CHAPTER THREE

Engineering Planning and Design

Planning, design and management are the core activities used to drive an engineering project from its inception through to a successful conclusion. These are essentially problem-solving processes. In this chapter we first look at a simple, common-sense method for solving open-ended problems that provides us with a methodology for undertaking engineering planning and design. The main steps in the processes of planning and design are discussed in some detail. Some important related considerations are also mentioned, including safety and risk, the role of codes and regulations, and legal and social issues. Alternative, non-traditional approaches to engineering work are also discussed, including the agile approach and sprints and scrums. Wicked and intractable problems are discussed briefly. In an appendix, a planning example is discussed, which deals with the future water needs of a small coastal city.

3.1 TERMINOLOGY

As we have seen in previous chapters, the terms planning and design are not mutually exclusive, and there is overlap in the way both words are used. Broadly speaking, *planning* is undertaken to ensure that a proposed action will be successful. It involves deciding on the goal that is to be achieved by the action, and then identifying the steps needed to achieve the goal. These steps, when clearly formulated, constitute a *plan*. Planning is a crucial step in any engineering project. *Design*, as distinct from planning, is undertaken to produce the information needed to create a new physical system. Design work is also undertaken when an existing system is to be modified and improved. *Management* refers to the effective use of available resources to achieve a designated outcome. Management is the means by which the results of engineering planning and design are implemented and brought to a successful conclusion.

In this book, we will refer to the *design of physical objects*, and to the *planning of operations and processes*, in short: to the *design of hardware* and the *planning of software*. Accordingly, we design a bridge, but plan the process of its construction. Design work is undertaken with the purpose of determining precise details of devices, machines, and other physical objects, so that they can be manufactured or constructed. Planning work is undertaken to determine the details of the procedures and processes which form part of any engineering project.

These descriptions of planning, design and management can be sharpened if we apply the systems terminology of Chapter 2. An engineering project is thus undertaken to change the current state of some part of the physical infrastructure to a preferred new target state, either by introducing new systems and processes or by modifying existing ones. The planning for an engineering project begins with a - study of the current state of the infrastructure and proceeds to the identification of the desired future target state. It also involves working out the steps needed to change the present state into the new state. Design is the process of determining the details of any required new systems (or the details of modifications to be made to existing ones) that are needed to achieve the desired changes to the infrastructure. The purpose of management is to bring about the changes efficiently, in a designated time frame, and with an effective use of available resources.

By way of example, consider a project that aims to improve the quality and quantity of water to be delivered to a township over the next 25 years. In the initial planning work, it is first necessary to determine details of the present water supply system, and in particular the quantity and quality of the water currently used together with details of the delivery systems. It is also necessary to evaluate the expected demographic changes in the city over the planning period, including increases in physical size and population, changes in business and industry activities, so that future water requirements can be estimated. Possible new sources of water may be required, such as groundwater and domestic rainwater tanks, and possible sites for new reservoirs and dams. Combinations of the various alternatives will also be considered. Additional options in the case of inadequate water sources may include recycling of water, the use of pricing policies to curb demand, and the construction of desalination plants if there is ample salt water close by. The progressive changes to the water supply system during the planning period, to allow for the increasing demands for water, will be an extremely important planning outcome.

Design work for the project would be needed for any new components, or modifications to existing components. For example, if a new dam is to be constructed, design work is needed to determine the size, shape and other details of the dam wall, and how the wall is to be keyed into the valley sides and base at the chosen site. But before the design work can begin, it will be necessary to identify and survey possible sites and to obtain data on rainfall and runoff patterns, as well as relevant geological information. Careful planning is needed to determine the sequence of steps for preparing the site and constructing the dam wall. The resulting construction plan for the dam will include activities such as providing access roads to the site, bringing in heavy equipment, excavating soil and rock, shaping and preparing the foundations, grouting unsound regions of bed rock, and progressive construction of the main wall. Design work is also needed for the downstream components of the delivery system, such as pipes, pumping stations, holding tanks, and pressure tanks.

Comparable planning and design work would be needed for any other options that are chosen. The planning and design activities themselves need careful management, as do all the steps in the implementation phase of the project. Progress needs to be monitored regularly to ensure that the design and planning work proceeds on time and within budget.

The term *project planning* is applied to the overall planning of the project, while the planning undertaken at sub-project level is often referred to as *activity planning*. The planning required to carry out a particular step in an engineering project is thus activity planning. The planning of an activity results in a sub-plan, or component, of the project plan.

Using an hierarchical view of planning, Griffis and Farr (2000) go further and use the term *program planning* for planning at a broader level where, for example, various related engineering projects are identified and sequenced, taking account of available resources. Program planning thus takes place at the regional, state or national level. A program would include a number of projects that are to be carried out together or in sequence. A flood mitigation program in a fertile river valley might include the construction of several dams in the upper reaches, silt dredging near the river mouth and the building of levy banks in intermediate regions along the river.

Although our focus here will be on project planning and activity planning, we need to mention several other types of engineering planning. *Strategic planning* is undertaken by businesses and other organisations to produce long-term plans that are aimed at their continued successful operation and survival. Another form of long-term planning, of interest particularly in situations where the future is uncertain, is *scenario planning* (Meier et al. 2016). As an example of scenario planning, NASA and ESA (the European Space Agency) have developed a joint experimental program to test whether the impact of a relatively small missile could nudge an asteroid out of a collision path with the earth (Cosmos *Community Input,* April 2017). According to *Cosmos*, a different approach is being studied by the Makeyev Rocket Design Bureau in Russia, which aims to design and construct a missile that could destroy asteroids if they come dangerously close to earth.

The design activities in an engineering project can be broken down into tasks and sub-tasks. This breakdown is needed to deal with the complexity inherent in a large infrastructure item such as a dam, a road, a bridge, a building or an airport. In the design of a unit that is to be manufactured in large numbers, such as a washing machine, a mobile telephone, or an automobile, the design is undertaken using the hierarchical approach. It is also used in the planning of processes, such as the manufacture and delivery of ready mixed concrete to building sites in a city.

Planning and design are complex activities; so complex, usually, that they can only be carried out iteratively, with considerable trial and error. It will be appreciated that the activities of planning, design and management for a large project will be closely inter-related and will probably overlap. Basically, they are all problem-solving activities.

3.2 DEALING WITH ILL-DEFINED AND OPEN-ENDED PROBLEMS

In Chapter 1 we saw how engineering problems can be complex, open-ended and ill-defined. The systems approach was introduced in Chapter 2 to deal with complexity in engineering systems and in engineering problems, but it does not provide a means to solve open-ended problems. We now consider how best to deal with open-ended and ill-defined problems.

An ill-defined problem is one that is vaguely or ambiguously formulated. There are good reasons why engineering problems are initially poorly defined. The need for an engineering project can gradually become evident over time as inadequacies in the infrastructure are experienced. Community dissatisfaction leads to demands for improvements. In such situations the needs of the community may be expressed forcefully, but not necessarily precisely and unambiguously. This is how some large engineering projects begin. The first step is to identify and clearly formulate the real problem.

Even when an engineering problem has been clearly formulated and stated, it will be open-ended, in the sense that there will not be a single "correct" solution. Indeed, a characteristic of engineering problems is that there are alternative, potentially acceptable solutions. The problem is not to find "the" solution but rather to find the "best" solution. For example, road traffic congestion in a part of a city might be dealt with by increasing the capacity of the existing roads. An alternative could be to introduce an efficient and cheap public transport system. Some social engineering might also be considered, by modifying the starting and finishing times for employees of industries and businesses in the problem region.

At the commencement of an engineering project, the initial state will not be known precisely and the target state is still undefined. In some situations it may be very difficult to identify the required target state and, in a worst case scenario, it will not be possible to know whether the correct engineering decisions have been made until the project has been completed. For example, the planning and design for a new and improved model of an automobile requires a great deal of expensive engineering work, and then manufacture, but the introduction of the new model is, in the end, a risky commercial venture. Its success can only be tested in the market place after the engineering work has been concluded. The open-ended nature of engineering work raises a number of important questions. In particular:

- how do we solve an open-ended problem if there is not going to be a unique, correct solution?
- how can we know if we have found a good solution to an open-ended problem?
- how do we go about identifying alternative solutions to an open-ended problem?

To find answers to such questions we need to look at problem-solving strategies.

3.3 METHODOLOGY FOR SOLVING OPEN-ENDED PROBLEMS

People use a range of problem-solving strategies in their everyday life. One popular procedure is to choose a method (or even a solution) that was successfully used in the past. This approach might work well in relatively simple situations, provided the problems, past and present, are identical, or very similar in nature. Difficulties will arise if there are substantial differences between the present and past problems.

In engineering work, it can be useful to draw on past practice for ideas for solving current problems. However, it is dangerous to rely exclusively on this approach. Adaptation is always needed, because differences inevitably exist between past and present engineering problems, and great care must be exercised to ensure that these differences are allowed for. Furthermore, past practice is not relevant when a problem has new features. Often there is no relevant, reliable past practice to rely on and engineers must then create innovative, new approaches.

Problem-solving strategy

When faced with a problem that is both ill-defined and open-ended, common sense suggests that the first step should be to clarify the problem and re-state it in clear and unambiguous terms, in so far as this is possible. If a range of alternative approaches can be found, after the problem has been clearly formulated, then the initial instinct may well be to choose the most "obvious" one and develop this into a solution. The obvious or instinctively most acceptable solution is likely to be one that has been used previously and that we are therefore familiar with.

On reflection, however, it becomes clear that intuition alone will *not* lead necessarily to the best, or even to a good, solution. Rather than concentrating initially on a particular solution, it is better to take just the opposite approach and look for as many different solutions as possible, that are feasible and promising. To be able to do this, we need to formulate the problem in general (not over-specific) terms so that unusual but promising solutions are not excluded.

Our search for unusual but promising ideas will not be successful if we use convergent thinking and rely on an analytic approach. We need to use divergent, lateral thinking. Creativity is extremely important because we are seeking unusual, non-routine solutions. In Chapter 4 we shall look at the question of creativity and how creative approaches to problem solving can be developed.

If we are successful in creating a range of different and promising solutions to our problem, our next task is to evaluate them, compare and rank them and hence identify the best approach. These simple thoughts lead to a problem-solving strategy which can be applied to poorly formulated, open-ended problems. The steps are listed in Table 3.1.

Table 3.1 Strategy for solving complex, open-ended problems

Step	Action
1	Formulate the problem clearly but in general terms
2	Develop a wide range of promising approaches for solving the problem
3	Evaluate and compare these approaches and hence identify the best one
4	Work out the details of the solution, based on the best approach
5	Implement the solution

Methodology for complex engineering problems

The strategy of Table 3.1 will be appropriate for relatively simple, open-ended problems where it is easy to evaluate and compare the alternative options. This may be the case in simple activity planning tasks. If, however, the problem has many, relatively complex, alternative solutions (and this is typically the case in engineering work) then an enormous amount of effort would have to be expended in the third step. A full set of designs and plans would have to be created for each approach. This would be extremely time consuming, costly and inefficient, because it would mean solving the detailed problem many times, once for each option.

For example, if we consider a harbour city and the problem of choosing the most suitable water crossing for the road traffic, there may be a dozen main options, including bridges of various types at different sites and under-harbour tunnels with alternative routes. Each bridge and tunnel option will be unique. If the problem solving strategy of Table 3.1 were applied unmodified, it would be necessary to carry out detailed designs for each option, in order to make proper and fair comparisons. The design and planning costs in engineering work are always substantial and in this case they would be many times the cost of a single design, and prohibitive. The bill for the planning and design work alone would take up a large portion of the budget.

Planning and design for the Great Pyramid of Giza

Studies of the great pyramid of Khufu (or Cheops) have shown how complex and ingenious the planning, design and construction for this mammoth engineering undertaking must have been. The pyramid, located on the outskirts of present day Cairo in Egypt, was built more than four thousand years ago. It has a 230 m square base and covers an area of 5.3 hectares or 13 acres. Over 140 m high, it is the greatest monumental construction of antiquity. Apart from its special chambers, the pyramid originally consisted of three main components: a massive inner core of stone blocks, a thin surface cladding of white limestone, and an intermediate fill layer between the cladding and core. The surface cladding must have given the construction a spectacular appearance. It has been vandalised over the millennia. The main inner core contains over 2 million large stone blocks of limestone and granite, mostly weighing between 2 and 6 tonnes. These were sourced from various quarries, then sized and shaped before being transported by Nile barges to the site, where they were moved on rollers and raised to the working level (up to 140 m high) before being placed precisely in position. One theory suggests that a temporary inclined helical ramp was built around the partially completed pyramid and used to move the blocks up to the working level. It is estimated that the project was completed in a little more than twenty years by around 20,000 men working in small teams.

Pyramid *design* was complex and ingenious. In earlier pyramids the stone blocks were given a slight inward inclination to improve stability and reduce settlement. The great pyramid was constructed on bedrock which had been cleared, levelled and shaped to give stability and prevent settlement. The blocks were placed in horizontal layers, generally with larger blocks at lower levels and with smaller blocks in the higher layers. Corbelled ceilings with granite beams were used for special rooms, and stress-relieving chambers were introduced above the burial chamber.

The *planning* for the construction must have been of the highest order, comparable with that needed for a modern monumental engineering project. On average it was necessary to transport, deliver, raise and place about 300 blocks per day. With say a twenty-man team to look after each block, an average on-site workforce of above 6000 would have been needed. However, it seems that the main building work took place during the yearly flooding of the Nile, when agricultural work could not be undertaken. The building site must have then been a hive of activity. Even looking after the needs of the workforce would have been a highly complex exercise in planning and logistics.

The planning, design and management skills evident in the construction of the Khufu pyramid had been acquired by experience and trial and error over generations of pyramid building. The name of Imhotep, a vizier, medical doctor and scribe, is associated with pyramid design and construction, in particular the step pyramid of Saqqara. He is perhaps the first engineer to be known by name. The vizier responsible for the great pyramid is thought to have been Hemiunu.

Sources: DTV Atlas (1974); Craig B. Smith (2004)

A modification to the strategy in Table 3.1 is needed. The costs in time and effort in the planning and design phases can be reduced enormously if, instead of fully evaluating every option, we use an incremental approach, and start with simple and rough comparisons of the options. On the basis of quite limited information it will usually be possible to identify and eliminate the less competitive options. This first step is not costly because we are using simple, approximate, order-of-magnitude calculations. A second, rather more detailed, evaluation of the remaining options then allows a further cull to be made. Proceeding step-by-step in this way, with increasingly detailed calculations, we obtain a short list of the most promising approaches. For this strategy to work, we must have a range of models and analysis methods that vary from simple and rough, up to accurate (and presumably complex). We have already discussed modelling and analysis in Chapter 2, where we saw that a range of approaches of varying complexity, and therefore accuracy, can be developed in most engineering fields.

Proceeding step-by-step in this way, we eventually identify a single best option. If not, we will at least have a short list of the most promising options and we can then proceed to a final round of comparisons in which we use the most accurate analyses and calculations.

With this methodology we substantially reduce the total amount of effort. Furthermore, the more detailed calculations are made for the more promising options. The steps in this modified methodology are listed in Table 3.2.

Table 3.2 Methodology for solving complex, open-ended problems

Step	Action
1	Formulate the problem clearly and in general terms
2	Develop a wide range of promising approaches
3	Choose criteria for ranking the alternative approaches
4	Cull the least promising approaches using simplified evaluations
5	Cull progressively, with more detailed evaluations, until a short list remains
6	Choose the best approach from the short list, using detailed evaluations
7	Develop the best approach into a detailed solution
8	Implement the solution

Iteration

It might appear from the discussion so far that we only have to follow the linear sequence of steps in Table 3.2. This is not so. As the design and planning work proceeds, it will often become clear that a modification, improvement or correction is needed in one or more of the steps already completed. In Step 4, for example, when a new and unusual, but promising, approach is being evaluated, it might be found that the original problem statement in Step 1 is unnecessarily restrictive. Rather than staying rigorously with the original problem statement it is best to go back and restate the problem in a more encompassing way, as our aim is to obtain the best solution. Likewise, when alternatives are being compared and ranked in Steps 5 and 6, it might become clear that an improved problem statement will allow improvements to be made to some of the approaches.

Even in the final phase, when the short-listed alternatives are being ranked and ordered, it might be found that some approaches have been unnecessarily penalised or even eliminated because of arbitrary, unnecessarily restrictive criteria. A reformulation of Step 3 would then be justified if it can lead to a better solution to the problem. It might even be possible to modify some approaches in Step 6 to achieve more favourable evaluations and hence a better solution to the problem. Iteration is an essential ingredient in this methodology.

In some situations it may be advantageous to undertake several steps simultaneously. If it is difficult to choose good evaluation criteria in Step 3, before the alternative approaches have been examined, it might be preferable to undertake Steps 3 and 4 simultaneously. A possible complication then to be avoided is unintentional bias in the choice of criteria that favours an intuitively appealing and favoured approach.

We will now see how this methodology is applied to the processes of planning, and then design.

3.4 ENGINEERING PLANNING

A methodology for undertaking engineering planning is shown in Figure 3.1. It follows closely the problem-solving methodology listed in Table 3.2 but typical feedback loops have been added to emphasise the need for iteration.

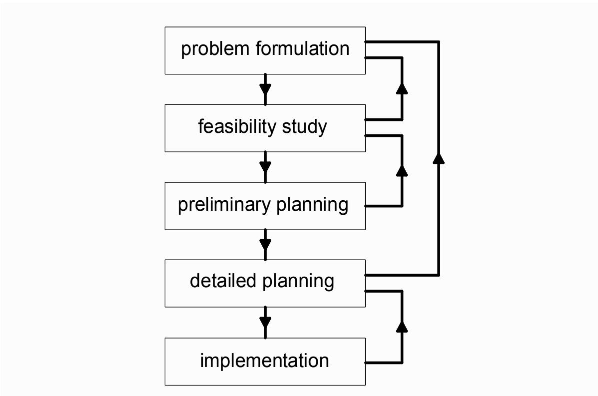

Figure 3.1 The process of engineering planning

There has also been a regrouping of the steps from Table 3.2 into five main phases, in order to conform with common engineering usage. Some new terminology has been introduced. In particular, the step of choosing the evaluation criteria (Step 3 in Table 3.2) has been combined with Step 1 to become the *problem formulation* phase. The *feasibility study* incorporates Steps 2 and 4, while *preliminary planning* consists of Steps 5 and 6. Step 7 has been renamed *detailed planning*.

The overall aim of the initial problem formulation phase is to clarify and, if possible, quantify the problem. This is not as simple as it may at first appear because engineering problems are usually many faceted. For example, *constraints* always apply to an engineering project, and limit in various ways the approaches that can be taken. Engineering projects are always constrained by limits on overall cost, on available time, and on the quantity of materials and human resources that are available. Account needs to be taken of these constraints in the initial problem formulation phase.

The *feasibility study* is the second phase of the process in Figure 3.1. This term emphasises that there might not be a feasible solution. The desired outcome from this step is of course a short list of acceptable approaches, which will demonstrate feasibility. As already mentioned, the intention at this stage is not to focus on a specific approach, but to find as wide a range of different and contrasting feasible alternatives as possible.

The preliminary comparison of alternatives commences during the feasibility study, after the range of options has been identified. This allows us to test out the evaluation criteria and to modify them as necessary. The feasibility study continues until we have a short list of good, feasible options. If no feasible approach can be found, then we must abort, postpone or modify the project. Reasons for not finding a feasible solution might be related to difficulties in satisfying the constraints that are imposed on the solution. For example, costs might be unexpectedly and unacceptably high for all alternatives. Sometimes the technology will not be sufficiently advanced to allow an economical and safe solution to be formulated. If no feasible solution is found, an option is to repeat the feasibility study, but with relaxed constraints and less optimistic goals.

In the third phase of the process, *preliminary planning***,** further rounds of comparisons and evaluations are carried out, in order to identify the best option. The comparisons now require more detailed analysis and evaluation than previously. If one of the alternatives stands out clearly from the others, then the preliminary planning phase can be quickly and easily completed. On the other hand, if the alternatives are closely matched, this phase can become protracted because of the need for increasingly detailed comparisons.

The purpose of the *detailed planning* phase is to take the best option, when it has been identified, and develop it to work out all of the details needed to undertake the implementation. If much analysis and evaluation work has already gone into identifying the best option, then there will be correspondingly less detailed planning work needed. The end result of this phase is a detailed plan for implementation. However, this might still not be the final plan. Problems can arise during implementation that make it necessary to revisit some of the earlier steps. Indeed, the plan will not be finalised until the project is completed. There is an often quoted statement: it is not the plan that is important, it is the planning.

The last phase, *implementation*, may require the construction or manufacture of new components of infrastructure or the implementation of new processes. At first sight, implementation may seem to be a separate part of the project, to be undertaken when the planning and design work has been completed. This is not so. Whatever form the implementation takes, it is almost always necessary to return to and revise some of the earlier planning work.

In later sections of this chapter we will discuss in some detail how to undertake each phase of the planning process. Before doing this, however, we will discuss the phases of the design process.

3.5 THE DESIGN PROCESS

The design process shown below in Figure 3.2 parallels that in Figure 3.1 for planning, although there are some differences in terminology. In particular, the term *concept design* has been used to describe the second phase of the process, when alternative approaches are sought. The emphasis here is on finding alternative concepts, or design options, rather than on investigating feasibility. Despite this difference in wording, the aim of the second phase is the same in both design and planning: to produce a short list of the best feasible options for solving the problem.

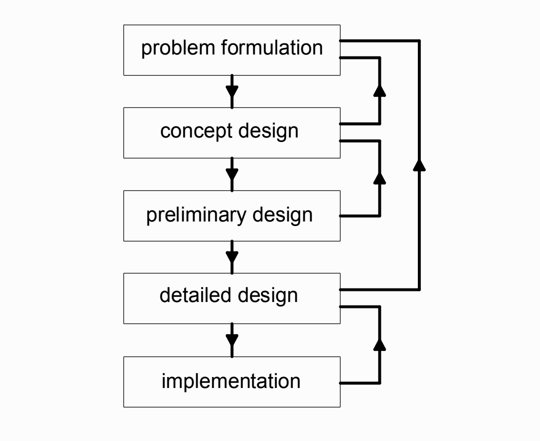

Figure 3.2 The design process

In the structural design of a bridge, the concept design phase is undertaken with the purpose of finding suitable alternative structural forms that provide safe "load paths" for the design loads. The load paths carry the applied loads, such as self-weight, vehicular loads and wind loads, through the different structural components and into the supporting foundations. For a large-span bridge, the alternative structural forms might include an arch, a suspension bridge, a cable-stayed bridge and a multiple span system of beams with intermediate piers.

Initially, the aim is to produce a wide range of alternative, promising concepts, but then to reduce these down to a short list, using the evaluation criteria developed in the problem formulation phase, using simplified calculations and approximate models and analyses.

The most general, far-reaching and financially most important design decisions are made in the initial stages of the concept design, when new, original and unusual approaches are sought. As the design proceeds towards the detailed phase, the design decisions become more and more specific, and they have less impact on overall costs.

In Figure 3.2, the terms *preliminary design* and *detailed design* correspond to their counterparts in Figure 3.1. The purposes of these phases are similar in both planning and design and, as we shall see, they are carried out in the same way. The purpose of the preliminary design phase is to study the short-listed concepts in sufficient detail to allow the best concept to be identified. If it is difficult to choose from several very good concepts, then successive rounds of calculations and comparisons of increasing complexity are needed. These studies may become, in effect, detailed designs. It is not unusual for the preliminary design phase to blend into the detailed design phase, with detailed designs being carried out for several of the very best options.

In the design of a dam for a water supply system that was planned for the Hastings district in New South Wales, Australia, 24 sites were identified in an initial study. During preliminary design this was narrowed to two, before the best was chosen for the final design (Thompson, 2005).

In the detailed design phase, the aim is to take the best approach, now identified, and generate all the information needed to allow full implementation. If one concept has been clearly identified at an early stage as the best, then a fair amount of additional, detailed work will be required in this phase. On the other hand, the effort needed in the detailed design is correspondingly reduced when the chosen concept has already been investigated in some detail.

As previously noted, reconsideration of previous phases of the design may become necessary when implementation is underway. Poor engineering design will almost always be the result if inadequate attention is paid to how the design is to be constructed or manufactured or otherwise implemented.

Although Figure 3.2 adequately represents the engineering design process, some designers prefer to describe the process slightly differently. The term *preliminary design* is sometimes preferred to concept design. It is also not unusual to treat problem formulation as a part of concept design. The design process could then be described as a three-phase sequence consisting of concept (or preliminary) design, detailed design, and implementation.

Irrespective of the way the design process is described, the activities of problem formulation, concept design and preliminary design (in the sense explained above) are the basic steps. We have chosen here to describe design in terms of the five phases of Figure 3.2. There are two reasons for this: firstly, the importance of problem formulation in design is highlighted; secondly, this formulation emphasises the close similarities between the processes of planning and design.

What is not shown in Figure 3.2 is how the need for design work is often first recognised during the project planning process. This is when the need for a new physical system might first be identified. Initially the need is not formulated very clearly or precisely, so that problem formulation remains an important step to be undertaken at the commencement of the design process. The following statement by Richard Seymour, and quoted by Liston (2003), emphasises the crucial role of problem formulation in engineering design:

> *Something which is often forgotten or misunderstood is that the vast majority of the work involved in design is finding out what the problem really is– and it's rarely what you think it is. More often than not the client is asking the wrong question. Once you've found out what the problem really is, then things virtually design themselves because you've so comprehensively understood the problem that the solution is self-evident.*

3.6 COMMUNITY INPUT

Large engineering projects are designed to improve the physical infrastructure, and the community as a whole are beneficiaries. Nevertheless, a minority of people can be seriously disadvantaged by even the most successful projects. For example, when upgrades are made to access roads into a city, land acquisition can disrupt the lives of people who live and work in the affected areas. In such circumstances, financial compensation can become an important part of the process.

People have the right to know about proposed new developments that will impact on their lives, and they also have the right to express opinions and concerns about such developments, and indeed to take part in the decision making processes. In many countries, freedom of information laws ensure that information is available to the community on proposed new engineering projects. When large-scale engineering work is to be undertaken, the sectors of the community that are likely to be affected need to be advised and brought into the process, not only through written information but also via public meetings and consultations. The views of individuals and groups in the community need to be known during the initial planning phases of the project and also as work progresses.

Differing views are normal in any group of people. Alternative and opposing views can arise in regard to an engineering project, and will usually be accomodated in the community consultation process. A compromise view is often reached which is acceptable to, if not welcomed by, all participants. Unfortunately, this is not always the case. Occasionally, opposing or competing community views of a proposed engineering project can become entrenched, that seem not to be resolvable. The term *intractable* has been applied to such situations, and the associated problems have been referred to as *wicked*. These are rare, but do occur, and are discussed in some detail in Section 3.14 below.

3.7 PROBLEM FORMULATION PHASE IN PLANNING AND DESIGN

Table 3.3 below contains a checklist of actions that can assist in the problem-formulation phase of engineering planning and design. The terminology used comes from Chapters 1 and 2. Some of the actions are information-gathering activities while others are aimed at formulating and, to the extent possible at this stage, quantifying the problem. Consultation with the community and its representatives will often be required. Although intended specifically for planning and design, these actions can be useful in problem solving generally. We now discuss them in turn.

Identifying the problem as part of a wider problem

As we have already seen, an engineering project can begin as a response to perceived needs in the community, and the objectives may be initially poorly defined. The problem as stated may be too vague; alternatively, the problem may be stated in over-precise terms which imply an “obvious” solution. In the latter case, the implied solution will rarely be the only possible one, and may not be the best one. It is therefore important to begin the problem formulation phase by trying to identify the problem as part of a wider or larger problem.

Table 3.3 Checklist of actions for the problem formulation phase

Action
Identify the problem as part of a larger or wider problem
Identify the relevant engineering system as part of a wider or larger system
Identify the components of any relevant system
Find interest boundaries for the problem
Determine the real underlying needs that are to be addressed
Gather relevant background information
Search for possible side-effects
Identify constraints
Specify objectives and identify possible conflicts among objectives
Specify design criteria, performance requirements and operating condition, as appropriate for each new system
Devise measures of effectiveness

By way of example, we return to the problem of providing traffic access between two parts of a city separated by a waterway. Suppose that the cross traffic is already catered for by several bridges which cannot handle the increased traffic volumes. The "obvious" problem might be seen as providing an additional bridge to cater for present and future traffic. Is this a statement of the problem, or is it statement of a solution to a problem? A broader problem statement would be: how to improve the cross-harbour traffic flow. An advantage of this statement is that it widens the range of possible solutions. It is now possible to consider a tunnel, a range of small peripheral bridges, various forms of water transport, or even air traffic as alternatives. This example was used by Noel Svensson in his book on engineering design in 1974.

In fact, the city of Sydney has been faced with a traffic problem of this nature for many years. In the 1950s there was a single bridge to carry traffic across the harbour between the northern and southern suburbs. A second bridge was constructed on the periphery of the harbour at Gladesville, but traffic volumes continued to grow and traffic congestion became worse. There were community calls for another large harbour bridge. The next step was in fact to construct a tunnel to address the cross-harbour traffic problems in the medium term. The tunnel, integrated into the arterial roads of the city, was initially successful. However, as the city continues to grow so too do the problems of traffic congestion. New solutions are needed.

It is useful to further widen our example. Is the real problem simply one of regularly increasing the traffic capacity on all the main routes in response to growing volumes? A broader problem statement might be to reduce or eliminate the current and future traffic congestion. This statement allows more varied approaches to be considered. It allows, for example, a reduction in peak traffic by staggering starting and finishing times for various industries, and the use of flexitime in offices. It also encompasses initiatives such as imposing surcharges on traffic that uses critical facilities at peak times, and encouraging the increased use of public transport. A form of congestion tax has been introduced in cities such as Singapore and London to limit the number of vehicles entering the inner city area.

Broadening the problem statement does not disallow the initial “obvious” solution. On the contrary, it opens up the problem to a range of alternative, competing solutions and so tests the adequacy of the “obvious” solution.

Identifying each engineering system as a component of a wider system

To assist in identifying the problem as part of a wider problem, it can be useful to identify the relevant engineering system as a component of a larger or wider system. In the above example the broader problem statements have focused on the transport system, of which a bridge is just one possible component.

It can be useful to take the problem-broadening technique further. In the above example, is the problem purely one of achieving an efficient city transport system? The costs involved in providing roads, tunnels and bridges to improve the traffic network of a large and sprawling city run into many billions of dollars. When such expensive traffic options are considered, other radically different possibilities deserve consideration. It might be possible to achieve a more workable city by reducing the need for cross-harbour traffic. Here we are extending our discussion beyond traffic engineering and into the realm of town planning. We can go further: is it the best use of resources to improve road transport in an already congested city? Even if the road transport system were to be improved, the result is likely to be more city growth, followed by further congestion and yet more calls for improvements to the again-inadequate transport system. An alternative and better use of the resources might be to introduce decentralisation schemes and encourage the relocation of industry and population away from the city, into regional growth areas. We have now moved on from town planning questions to a consideration of regional planning and various associated political issues.

Identifying interest boundaries for the problem

How far should the process of problem broadening be taken? Clearly we could extend the bridge argument further, beyond regional planning and into areas of national or even international planning. At some stage the problem broadening argument breaks down. How do we recognise this stage? The questions cease to be relevant when they are so broad that new issues will barely influence the problem statement. This occurs when the expanded system is so large that the original problem (in this case, the need for a bridge, or some alternative) ceases to be relevant. When this happens, we have clearly gone too far.

The limit, where the problem has been widened to the extent that the original problem is of marginal relevance, is referred to as the *interest boundary* for the problem. The relevant solution options will be found within this boundary. In Figure 3.3 the interest boundary is shown for the bridge example previously discussed. In this case the very large costs indicate that the interest boundary should certainly include the city system and perhaps extend to the surrounding region or even state.

The construction of a large bridge in a small country can become an international issue. An example was the K-B Bridge in Palau, a small island nation in the Western Pacific, somewhat less than a thousand kilometres west of the Philippines. The bridge was constructed in the 1970s with aid money from the

United States when Palau was its protectorate. At the time, the bridge was the largest prestressed concrete box-girder cantilever arch construction in the world, linking the two main islands of Korror and Babeldaob. It served a crucial purpose for the whole population of Palau because essential services, including the airport and power generation equipment, were located on one island while most of the population lived on the other. The bridge collapsed suddenly and apparently without warning in July 1996, shortly after it had undergone extensive refurbishment. Life in Palau was severely disrupted, even though a ferry connection was established between the islands. The construction of a new bridge was clearly beyond the resources of Palau and had to wait until it could be undertaken with international aid. The interest boundary in this case extended well beyond national boundaries.

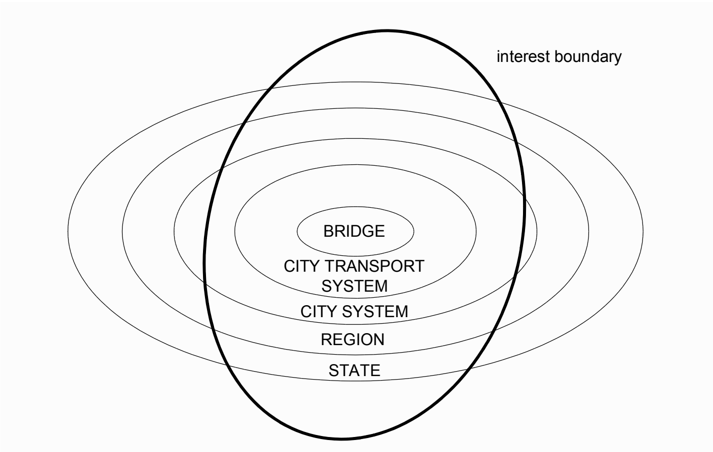

Figure 3.3 Problem-widening: interest boundary for a bridge.

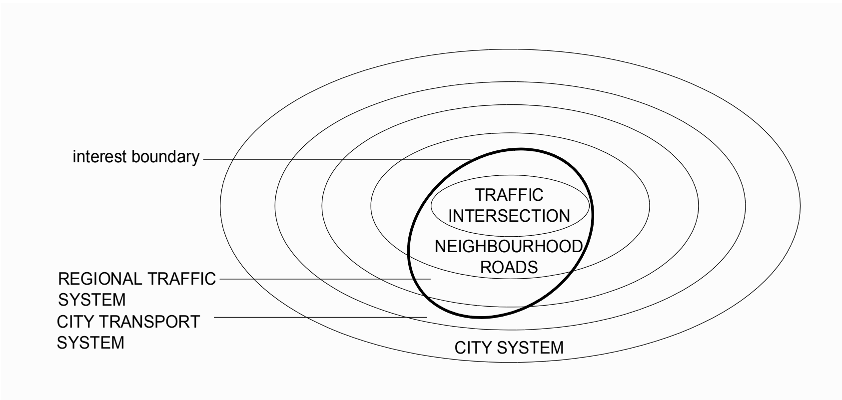

Figure 3.4 Problem-widening: interest boundary for a traffic intersection.

As another example of an interest boundary, we noe choose a relatively small one, but again in the field of traffic engineering. We consider the redesign of a hazardous traffic intersection in a suburban area.

The traffic intersection may initially be seen as a part of the local traffic system, consisting of the intersection and the immediately adjoining streets. This can in turn be regarded as part of the traffic system in one region of the city. The interest boundary is indicated in Figure 3.4. In this case the costs of the proposed project are a small proportion of the annual road transport budget. Conditions at the traffic intersection are of only marginal relevance in relation to the efficient flow of traffic through other regions of the city.

In summary, the problem-broadening process should be halted when a further widening of the boundary has only a marginal impact on the original problem statement. The interest boundary can be identified in this way.

Determining the real underlying needs as distinct from the stated needs

The real needs that initiate an engineering project are not always those that are initially perceived. The process of problem widening and the identification of the engineering system as a component in a wider system usually lead to a better understanding of the real needs. In the bridge example, the need is not for a bridge *per se*, but for a reduction in traffic congestion, or, possibly, a more efficiently functioning city. When the needs are properly identified the problem can be formulated in a more general and much more useful way.

In situations where the size and scope and influence of a project are limited, it may be much easier to identify the relevant underlying needs. As an example, consider the construction of a swimming pool as part of a house design for a private client. Before the design work is undertaken the real needs of the client have to be clarified. The pool may be needed for swimming training, for diving, for exercise, or for social entertaining and relaxation. It might be required mainly for prestige reasons, or for a combination of reasons. In each case a different design could be appropriate. The problem statement should be formulated through sensitive discussions with the client.

The attempt to identify underlying needs sometimes moves attention away from purely technical problems towards social issues and political problems, especially when the proposed work is large in magnitude and costly. This is almost inevitable if large sums of public money are to be spent. As the problem-widening and system-widening processes are undertaken, the questions acquire an increasingly political and social flavour and require community input.

Gathering relevant background information

When work commences on a new project there is usually a lack of relevant background information. This has to be gathered as early as possible, and before the problem formulation phase is completed. The required information may be scientific and technological, but it may also be non-technical and sociological, legal or political in nature. The data-gathering exercise may require consultation with the community, the use of libraries, the internet, textbooks, and databases. Sometimes it will be necessary to gather field data and conduct laboratory tests, as for example when the properties of a foundation material have to be determined.

The type of information needed in engineering work is unlimited. When international one-day cricket matches were initially planned in Australia, a lack of suitable turf wickets was an important problem and the design of replaceable, transportable turf wickets was investigated. In this case the necessary background information included the way the game of cricket is played as well as the laws that govern the game. Detailed horticultural information was needed on the appropriate types of grass for preparing turf wickets, how to grow the grass, and the depth of soil needed, not only to allow the grass to grow but also to provide the right "bounce". Other information was needed on how to achieve the best type of drainage and compaction, and the required wearing properties of the turf. The structural engineering questions, relating to creating a rigid, transportable structural tray to support the pitch, seem relatively uncomplicated. In unusual projects, engineers will rarely have adequate knowledge or training in the relevant specialist fields. It is necessary to gather information rapidly and may require working in association with consultants and other professionals with specialised knowledge.

As a further example, consider the relocation of arterial roads in a suburban area. There is an obvious need for technical information concerning the soil properties along the proposed routes as well as the present and expected future traffic volumes. To obtain this information programs of soil testing and traffic counting might be undertaken. Other relevant background information of a quite different nature relates to the social structure of the community through which the roads are to pass, for example the location of the roads in relation to natural community boundaries, including the catchment areas for local schools. The political implications of such a project, measured in terms of votes gained and lost, may also turn out to be important background information, influencing any political decisions on whether or not the project proceeds.

Searching for side effects

Each engineering project is designed to bring about some change in the world in which we live. Although the intention is to improve the infrastructure and thereby satisfy some community and individual needs, it is inevitable that there will be side effects. These may be obvious and desirable, but also hidden and undesirable. They may only become evident after a considerable period of time, when the project has been completed and is in operation. In the case of a large-scale project there will usually be a wide range of side effects, some beneficial and some detrimental.

The identification of side effects should begin as early as possible during problem formulation but should continue into the evaluation stages because some side effects will depend on the chosen solution. It is clearly important that the relevant side effects be identified and allowed for when the costs and effectiveness of each alternative approach is evaluated.

Some disturbance of the environment may be inevitable when a large infrastructure project is undertaken, and environmental side effects can become a focus of community attention. If a road or freeway is constructed, either in an urban or rural development, some modification of the surroundings is involved, such as the demolition of existing older buildings. It may involve cutting into a hillside or filling in part of a valley floor in the countryside. Even when a large-span bridge is constructed across a valley to lessen the physical effects on the environment of the roadway, there is a visual impact. Of course the impact may be pleasing to many, but a serious problem to others.

A side effect of improved car security

In a report in the Australian Newspaper of 5th June, 2006, a rise in the number of "car jackings" was attributed by police to improved "immobilisation technology". The new technology had made the theft of unattended late model vehicles almost impossible. According to the newspaper report, thieves had therefore taken to "holding up drivers across Sydney's wealthy suburbs".

In 2011, work commenced on a high road bridge to cross the valley of the Mosel river in Germany. The main purpose of the bridge was to improve links between the city of Frankfurt and Dutch and Belgian harbours. However, as reported by Asimov (2010), the project became controversial, and serious opposition developed, when adverse side effects on the wine industry and tourism in the region were identified.

Technical side effects may be advantageous or disadvantageous for a project. The provision of lift wells and associated walls in a multi-storey building design improve the resistance of the building to lateral loads. Non-technical side effects can become significant, such as increased or decreased job opportunities, which may be temporary or long lasting. The influence on the tourist industry of the construction of a monumental, iconic building, or the development of water sports and recreation facilities following the construction of a dam, are examples of non-technical side effects which may have an effect on the outcome of a project. They need to be identified and spelt out in the problem formulation phase.

Identifying constraints

It is important in the problem formulation phase to identify the constraints that apply to the problem. Constraints restrict the possible solutions to a problem, and arise in various ways. They may be technical, legal, economic, social, environmental or political in nature. Monetary cost is a constraint that applies in one way or another to every engineering project. Constraints arise if certain side effects are unacceptable or undesirable, such as excessive atmospheric pollution. Technological limitations create other constraints.

Legal constraints apply, for example, to building construction. They limit the maximum footprint size of a building on a city building site and also the maximum building height. Other examples of legal constraints are the emission control requirements for automobile engines and the minimum requirements for fire protection and toilet facilities in buildings that house people.

Legally enforceable industry standards are often the means by which constraints arise in engineering design. Limits for noise control and thermal insulation thus apply in the design and construction of apartment buildings. Design constraints may be introduced for the different components that make up a system so that they fit together and work in harmony with each other. Constraints can sometimes be quantified as physical limits or as minimum performance requirements which must be achieved.

Identifying Constraints: Power supply for Waterfall Gully

As already noted in the main text, much of South Australia's power is carried on the distinctive steel and concrete Stobie poles. However, there are situations where these cannot be used. In the late 1970s the increasing demands for electricity in Adelaide's eastern suburbs led the state electricity body, the Electricity Trust of South Australia (ETSA), to investigate the provision of additional capacity to suburbs adjoining the Adelaide Hills. This required 66kV power lines to traverse difficult terrain over a number of hills.

Various constraints were identified in relation to the location and nature of the proposed work, such as:

Cost and visual appeal: although underground power lines would have been preferable from a visual point of view, the cost of this solution had recently increased significantly and essentially ruled out underground lines as an option.
Legal: planning approval was required from the Department of Environment and Planning and this led to further constraints on what could be installed.
Environmental: the Department of Environment and Planning imposed constraints in terms of visual amenity and the physical environment, including limiting the scope of roads that might be used to access the area.
Social: although the residents of nearby councils were the beneficiaries of the new power supply, they exerted significant social and political pressure on the planners in an effort to maintain their views and the natural characteristics of the area.
Technical: without the ability to drive roads and tracks through the area a solution had to be developed using available technology. The solution was built around the use of a helicopter. This had technical constraints associated with it, because there was a limit to the load that could be lifted, in this case a spare carrying capacity of less than 140kg.

The constraints that were imposed left few viable options. The one that was chosen was to build and partially assemble three steel structures. The components were to be brought to the site by helicopter and bolted together while secured by guy ropes.

Difficulties encountered in assembling the pylons, coupled with other issues, led to the deaths of four workmen who were on one of the structures when it suddenly fell to the ground during an operation designed at securing it in alignment. Three died instantly and the fourth was pronounced dead on arrival at the Royal Adelaide Hospital.

Source: Grabosky (1989)

The unavailability of certain resources can lead to other constraints. For example, telephone poles were commonly made of wooden tree stems in most parts of Australia in the mid-20th century. However, the lack of trees in country South Australia severely constrained the use of timber and led to the early and widespread use of a steel-concrete composite pole, called a Stobie pole after its designer. Stobie poles have been a distinguishing feature of the South Australian landscape for many decades.

Another important constraint is time. Completion deadlines are crucial constraints in the construction of sporting complexes and facilities to be used every four years for the Olympic Games. The timelines for construction are determined by the set dates of the games and have to be met, in one way or another.

Physical constraints apply to some engineering problems. In the early stages of the design of the Gateway Bridge in Brisbane, Australia, a minimum clear height above water level at mid span was required in order to allow shipping to pass under the bridge. On the other hand, a maximum overall height limit was imposed to give air clearance for flight paths to the nearby airport. The initial constraints on minimum and maximum heights clashed for this bridge and no solution was possible until the constraints were examined more closely and relaxed.

In the case of large engineering projects with overt government support, it is not unusual to find that political considerations lead to explicit or implicit constraints on the engineering work. Local sourcing of materials and the creation of employment are frequently negotiated before any engineering work is undertaken and become constraints on the engineering work. Such constraints have to be identified early in the problem clarification phase of the project.

Defining objectives and identifying conflicts among objectives

It is important to have a clear and unambiguous statement of the goals and objectives of any engineering project. This is, in effect, a statement of the problem, and of what is to be achieved. While it is important to clarify the initial problem statement, it can be advantageous not to finalise it until at least some of the background information has been collected. In particular the process of identifying relevant systems as components of larger systems and identifying the problem as part of a larger problem can assist in identifying the objectives.

Furthermore, engineering projects usually do not have just one, but rather a number of different objectives, and some objectives are very likely to conflict with others. The twin requirements of maximum performance and minimum cost are always going to be in conflict. It is always necessary to identify potential conflicts among the objectives.

For example, a dam can usually be used both to store water for supplying to a township or region and to assist in reducing down-stream flooding. Some dams are also designed for electricity generation. For effective storage, the dam should be kept nearly full, whereas for flood prevention it needs to be nearly empty and able to accept runoff after heavy rain. The operating policy for the dam has to recognise and allow for the implied conflicts.

Potential conflicts among objectives must be explicitly recognised. The question of how to deal with conflicting objectives will be discussed in some detail in Chapter 9.

Specifying design criteria, performance requirements and operating conditions

The goals and objectives of a project are expanded, clarified and quantified through the use of design criteria. Performance requirements and operating conditions are used jointly to specify how the system that is to be created must perform. These are used both in the detailed phases of planning and design, and in the preliminary phases to evaluate and rank alternative approaches and concepts.

In the creation of a physical system or device it is necessary to determine both the conditions under which it will operate and the level of performance that will be required. For example, if a pipeline is to be used to move natural gas from a production field to a consumption site, the performance requirements for the system will include the maximum and average quantities of gas that will be transported in a time period, as well as the minimum life of the operation. Such information is also needed for the planning and design of other components of the overall system, such as storage tanks and pumps.

The operating conditions of interest in the pipeline might include the variation in ambient temperatures throughout the year, the magnitudes of possible seismic action, and the chemical properties of the gas in relation to its effect on the pipe material.

Clear and unambiguous statements of goals, objectives, design criteria and performance requirements are particularly important should the completed project or system not reach expectations, with resulting legal dispute.

Safety and reliability are further performance requirements which require very careful consideration. They are discussed briefly in Section 3.13 following, and in more detail in Chapter 11.

Devising measures of effectiveness

The goals and objectives of a project are expanded, clarified and quantified through the measures of effectiveness, which are used in the feasibility study phase of project planning and in the preliminary and the detailed design phases. When a project has more than one objective, one or more measures of effectiveness are needed for each specific objective, and ideally with an overall measure that takes account of the different objectives.

Total cost is often appropriate as the overall measure of effectiveness. This is the case if the various objectives can be stated in terms of equivalent cost. Overall cost is also appropriate if the various objectives can be reformulated as minimum performance requirements, or as constraints that have to be satisfied. Not all situations lend themselves to monetary evaluation. For example, the measures of effectiveness might need to take account of matters such as aesthetics, environmental effects, risk of injury and loss of life.

Even when cost is used as the measure of effectiveness, conditions can become complex if carefully analysed. In the replacement of the superstructure of a bridge, total initial cost might at first appear to be entirely appropriate, so that it would be a simple matter to choose, say, from construction based on steel trusses, steel plate girders, in-situ reinforced concrete girders and precast, prestressed concrete girders. Purely in terms of cost of construction the plate web girder solution may be a clear winner. However, when maintenance costs are taken into account for the expected lifetime of the bridge, which may be between 50 and 100 years, the reinforced concrete girder solution may take precedence. But other factors might also influence the decision, such as the need for minimum disruption to traffic during construction. The problem is now to establish a time-cost trade-off. This might lead to the choice of a prefabricated truss system. Yet again, if appearance is important, as well as cost and time needed for construction, an extremely difficult trade-off has to be made between monetary value and appearance. The precast, prestressed concrete solution may now be competitive.

The manner in which the measures of effectiveness are formulated can be enormously influential in determining the direction that a project will take. In some circumstances an engineering project might be undertaken without the explicit use of a measure of effectiveness. For example, a design engineer might choose a design approach subjectively without a study of alternatives and a measure of effectiveness. If the project is small, the argument could be that an exhaustive problem formulation study would only add to the cost of the project. There are inherent dangers in such an approach, and they should be evident from the discussions to date. One possibility is that the wrong problem is solved. Errors of judgement easily occur if there is no measure of effectiveness. Even an attempt to define a measure of effectiveness can provide a fresh starting point, because it gives new insight into the project.

Iterating

The various activities listed in Table 3.3 all occur within the problem formulation phase; nevertheless, they may need to be undertaken iteratively. The type of background information that is required becomes progressively clearer after some attempt has been made to identify side effects and constraints and possible approaches. Likewise, some of the constraints and side effects are more easily recognised after some background information has been gathered. It will also be necessary to return to the problem formulation phase as we proceed through the later phases of planning and design.

3.8 FEASIBILITY STUDY AND CONCEPT DESIGN

The purpose of the feasibility study in planning is to show that the project can be carried out successfully. When a short list of promising alternative approaches has been identified, any one could form the basis of a solution. Likewise, the aim of the concept design phase is to establish a short list of promising concepts, each of which may result in a successful engineering design.

It is emphasised that it is best to begin with a wide a range of alternatives. We have seen how each option can be investigated superficially in order to cull non-feasible and non-competitive candidates. A further study, with a somewhat more detailed analysis of each option, leads to a further culling. The culling continues, using additional information, until there is a short list of feasible, promising options. A list of steps that can be useful in the feasibility study and in concept design is shown in Table 3.4. The steps are discussed below.

Table 3.4 Checklist of actions for feasibility study

Action
Check available resources
Investigate and quantify the constraints
Develop as many promising concepts as possible
Compare alternative concepts using the measures of effectiveness
Progressively eliminate non-competitive approaches
Modify the problem formulation as necessary
Modify the measures of effectiveness as necessary
Scrap or defer the project if no feasible approaches can be found
Identify the most promising concept

Checking available resources

Resources are used up in the course of an engineering project and an initial check is needed to ensure that sufficient resources will in fact be available. Resource availability (or non-availability) can determine the viability of particular options, so that this check should be undertaken with all alternative concepts and approaches in mind.

It is necessary to consider human, financial and technical resources, as well as any special materials and machinery that will be needed during implementation. Engineering expertise and scientific knowledge are resources, as are relevant trade and craft skills. Specialised design and analysis skills may be required. Time is a resource because engineering work always has to be completed within a limited time frame.

Investigating and quantifying the constraints

The technical and other constraints that have been identified in the problem formulation phase have to be investigated and, if possible, quantified. Some constraints are legal-technical, and are quantified in codes and standards and in legislation. In the design of a large city building, constraints on overall height, minimum services for water, sewerage, fire protection, thermal and acoustic insulation and even vertical transport, are imposed through the relevant ordinances and building acts.

Developing as many promising concepts as possible

This is the key step in the entire processes of engineering planning, design and problem solving. The success of any design or planning work depends on the range, quality and appropriateness of the approaches and options that are generated. As already emphasised, diversity in the alternatives is important. Innovative and creative new approaches, as well as traditional and proven ones, should be included in the initial list of alternatives. It is by no means clear whether an innovative new approach or a well-tried standard approach will eventually prove to be best. Both types need to be investigated.

The technique of problem-widening, described previously, should prevent an overly specific problem statement that would otherwise stifle new and unusual approaches. Creativity is central to this activity and is discussed further in Chapter 4, together with techniques that may prove helpful in the search for new and different options.

Comparing alternative concepts and progressively eliminating non-competitive approaches

The preliminary comparison of the options, made using simple calculations and preliminary information, will allow the poorer options to be culled. In the design of a highway bridge to cross a river, rough order-of-magnitude design calculations are sufficient to provide very approximate sizes for the main structural components of alternative systems. This allows preliminary costs to be estimated and for checks that the constraints and operating conditions are met. Information on costing is provided in Chapter 8.

In further rounds of comparisons, the increased accuracy of the analysis and design calculations lead to more refined comparisons and further culls.

Modifying the problem formulation as necessary

The need for an iterative approach throughout the problem solving process has been emphasised. Modification of the original problem statement may be needed during the feasibility study. As work proceeds and new and unusual approaches are considered and investigated, the understanding of the problem is inevitably improved, so that a better formulation of the problem may be possible. New and unexpected approaches can challenge the validity of the original problem statement, particularly in regard to the measures of effectiveness that are used to compare and evaluate the alternatives.

Scrapping or deferring the project if no feasible approaches can be found

If none of the options are feasible, perhaps because they do not satisfy constraints relating to time, cost or resources, then the project cannot proceed. It might be best to cancel the project, or to defer it until technical knowledge has improved to the level needed, or until additional resources become available. Another possibility is to look for new, innovative approaches that will make the project feasible. Yet another possibility is to reformulate the problem with different, more modest goals and less severe constraints.

3.9 PRELIMINARY PLANNING AND DESIGN

The purpose in this phase is to bring the search for the best option to a positive conclusion and to identify the approach that will lead to the best solution of the problem. Each short-listed option is investigated in turn and in sufficient detail to allow comparisons and rankings to be made, using the measures of effectiveness.

Even at this stage, very accurate comparisons are avoided if at all possible because of the cost implications. On the other hand, if alternatives are eliminated on insufficient grounds, the most appropriate alternative might also be incorrectly eliminated. The step-by-step approach therefore continues until all but one of the alternatives are eliminated.

Although attention is focused on the original options that emerged from the feasibility study, the search for new and better alternatives should not be discontinued. Modifications to existing approaches should be made in the later stages of the process if improvements are achieved. As work proceeds, there can be a build up in expertise which can lead, even at this stage, to further improvements and changes to the original problem statement and to the measures of effectiveness, as well as to new or modified design or planning concepts.

3.10 DETAILED PLANNING AND DESIGN

The aim now is to work out the details of the solution that are needed for full implementation. For example, at the end of the preliminary design of a reinforced concrete bridge the form of construction and the approximate overall dimensions of the component members will have been chosen. It is now necessary to fix the details, including final member sizes, the amount, type and location of the reinforcement in each member, non-structural fitments, concrete strength, concrete finishes, special road surfaces, handrails, bearing pads to support any main girders, and storm water pipes, so that full construction plans and specifications can be prepared.

Accurate calculations are needed in the detailed phase. But even here, iteration may become necessary, for example to develop alternative trial details for some components. If adjustments are made to the design details, with the aim of improving performance or decreasing cost, a new analysis might be needed to check whether the improvements have in fact been achieved. Such iterations continue until an effective and economical design or plan has been achieved, that meets all the requirements.

It is in the detailed phase of planning and design that optimisation techniques may be employed. If the behaviour of a component lends itself to theoretical modelling, it should be possible to improve the design by mathematically optimising the parameters that define or characterise the component. The process of optimisation is discussed in some detail in Chapter 13, together with various mathematical optimisation techniques.

At all stages of the detailed design, checks are made that the design constraints are not violated. In some situations overly severe constraints may add disproportionately to the cost or detract from the effectiveness of a solution. Even during the detailed planning and design phase it may be advisable to modify decisions made previously in the problem formulation phase.

In the detailed design of the components of a system, the primary focus should be on the overall operation and cost of the parent system. If the design of a component has a disproportionate effect on overall cost and effectiveness, then modifications may be possible for this component and for the interacting components, so that an improved overall design is achieved. If components are to be manufactured in quantity it may be desirable, depending on the nature and expected cost of the component and the number to be produced, to construct prototypes and test and modify them as an adjunct, or alternative, to the theoretical analyses.

The important final step in the detailed design and planning phase is full documentation, with a permanent record of relevant calculations and analyses and any other investigations that have been used to produce the final plan or design.

3.11 IMPLEMENTATION

Implementation of a plan, a design or a solution to an engineering problem can take many forms, depending on the context of the work. Special engineering fields with their own undergraduate programs and text books are devoted to the different types of implementation, such as construction engineering and manufacturing engineering.

Poor engineering design occurs when inadequate consideration is given to how the design is to be implemented. Constructability is an important criterion that is too often forgotten in the structural design of buildings. An undue focus on optimum design can lead to an elegant design with a minimum use of materials, but exorbitant construction costs.

We have specifically mentioned (if only briefly) the implementation phase here as a reminder of its importance in the overall scheme of planning and design.

3.12 THE SOLUTION-FIRST STRATEGY

The sequence of steps shown in Figures 3.1 and 3.2 follows from the methodology for solving open-ended problems. The necessity of iteration, and the advantages of sometimes undertaking several steps simultaneously, have been mentioned.

In some situations a rearrangement of the sequence shown in Figure 3.1 or 3.2 may be advantageous. It can be argued, for example, that choosing the evaluation criteria *before* the range of alternative approaches has been identified can prove to be an overly analytic approach. An alternative is to choose the evaluation criteria after some or all of the options have been identified. This may sometimes be a better alternative, although it may also introduce an unintentional bias in the criteria that favours some approaches over others. A better alternative might be to undertake these activities simultaneously. Various rearrangements of the sequence are possible and desirable in special circumstances.

To emphasise the fact that alternative sequences may be appropriate in some circumstances, we now discuss briefly a solution-first strategy. This stands in sharp contrast to the sequence in Figures 3.1 and 3.2. Numerous examples can be found in the history of engineering where an important project has *not* commenced with the identification of a problem but, on the contrary, has started with a potential solution. The task is then to search for an appropriate problem. A good technical idea may arise from some technical or scientific development, or by bringing new, potentially useful knowledge from another field of engineering.

Post-it Notes® (the adhesive that wouldn't stick)

The development of the Post-it note pads is a good example of the application of the solution-first strategy. In 1968 a 3M scientist, Dr Spence Silver, discovered a new type of adhesive, one that was quite different from anything currently available but whose properties defied conventional use. Dr Silver tried for five years to generate some interest in the new product, but because it was apparently inferior to existing adhesives he was unsuccessful.

Eventually a company researcher, Art Fry, took notice of the adhesive and its properties and started using it as a bookmark. The advantage here was that it was sticky enough not to fall out, but not so sticky that it left a residue on the page. By using the adhesive in this way it was soon noticed by others around the 3M Company and the idea of a lightly adhesive note pad soon developed.

The Post-it® note was introduced commercially in 1980 and named outstanding new product by 3M in 1981.

Source: 3M (2006)

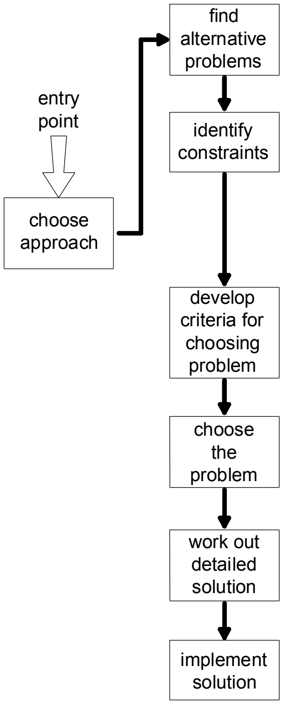

Figure 3.5 Solution-first approach to problem solving.

Ideas may arise concerning applications of new materials with unusual and useful properties that have been developed in non-engineering fields. Such scenarios lead to the search for possible applications of new ideas.

The solution-first approach shown in Figure 3.5 applies to such situations. A specific solution is the starting point to the procedure, which is a rearrangement of Figure 3.2, the steps being similar to those already discussed. This again emphasises the important point that engineering problem solving is an iterative activity. The entry point to the process is not of prime importance.

In a similar vein, Rogers (1983) has argued that answers often precede questions. He has suggested that while organisations face many problems, they typically possess only limited knowledge of a few innovations that can offer solutions. The chance of identifying an innovation to cope with a specific problem is therefore small. However, by commencing with an innovative solution there is a good chance that it can be matched to some problem facing the organisation. According to Rogers, a strategy for organisations is thus to scan for innovations and to try to line up a promising innovation with relevant problems.

3.13 OTHER ASPECTS OF PLANNING AND DESIGN

Risk, safety and failure

Once the goals and objectives of an engineering project have been established, the expectation is that they will in fact be achieved. However, engineering work inevitably involves some uncertainty and risk, and the possibility always exists that a system or a component will not perform as expected, or indeed that the entire project will not fulfil all of its objectives. When any engineering work is undertaken there is a risk of failure that, although small, is real and unavoidable. However, the levels of risk are controllable to some extent, and can be reduced to very small values that are acceptable to the community.

It is important to note that the term “failure” can mean different things to different people, and within the context of engineering work, it can be used with different meanings in different contexts. By way of example, consider the design and construction of levee banks as part of a flood mitigation scheme in a river valley. For the general public, and especially for people living in the valley, the word failure would be used in the event that the floodwaters overtop the levee banks and flow onto the adjacent land. In this sense, the word failure refers to a temporary condition, from which the system can recover. Indeed, the designers would have considered the risk of the flood event and the levee banks would have been constructed to resist the physical forces that occur during flooding, so that they will remain viable after the flood waters have receded.

However, in the design of the levee banks the engineers face several problems. Firstly, the maximum rainfall event that will occur over the design life of the project is unknown, and no upper bound can be placed on it. A second problem facing the designers is that the financial and physical resources available for the project will be limited. It is not therefore feasible to create a system that will contain all flood levels, irrespective of the intensity of the rainfall. Given these limitations, the task of the design engineer is not to create a system that will never “fail” in the sense that the floodwaters will overtop the banks, but rather to create a system that will successfully accommodate large rainfall events “most of the time”. The realistic design aim is therefore for the levee banks to prevent flooding, except for the extremely large rainfall events that will occur about once in every thirty years (or perhaps fifty years or even a hundred years, depending on the resources available and the resulting damage from overtopping). In one sense the system fails whenever the banks are overtopped, as we have seen, but from the design engineer's point of view the levee banks will be a success provided they reduce the frequency of flooding to an acceptably low frequency, of about once in every thirty (or so) years. For the designer, failure occurs if the levees are overtopped more frequently than once in thirty years on the average. In this example, the term "failure" has two quite different meanings, both of which are legitimate.

From the designer's point of view, a practical and useful engineering approach is to say that failure occurs if the performance of the system does not meet the performance levels that were set for it. These performance levels are carefully chosen during the design process when the minimum performance requirements, the design criteria and the effectiveness measures are identified. Nevertheless, in the previous example the system must be designed so that it can recover from flooding. We could also say that the system suffers a temporary failure during each flooding. In this text, and especially in Chapter 11 (which deals with risk and reliability), both meanings of the word failure will be used, but the meaning will be made clear from the context.

In regard to an engineering project, we can say that failure occurs if the aims and objectives of the project are not substantially achieved. Another quite different kind of engineering failure can occur if unintended, unpredicted and unacceptable side effects arise from the engineering work. Such failures can arise from errors made in the initial investigation stages of the project and from an incomplete and inadequate understanding of the problem.

Irrespective of the way we choose to define failure, there can be many different possible forms, or "modes", of failure to consider. Furthermore, the consequences of the different failure modes can vary enormously. The consequences may be very minor, such as when a pump in a water treatment plant breaks down, or they may be catastrophic, as in the collapse of a dam with loss of property, injury and even loss of life. Minor engineering failures are not uncommon, but the catastrophic ones, such as the collapse of a building, a bridge or a dam, are fortunately very rare.

Turning to an example from the field of structural engineering, we note that many different modes of failure are possible in critical cross-sections of a reinforced-concrete girder in a building frame. These include failures in flexure, shear, torsion, tension and compression, and various combinations. There are other possible modes of failure of the entire member to consider, such as excessive deflection. The many different failure modes have very different consequences, varying from severe (a torsion failure followed by a partial building collapse) through to minor operational disruption (excessive deflection under a temporary overload).

In any project, the designer must identify the possible modes of failure, evaluate the likely consequences of each mode, and design the system so that there is an acceptably low risk of failure appropriate for each mode. The level of risk that is acceptable will depend on the mode of failure and on the consequences of the failure.

There are many possible causes of engineering failure, ranging from human error and poor material quality, through to catastrophic natural events, such as severe earthquake or extreme flood. Human error can occur by miscalculations made in the design phase of the project, or by errors made during the implementation phase, or by mismanagement or accident during the operational phase.

The cause of a catastrophic failure may even be a very unlikely event that has been foreseen and allowed for in the planning and design phases. In the original design of the Tasman Bridge in Hobart, Australia, careful consideration was given to the possibility of a ship colliding with the main piers. Although this was considered to be a remote possibility, steps were taken in the design to limit the effect of such a collision (New et al, 1967). Nevertheless, the unlikely event occurred in January 1975, when a ship did collide with a pier of the bridge. The collapse of the main bridge deck had catastrophic consequences, with tragic injury, the loss of twelve lives and severe disruption to life in Hobart (Laurie, 2007).

It is not uncommon for the actual use of resources during the implementation phase of a project to be greater than was allowed for in the planning phase. Also, engineering projects are not always completed within the planned time schedule. Such over-runs on cost and time may be due to errors made in the planning, the design or the implementation phases of the project. They may be caused by supply chain problems, or even by extreme weather conditions. The over-runs may be small or large, but, strictly speaking, these are failures in the sense that we are using the word.

In open-cut mining projects a great deal of planning effort goes into minimising and managing risk, but it is accepted that accidents are unavoidable. Rescue and recovery operations are therefore included in the planning, design and on-going management of such projects. In petroleum and crude-oil handling facilities, all procedures are carefully planned and monitored with the express purpose of preventing fire and explosion. Accident, fire and explosion cannot be prevented completely, and have to be allowed for in the planning and design of such projects. Management procedures are carefully worked out to handle accidents when they occur, in order to minimise the consequences.

Even with the introduction of ingenious fail-safe concepts, the probability of failure in real engineering systems cannot be reduced to zero. The incremental cost of reducing risk increases sharply as the risk level decreases. In other words, it is extremely expensive to achieve a marginal increase in safety when the safety level is already high. Eventually a stage is reached in any design situation where the cost of improved safety is impossibly high. Engineering design must therefore deal with calculated risk and, in rare cases, the prospect of malfunction and failure.

Given that an element of risk is inevitable in engineering work, one of the difficult decisions is what is an acceptable risk level to be applied in planning and design. If the risk is too high and the safety requirements too low, the rates of occurrence of failure will be unacceptable to the community. If the risk levels are set too low, the cost of achieving the safety levels becomes unrealistic. A consequence of extremely low risk levels and high project costs is that fewer important projects can be undertaken. Methods for risk management and for dealing with failure always have to be analysed in detail. They are discussed further in Chapter 11.

While engineers understand that absolute safety is not an achievable or a feasible objective, this is not always appreciated in the community, or in legal circles. The risk levels adopted in engineering work have an indirect effect on the entire community, in regard both to the safety levels achieved and to the cost of the engineering infrastructure. It is for this reason that national codes and standards provide guidance and set minimum safety and performance requirements in many fields of engineering.

3.14 INTRACTABLE PROBLEMS AND SYSTEMS

The procedures for planning and design that we have discussed so far in this chapter make use of systems concepts that were introduced in Chapter 2. In effect, they provide a common-sense approach to the solution of complex problems which are ill-defined and open-ended.

Are all engineering problems amenable to this common-sense (and traditional) systems approach? Do all engineering systems lend themselves to decomposition and analysis?

It has been observed that some real world problems are too ill-structured to be dealt with using the standard systems approach. These have been described as *wicked problems*, as distinct from the *docile problems* that are amenable to standard approaches (Rittel and Weber, 1993). Wicked problems usually have a strong human dimension, for example when a number of individuals and groups of people are closely involved, both in the problem itself and in defining and finding an acceptable solution.

It has also been suggested that some real world systems do not lend themselves to standard planning and design techniques. A distinction has been drawn between *hard systems*, for which the procedures described in this book are applicable, and *soft systems*, which are intractable. Soft systems have been described as highly complex, lacking any clear structure, and possibly containing uncoordinated sub-systems that pursue their own independent goals. Again, such problem systems usually have a human dimension. A *soft systems methodology* has been developed by Checkland (1984) and his co-workers at the University of Lancaster for dealing with complex, intractable problems that are related to soft systems. It has also been suggested that the self-contained, limited, engineering project may not be the best way to deal with soft systems, and that alternative approaches may be more successful.

Wicked problems

Wicked problems have been discussed since the 1970s in regard to social planning and management problems that involve human activity, and more recently in regard to engineering planning, design and management. As already discussed in Section 3.6, there is an important human element in most modern engineering work, and community consultation and community input normally lead to acceptable decisions and successful outcomes. On the rare occasions when this is not the case, problems can become wicked, and this is usually because conflicting views and opinions in the community. According to Rittel and Weber (1993), wicked problems cannot be adequately formulated because additional relevant aspects are continually brought up for consideration. They suggest that a solution only occurs when a decision is made that the current trial solution is "good enough". It follows that there is no correct or best solution to a wicked problem, only that alternative solutions can be identified, compared and ranked. They also consider that each wicked problem will be unique, and that each wicked problem will lead to another problem.

Perhaps inevitably, sub-classifications of wicked problems have been proposed: *super-wicked problems* have been defined as wicked problems which have serious time constraints imposed on them, and which are partly caused by the same people that are dealing with the problem. The term "*mess*" was introduced by Ackhoff (1974) to describe a set of inter-related problems, or a system of problems. Further information on wicked problems and social messes can be found in the book by Ritchey (2011).

Various strategies have been proposed for dealing with wicked and intractable problems. When a problem is made intractable by the involvement of many paticipants with opposing views, an *authorative approach* may be possible. A small group of carefully chosen people, including experts, is given the responsibility of coming up with a solution. This approach is time-efficient because it sidesteps the need to deal in detail with the competing views and beliefs of the interested parties; however, it relies on the perspectives and experience of the group of people chosen to deal with the problem. An entirely different approach is to invite solutions from all persons and parties involved with the problem, and then to evaluate them and identify the best one. This is an *adversarial approach*. It can lead to tensions in the community and mutual distrust. A *compromise approach* has also been proposed, whereby an attempt is made to include all people who are likely to be affected, and to achieve collaboration using meetings and discussions to clarify the issues among competing interests. This approach will be very time consuming, but can lead to a solution that will be satisfactory to the majority of people, optimal for a few, and unsatisfactory for a minority. Compensation is always an added option for dealing with those significantly disadvantaged by a project.

In important engineering projects it is certainly true that very large numbers of people become involved, in one way or another. When different interested groups hold entrenched views, the project can take on a political dimension so that the engineering problems display the characteristics of wicked problems. Community consultations and negotiations then become very important, but may require additional political input.

Some commercial engineering problems can be exceedingly costly and can only be evaluated as successes or failures after they have been completed. Examples are to be found in the design, manufacture and marketing of new innovative appliances, and even of new models of automobiles and aeroplanes. In this respect the planning and design problems have the characteristics of wicked problems, although the normal procedures of planning and design and open-ended problem solving are applicable.

In previous generations, an authoritative approach was commonly taken to large engineering projects undertaken for the public benefit. A small group of politicians, engineers and other professionals were responsible for the decisions that affected the lives of many people.

Today, large, important and controversial engineering projects receive continuing public scrutiny, beginning at the initial stages of problem formulation.

Public opinion and comment are openly sought. This does not mean that the engineering methodology is not used. Rather, it means that the relevant phases of the planning and design processes can receive useful input from the public, and that the community will be well-informed and can become involved in the decision making processes. Nevertheless, on rare occasions agreement might not be reached, perhaps due to opposing, entrenched opinions, and political input may then become necessary. There is a growing literature on wicked and super-wicked problems on the internet which makes for interesting and useful reading.

Soft systems methodology

Checkland (1984) and his research group at Lancaster University in the United Kingdom, and other researchers, drew a distinction between hard systems and soft systems. Hard systems are relatively well-defined and lend themselves to traditional evaluation and analysis using the procedures presented in this book. In contrast, soft systems are ill defined and possibly indefinable because individuals and groups of people with differing views become involved and do not agree on what constitutes the system and the purpose of the system, nor on the problem that is to be solved. The idea of soft systems was originally developed in regard to problems in management and business, but is applicable to some engineering problems, particularly those which involve opposing views with political and sociological elements.

The soft system methodology proposed by Checkland and further developed by other writers is usually presented as a seven-step process. It is a sociological process rather than an engineering process, and is aimed at achieving accord among people and groups with radically differing views. Further details of the soft systems methodology can be obtained from a variety of internet sources.

When an engineering problem is intertwined with sociological and political issues, the standard systems concepts and planning and design methodologies can become unworkable in the face of divergent and opposing philosophical and political views in the community. In such situations sociological and political input is needed to allow a basic starting point to be found for developing an engineering solution.

Agile software development

If engineering problems and systems become intractable, it is usually because there are social, political and business issues to be resolved. But this is not always the case. Developers of large, complex, computer software packages have found that traditional planning and design approaches are inappropriate because of the extreme complexity of the systems being developed, and the length of time needed to create the complete, final plan or program, and then bring it into operation. Multi-purpose, multi-faceted software packages are quite different to, say, a piece of engineering hardware, such as a bridge, which must be brought into use as a complete entity. In contrast, various parts of a large software package can be developed, delivered and put into use long before the complete package has been conceived, let alone created. Some business software packages fall into this category. In their final form, these packages gather enormous amounts of data that fluctuate second by second; they then process, evaluate and analyse the data and so provide rapidly changing advice concerning the financial markets.

An alternative, *agile approach* to software development has become popular, which allows solutions to evolve progressively and adaptively, with different teams working simultaneously on coding diverse parts of the package. The emphasis is on the early production of working software and the regular delivery of additional components. Close collaboration among the teams of developers is obviously necessary. However, the approach also encourages close contact between the developers and the end users of the package. Furthermore, it allows changes to be made to the overall requirements and function of the package, even at late stages of development. This is an adaptive approach in which, initially, there is no accurate statement of the requirements of the end product. On the contrary, the requirements can change and develop over time and as the detailed work progresses.

This is a radical departure from the traditional methodology in which implementation begins as the detailed planning and design come to an end. Some proponents of the agile approach have emphasised that they are not promoting a different methodology, but rather the principles of a different approach.

The origins of agile thinking in software development can be traced back to the latter decades of the 20th Century, but the approach gained real momentum at the beginning of the new century, when varying views on agile principles (and even including a manifesto) were presented on the internet and published (Highsmith et al 2001). Generally speaking, the agile approach incorporates the following ideas:

- customer satisfaction is to be achieved by the early and frequent delivery of useful software;
- working software is the main measure of progress;
- adaptability is paramount, allowing requirements to change, even in the late stages of a project;
- close co-operation is needed, not only among the teams developing different parts of the software package, but also between users and developers; and
- teamwork and good communication are essential among the self-organising development teams that progressively produce the architecture and overall requirements.

In summary, the agile approach emphasises an adaptive, iterative and evolutionary approach to software development, rather than the traditional sequential approach of plan-design-implement.

Not surprisingly, many procedures have been used in implementing the agile approach. We will consider just one, called *scrum*, which is used to manage the work of a software development team. The aim is quick delivery of software, with an ability to respond rapidly to changes in requirements, to emerging technologies, and to changing user requirements (Schwaber and Beedle, 2002). The word "scrum" comes from the game of rugby football. In the scrum approach, a small team works closely together to produce new software components on a continuing, regular basis. Various roles are allocated to the team members. There is a product owner, who represents the interests of the customer or end user, but is also responsible for communication. The scrum master is the facilitator. A small team, usually of three to nine people, undertakes the development of software increments.

Work is undertaken in short *sprints* which typically last just several weeks, the aim being to produce useable software by the end of each sprint. A planning meeting is held at the start of the sprint to clarify the aims and the detailed work to be undertaken. A short stand-up meeting is held daily during the sprint and this is called a scrum. Each team member reports on progress made since the previous scrum, on the proposed work for the coming day, and, importantly, on any impediments that have been encountered.

Further detailed information on the scrum method, and on other agile methods, are to be found on the internet. Of course, problems have inevitably been experienced in the introduction of the agile approach, some of which have been documented. One recurring difficulty is accurate budgeting for an agile based project.

Agile management methods in engineering

It has been suggested that agile methods may be useful outside of software development and in engineering management and business management. The agile approach has been proposed for use in the automated development of engineering products such as computers, motor vehicles and medical devices. A suggested advantage of the agile approach in management is that it is much easier to deal with change and with unexpected occurrences when work is organised in short sprints. It is too early to judge how successful agile methods will prove to be in traditional engineering management applications. New engineering applications of the agile approach will be followed with interest.

A potential problem in applying the agile approach, and one not to be underestimated, is how to achieve a smooth and successful changeover from one mode of operation to another. Even when significant advantages are to be found in employing an agile approach, a too-rapid change in the management approach would cause disruption in any organisation. Careful planning for the changeover would be essential. A useful approach might be a step-by-step "hybrid" alternative, in which some suitable parts of the project are chosen and managed using agile principles. Components of both approaches could in fact be cherry-picked to obtain advantages from both approaches

3.15 SUMMARY

Large engineering projects require extensive planning and design work that is mainly carried out prior to the implementation phase. A major part of this chapter is devoted to describing and explaining procedures that are suitable for undertaking engineering planning and design. These procedures are based on a common-sense methodology of open-ended problem solving.

The processes of planning and design have many features in common, and in practice the terms are not mutually exclusive. However, we have used the term *design* when a physical object (or hardware item) is to be created, and the term planning when a non-physical object such as an operation or a process (or software item) is to be created. Despite this distinction, the processes are very similar, and we have emphasised the similarities in Sections 3.4 and 3.5 of this chapter, where the procedures for planning and design arew discussed.

The traditional plan-design-implement approach to engineering work is well suited to large and small engineering projects which deliver new items of infrastructure, or improvements to the existing infrastructure. Even when an engineering project is widely approved and leads to improvements in the physical infrastructure that will be enjoyed by the community as a whole, there are usually individuals and organisations that will be seriously disadvantaged. Financial compensation is a means of achieving equity in such situations.

Individuals and organisations in the community can become stakeholders when they take a keen interest in an engineering project, and can become active participants in the decision making processes. Public consultation is a normal part of modern engineering planning and design, and can be beneficial to all. The outcomes from public participation can be very positive, provided time and resources are allocated appropriately.

In some circumstances, however, problems can arise in the consultation process, especially if there are differing and entrenched views in the community. Sociological and political issues can then become intertwined in the engineering work. The consultation process may then end in controversy, without easy resolution. The terms *wicked* and *intractable* have been applied to such situations. When they arise, the plan-design-build approach may require political and/or social intervention. Wicked and intractable problems are relatively rare, but techniques for dealing with them are needed, and are discussed in Section 3.14.

There are some engineering problems for which the traditional approaches, described in this chapter, do not work satisfactorily, even when there are no social and political issues. Computer software development is a prime example. The *agile* approach has been developed specifically for the management of software development work, and various procedures, including *scrum* and *sprint*, have been developed and are now used to apply agile principles. There is potential for the use of these alternative approaches in traditional engineering planning and design, but substantial applications are still to come.

PROBLEMS

3.1 What are the main engineering problems to be faced in establishing a permanent human settlement on the moon?

3.2 How would you undertake a feasibility study for the problem of creating a lunar base to house between 10 and 25 persons in a reasonably comfortable environment for living and for undertaking scientific work? List the steps you would use in undertaking this feasibility study. Describe each step in a short paragraph and mention what you see as the key considerations. For example, if one of the steps is to obtain background information, what kind of information would you want to obtain?

3.3 What are the main engineering problems to be solved in establishing a small permanent Antarctic base for, say, twenty scientists? Describe briefly the steps to be taken in the concept design for such a base.

3.4 Consider the energy supply and distribution system of the city where you live. How would you undertake a planning study to provide adequate energy over the next thirty years? What background information would you want to gather in undertaking this study? List several alternative sources of energy that might be used to increase supply to meet demand. What other energy options would you consider in your study?

3.5 In constructing a building it is usual to begin from the foundations and work progressively upwards, floor by floor. Is this the only way to undertake building construction? Can you think of any situations where construction follows another sequence? Under what circumstances might it be advantageous to develop an alternative construction sequence?

3.6 The Government of South Australia is considering developing a nuclear waste storage site in a remote area of the state. Go through the steps of problem formulation for this project using Table 3.3 as a guide. Include in this process a list of the background data that you would require in order to adequately formulate the problem,

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APPENDIX 3A: PLANNING FOR A CITY WATER SUPPLY SYSTEM

As an example of how the steps listed above in Tables 3.3 and 3.4 are used in the early phases of a project, we now discuss briefly the planning of the future water supply for a small coastal city in a very dry climate for, say, a 30 year period. The city of Adelaide in South Australia is the focus for the discussion. The aim here is not to provide valid, long-term conclusions in regard to the needs of this city. The emphasis is on the process, not the results. We will restrict our attention to the problem formulation step and the feasibility study.

Problem formulation

The steps in problem formulation, listed in Table 3.3, are applied (in hindsight) to the planning of the water supply system for the problem as it was in the year 2010 .

Identifying the problem as part of a wider problem

Given that there is already a serious lack of water throughout the region, the problem of planning for the future water supply in Adelaide has to be considered as part of the wider problem of providing water for the entire State of South Australia. Although about 70 per cent of all economic activity in South Australia occurs in Adelaide, an attempt to look at the Adelaide water supply problem without reference to the water supply problems of neighbouring areas, including industrial cities such as Port Augusta and Port Pirie, the South Australian wine industry and other rural industries, would be a serious mistake. The fluctuating demand for water in remote regions of the state, generated by extractive industries and mining operations, is also relevant and needs to be taken into account.

The geography of southern Australia and its lack of river systems makes it necessary to identify the problem as part of a wider problem: the management and use of water throughout the Murray-Darling river basin, which extends through three states in the eastern region of the Australian continent. This basin supplies the majority of the water used in South Australia, but there is significant upstream use of Murray water before the river enters South Australia, and this restricts the amount of water available.

The apparent change in climate that has occurred in recent years in the region (but also in many other parts of the world) suggests that there might be global aspects to this “local” problem.

The water supply system for the city also has to be looked at as one among many system components that make up the physical infrastructure of the city. Other components of particular relevance are the sewerage and storm water systems, which have to take up most of the input water, but are also potential suppliers of additional (processed, recycled) water. The parks and gardens and other public areas place significant demand on water. The transport system and the energy generation and supply systems are other components of the city system, as are industrial regions and the suburbs where people live.

Relevant background information

Quantitative data on the current state of the water supply system and its desired future states in thirty years time and in intermediate times need to be gathered. The population of Adelaide was a little over a million in 2010, when the water supply system provided about 200,000 ML per year. In addition, a little under 100,000 ML was used in neighbouring rural areas including the Adelaide Hills. On the demand side, about 45 per cent of city water was used by suburban households, about 28 per cent went to primary production, but only 10 per cent went to the commercial and industry sectors. Community use (including parks and gardens) made up the remainder, about 17 per cent.

Looking specifically at households, we find that about 40 per cent of domestic water went into gardens and other outdoor uses, such as swimming pools. Bathrooms (baths and showers) took up 20 per cent, with toilets at about 11 per cent, while laundries and kitchens use around 16 and 11 per cent, respectively.

On the supply side we find that although the water for the city comes from a variety of sources, in 2010 the two main ones were, firstly, the reservoirs and catchment areas in the Adelaide Hills, and, secondly, water pumped from the River Murray. Other minor sources of water for Adelaide include groundwater, rainwater tanks and storm water. In a "normal" year the two main sources provided roughly 60 and 35 per cent respectively of the water for the city and surrounding rural areas, but in "dry" years, such as 2007 and 2008, the component from the Adelaide Hills reduced to between 10 and 20 per cent. The additional water was obtained by extra pumping from the Murray, and severe restrictions were placed on the outdoor use of water.

These figures give a broad picture of the supply and demand situation in and around the city in 2010. Similar figures for the rest of the state, and indeed for south-eastern Australia provide additional important background information. For example, of the water available from the River Murray, about ten per cent went to towns and cities, while the rest was used in irrigation. Throughout the state there were about 50 small desalination plants in 2010, usually located in small and isolated regions such as Penneshaw on Kangaroo Island.

Background information is needed on the desired "target" state of the system in thirty years time, and at intermediate times. Such information regarding future demand necessarily depends on expected demographic changes to the city and state, and cannot be as reliable as the data on the current state. It could therefore be advantageous to look at several alternative scenarios, including optimistic, pessimistic and most likely, in order to obtain a range of figures for the target state.

The future population of Adelaide has been estimated to be about 2 million by the year 2027, and 2.5 million by 2050. The document "Waterproofing Adelaide", prepared by the Government of South Australia, suggests a demand of about 230,000 ML in the city in 2025. This unexpectedly low value may include some allowance for a curb on demand as the result of future pricing policies. Even so, it is worrying when compared with the predicted supply figures for 2025 from present sources, which are about 190,000 ML in a dry year and 250,000 ML in a normal year. One reason for the relatively low supply figures is the reasonable assumption that climate change will continue and will, for example, reduce the available water from the Adelaide Hills by at least ten per cent.

It is clearly important to look for possible new sources of water in the feasibility study. Given the unavailability of new, plentiful and cheap sources of water in the surrounding hills, wider possibilities have to be considered. In anticipation of the steps in the feasibility study, we can see that background information will be useful on processes such as water desalination and recycling of used water, as well as methods for improving the efficiency of use of the existing sources of supply. Approximate (order-of-magnitude) information would be useful on more radical options such as the transport of icebergs (or iceberg water) from the adjacent Antarctic Ocean and measures to modify the location and quantity of rainfall. Another option requiring more accurate background information is the possibility of adjusting water usage in the south east of the country, perhaps through the marketing and trading of water and water rights.

Other relevant background information relates to the quality requirements of water when used in different ways. Clearly the quality of water needed for drinking and cooking is not the same as for irrigating public parks and gardens or for flushing toilets.

Regular updating of information

Predictions into the distant future for water supply are necessarily unreliable, concerning extremes of weather and other natural phenomena, are necessarily unreliable, but in the long term, extremes will undoubtedly occur in rainfall on catchment areas and flow in the River Murray. Procedures could be used to anticipate extreme events, including sensitivity studies and Monte Carlo simulation, but real data in the intervening years will be far more valuable than theoretical predictions. It is therefore essential that important data be gathered progressively so that the program can be revisited and updated regularly, perhaps every year or every two years. This updating must begin immediately and continue while the project is underway, and also after it has been completed, so that modifications can be introduced in a timely manner and at minimum cost.

It must also be remembered that planning is not being undertaken solely for the supply of water at some remote future time. Adelaide is a functioning city and requires an ongoing plan to provide adequate water throughout the intervening years up to the target year of 2050.

Underlying needs

While a useful picture of future domestic, industry and rural water needs can be built up for the planning period, the severe lack of water raises important questions that highlight the differences between needs and requirements. Specifically, considering the relatively high domestic use of water, with 40 per cent going to gardens and other outside applications, an important question is whether a distinction needs to be made between the quality and cost of water when used for different purposes. Such questions arise when we look at the underlying needs, as distinct from demands, for water. This leads to the further question of whether water of varying quality should be supplied with pricing policies related to cost of supply. At present, almost all water is supplied at the one quality level. The issue of water trading focuses attention on the difference between needs and demands. Such questions are relevant when we undertake the feasibility study. Our purpose here is not to try to answer such questions, but to illustrate the process.

An important step in the planning process could well be to place relevant questions before the community for discussion and debate. Already in the year 2006 in various country communities in Australia questions were being examined, such as the acceptability of recycling water as a way to boost the capacity of town water supplies.

Side effects

Increasing pollution of the waterways in the Adelaide Hills and pollution and salinity problems in the River Murray are already prevalent. Worsening pollution is an obvious side effect to be expected in the present project. The side effects of depleting ground water through aquifer pumping are not well appreciated in the community, but require investigation. Increased salt in the aquifer water and overall deterioration of quality could become serious side effects should there be a significant increase in the use of ground water supplies. Over-use of river water generally means reduced flow, with adverse effects such as silting, algae blooms and other adverse environmental effects on the biota. Cessation of river flow and closure of the river mouth is likely. Closure has already occurred at the Murray mouth, and the local community is well aware of the consequences.

Other side effects include increased salinity in the river water of the Murray due to increased pumping, and the need for correspondingly more expensive treatment procedures to achieve adequate water quality. Another consideration is the inhibiting feedback effect of poor quality water on industrial expansion, city development and the rural and wine industries.

Constraints

Constraints derive from state and federal regulations regarding water quality, environmental impact, land resumption, health regulations, city planning and zoning, and water use. World Health Organisation standards for water quality and health also serve as constraints. Current intrastate agreements on the allocation of water from the Murray-Darling basin impose severe constraints on the available options for the city of Adelaide. In this regard the possibility of modifying existing laws and regulations has to be considered, with the re-writing of state and commonwealth agreements.

Objectives

In the statement of objectives, account has to be taken of the demands and needs for water, and the likely limits on supply. Water scarcity and interstate and intrastate competition for this limited resource also have to be considered in the statement of objectives. A rather general statement is as follows:

> *To match, as closely as is economically and technologically feasible, the quantity and quality of water provided against the realistic needs of the various uses (domestic, industry and irrigation) and to provide security of supply over the planning period.*

This formulation treats both demand and supply as variables. On the other hand it skirts the problem of differentiating between need and demand. The prediction of realistic figures for demand versus need thus becomes a central task to be undertaken in this project. The above statement does not stipulate that water will always be available without restriction, for example in times of severe drought, although some minimum level of supply is clearly implied.

The linked concepts of technological and economic feasibility allow for changes and improvements in technology over the planning horizon. For example the economic feasibility of desalination plants is likely to improve substantially in the next decade, assuming that there is continued development and improvement in efficiencies in the relevant technologies.

Performance requirements and operating conditions

The water supply system will have to accomodate a progressive increase in the quantity of water to be supplied through the planning period, and not just in 2040. A wide variation in conditions in this period must be expected, including effects such as progressive climate change and alternating drought and flood throughout the state and in the upper reaches of the Murray-Darling system. Drought and flood can even occur at the same time in different parts of the system. In taking account of these possibilities, it will be necessary to specify minimum limits on the quantities of water to be supplied on a daily, weekly and yearly basis. Quality limits also have to be specified. Separate statements of the requirements for domestic use, industrial use and irrigation use may be needed. Above all, the performance requirements have to be realistic and achievable.

Measures of effectiveness

Total cost in dollar terms is one prime measure of effectiveness, but certainly not the only one. Another measure is needed in regard to the reliability of supply, which can be measured, for example, by the number of days per year when restrictions occur. Another measure may be needed for the quality of the water supplied, taking account of the average and peak salinity levels. Adaptability of the supply system to unexpected changes in demand over the medium term (in other words, system robustness) is another possible measure of effectiveness.

A combined measure of effectiveness might be made in terms of the dollar cost per unit of water supplied, using penalty costs to take account of reliability and adaptability. Such a measure of effectiveness can be broadened to allow for water being supplied at several different quality levels according to different uses. This leads to a separate measure of effectiveness for the different water quality levels considered. A single overall measure of effectiveness, again in dollar terms, could be obtained by differential costing of the different quality levels. The present comments are intended to show how a measure of effectiveness might be developed. They are not meant to indicate preferred options.

Feasibility study

We now look very briefly at the steps listed in Table 3.4, as they apply to the present example.

Checking available resources

In addition to the main resource, water, we have to consider the financial resources that will be available, and the technical resources and expertise that will be needed to undertake the project. When each specific option is considered, such as the construction of a new dam or the construction of a desalination plant, the specific resources and expertise have to be investigated.

Investigating and evaluating constraints

Some of the constraints to the problem have already been mentioned, such as the regulations and laws concerning water quality. It will be necessary in the feasibility study to investigate and study them to observe how they will affect the possible options and solutions.

Developing promising concepts

Some of the possible options for dealing with the problem have been foreshadowed in the previous discussion. Consideration has to be given to increasing the use of the available but presently unused water resources, such as the storm water which flows into the sea. An improved efficiency in the use of other existing resources is another important option, for example by reducing the losses that occur due to evaporation from open water surfaces and leakage from reticulation pipes. Another option is legislation to require the installation of domestic rainwater tanks. Further options that are more costly include desalination, recycling and reuse of treated wastewater. More radical approaches, which may appear at first sight not to be feasible, include the harvesting of icebergs from the Antarctic Ocean. The possibility of actively changing the climate to increase rainfall falls into this category.

A more obvious and potentially very effective approach is to curb the increase in demand for water, and possibly even reduce demand, through pricing policies coupled with education programs to alert the community to the real costs of water and to methods for effectively reducing its use.

Technical evaluation is needed to determine the relative costs, the feasibility and the quantities of water that can be delivered by each of the approaches. It is unlikely that any one approach will be adequate in itself. It is far more likely that a range of the cheaper and more effective measures will be used simultaneously so that, together, they produce the volume of water needed.

While some of the approaches listed might not be feasible today, we must remember that although the planning horizon is thirty years, the need for water will not suddenly stop in 2040. With improving technology and new scientific discoveries, we can confidently expect that some of the options that today seem unlikely will become quite realistic over time and may well be introduced at later stages as the century progresses.

Comparing alternatives and eliminating the non-competitive options

In this project we are dealing with a scarce resource, water, and, as already mentioned, a mixed strategy is likely to be appropriate. The employment of some options and not others will be decided on the relative costs and efficiencies, which will undoubtedly vary over the planning horizon.

The example being discussed here is different to many engineering projects, in that the best solution here will *not* be found by progressively eliminating all but one from a list of options. The nature of the problem means that a mix of options will be required, with only the clearly uncompetitive ones eliminated.

An evaluation of viable options can lead to their ranking in terms of initial set-up cost, cost per unit volume delivered, and total amount of water deliverable.

Such a ranking could then be used to make decisions on the mix of options to be employed initially and at subsequent stages during the planning period. Regular updating of the list, especially when new developments and discoveries are made, will allow decisions to be made on when specific options should be taken up. At the beginning of the century, unlikely options such as desalination, rain making and harvesting icebergs should not be discarded and forgotten; they may well become attractive in time, as conditions change, and as the options initially employed are exhausted.

Post script

Detailed information and numerical data on the supply of water to Adelaide, and to the state of South Australia, are available from two planning documents that were released by the South Australian Government. The earlier document, from 2005, was entitled “Water Proofing Adelaide”, and presented a plan for ensuring water for Adelaide up until the year 2025. The second document, undated but apparently from the year 2010, was entitled “Water for Good”, which extended the planning horizon to the year 2050”.

The second plan was produced just 5 years after the first one. The reason for this may well be that in the years 2006 to 2009 the water inflows into the River Murray system were unprecedentedly low, and provided just a very small proportion of the average yearly inflow. The River Murray has been traditionally the main source of water for the city of Adelaide, together with local catchment areas. As a consequence of this apparent, sudden change in climate, a desalinisation plant was commisioned in 2014 with an annual capacity of 100 Gl, about half of the city’s usage. Following the construction of the desalination plant, rainfall increased and the traditional sources of water have been more plentiful. In the period up to 2017, the desalination plant had not been used to capacity, except for short trial runs.