gentleman - my neighbor says he is a crackpot!"

As he enters the conference room, Joachin gets his first look at Thaddeus P. Vindebagg - the new professor. He knows that it is this worthy because of the outsize badge Vindebagg wears, announcing to all and sundry his moniker. In addition, it proclaims his profession to be that of "Professional Concept Generator and Expeditor". The badge is only the beginning. Vindebagg is wearing a tunic made of patchwork, silvery corduroy trousers and shoes that have mates but not in this room. Joachin suspects that the socks, if Vindebagg wears socks, match about as well as his shoes. His hair is beyond the ability of any mortal barber to bring under control. But the man's face draws attention away from the scenic tour that is his attire. His eyes are alert and penetrating, and it is almost as if one can see a computer screen behind these eyes, constantly scrolling past new ideas being generated.

"Don't be put off by the clothes, friend, even though they do make me look a bit crack-potish," says Vindebagg, echoing Joachin's first thought.

"Thaddeus P. Vindebagg, at your service. As you can see from my badge, my business is conceptualizing and idea generation, and helping other people do the same. The clothes are to jar people out of complacency and to demonstrate the principle of synthesizing a new artifact from an unlikely set of concepts. But enough of that. I've come to discuss developing a concept of my own."

"My name is Joachin Witherspear, but I am unsure why you would want to speak to me. There are many professors here, senior to me, and with better contacts in industry. I am very much the new kid on the block," returns Joachin.

"Well, in truth I asked to speak to your chairman. I thought you were a bit young. Now I see what your chairman thinks of me."

"Wait a minute, I am not without talent or competency. I do hold the Bosh nef Storey Fellowship."

"Ah, Bosh nef Storey ...", muses Vindebagg, "there was an engineer with imagination and vision. Not like some of these around today. Well, perhaps you are the best bet after all. Would like to hear my concept?"

"I am here, so I might as well listen. Please, go ahead."

His face becoming ever more animated, Vindebagg pulls out diagrams, sketches and scribbled paragraphs from his overstuffed satchel. Spreading them on the conference table, he begins, "You see, it has to do with harnessing the wind..."

"I see why you are having so much trouble with this concept," interrupts Joachin, "From what I have seen so far, there is very little wind on Vayu, just a pleasant breeze. Besides the sun shines all the time, except for the hour of rain every day, so you can harness the sun for energy. This idea will never sell on Vayu."

"It is true there is little usable wind on Vayu. This is why it is such a good world for growing food. Very little wind erosion occurs and the weather is mild," lectures Vindebagg, adding testily, "But I never said that I wanted to 'sell' the idea on Vayu. There are other worlds..."

"I'm sorry, please continue."

"Quite all right. The concept got its start when I was reading some books of history about wind power. Sailing ships and windmills, that sort of thing. But what I thought would be interesting, would be if we were able to able to harness the wind and store it as energy..."

"And then use it later at a site remote from where the wind source is. Of course, I was blocking thoughts before, but now I see what you are getting at," says Joachin excitedly. "We could use such a device to power vehicles and such on my home planet, Gleesong. (They call it that because the wind blows all the time so that it sounds as if someone is constantly singing. We are a resource poor planet and the weather is mostly cloudy so that solar energy is right out. Presently, we are importing nuclear fuels to provide energy, and even though there is no danger of melt-down in our power plants, we still have a waste disposal problem. The government has begun building windmills to provide power, but no one has thought of using it to power vehicles. We are still using fossil fuels at present!”

“Then we agree, this is a concept that must be pursued, Joachin, but we must have some energetic young people, without preconceptions, to help us.”

“We can get the Design class to take this on as a project, Thaddeus,” says Joachin, adding, “But we need a name, or phrase, to rally around ... hm ... How about, **Wind B**lown **A**pplications **G**roup **- WindBAG**!”

“Perfect, just perfect,” beams Vindebagg. “This is what I call concept generation indeed.”

Task. Design, build and test a system capable of converting wind energy into some more useful form of energy and then store this energy in some compact, transportable module. The wind source will be represented by a household electric fan, and the energy modules must be used to propel a vehicle, carrying as large a payload, over as long a distance as possible, subject to the restrictions and conditions.

Conditions

1. The vehicle will be required to traverse a track to be specified.
2. No guide wires of any kind will be allowed.
3. After the vehicle has traversed the track, its total distance traveled will be measured.

Performance Tests. The mechanism that is to be tested shall consist of a conversion/storage device, energy modules and a vehicle. In the first part of the test, each group will be given 5 minutes to convert and store as much energy as their design allows. The energy modules shall then be integrated with the group's vehicle, the payload added and two runs shall be made.

The performance run will be scored by two measurements. These are:

i. The useful load carried by the vehicle (payload).
ii. The distance traveled by the vehicle.

The useful load carried by the vehicle (payload). This measurement demonstrates the useful work down by the vehicle and energy module.
The distance traveled by the vehicle: The distance traveled by the vehicle will be used in the calculation of points for this portion of the

performance test. Once the vehicle has crossed the start line it shall not be aided in any way to complete traversing the course.

Each system will be required to go through the performance test twice. Students will be allowed two (2) minutes to set up their system before each run on the course, which includes installation of modules and payload. The system must be removed from the competition area within one (1) minute after completion of the test. Penalties will be levied if the set up and removal times are exceeded.

The points for each part of the performance test will be calculated as follows:

i. Points for payload.

$$P_1 = \left[\frac{\text{Weight - Weight}_{min}}{\text{Weight}_{max}\text{ - Weight}_{min}} \text{ x } 50 \right]$$

where
Weight is the payload,
Weight_{max} is the maximum payload any group's vehicle is carries, and
Weight_{min} will be determined later.

ii. Points for distance

$$P_2 = \left[\frac{\text{Distance - 10 feet}}{\text{Distance}_{max}\text{ - 10 feet}} \text{ x } 50 \right]$$

where
Distance is the number of feet traveled by the vehicle in a straight line, and
Distance_{max} is the maximum distance traveled by all the vehicles.

The original points for each performance will be the sum of the above points after deductions due to penalties, i.e.,

$$\text{Original Points (OP)} = P_1 + P_2 \text{ - (Penalties)}$$

The sum of the original points from both runs of the performance test will be the group points. The group with the most points will be judged ti be the winners of the competition.

5.3.11 SHARK: Speilbaum's Hasty Amphibious Retrieval of Klepp

klik.
BING!

The time is five o'clock. Later on this evening, there will be highlights of the 111th Gardening Olympics on VVC One. But, now on VVC Two, we have the Witless News.

"Good evening and salutations, friends, this is Guy Friendlee speaking to you from the studios of Vayu Video Company, or the Veev, as we like to call it. Welcome to another evening of Witless News, the news programming that not only reports the news to you, but forms your opinions as well.

"First up is a story filed by Skip Dweebling, who is on the southwest coast tonight, in the town of Twitsdown. The Twits seem to have something that is clogging their harbor. Better their harbors than my drains. Over to you, Skip!"

"Thank you, Guy. Here with me tonight is the Head Twit and Harbormaster, Lloyd Speilbaum. In addition to chairing the Twitsdown city council and overseeing the workings of the harbor, Mr. Speilbaum has a longtime experience with the coastal areas and their flora and fauna. Mr. Speilbaum..."

"Please, call me Lloyd."

"All right Lloyd, just what seems to be the problem here in lovely Twitsdown?"

"Well, as your boss said, we gotta lotta Klepp clogging up the harbor..."

"Excuse me, Lloyd, but please watch your language. This is a family show. Now, you were saying about the 'stuff' in the harbor?"

"Yes, well anyway, the Klepp is ..."

"Really, Mr. Spielbaum, I must ask you ..."

"Mr. Dweebling, if you let me finish I can explain. Klepp, spelled K-L-E-P-P, is the name of an aquatic plant that floats on the top of the water. They have some uses, for example, they make a pretty good stew, and their are a number of useful chemicals and such that can be extracted from them."

"Oh, so all the, er, Klepp in the harbor should be a boon to you then, right?"

"Weeell, not exactly. You see, although we do have a Klepp industry in this area, with Klepp retrievers, Klepp boats, and a couple of Klepp processing plants, our biggest industry is really fishing for Purplefin, which are a deep-water fish. Apparently, there has been some extraordinary volcanic activity, which has cause all this Klepp to drift into port. There is so much Klepp in Twitsdown now that we can't get out to sea to fish for Purplefin. The Klepp men can't even get away from the docks to retrieve Klepp."

"I see. You are having problems clearing out the old Klepp before new Klepp shows up."

"Exactly. Given time, we could clear the harbor of Klepp, working from dockside out. But new Klepp keeps drifting in. We can't keep up!"

"Yes, but hasn't the government sent some help?"

"Yes, they sent some eggheads down from the University of Vayu to 'help'. I've told them that whatever they come up with, it has to be launchable from anywhere on the harbor. It has to be fast to get to new clumps of Klepp coming in from various directions, and it would be nice to retrieve the stuff - maybe it could pay for this operation. Other than the government eggheads we are on our own."

"No disaster relief funds?"

"They said it wasn't a disaster yet. By the time it becomes an official disaster we'll all have moved on to other places. Twitsdown will become a ghost town."

"So the future of Twitsdown rests on the shoulders of the egg... er, academics from the University."

"That's about the size of it, Skip."

"Well, thank you for your time, Mr. Speilbaum and I wish you and the rest of the Twits best of luck in your hasty amphibious recovery of Klepp."

"Now back to the studio and Guy ..."

klik.

Task. Design, build and test a SHARK system capable of moving overland a distance of three (3) meters, and then enter a harbor, (modeled in this instance by a child's wading pool. The SHARK must cover the three meters as rapidly as possible. Upon entering the 'harbor' the SHARK must retrieve as much Klepp as possible within set time limits. The design and construction of the SHARK are subject to the restrictions and conditions.

Restrictions

i. The total system weight (dry) should not exceed one thousand, five hundred (1500) grams.
ii. The system at rest should fit in an imaginary globe one-half (1/2) meter in diameter.

Performance Tests. The performance of SHARK will be tested in two areas:

i. Land speed - this event will measure the speed of the SHARK over a distance of three (3) meters.The course begins at a start line three (3) meters away from the 'harbor' and finishes in the 'harbor'. Timing begins when the foremost part of the SHARK crosses the start line and ends when the SHARK enters the pool.

ii. Retrieval rate - This is a measure of how much Klepp the SHARK can retrieve. Upon entering the water, the SHARK will have two (2) minutes to retrieve as much Klepp as possible. In the test, Klepp will be represented by styrofoam packing 'peanuts'. The number of peanuts collected or retrieved by the SHARK in two (2) minutes will be counted and expressed as a rate: Klepp retrieval per minute.

Each group will be allowed to put their SHARK through the test twice. Groups will be allowed two (2) minutes to set up for a test and one (1) minute to remove their device from the testing area.

i. Points for land speed.

$$P_{speed} = \left[1 - \left(\frac{Time - Time_{min}}{Time_{max} - Time_{min}} \right) \right] \times 25$$

where
Time is elapsed time over the three meter course,
$Time_{min}$ is the minimum elapsed time any group's SHARK requires to cover the course, and
$Time_{max}$ is the maximum elapsed time any group's SHARK requires to cover the course.

ii. Points for retrieval rate.

$$P_{retrieval} = \left[1 - \left(\frac{Rate - Rate_{min}}{Rate_{max} - Rate_{min}} \right) \right] \times 25$$

where
Rate is the retrieval rate for the SHARK,
$Rate_{min}$ is the lowest retrieval rate achieved by any group,
$Rate_{max}$ is the highest retrieval rate achieved by any group.

iii. Total points.

The total points for a test will be the sum of the above points minus deductions due to penalties, i.e.

$$\text{Original Points (OP)} = P_1 + P_2 - \text{(Penalties)}$$

The final score for a group will be the highest from the two tests. The group with the most points will be judged as winners of the competition.

5.3.12 LIFT: Low-Tech Invention Foiling Tolzar

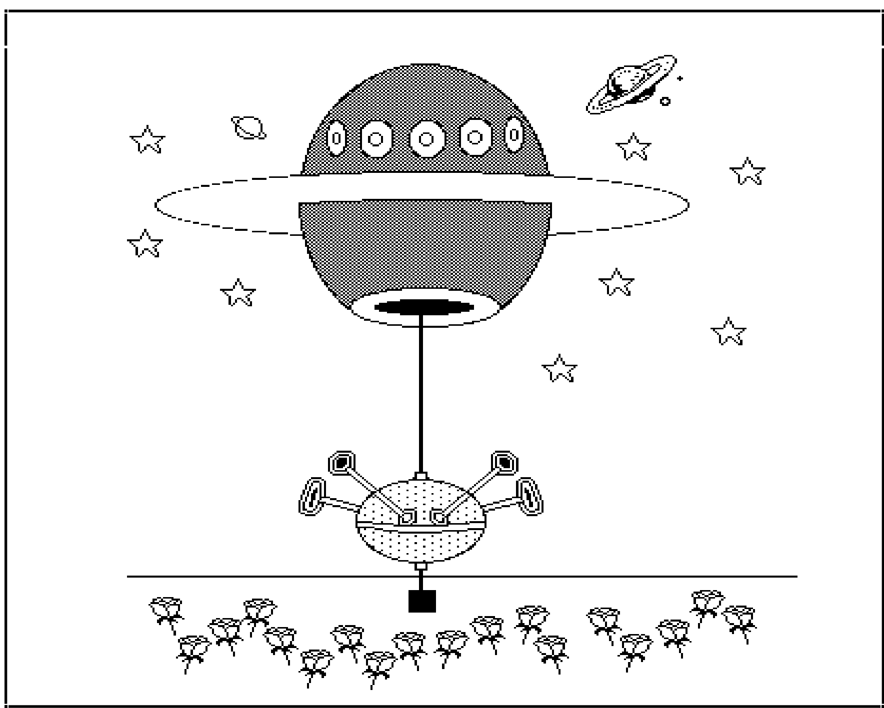


Figure 5.7. Project LIFT

The inhabitants of planet Vayu awoke one morning to find the sky darkened by a huge black spaceship hovering above their settlement. It was not long before this ship was recognized as belonging to Tolzar, a galactic pirate from the alien planet of Zertsim. The aliens soon made clear their demands upon the Vayuns: they wanted the entire supply of Rosa Vayunii, a plant unique to the planet, which contained a protein used throughout the universe to alleviate the effects of aging. The Vayuns depended on trade of Rosa Vayunii for their very survival.

The aliens had suspended through a hatch in the bottom of the space ship a cable with a weight at its end which hung about a meter clear of the ground. Down this cable theylowered a molecular beam disintegrator unit (m.b.d.) until it stopped about three quarters of a meter above the weight. The m.b.d. was positioned in the middle of the crop of Rosa Vayunii. Despite the high-tech nature of the m.b.d., it was triggered only when an old fashioned radar unit (incorporated within the m.b.d.) detected anything moving within its scanning beam. This beam scanned continuously through 360^{o} and was effective from the horizontal plane to an elevation of 45^{o}. When the radar detected movement, the m.b.d. fired a broad beam that was capable of destroying any object within close range.

The situation was desperate for the Vayuns. At a meeting the following evening, most of the Vayuns spoke in favor of the crop being surrendered immediately to get rid of the aliens. Only a tall young man spoke against the idea. “They would come back when the next crop is ready.” he pointed out. “Giving in to their demands is no solution.” Everybody stared at him as he continued, “My name is Gora-al-Bera, new design instructor at the University of Vayu and I have the beginning of a plan. There are no infra-red or other persons sensor associated with the m.b.d. so it should be possible to push or drag a device into position beneath the m.b.d. provided everything stays below the zone scanned by the radar beam. The ground immediately beneath the m.b.d. is marshy and cannot stably support any structure. Therefore the device must be made to attach to the cable beneath the m.b.d. and lift it up the cable until it passes through the hatch and into the space ship. The diameter of the hatch is little more than half a meter, so there are some size restrictions on the device.

“The movement must be very gentle and the m.b.d. must not be tilted, otherwise it may fire its beam and destroy our crop - and us with it. The interior surfaces of the spacecraft are not likely to be radar-invisible, although the outer surfaces certainly are. Hence, as the m.b.d. is lifted through the hatch, the movement provides a signal for the radar detector which then will fire the m.b.d. and destroy the space ship.”

The young man's plan at first met with some opposition. Someone suggested that it would only anger Tolzar without having any chance to succeed. Others worried about possible danger to the people below if anything went wrong. But the voice of Gora-al-Bera raised over the crowd, "There is no other option, our survival depends on our ingenuity. My students will take the task of designing and building the artifact. I assure you that Vayu will be saved!”

And so, project LIFT came into being: Low-Tech Invention Foiling Tolzar.

Task. Design, build and test a device capable of raising a specified payload five meters, using a vertically hanging rope for guidance and support. The payload comprises a plastic saucer and a ping-pong ball (representing the m.b.d.), with the ping-pong ball resting unsecured in the saucer. You are expected to reach the five meter mark (simulating the spaceship) with the ball in the saucer and, in addition, as fast as possible to avoid possible detection by the crew. The project is subject to the following restrictions and conditions.

Restrictions

1. The saucer containing the ping-pong ball is not to slide concentrically on the rope, but must be carried eccentrically by the LIFT.
2. The entire lifting device must remain below the top edge of the saucer throughout the lift.
3. The LIFT device, including the saucer and ping-pong ball, should not exceed one thousand (1,000) grams.
4. The LIFT at rest should fit in an imaginary globe five hundred (500) millimeters in diameter.
5. Each group will be allowed to provide their own rope. It should conform, however, to the specifications given in class. Any deviations will result in the disqualification of the project.
6. Use of chemical energy of any kind, including electric batteries as a power source, is strictly prohibited.
7. All energy must be contained in the device. No external connection or contact is permitted after releasing the device.
8. You will have to provide the 2 kg mass allowed to tense the rope, as well as a hook to tie it to the anchor that will be provided.
9. The rope should have appropriate marks indicating the beginning and end of the 5 meter run.
10. The saucer and ping-pong ball provided by the organizers may not be modified in any way by the competitors. The free

movement of the ping-pong ball within its saucer may not be restricted in any way by the competitors. The saucer must be supported from below, with nothing above its top edge.

11. The LIFT must lock onto the rope at the highest point of its ascent.
12. The ping-pong ball must be in the saucer at the end of the ascent and after the LIFT has locked into the rope. In the ball leaves the saucer, the run shall be declared invalid.
13. A LIFT that does not move for 10 sec at any stage after being released shall be deemed to have completed its run.

Performance Tests. The performance of the LIFT mechanism will be assessed as follows:

i. Travelling speed - This test will measure the speed of the LIFT mechanism in travelling along the rope and reaching the hatch. The clock is started when the LIFT mechanism begins to climb the rope, at point T_1, and ends when it passes point T_2.
ii. Stability - This is a measure of how stable the LIFT mechanism is in travelling along the rope. Stability will be measured using a sensor made of a ping-pong ball in a plastic saucer. The longer the distance traveled with the ball remaining in the plastic saucer, the more stable the device and the more points the group will get.

Each group will be allowed two test runs. Groups will be allowed three minutes to set up for the test and two minutes to remove the mechanism. Extra time will be penalized.

i. Points for Travelling Speed

If the ball does not fall from the plastic saucer:

$$P_{speed} = 25 \text{ x } \left[1-(T-T_{min})/(T_{max}-T_{min}) \right]$$

where

T is elapsed time to travel the distance D between the two red marks

T_{min} is elapsed time for the most competitive LIFT

T_{max} is elapsed time for the least competitive LIFT

If the ball falls from the LIFT:

$$P_{speed} = 0$$

ii. Stability

$$P_{stability} = 25 \text{ x } (D/5)$$

where
D is the distance traveled by the LIFT from the start red mark until the ball falls.

iii. Total points

The total points for the test will be the sum of the above points minus deduction of penalty points:

$$\text{Points}_{\text{total}} = P_{\text{speed}} + P_{\text{stability}} - \text{Penalty}$$

Penalty points:
Exceeding set-up and pull-down time:
2 points for every 15 seconds.

The final score for the group will be the highest from the two test runs.

The group with the most points will be judged the winner of the competition.

5.3.13 DROP: Delivering Radiosensitive Oval Payload

The faces of the Vayun planetary council were grave as the citizens squeezed into Bosh Hall for the emergency meeting. Whatever the crisis, it must be serious to get so many old fossils (oops - so many eminent scientists and engineers, thought young Lara nef Storey, correcting herself) out of their laboratories and classrooms. Even Nasim vel Nathan, Chief Engineer of Vayu, looked concerned as he approached the platform. *Chief Engineer, ha*, she thought, as she strained her neck to see over the shuffling crowd. Everyone knew there'd been no true engineers on Vayu in years, not since her great-grandmother Sonya had ...

An annoying tug at the arm distracted her. It was her boyfriend, Jered (*Significant other*, they called it these days. Bosh, what a decadent society!) Like her, he was a sophomore engineering student at the University of Vayu. They had gone through design classes together, and grown to like each other - why, she wasn't sure - he wasn't exactly a hunk. Maybe it was their shared frustration at having worked on the same old design projects their fathers had. She pulled back on her arm in protest.

"Be careful, Lara," he whispered. "You know we're not supposed to be in here. What if Dr. Redor sees us. We could be arrested, or thrown out of the University, or …"

"Oh, quiet. The worst they'll do is throw us *outside*. Before they do let's at least try to find out what's going on," she said as she began to worm her way through the crowd, pulling him reluctantly along.

"Citizens of Vayu," began the Chief Engineer, "we are faced with perhaps the greatest crisis since the great Bosh nef Storey saved our world from the evil Phoenix (oohs and ahs). The mining world of Heslar, the only source of the isotope called hyperium has suffered a coup d-," he cursed, wondering what idiot was running the teleprompter. Oh well, he'd have to wing it. "Ahem - a revolution. The Heslarii government has raised the price a hundred times over and threatened to cut off the supply altogether if we don't pay a yearly tribute. As most of you know, hyperium is vital for use in cooling proton-proton fusion reactors. Without it, every power station on Vayu will have to shut down in four months, and all spacecraft will be grounded. Unless our engineers can find a new energy source, Vayu will be back in the Stone Age."

Lara staggered in disbelief. How could they develop a new energy source in four months when they could hardly keep the old ones running? This would mean going back to more primitive sources of power - wind, solar, or (perish the thought) petroleum. The Golden Age when Vayun engineers had been the envy of the galaxy would be forgotten, and her career with it.

"Wait," cried a voice above the din. It was Han ken Sodo, retired physicist from the Vayun Institute of Technology (VIT). "There may be an alternative. The abandoned nuclear test sight of Au-Shen can be used to convert beta ore into hyperium. Because of the intense radioactive field emanating from the site, a properly placed critical mass of beta ore encased in a thin shell of polycalcite, lets call it the egg, will rapidly decompose at the rate of ..."

"Get to the point," said the Chief Engineer.

"The point is, it should take less than four months for the transformation of beta ore into hyperium."

A gruff voice interrupted, "This is not a textbook problem old man, this is the real world." It was Mining Director Hesto din Kaja. "The only problem with your idea is, it can't be done." He sarcastically snorted. "No man has been able to survive the intense radiation for more than 70 seconds, not to mention that there is a hundred foot high unidirectional electromagnetic force field (which keeps unsuspecting wanderers from entering the area), surrounding the sight."

There was a chorus of murmurs, all in agreement that Vayun technology was not up to the task.

"Stop it!" shrieked a voice which Lara was surprised to find was her own. "I can't believe what I'm hearing. Surely there must be a way of planting this egg. What's happened to Vayun ingenuity, anyway?"

Jered gasped as he tried to move away from his young friend. *Now she's done it. It''ll be exile to the ice planet Griswold for the both of us!!*

"And who are you, young lady, to question OUR judgment?" said the Chief Engineer as the guards closed in upon her.

"Lara nef Storey." Murmurs filled the hall at the legendary surname. "It was my ancestor Bosh nef Storey who saved our planet from the Phoenix, and from the Imperial warmongers, and who founded the University of Vayu, and MY Greatgrandmother Sonya who designed the first skycranes linking Vayu to the orbital cities of …"

"We are well aware of Vayun history, thank you," interrupted the Chief Engineer, motioning the guards to let her speak. "Very well, what do you propose?"

"Well," she said, getting more sure of herself, "why not design a vehicle which could go over the force field, deposit the egg, and leave the area in less than 70 seconds? There is a sixty foot high abandoned observation building right next to the site which we could use as a launching pad for our vehicle. We have dozens of capable engineering students here who haven't had a *real* design project in years, anyway."

At that, Dr. Redor stepped forward, smiling at his young students. "By Bosh, Chief Engineer, it just might be possible. We could build and test a prototype, at least. Couldn't we, students?" he growled. Both nodded their heads in submission.

The Chief Engineer smiled. "Very, well. Citizens, it seems that the name of nef Storey must come to the rescue of our beloved planet once again. You, young lady, will lead a team of students to design this - this device for Delivering Radiosensitive Oval Payload. Good luck, and remember that all of Vayu is counting on you."

Task. To design and build a vehicle that will launch itself from the top of a twenty four by sixty (24 x 60) inch table twnety nine (29) inches high carrying an egg. The vehicle has to jump over a 55" high barrier placed twenty four (24) inches away from the edge of the table and then land inside a marked area. After landing, the vehicle will deposit the egg as close to the center of the marked area as possible and then move out of the area as quickly as it can. The vehicle should not remain inside the marked area for more than sixty (60) seconds. The set up for the competition will look as shown in Figure 5.7.

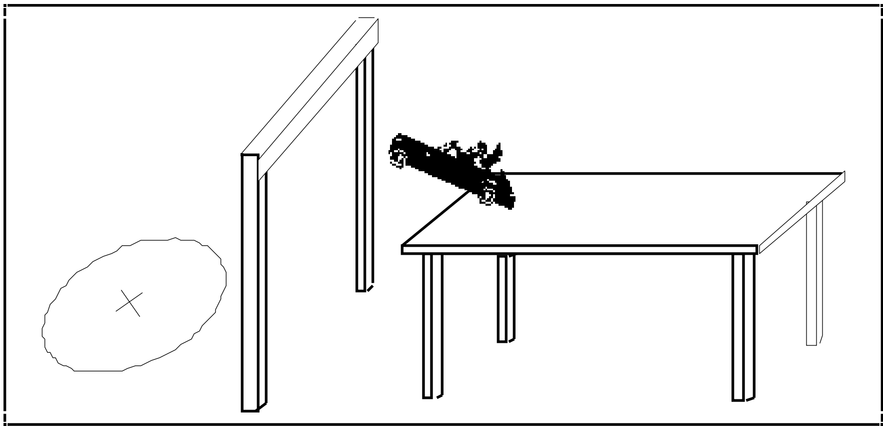


Figure 5.8. Schematic solution to Project DROP

Performance Tests. The projects will be judged on the following aspects

i. Safety

P_{sty} = 30 points

If the egg is transported and released unharmed inside the marked area. 30 pts

If the egg cracks but is released after the vehicle has landed. 20 pts

If the egg is released in mid air. 10 pts

If the egg is never released. 0 pts

ii. Accuracy

P_{acc} = 40 points

Points for accuracy of drop will be awarded according to the following scheme

$$P_{acc} = P_j + P_l$$

where

P_j = 20 if the vehicle jumps over the barrier
= 0 if vehicle goes under the barrier

$P_l = 20 (1 - X/R)$

X = Distance from where the egg is placed to the center of the target area.

R = Radius of the target area.

iii. Speed

P_{spd} = 30 points

$$P_{spd} = 20 \times \left(\frac{T_{max} - T}{T_{max} - T_{min}} \right) + 10$$

where

T_{max} = The maximum time, under sixty (60) secs., taken by any competitor.

T_{min} = The minimum time taken by any competitor

T = The time taken by your vehicle

All times measured in seconds.

Zero points will be awarded for speed if the vehicle stays in the target area for more than sixty (60) seconds.

5.3.14 SCALE: Shaft Climbing Contraption to AnnihiLate the Enemy.

As Lara recovered from her unconscious state she slowly became aware of the heat and the damp. She rubbed her gummed shut eyelids, then lay there, staring at the ceiling, experiencing a feeling of dislocation, not knowing in those first waking moments just where she was. She looked around and saw Dr. Redor and her friends slowly recouping from their dazed state. Gradually, as they regained their senses, the severity of the situation dawned upon them.

"By Bosh, what happened?" asked Sorekk.

"Seems like we were knocked unconscious by some kind of an accidental gas leak," Deckert tried to rationalize.

"Doesn't seem like an accident to me." Lara mumbled, pointing towards what seemed like empty gas shells lying on the control room floor.

"Where are the security guards?" shrieked Jered.

"Let us check the other rooms to see if we can find anyone." Deckert suggested.

• • •

Yuland was a new Hi-Tech landing station built on Andron, one of the three moons of Vayu. Lara and her classmates, along with Dr. Redor, had come to visit this feat of Vayun technology. The station was not yet operational and was supposed to be inaugurated the following week on

Bosh nef Day, to commemorate Vayus' entrance into the new age. But this advance of Vayu technology was viewed with much bitterness and animosity by the antagonistic Tolzarian government. The commissioning of the Vayun base on Andron would mean that Vayuns would now be able to mine the much demanded metal ore, Zapini, used throughout the universe in the manufacture of superconducting cables. Andron was known to have huge deposits of Zapini several feet beneath its rugged surface. Till now the Vayun technology was not up to the task of being able to take advantage of Andron's resources. But it seemed that with the new base, Yuland, the job would no longer be impossible. Yuland provided a landing base for Vayun ships with a long shaft extending beneath the rugged surface, which was to be used for transporting the ore as well as people from the underground mining facility. It certainly was a major technological achievement for the Vayuns.

The Tolzar government had other plans for the Andron base. All these months they waited for the Vayuns to finish construction so that they could seize the facility and use it for their benefit. Since the place was guarded only by a handful of inexperienced security personnel, they figured that capturing the base would not be a big problem. Roscow, the commander in chief of the Tolzarian armed fleet, led a small contingent to capture the Andron base. Indeed the take over was not at all difficult, the attack of the Tolzars was too sudden as well as too thorough and complete. The inexperienced Vayun security personnel were taken totally by surprise; no one expected an assault of any kind. In a few minutes the Tolzars had managed to destroy the main transport lift and disengage all the communication antennas. After rendering the base ineffective, Roscow decided to return to Tolzar with the good news of their success, so that the Tolzarian engineers and work force could come and take control of the base and start mining operations. Roscow knew that the security personnel trapped in the underground establishment had enough supplies to last them till they returned, and with the lift completely destroyed, it was highly improbable that they could find a way to get out of the underground building. But just as an added precaution he left giant helium balloons hovering above the launch pad to prevent any ships from taking off from the platform, a simple but effective way of paralyzing a landing base without unnecessary damage. He also left some of his men to keep an eye on the base, with enough ammunition to guard against any contingencies.

• • •

. . . Lara and her friends soon found the five security personnel who quickly briefed them about the entire situation.

“If only we could get a few men to the top of the shaft I am sure that we can takeover the Tolzarian guards,” said Lnonwiss, the Chief of Security.

“But what good will that do?” remarked Stefer, a security officer. With the communication antennas destroyed and those balloons hovering above the platform there is no way we can call for help from Vayu in time.”

“You are right,” agreed Lnonwiss, “We will also have to figure out a way to destroy those balloons.”

“But how are we going to do all this, we don't even have suitable equipment to work with!!” exclaimed Stefer.

“I am sure we can do something with what is available.”Lara proposed innocently.

“Oh yeah - I am sure you can!” Stefer snapped sarcastically.

“Now Lara might be right here.” Dr. Redor interjected, “I think if we put our heads together we just might be able to design a vehicle that would accomplish the task.These students here have constructed similar projects as part of their design course at VIT (Vayu Institute of Technology) and I am sure they will take up the challenge.”

“But this is not a stupid class project - this is the real thing.” Stefer screamed in disbelief. “Do you have any idea what will happen if this vehicle of yours fails to do the job? We will all be dead!!”

“I am fully aware of the risks Mr. Stefer, but does any one have a better suggestion?” Dr. Redor remarked calmly.

Suddenly the room became very quiet as everyone stared at each other. “Very well then.” Lnonwiss finally broke the silence, “We will go ahead with your plan Dr. Redor. Ask your students to begin work on this vehicle.”

Task. Design a self contained climbing device that will climb vertically inside a pipe of approximately fifteen (15) cm diameter about one hundred and eighty five (185)cm tall. The device should be designed to travel through the distance in the shortest possible time carrying a maximum amount of payload. The device should stop on reaching the top of the pipe and will have to burst six (6) balloons attached symmetrically to the periphery of a collar at the top. The device can be no longer than 25 cm.

Rules and Restrictions

1. The vehicle, excluding the payload, should not be longer than twenty five (25) cm.

2. The payload has to be separate from the vehicle. The vehicle weight is not included in the payload and the vehicle should be able to perform all the task with or without the payload.
3. The device will have to be released from a loading platform by hand or by activating a button, lever, or clutch, etc. The contestants will have to design their own loading platform.
4. On reaching the top of the pipe the device will have to burst six balloons, attached symmetrically on the periphery of a flat platform.
5. Any kind of power source can be used as long as it is safe for indoor use.
6. Each contestant will be allowed three trials and the best of the three will be used. In case of ties, the average of three trials will be used.
7. The maximum time allowed for each trial, from release of the vehicle till the popping of the balloons, is 90 seconds. However, the maximum time allowed for a vehicle to reach the 150 cm mark with the payload is 60 seconds.
8. A set up time of two minutes will be given at the start of each run.

Performance Tests. The Project will be judged on the following aspects

i. Distance Climbed

$$P_d = 25 \times (d/d_{max})$$

where

d = distance climbed by your vehicle $\leq$ 150 cm

d_{max} = 150 cm

ii. Time Taken

$$P_t = 25 - 20 \left(\frac{t - t_{min}}{t_{max} - t_{min}} \right) \quad \text{if } d \geq d_{max}$$

else

$$P_t = 0 \quad \text{if } d < d_{max} \quad \text{or} \quad t > 60 \text{ secs}$$

where

t = time taken by your vehicle to reach the 150 cm mark

t_{max} = maximum time taken by any competitor to reach the 150 cm mark

t_{min} = minimum time taken by any competitor to reach the 150 cm mark

iii. Payload Carried

$$P_p = 25 \times (W/W_{max})$$

where
W = weight carried by your vehicle

W_{max} = maximum weight carried by any competitor

iv. Balloons Popped

$P_b = 18 \times (n/6)$

where
n = number of balloons popped by your vehicle.

5.3.15 SPECTRE: Self Propelled Efficient Collector for Trash in Radioactive Environments

"Unloading completed. Preparing to release anchor."

The disembodied voice from the microphones filled the small control tower. Renig Klony turned his head towards the southern window to look at the superblimp anchored about a mile away. Against the bleak cold backdrop of southern Russerica, the superblimp was hovering silently above a steel tower and was anchored by three large ropes. The blimp was connected to the tower by a long telescopic tube. Even as he watched, the telescopic tube was retracted into the tower and the anchor lines were released and roped in by the blimp. Now the superblimp began its long and slow journey back to the northern continent. These colossal airships, the superblimps, had been a result of an intense drive towards fuel economy. Running on a combination of solar power and hydrogen fuel these monsters had proved to be the cheapest method for bulk transport.

Even as he turned to his viewphone Renig could imagine the activity in the processing plant under the steel tower. The long conveyer belts, the fully automated packing machines, the rolls of lead sheet used for containing the radiation and finally the neatly packaged boxes coming out of the elevator to be sent to the storage satellites. Time to check if the new consignment of uranium ore had been received without problems. He called his deputy who was in charge of the plant operations. "Everything going fine, Renig! Why don't you go home?" End of another uneventful day at the Vayun Radioactive Material Handling Center.

On the way out, he stopped to say good-bye to Jered, their summer intern from the University of Vayu.

“How’s it going, Jered!”

“I have just finished some calculations which show that by changing the scheduling of the packing machines a little, we could get an improvement of zero point eight percent in the processing speed. Can I get permission to change the master code for the processing plant?”

“Good work! But I am afraid you can't change the code. Even I don’t have the security clearance for making the changes but let me find out what can be done.”

• • •

Next day was a cold and cloudy day. The weather center had put out a tornado warning.

“This is SB-323 requesting permission to dock. I have some radioactive stuff from the Kryptonne National Laboratory.” The KNL had been conducting some experiments on the effects of severe radiation on plants of various types and this generated a great deal of radioactive plant waste. “The wind speeds are pretty high and also we have strong gusts, are you sure you can handle the docking?”

“No problem! I have done this a hundred times in worse weather.”

"OK! Go ahead!" Even after giving permission Klony was a bit worried. He watched as the connecting tube went up and the anchor lines came down. It started raining lightly.

Fifteen minutes later, he first saw it as a dark shadow in the corner of his eye. It was a TORNADO! And it was heading straight for the blimp! With a sinking feeling in his stomach he watched as the silent drama unfolded in front of his eyes. First there was the blur of the tornado hitting the blimp then the connecting tube collapsing in slow motion and finally the trash from the blimp streaming out in a cascade. And finally, the blimp crashing to the ground like a fallen Goliath.

The sound of the alarm ringing brought him back to the reality of the accident. Taking a deep breath, Renig plunged into action. First, the pilots had to be taken to the hospital. Next, call for help in fixing the blimp. That could take a few weeks. The tower had to be fixed immediately. The trash! How do we pick up the trash?

He immediately called for an emergency meeting of his entire technical staff.

• • •

"How do we handle the trash?"

"What about using our robots?"

"Most of our robots are on loan to the South Pole study group for the next three weeks. There are only six robots here and these are the old models of the 8600 series. Gobble up batteries like crazy!"

"How long will our battery supplies last?"

"I don't think that's our main problem. We should be thinking about the question of time. Can the robots handle the waste before it starts spreading all over the base?"

"My most optimistic estimate for cleanup using all six robots is about three days, what with battery recharging and all that."

"That's too long. Not acceptable! Remember that the radioactive waste can seep underground given that much time and a little rain."

"We will have to use some of our men to help the robots," Renig said with a tone of finality.

There was a brief uncomfortable silence in the room. Everyone in the room was aware of the severe discomfort of going into the cold wearing those thick radiation suits.

"Ask for volunteers and give them quadruple pay for the work."

Let the paper pushers and the penny pinchers in the Ministry of Industry bother about the expense of the cleanup, Renig thought. His job was to get the cleanup done as fast as possible.

"Don't you have some special equipment just to handle such spills?" asked Jered tentatively. The older heads in the room turned to fix their somber gaze upon the young intern. He was just beginning to regret his inopportune question when Renig answered in a patient voice.

"No! We don't have any. We have been asking for a specialized vehicle to handle such spills for the last five years, but each time the ministry has shot down our proposals."

"What were their reasons?" a slightly emboldened Jered queried.

"Cost, cost and cost! Same reason every time. All the proposed designs were too expensive to build. And considering that this machine would have no other use, I had to grudgingly agree with the ministry's opinion that they were too expensive."

"I know that it would not help the present situation but what if someone were to come up with an inexpensive device to pick up and compact the trash. Would you be willing to fund a project at the university?"

"I can't promise anything but I will do my best to sell the idea IF it is not too expensive."

By this time Jered was hardly paying attention to the reply. His mind was racing ahead with all kinds of ideas.

“This trash collector could use the tower itself as a guide for its movement.”

“Yes and no. I personally don't think that we want to put any more hardware on the tower but if need be we could fix something to the tower.”

“If you will excuse me, I will talk to my professor right now and get the ball rolling.”

As Jered walked towards his office, he was already thinking of a catchy acronym for the design problem ....

Task. Design and build a self contained vehicle that will pick up paper and/or styrofoam cups scattered in a circular area. The cups should be stored in a compacted form in a storage area that is a part of the vehicle. To guide and assist the vehicle in running in the designated circular area a string and pole arrangement would be made as shown in the schematic figure. After picking and compacting the cups, the vehicle must come to a stop as close to the center pole as possible. Points will be awarded on the basis of the number of cups picked up, the final volume in the compacted form, and the distance from center at the end of delivery. A list of rules and restrictions for the project is provided giving the details of size limitations, competition rules, and other specifics. The vehicles should comply with all the conditions set forth in the rules and restrictions for this project.

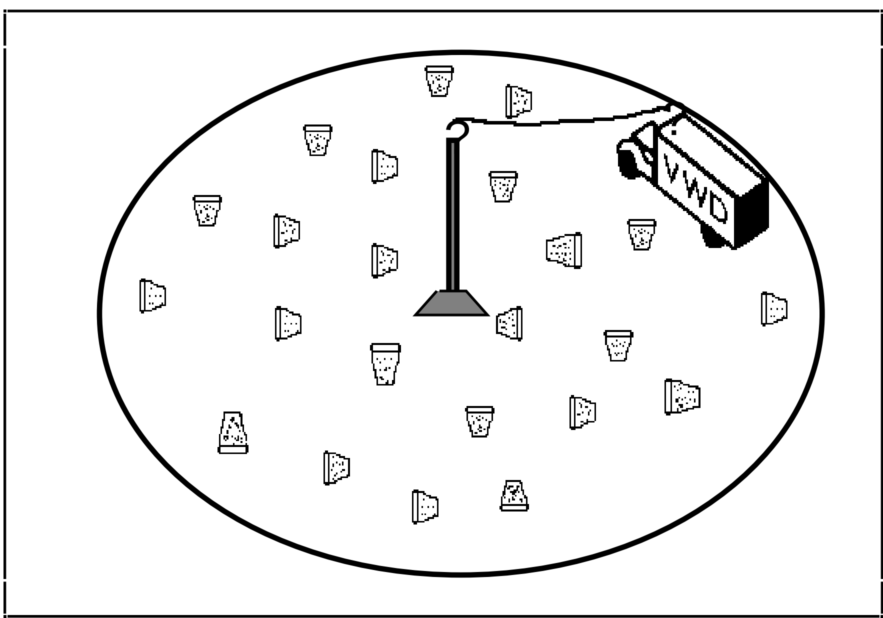


Figure 5.9. Schematic solution to Project SPECTRE

Rules and Restrictions:

1. The entire vehicle should fit inside a rectangular box of the following dimension
   length 60 cm
   width 25 cm
   height 25 cm
2. The vehicle has to be self contained and should be activated at the start by a simple on/off switch or some similar mechanical action. However, at the end of the run the vehicle has to come to a complete stop on its own.
3. There is no restriction on the type of power source except that it should be safe enough for indoor use.
4. The guide string will be attached to a sixty (60) cm high pole placed in the center of the contest area.
5. The guide string is provided to help the vehicles in navigation, however its use is not a mandatory requirement. A five point bonus will be awarded to the projects that do not use the guide string.
6. The radius of the circular contest area would be two (2.0) meters and the circular area would be marked on the Atrium floor in the Old Engineering building. (The contestants should make a note of the Atrium floor surface in designing their device.)
7. The contestants would be responsible for providing the garbage to be picked and compacted. This should consist only of paper and/or Styrofoam cups no smaller than 12 oz. If larger cups are used they should be one of a standard size, i.e., 16 oz, 20 oz, 24 oz, and 32 oz.
8. The cups would be scattered randomly in the contest area by the administrator, **not** by the contestants.
9. A contestant will have up to maximum of two (2) minutes to complete a run.
10. Each contestant will be allowed two trials and the best of the two will be used. In case of ties, the average of two trials will be used.

Performance Tests. Points will be awarded according to the following scheme

i. Speed

$$P_s = 25 - 20 \left(\frac{t - t_{min}}{t_{max} - t_{min}} \right) \qquad \text{if } t \leq 120$$

else

$Ps = 0$ if $t > 120$

where

t = the time, in seconds, taken to complete a run.

t_{max} = maximum time taken by any competitor to complete the run

t_{min} = minimum time taken by any competitor to complete the run

The time will be measured from start till the vehicle comes to a complete stop.

ii. Trash Carried

$$Pt = 25 \left(\frac{N}{N_{max}} \right)$$

where

N = number of cups picked up by the vehicle

N_{max} = maximum number of cups picked up by any competitor

iii. Degree of Compactness

$$P_c = 25 - 20 \left(\frac{V - V_{min}}{V_{max} - V_{min}} \right)$$

where

$V = V'/N$ (storage volume per cup)

V' = The compacted volume at the end of the run

N = The number of cups picked up

V_{max} = The maximum per cup volume for any competitor

V_{min} = The minimum per cup volume for any competitor

iv Accuracy

$$P_a = 25 - 20 \left(\frac{D - D_{min}}{D_{max} - D_{min}} \right) \qquad \text{If } D \leq 200 \text{ cm}$$

else

$$Pa = 0 \qquad \text{If } D > 200 \text{ cm}$$

Where

D= distance of the vehicle from the center at the end of the run

D_{max} = maximum distance for any competitor

D_{min} = minimum distance for any competitor

5.3.16 PROBE: Prompt Recovery of Bosh's Expedition

After the brief noonday shower, the wind herded the rain clouds away from the sun, leaving a landscape that looked as pristine and peaceful as if it had just been created. The fish jumped and splashed in the gem-like lake, and the birds and small woodland animals frolicked in verdant splendor. It was shaping up to be another beautiful, relaxing afternoon at Bosh nef Storey's vacation home.

Nice, Bosh thought, very nice. Too darn nice, he said to himself for the umpteenth time. Too much nice and no challenge can kill a man. Or at least cause his brains to dribble out his ears like so much oat bran mush. There must be some challenge left on Vayu!

“Bring me yon atlas, wife,” Bosh roared in his best adventurer's voice. “I must needs find a challenge worthy of my talent and skills.”

“Oh don’t be such an old poot,” replied his wife, handing him an atlas of Vayu. “I don’t see why you don’t just relax and enjoy this time away from the University. They have given you an extended sabbatical - you can do as you please, since you have already done so much for the University.”

“I am afraid that this so-called sabbatical is more of a device to get an old man out of their way. I don’t expect them to take me back. But I am not angry with them. Change is important. One must evolve, personally and professionally, to keep advancing. There is no standing still, no looking back. The University must evolve and so shall I. I must continue to seek more knowledge, to push back the boundaries of ignorance...”

“O Bosh, don’t make a huge oratory, just do what you will,” his wife said, as she turned to go back to the grandchildren. “What an old poot you are!”

Ignoring this last, Bosh turned to his atlas. He spent the afternoon poring over the book. It was an old-fashioned atlas, the continents, mountain ranges, forests, deserts, rivers, lakes and oceans drawn in the old style. However, the maps were based on the latest data available from satellite photography. But what he loved most about the atlas were the descriptions of legends and stories associated with places.

As the pages turned, in his mind's eye he visited Touchdown, the original landing site of the colonists and fought the Gronks - legendary beasts they encountered. He walked the streets of the industrial cities, and felt the might of their machines, before the War destroyed them. He even relived his earliest triumph - the destruction of the evil Phoenix, that criminal mastermind who sought to use Vayu for personal gain. But these were all history, there were no challenges to be found in them.

Finally, as the sun sought shelter below the horizon for the night, Bosh found his challenge. A small island, called Gnayan, rarely visited, uninhabited, unremarkable except for an old legend associated with it. The island had four rivers emptying into the ocean at the four points of the compass. No one had seen the sources of the rivers, and even the satellite cameras could not pick out the river sources amongst the rugged terrain. Legend had it that the rivers shared a single source, and that whosoever drank from the source would receive Total Enlightenment.

Well, thought Bosh, the magical drink of water is probably just a fairy tale. If I were to find the river sources, be it a single source or several, that would be enlightenment enough, challenge enough for this old man. I must begin making my plans.

Bosh to Find Rivers' Source

VAYU CITY - Bosh nef Storey, Distinguished Professor at the University of Vayu and Hero of Vayu several times over, announced plans for an expedition to Gnayan Island. At a press conference held at the University of Vayu, Bosh told reporters that he planned to search for the sources to the four rivers on the island. He expects the expedition to take four to six months, during which time he will be in contact with the outside world by radio.

Legends about the island speak of a single source that feeds all four rivers. The legends also speak of supernatural powers available at the source. When asked if he was seeking a fountain of youth, Bosh replied, "No, I am seeking a fountain of knowledge, which I will find regardless of the number of river sources."

Although this appears to be a dangerous expedition for a man of such advanced years, the University is supporting Bosh's plans fully.

"Yes, we expect Bosh to make contributions to geographical discovery as significant as his work in engineering. Bosh has our support and best wishes," commented University President Marsha lin Monty. "We take great pride in Bosh's endeavors."

When asked if this were merely a smoke-screen to hide the fact that Bosh was recently placed on an indefinite sabbatical, UV officials had no comment.

Please Rescue Our Bosh Expeditiously

VAYU CITY - University and government officials announced today that the expedition to Gnayan Island is considered lost. Four months have gone by since the last contact with Bosh nef Storey and there has been no sign of the expedition. The Vayun Coast Guard has been patrolling the skies and seas around Gnayan Island but nothing has been discovered except the expedition's abandoned base camp on the beach.

The expedition left six months ago to discover the source of the four rivers on the island. Reports of their findings and status were transmitted by radio every day. Two months into the expedition, the transmissions ceased, apparently due to the static caused by the unusually high amount of naturally magnetic materials on the island.

When asked if all hope was lost, University of Vayu President, Marsha lin Monty replied, "Of course not. Bosh is a very resourceful individual and his party was well equipped, with supplies for more than a year. They may still be exploring. We have declared the expedition lost so that we can organize a rescue mission - which will be handled by experts from the University, of course."

One such expert is Josiah Witherspear, Director of the Transportation Engineering Laboratory and a colleague of Bosh nef Storey. Dr. Witherspear is in charge of the effort to develop a suitable rescue vehicle.

When reached at his lab, Dr. Witherspear commented, "Yes, we have to develop the ultimate all terrain vehicle. Bosh went in on foot - we don't have that much time since we have to cover so much ground in so little time. We must have a vehicle which can negotiate broken ground, navigate rivers, climb steep inclines and traverse snowy slopes - all without as little modification as possible to save time."

"We have a number of teams working on this problem. All want the honor of designing and building the vehicle to recover Bosh. But there is so little time ..."

Task Statement. Each PROBE will be required to race over a course as quickly as possible. They will have to negotiate the following types of terrain, see Figure 5.10:

- Across flat, broken ground,
- Up a flowing river,
- Climb an incline, and
- Traverse a winding ski slope.

Each PROBE device is attended by a crew. This crew can only touch the PROBE between terrain sections. At this time they can reconfigure the PROBE for the next terrain section, but the clock is running, so little or no conversion is desirable.

It is desirable that besides maneuvering over the terrains the probe vehicle should also be able to carry supplies and other necessary equipment. Therefore, each PROBE will also be judged on the amount of payload that it can carry over from start to finish.

The other task required of the PROBE is that it should provide an effective signal to assist in the search for the expedition. The signal would be a loud alarm or siren sounded at the end of the run.

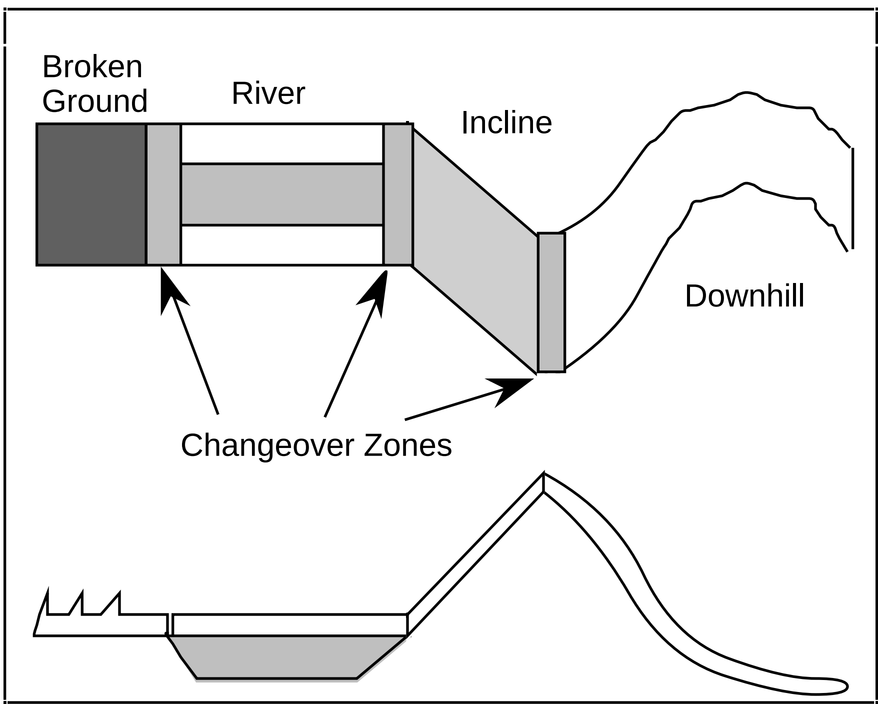


Figure 5.10. Test track for Project Probe

Rules and Restrictions

1. The entire vehicle should fit inside a rectangular box of the following dimension
   length 30 cm
   width 20 cm
   height 20 cm
2. The vehicle has to be self contained and should be activated at the start by a simple on/off switch or some similar mechanical action. Remote control of any kind is not allowed.
3. If the group chooses to make changes in the changeover zone, then the vehicle has to stop inside the changeover zone by itself. The group can only touch the vehicle after it comes to a complete stop in the changeover zone.
4. There will be a finish line marked 40 cm from the edge of the slope. The vehicle has to stop as close to the finish line as possible.
5. There is no restriction on the type of power source except that it should be safe for indoor use.
6. The payload to be carried by the vehicle should not violate the size restrictions. The vehicle and the payload together should fit within the dimensions given in rule 1.
7. The payload should be easily detachable from the vehicle and will be weighed at the end of the entire run.
8. The siren or alarm to be sounded at the end of the run should be loud enough that it can be heard within a radius of fifteen (15) meters.
9. Each contestant will be allowed two trials and the best of the two will be counted. In case of a tie, the average of the two runs will be used as a tie breaker.

Performance Test. Points will be awarded according to the following scheme

i. Speed and course completion

$$P_{speed} = \left\{ \left[1 - \left(\frac{t - t_{min}}{t_{max} - t_{min}} \right) \right] \times 60 \right\} - 15\,n$$

where
t = the time, in seconds, taken to complete a run.

t_{max} = maximum time taken by any competitor to complete the run.

t_{min} = minimum time taken by any competitor to complete the run.

n = number of terrains not negotiated

Time will be measured from the start till the vehicle comes to a complete stop.

ii. Payload Carried

$P_{load} = 25 \times (W/W_{max})$

where
W = payload carried by the vehicle.

W_{max} = maximum payload carried by any competitor.

iii. Bonus Points

All vehicles completing the course will get 10 bonus points. The Siren counts 5 points.

5.4 Closing Comments

It is hoped that these stories and projects will be helpful to instructors and coordinators of engineering design classes. Nothing about these projects is set in concrete, and it is hoped that they will be used in the manner appropriate to a particular curriculum. However, it is requested that the authors be acknowledged when any of the projects and/or stories are used.

It is felt that these stories will provide suitable and challenging design projects for students in mechanical design courses wherever and however the courses may be taught. The projects should be quite useful in a course where other design methods besides the DSP Technique are taught. However, it has been found that the Vayu projects are particularly suited to teaching and demonstrating the design method embodied in the DSP Technique. Design is decision making about conflicting objectives at different levels. The DSP Technique is a structured decision making technique, capable (in correctly trained hands) of solving decisions involving such objectives. The Vayu projects provide a laboratory for exploring this type of decision based design.