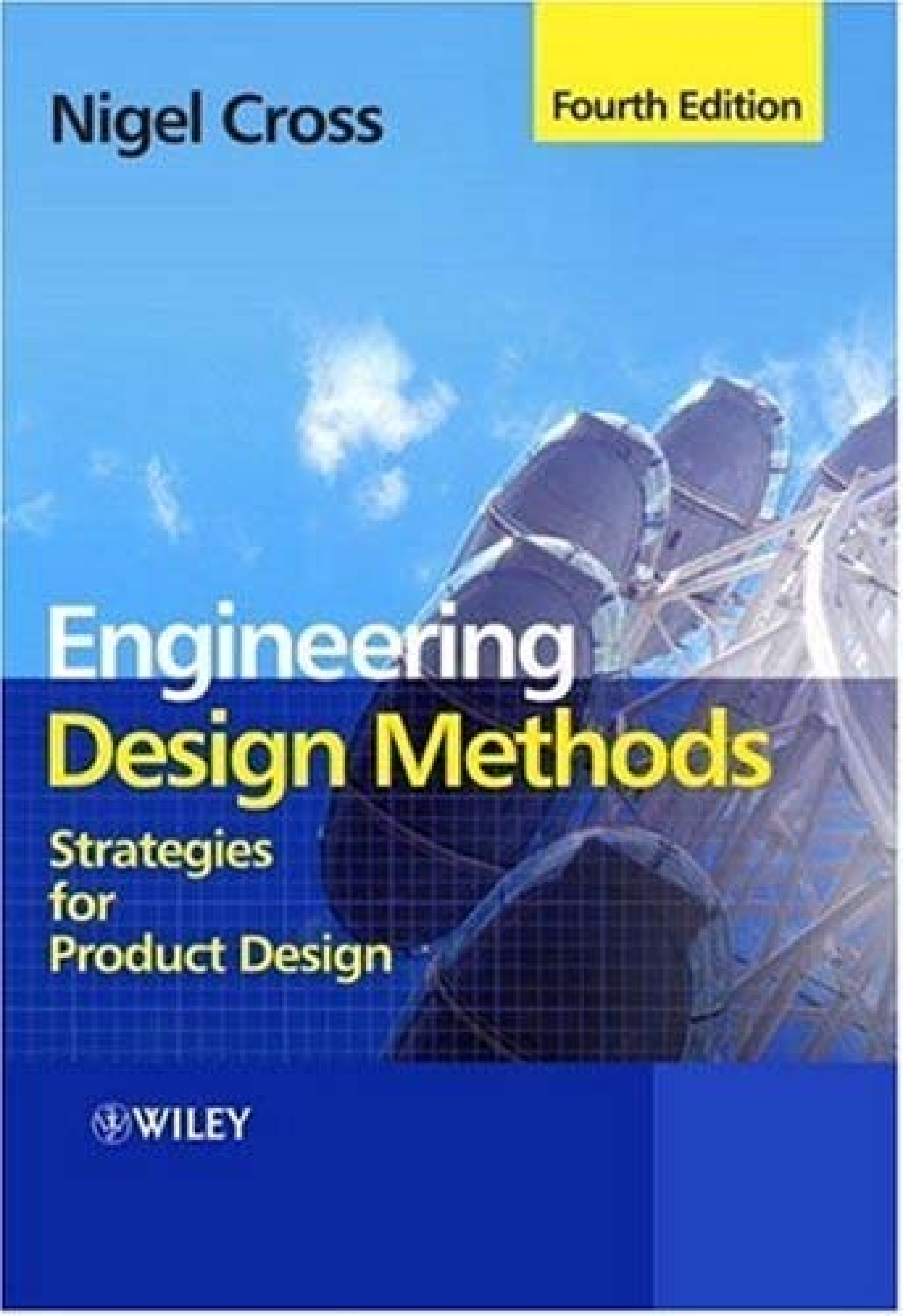

Nigel Cross

Fourth Edition

# Engineering Design Methods

## Strategies for Product Design

WILEY

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## Strategies for Product Design

THIRD EDITION

**Nigel Cross**
*The Open University, Milton Keynes, UK*

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# Introduction

This book offers a strategic approach and a number of tactics as aids for designing successful products. It is intended primarily for use by students and teachers of engineering design and industrial design. Its main emphasis is on the design of products that have an engineering content, although most of the principles and approaches that it teaches are relevant to the design of all kinds of products. It is essentially concerned with problem formulation and the conceptual and embodiment stages of design, rather than the detail design which is the concern of most engineering texts. The book can most effectively be used in conjunction with projects and exercises that require the exploration and clarification of design problems and the generation and evaluation of design solutions.

This third edition of the book has been fully revised and updated. The book has been structured more explicitly into its three parts, and two new chapters have been added: Chapter 2 on Design Ability, and Chapter 13 on Product Development. Chapter 2 develops and extends some brief content in the previous editions, drawing upon research into the nature of design ability by the author and others. Chapter 13 puts product design into the broader context of the business process of planning and developing new products. In the Design Methods chapters (Chapters 5–11), several new examples of the application of design methods in practice have been introduced.

The contents of the book are divided into three parts. Part One, Understanding Design, provides an overview of the nature of design activity, designers' natural skills and abilities, and models of the design process. Chapter 1 introduces the kinds of activities that designers normally undertake, and discusses the particular nature and structure of design problems. Chapter 2 considers and discusses the cognitive abilities that designers call upon in tackling design problems, and outlines some of the issues involved in learning and developing these 'designerly' skills and abilities. Chapter 3 reviews several of the models of the design process which have been developed in order to help designers structure their approach to designing, and suggests a new hybrid, integrative model that combines both the procedural and the structural aspects of the nature of design.

Part Two, Doing Design, explains the details of how to do design, at various stages of the design process. Chapter 4 reviews the new field of design methods, describes a number of methods that help to stimulate creative design thinking, and introduces the rational methods which are presented in the following chapters. Chapters 5 to 11 constitute a manual of design methods (the tactics of design), presented in an independent-learning format, i.e. students can be expected to learn the principle features of the methods directly from the book. These seven chapters follow a typical procedural sequence for the design process, providing instruction in the use of appropriate methods within this procedure. Each chapter presents a separate method, in a standard format of a step-by-step procedure, a summary of the steps and a set of practical examples concluding with a fully worked example. The seven methods included are:

objectives tree

function analysis

performance specification

quality function deployment

morphological chart

weighted objectives

value engineering

Part Three, Managing Design, is concerned with managing the design process, from the viewpoint of both the product designer and the business manager. Chapter 12 outlines a strategic approach to the design process, utilizing the most appropriate combination of creative and rational methods to suit the designer and the design project. Reflecting the approach that is implicit throughout the book, the emphasis is on a flexible design response to problems and on ensuring a successful outcome in terms of good product design. Chapter 13 puts the role of design into a broader perspective of new product development, showing that successful product design is framed on the one side by business strategy and on the other side by consumer choice.

The book embodies a concept of 'product design' that combines the two more traditional fields of engineering design and industrial design: the new concept of 'industrial design engineering'. Although intended primarily for students of product design – no matter whether their courses are biased more towards engineering or industrial design – the book is also useful as an introduction to design for the many teachers and practitioners in engineering who found this subject sadly lacking in their own education.

# Part One

# Understanding Design

# 1 The Nature of Design

## Design Activities

People have always designed things. One of the most basic characteristics of human beings is that they make a wide range of tools and other artefacts to suit their own purposes. As those purposes change, and as people reflect on the currently-available artefacts, so refinements are made to the artefacts, and sometimes completely new kinds of artefacts are conceived and made. The world is therefore full of tools, utensils, machines, buildings, furniture, clothes, and many other things that human beings apparently need or want in order to make their lives better. Everything around us that is not a simple untouched piece of Nature has been designed by someone.

In traditional craft-based societies the conception or 'designing' of artefacts is not really separate from making them; that is to say, there is usually no prior activity of drawing or modelling before the activity of making the artefact. For example, a potter will make a pot by working directly with the clay, and without first making any sketches or drawings of the pot. In modern industrial societies, however, the activities of designing and of making artefacts are usually quite separate. The process of making something cannot normally start before the process of designing it is complete. In some cases – for example, in the electronics industry – the period of designing can take many months, whereas the average period of making each individual artefact might be measured only in hours or minutes.

Perhaps a way towards understanding this modern design activity is to begin at the end; to work backwards from the point where designing is finished and making can start. If making cannot start before designing is finished, then at least it is clear what the design process has to achieve. It has to provide a description of the artefact that is to be made. In this design description, almost nothing is left to the discretion of those involved in the process of making the artefact; it is specified down to the most detailed dimensions, to the kinds of surface finishes, to the materials, their colours, and so on.

In a sense, perhaps, it does not matter how the designer works, so long as he or she produces that final description of the proposed artefact. When a client asks a designer for 'a design', that is what they want: the description. The focus of all design activities is that end-point.

### Communication of designs

The most essential design activity, therefore, is the production of a final description of the artefact. This has to be in a form that is understandable to those who will make the artefact. For this reason, the most widely-used form of communication is the drawing. For a simple artefact, such as a door-handle, one drawing would probably be enough, but for a larger more complicated artefact such as a whole building the number of drawings may well run into hundreds, and for the most complex artefacts, such as chemical process plants, aeroplanes or major bridges, then thousands of drawings may be necessary.

These drawings will range from rather general descriptions (such as plans, elevations and general arrangement drawings) that give an 'overview' of the artefact, to the most specific (such as sections and details) that give precise instructions on how the artefact is to be made. Because they have to communicate precise instructions, with minimal likelihood of misunderstanding, all the drawings are themselves subject to agreed rules, codes and conventions. These codes cover aspects such as how to lay out on one drawing the different views of an artefact relative to each other, how to indicate different kinds of material, and how to specify dimensions. Learning to read and to make these drawings is an important part of design education.

The drawings will often contain annotations of additional information. Dimensions are one such kind of annotation. Written instructions may also be added to the drawings, such as notes on the materials to be used (as in Figure 1).

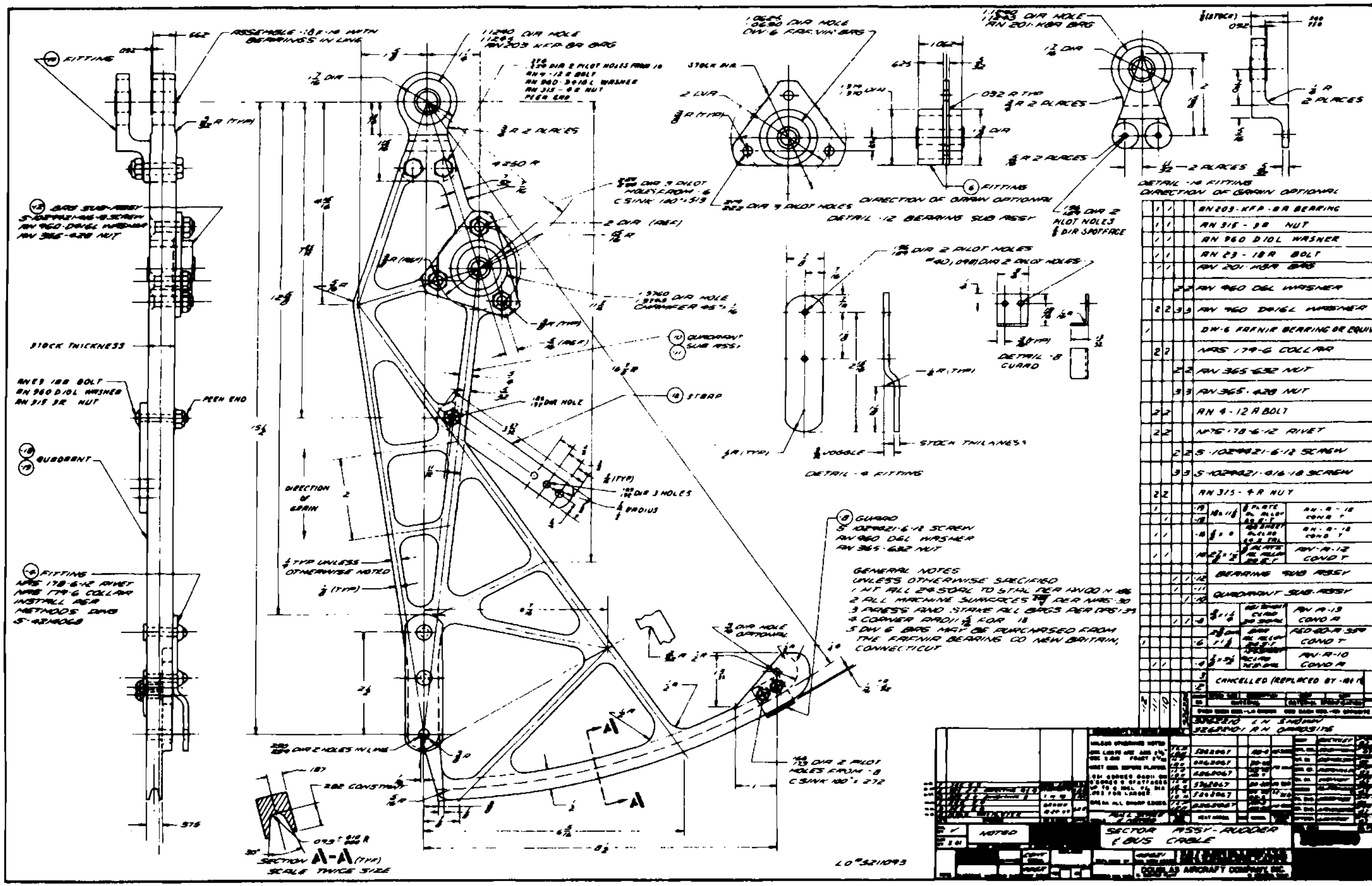


**Figure 1** Communication: a typical example of a conventional engineering design detail drawing

Other kinds of specifications as well as drawings may also be required. For example, the designer is often required to produce lists of all the separate components and parts that will make up the complete artefact, and an accurate count of the numbers of each component to be used. Written specifications of the standards of workmanship or quality of manufacture may also be necessary. Sometimes, an artefact is so complex, or so unusual, that the designer makes a complete three-dimensional mock-up or prototype version in order to communicate the design.

However, there is no doubt that drawings are the most useful form of communication of the description of an artefact that has yet to be made. Drawings are very good at conveying an understanding of what the final artefact has to be like, and that understanding is essential to the person who has to make the artefact.

Nowadays it is not always a person who makes the artefact; some artefacts are made by machines that have no direct human operator. These machines might be fairly sophisticated robots, or just simpler numerically-controlled tools such as lathes or milling machines. In these cases, therefore, the final specification of a design prior to manufacture might not be in the form of drawings but in the form of a string of digits stored on a disk, or in computer software that controls the machine's actions. It is therefore possible to have a design process in which no final communication drawings are made, but the ultimate purpose of the design process remains the communication of proposals for a new artefact.

## Evaluation of designs

However, for the foreseeable future, drawings of various kinds will still be used elsewhere in the design process. Even if the final description is to be in the form of a string of digits, the designer will probably want to make drawings for other purposes.

One of the most important of these other purposes is the checking, or evaluating, of design proposals before deciding on a final version for manufacture. The whole point of having the process of design separated from the process of making is that proposals for new artefacts can be checked before they are put into production. At its simplest, the checking procedure might merely be concerned with, say, ensuring that different components will fit together in the final design; this is an attempt to foresee possible errors and to ensure that the final design is workable. More complicated checking procedures might be concerned with, say, analysing the forces in a proposed design to ensure that each component is designed to withstand the loads on it (Figure 2); this involves a process of refining a design to meet certain criteria such as maximum strength, or minimum weight or cost.

This process of refinement can be very complicated and can be the most time-consuming part of the design process. Imagine, for example, the design of a bridge. The designer must first propose the form of the bridge and the materials of which it will be made. In order to check that the bridge is going to be strong enough and stiff enough for the loads that it will carry, the designer must analyse the structure to determine the ways in which loads will be carried by it, what those loads will be in each member of the structure, what deflections will occur, and so on. After a first analysis, the designer might realize, or at least suspect, that changing the locations or angles of some members in the bridge will provide a more efficient distribution of loadings throughout the whole structure. However, these changes will mean that the whole structure will have to be re-analysed and the loads recalculated.

In this kind of situation it can be easy for the designer to become trapped in an iterative loop of decision-making, where improvements in one part of the design lead to adjustments in another part which lead to problems in yet another part. These problems may mean that the earlier 'improvement' is not feasible. This *iteration* is a common feature of designing.

Nevertheless, despite these potential frustrations, this process of refinement is a key part of designing. It consists, firstly, of analysing a proposed design, and for this the designer needs to apply a range of engineering science or other knowledge. In many cases, specialists with more expert knowledge are called in to carry out these analyses. Then, secondly, the results of the analysis are evaluated against the design criteria: does the design come within the cost limit, does it have enough space within it, does it meet the minimum strength requirements, does it use too much fuel, and so on. In some cases, such criteria are set by government regulations, or by industry standards; others are set by the client or customer.

Many of the analyses are numerical calculations, and therefore again it is possible that drawings might not be necessary. However, specialists who are called in to analyse certain aspects of the design

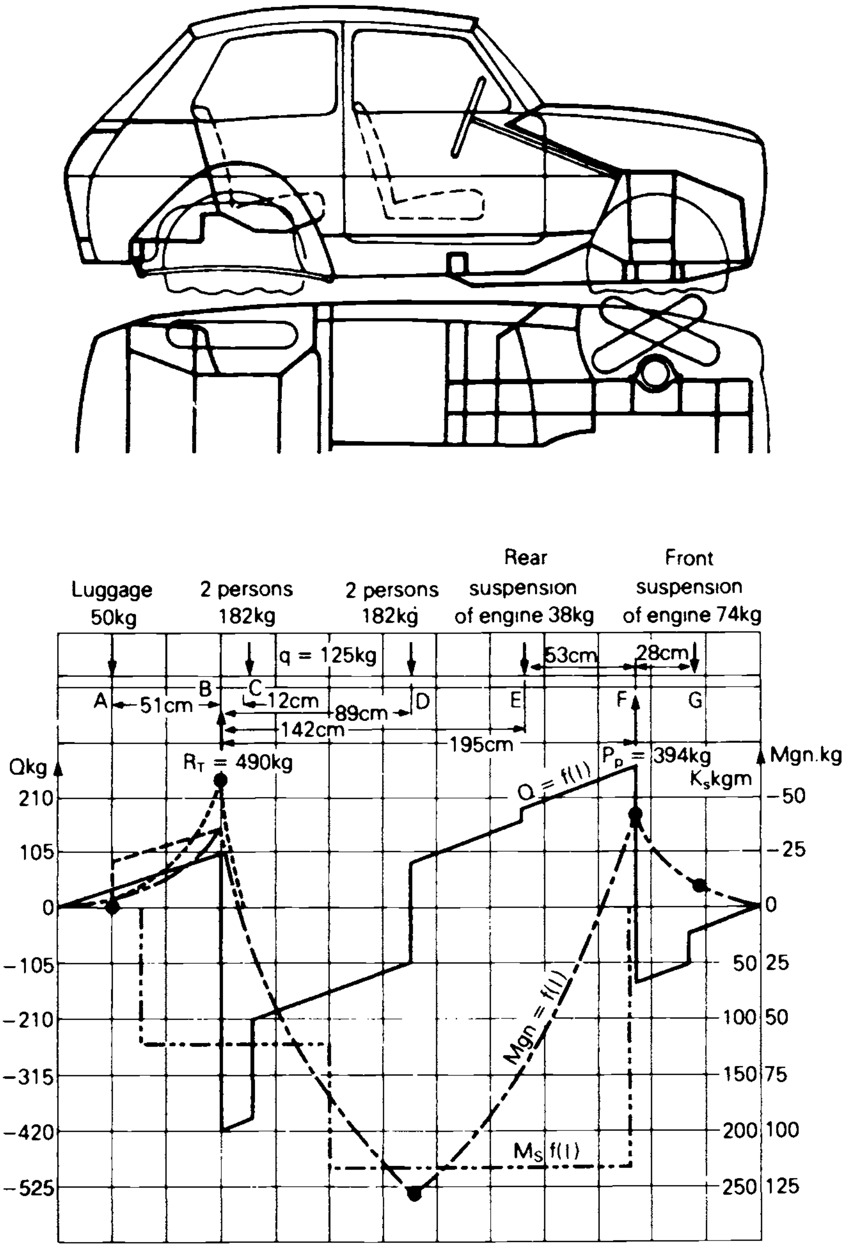


**Figure 2** Evaluation: calculation of the shear forces and bending moments in the body of a small automobile

will almost certainly want a drawing, or other model of the design, before they can start work. Visualizations of the proposed design may also be important for the client and designer to evaluate aspects such as appearance, form and colour.

### Generation of designs

Before any of these analyses and evaluations can be carried out the designer must, of course, first generate a design proposal. This is often regarded as the mysterious, creative part of designing, the client makes what might well be a very brief statement of requirements, and the designer responds (after a suitable period of time) with a design proposal, as if conjured from nowhere. In reality, the process is less 'magical' than it appears.

In most cases, for instance, the designer is asked to design something similar to that which he or she has designed before, and therefore there is a stock of previous design ideas on which to draw. In some cases only minor modifications are required to a previous design.

Nevertheless, there is something mysterious about the human ability to propose a design for a new (or even just a modified) artefact. It is perhaps as mysterious as the human ability to speak a new sentence, whether it is completely new, or just a modification of one heard, read or spoken before.

This ability to design depends partly on being able to visualize something internally, in 'the mind's eye', but perhaps it depends even more on being able to make external visualizations. Once again, drawings are a key feature of the design process. At this early stage of the process, the drawings that the designer makes are not usually meant to be communications to anyone else. Essentially, they are communications with oneself, a kind of thinking aloud. As the example of the concept sketch for the 1950s Mini car shows (Figure 3), at this stage the designer is thinking about many aspects together, such as materials, components, structure and construction, as well as the overall form, shapes and functions.

### Exploration of designs

At the start of the design process, the designer is usually faced with a very poorly defined problem; yet he or she has to come up with a well-defined solution. If one thinks of the problem as a territory, then it is largely unexplored and unmapped, and perhaps

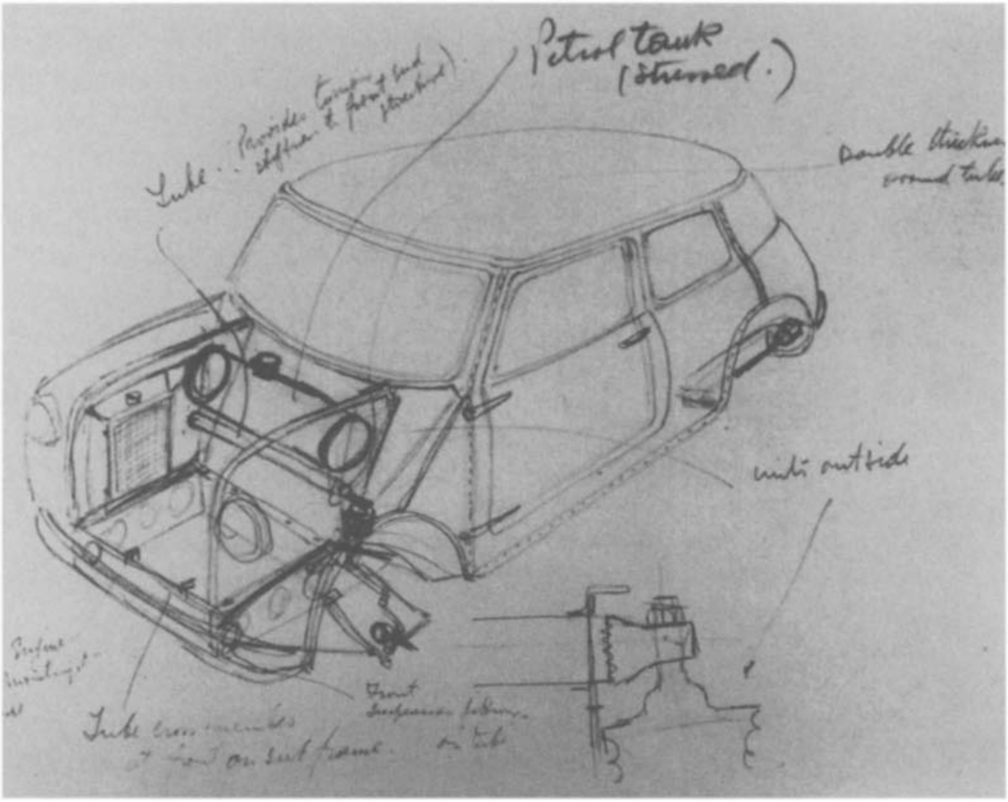


**Figure 3** Generation: Concept sketch for the Mini car by its designer Alec Issigonis

imaginary in places! As Jones (1981) has suggested, and as will be discussed in Chapter 12, it is therefore appropriate to think of the designer as an explorer, searching for the undiscovered 'treasure' of a satisfactory solution concept.

Equally, if one thinks of all potential solutions as occupying a kind of solution space, then that, too, is relatively undefined and perhaps infinite. The designer's difficulties are therefore two-fold: understanding the problem and finding a solution.

Often these two complementary aspects of design (problem and solution) have to be developed side-by-side. The designer makes a solution proposal and uses that to help understand what the problem really is and what appropriate solutions might be like. The very first conceptualizations and representations of problem and solution are therefore critical to the kinds of searches and other procedures that will follow, and so to the final solution that will be designed.

The exploration of design solution-and-problem is also often done through early sketching of tentative ideas. It is necessary because normally there is no way of directly generating an optimum solution from the information provided in the design brief. Quite apart from the fact that the client's brief to the designer may be rather vague, there will be a wide range of criteria to be satisfied, and probably no single objective that must be satisfied above all others, as suggested in the problem-solution 'exploration' in Figure 4.

## *Design Problems*

Design problems normally originate as some form of problem statement provided to the designer by someone else, the client or the company management. These problem statements, normally called a design brief, can vary widely in their form and content. At one extreme, they might be something like the statement made by President Kennedy in 1961, setting a goal for the USA, 'before the end of the decade, to land a man on the moon and bring him back safely'. In this case, the goal was fixed, but the means of achieving it were very uncertain. The only constraint in the brief was one of time – before the end of the decade. The designers were given a completely novel problem, a fixed goal, only one constraint, and huge resources of money, materials and people. This is quite an unusual situation for designers to find themselves in!

At the other extreme is the example of the brief provided to the industrial designer Eric Taylor, for an improved pair of photographic darkroom forceps. According to Taylor, the brief originated in a casual conversation with the managing director of the photographic equipment company for which he worked, who said to him, 'I was using these forceps last night, Eric. They kept slipping into the tray. I think we could do better than that.' In this case, the brief implied a design modification to an existing product, the goal was rather vague, 'that [they] don't slip into the tray', and the resources available to the designer would have been very limited for such a low-cost product. Taylor's re-design provided

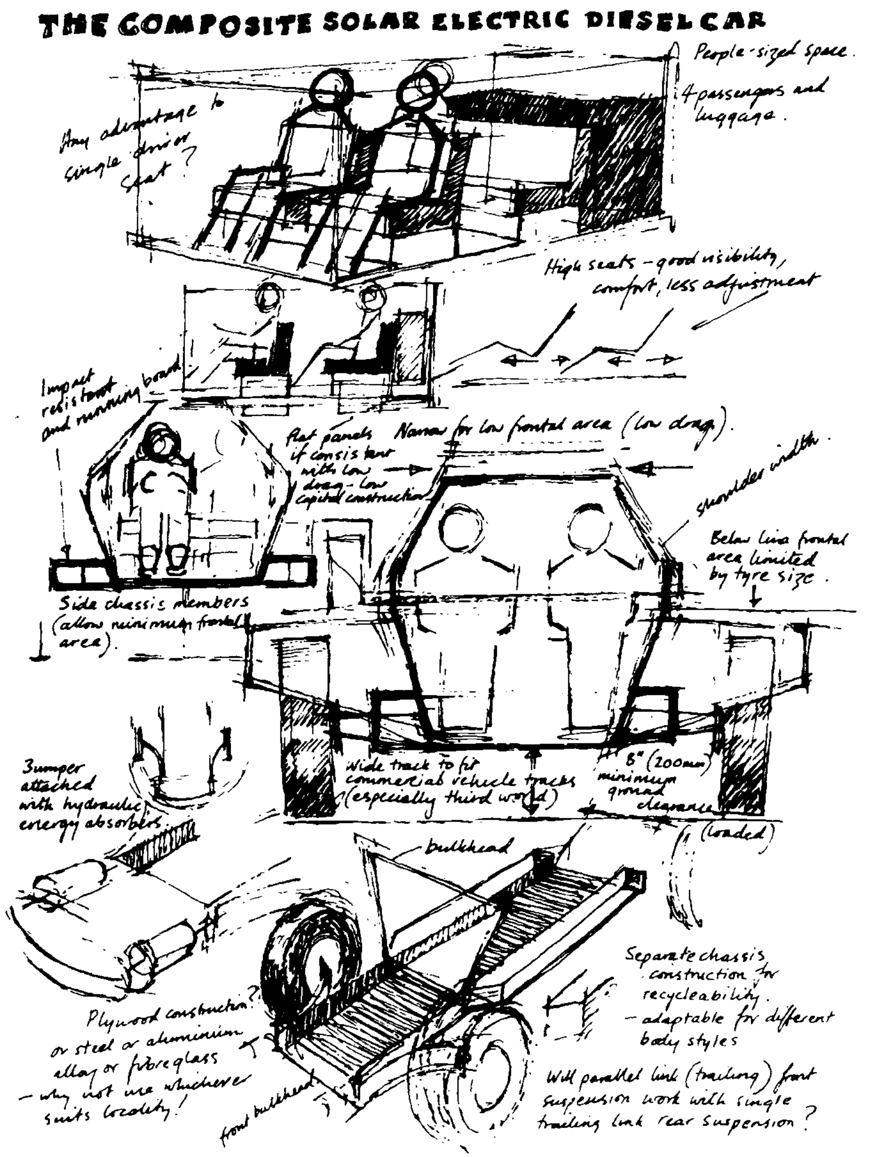


**Figure 4** Exploration: an example of problem and solution being explored together for the Africar, a simple but robust automobile suitable for conditions in developing countries

ridges on the handles of the forceps, to prevent them slipping against the side of the developing-tray.

Somewhere between these extremes would fall the more normal kind of design brief. A typical example might be the following brief provided to the design department by the planning department of a company manufacturing plumbing fittings. It is for a domestic hot and cold water mixing tap that can be operated with one hand. (Pahl and Beitz, 1984).

*One-handed water mixing tap*

Required: one-handed household water mixing tap with the following characteristics:

| | |
|---|---|
| Throughput | 10 l/min |
| Maximum pressure | 6 bar |
| Normal pressure | 2 bar |
| Hot water temperature | 60°C |
| Connector size | 10 mm |

Attention to be paid to appearance. The firm's trade mark to be prominently displayed. Finished product to be marketed in two years' time. Manufacturing costs not to exceed DM 30 each at a production rate of 3000 taps per month.

What these three examples of design problems have in common is that they set a *goal*, some *constraints* within which the goal must be achieved, and some *criteria* by which a successful solution might be recognized. They do not specify what the solution will be, and there is no certain way of proceeding from the statement of the problem to a statement of the solution, except by designing. Unlike some other kinds of problem, the person setting the problem does not know what the answer is, but they will recognize it when they see it.

Even this last statement is not always true; sometimes clients do not recognize the design solution when they see it. A famous example of early Modern Architecture was the Tugendhat House in Brno, Czechoslovakia, designed in 1930 by Ludwig Mies van der Rohe. Apparently the client had approached the architect after seeing some of the rather more conventional houses that he had designed. According to Mies van der Rohe, when he showed the surprising new design to the client, 'He wasn't very happy at first. But then we smoked some good cigars ... and we drank some glasses of a good Rhein wine ... and then he began to like it very much.'

So the solution that the designer generates may be something that the client 'never imagined might be possible', or perhaps even 'never realised was what they wanted'. Even a fairly precise problem statement gives no indication of what a solution *must* be. It is this uncertainty that makes designing such a challenging activity.

## Ill-defined problems

The kinds of problem that designers tackle are regarded as ill-defined or ill-structured, in contrast to well-defined or well-structured problems such as chess-playing, crossword puzzles or standard calculations. Well-defined problems have a clear goal, often one correct answer, and rules or known ways of proceeding that will generate an answer. The characteristics of ill-defined problems can be summarised as follows.

### *There is no definitive formulation of the problem*

When the problem is initially set, the goals are usually vague, and many constraints and criteria are unknown. The problem context is often complex and messy, and poorly understood. In the course of problem-solving, temporary formulations of the problem may be fixed, but these are unstable and can change as more information becomes available.

### *Any problem formulation may embody inconsistencies*

The problem is unlikely to be internally consistent; many conflicts and inconsistencies have to be resolved in the solution. Often, inconsistencies emerge only in the process of problem-solving.

### *Formulations of the problem are solution-dependent*

Ways of formulating the problem are dependent upon ways of solving it; it is difficult to formulate a problem statement without implicitly or explicitly referring to a solution concept. The way the solution is conceived influences the way the problem is conceived.

### *Proposing solutions is a means of understanding the problem*

Many assumptions about the problem, and specific areas of uncertainty can be exposed only by proposing solution concepts. Many constraints and criteria emerge as a result of evaluating solution proposals.