C1 Complexity in the Context of Engineering

C1.1 Overview

In the first part of this book we looked at the system concept; its basic nature as a mode of description, its use and meaning as a linguistic item, and its basis in the way the mind works. Above all, you hopefully gained a clear understanding of what we called *the systems approach*; the application of the system concept for the purpose of handling complexity. The second part was concerned with engineering, a subject you would know well, but we wanted to discuss some features of the profession that are sometimes overlooked, such as its long and successful tradition; the very substantial Body of Knowledge, its central objective of creating objects that, through their operation, provide required services to society, and that attaining this objective includes all activities which such creation and operation require.

This understanding of the system concept and of engineering is the foundation on which we now undertake the investigation of the application of the system concept to engineering, the subject of this third part of the book. There is a whole Body of Knowledge called Systems Engineering, and much of that will fit in with the outcome of our investigation, but there is a very subtle, but important conceptual distinction between Systems Engineering and The Application of the System Concept to Engineering. If we consider ISO 15288 to be the authoritative standard for systems engineering, then there is very little in the description of the processes in that standard that relates to a system approach. Already the title, *Systems and software engineering – System life cycle processes*, is an indication of the focus on the object as a system; something *is* a system, and then the engineering processes are tailored to suit it. And, as an aside, systems engineering does not get a mention at all, and design is treated only as architectural design. In contrast, we shall apply the system concept to the engineering processes in order to handle the complexity of the object; the object is then *described* as a system as a result of applying these processes. The description of a complex object as a system of interacting elements is neither new nor particular to engineered objects; it is the application to the process of engineering that is (relatively) new.

The purpose of applying the system concept to engineering is the same as for any other application – to handle the complexity of the subject matter by structuring it in a manner most suitable for processing by the brain. But before we look into how this could be achieved, we need to be clear about the nature of this complexity we want to handle; what are the sources of it, why has it become more of a problem in recent times, and how can we best describe or classify it? Complexity theory and complex systems have become very "in" subjects in the last ten years or so, with a focus on areas such as ecology, biology, and social systems and organisations, and much of the research activity in systems engineering is attaching itself to this bandwagon. But to what extent this is directly relevant to engineering, as we described it in Part B, is not obvious, and can only be ascertained by a critical examination of the problems encountered in engineering.

C1.2 The Nature of Complexity

What do we mean when we say that something is complex? That it has many sides or aspects to it, needs many variables or parameters to describe it, or consists of many parts? Or that it is hard to understand, needs many words to explain, or is difficult to predict? There are many different definitions and views on this concept [1], but usually we mean an unspecified combination of some or all of these and similar definitions, with the emphasis depending on the particular case, and in one way or another, complexity is related to the number of parameters required to describe behavior.

Complexity is a thoroughly human concept. Something is considered complex because it is difficult for us, as humans, to come to grips with and to work with; it has to do with the capabilities of our brain. It makes no sense to say that something is complex in itself, without putting it in the context of whatever entity is going to operate on it; what is complex to a human may be very simple for a computer, and vice versa. The difficulty we have in conceiving of something as a single entity once it has more than about seven parameters [2] is a characteristic of the brain. Indeed, the success of our whole system design methodology will depend on how well it exploits the strengths and avoids the weaknesses of our brains.

System complexity arises in two fundamental forms, as identified by Peter Senge [3]; namely *detail complexity* and *dynamic complexity*. Detail complexity arises from the volume of systems, system elements and defined relationships. This complexity is related to the systems as they are; their static existence. Dynamic complexity, on the other hand, is related to the expected and even unexpected behavior of systems during their operation. These two forms of complexity can synonymously be referred to as *structural complexity* and *behavioral complexity*. The concept of the structure of a system was introduced in Sec. A4.3, and with that description of interactions as links, a simple expression for the structural complexity is [4]

$$\chi = \frac{1}{n}\sum_{i=1}^{n-1} i \cdot \omega_i ,$$

where ω_i is the number of elements supporting i links to other elements. The values of χ for four simple structures are

Structure	Structural Complexity
Linear chain	$\chi = 2(n\text{-}1)/n$
Closed chain (circle)	$\chi = 2$
Central element (e.g. broadcast)	$\chi = 2(n\text{-}1)/n$
All-with-all (maximally connected)	$\chi = n\text{-}1$

However, in addition to the number of elements and relationships, factors such as linearity or non-linearity in relationships, asymmetry of elements and relationships determine the degree of complexity.

Dynamic complexity arises in systems that are either significantly influenced by humans or where humans are actually system elements, or, most commonly, both [5]. However, it is convenient to think of dynamic complexity as arising either externally or internally, because the former is more prevalent during the design of a project, whereas the latter is related to the ability of the system to respond to a changing environment during its operation, a subject that is treated under the heading of adaptive systems [6].

C1.3 Two Sources of Complexity as Drivers of Systems Engineering

The driver for the application of the system concept in engineering is the rapidly increasing complexity of the projects, and there are a number of sources of this complexity. The most obvious ones include the *size* of the systems, as exemplified by transportation, power, and telecommunications systems, the *number of interacting components*, as exemplified by a modern car or a computer system, and the *number of disciplines* involved, as exemplified by manned spaceflight. But, more generally, there are two underlying developments which may turn out to be the most important drivers of systems engineering.

The first one is that, for most of the last century, the development of new technology through research was seen as an imperative for developed nations, and there was such an appetite for new technology that almost any new development found an application and a market somewhere. Only in the last quarter did we start to notice some serious concerns about where all this technology was leading to, and whether its application was always in the best interest of society as a whole. The question started to shift from "can it be done?" to "should it be done?", and the increase in knowledge, both through travel and television, of what was happening in the world outside our own local community made us aware of the fact that we are all sharing the same limited resources and influencing a common environment. It is becoming clear that it is not just a matter of having better technology, it is also a matter of knowing how to apply this technology in the most appropriate manner. This requires an understanding of the interrelation of the application with its environment. While this was always within the scope of engineering, the immediate and direct benefits of introducing a new technology were usually so major that other effects appeared relatively insignificant.

Sometimes they were actually insignificant because the scale of the application was initially so small that the side-effects, which are generally dependent on the scale in a very non-linear manner, were also small; at other times they were simply assumed to be small because no methodology existed to handle the increase in complexity involved in a proper assessment. The former reason no longer holds in many cases; for technologies such as the internal combustion engine, irrigation, and power generation the applications have grown to such a scale that what was earlier side-effects have become major effects. The latter reason is no longer acceptable to society, and the legislative framework in which engineering takes place is continually being tightened to ensure that a holistic approach is being taken to determining all the effects of every project over its life cycle. The result is that a whole new dimension of complexity has been added to engineering, creating a strong demand for adopting systems engineering as an intrinsic component of the engineering process.

The second driver is to be found in the relationship between humans and technology, which in recent times has started to develop from a purely physical one to one involving cognitive aspects. This development is made possible by the advances in electronic data processing, and the computer itself is the best illustration of this. In the early sixties, the human-machine interface was via the card reader as input device and the line printer as output device; in between the computer operated autonomously. Twenty years later, the advent of the PC allowed a form of dialogue between the user and the machine, and today the development of the interface is about mutual understanding, or cognition. A simple example of this is the auto-correction function in a word processing program.

For systems, this development has meant that the human is no longer outside the system, as a user, but is increasingly an element of the system, and the behaviour of the human is an essential factor in the functionality of the system. As that behaviour is vastly more complex than that of any man-made component, the complexity of cognitive systems is moving system design into a new realm, one in which the application of the system concept will be the dominant paradigm.

C1.4 A Taxonomy of Complexity in Engineering Projects

We start this examination by recalling the view of engineering introduced in Sec. B2.3. Engineering activity takes place in the form of *projects*, and each project has a *purpose*; it is intended to achieve something, and the degree to which it achieves it is the measure of success of the project. Here is already a significant distinction between engineering projects and e.g. biological or ecological systems; the latter have no known purpose. They are very complex systems, and through research we are unravelling this complexity and so gain a better and better understanding of them; how they propagate, how they survive, their internal processes, their interactions with other species or parts of Nature, and so on, but this does not lead to any identification of a purpose.

The purpose of an engineering project falls into one of two groups, which we might characterise as internal or external to engineering, depending on whether the project is concerned with developing technology or applying technology, as discussed in Sec. B4.2. And again, as in that section and for much the same reasons, we shall focus on projects that apply technology in order to achieve an external purpose; a purpose defined mainly by people outside the engineering body that is to carry out the project. That purpose is generally stated as providing a *service*; while the *product* of the project that is to provide the service is the engineer's solution to the problem of providing the service.

The use of the words "service" and "product" introduced here needs to be clearly understood; these words, just as the word "system", have different meanings when used in different contexts. Throughout the remainder of the book, the *purpose of a project* is to fulfil a *need*, the *service provided by a project* is that which fulfils the need, and the *product of a project* is the engineered object that provides the service. In some cases, the service may be a service in the narrower sense, such as public transport, a financial service, health, or education; in other cases the concept must be broadened to include providing a product, such as providing a raw material. In this latter case, the product of the project is the object or facility that provides the raw material, such as a mine.

With this understanding, let us proceed by developing a taxonomy of the complexity encountered in engineering projects by considering *where* in the project the complexity arises. To this end it is useful to view a project as having four components,

- the requirements on the service to be provided;
- the environment in which the project is to be executed;
- the two bases, knowledge base and resource base (technology, manpower, facilities, etc.) needed to create and maintain the product that will provide the service; and
- the engineering process,

as shown in Fig. C1.1.

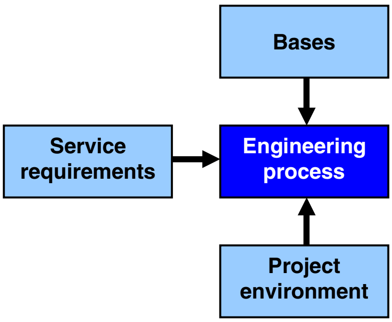

Fig. C1.1 A view of an engineering project as consisting of four components.

Due to the differences between these four components, it is obvious that when describing "where" complexity is found, it must be understood in a very generalised sense; the item that contains the complexity (i.e. the "location") may be a set of requirements, a specification, a body of work, or a physical object. And we might think of locations within the first three components as being "external" to the engineering process, whereas complexities within the engineering process are characterised as "internal", as indicated in Fig. C1.1 by means of the shading; this reflects the degree of (or lack of) control the project has over the sources.

The division into "internal" and "external" components is also useful in viewing the complexities in the engineering process as being of two kinds; those determined or induced by the external sources, and those that arise from the engineering process itself. The latter will be discussed in Sec. C1.3, and the view of two kinds of complexities will be very important in developing our approach to handling complexity within the engineering process in Ch. C2.

C1.5 Complexity in the External Project Locations

C1.5.1 The Service Requirements

The service requirements are generally formulated in the context of a *business case*; that is, the service is to be provided to a *market*, and the provider, or *principal*, will receive a revenue that makes the project worth his while. This immediately identifies two groups of service requirements; those determined by the market, and those determined by the principal. The former are the result of a number of factors, including fashion, culture, standard of living, and climate, and are therefore expressed in a variety of forms; sometimes quantitatively, but very often qualitatively in the form of preferences and desires. They all contribute to what the market perceives to be the *value* of the service. We will return to the concept of the value of a service many times in the following; for the time being, we might think of it simply as what the market is willing to pay for the service. This value then becomes a function of the parameters that describe the factors influencing it. As a concrete example, consider the project of providing a service well known to us all, the ability to access IT services on a mobile platform. A factor common to all realisations of this ability is the capacity of the battery to maintain the service between recharges. How does this factor influence the value of the service? If the time is less than, say, thirty minutes, the service would probably be considered to have little value, and once the time goes beyond, say, eight hours, the value does not increase much more, and we obtain the well-known S-curve shown in Fig. C1.2.

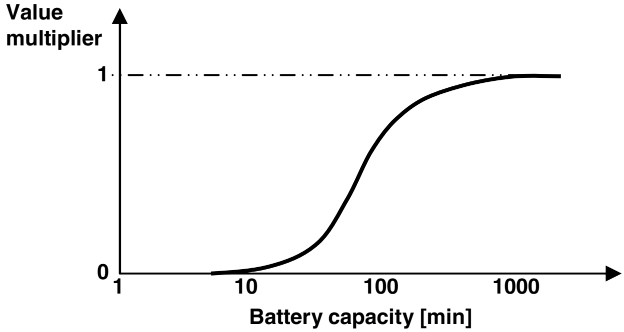

Fig. C1.2 The value of battery capacity in a mobile communications device, as an illustration of the S-curve.

However, there are also a large number of other factors influencing the value, including memory capacity, processing speed, the ability and ease of accessing content, weight, size, etc, and they are not independent, so that what we end up with is a value function made up of a complex set of interacting functions. Added to this is the fact that there is some uncertainty attached to most of these functions; firstly and inescapably, because they refer to the future; secondly, because there are numerous other factors, not directly related to the service itself, that influence people's perception of the value of this particular service, such as competing services and changing social attitudes; and thirdly, because of the rapid increase in the cost of obtaining the market information as a function of the accuracy of the information. So, not only is there a complex set of interacting functions, but the parameters defining these functions are themselves probability functions.

In its simplest form, a business case evaluates the viability of introducing an additional amount of an existing service into an established market; three examples are

- the provision of additional coal through the development of a new coal mine;
- the provision of additional energy through the development of a new wind farm; and
- the provision of additional transport capacity through the construction of a new tollway.

In all three examples the requirements of the market on the nature of the service are well defined; the factors of significance in the value function are all external to the service itself. In particular, government legislation regarding greenhouse gas emissions and subsidies for green power, advances in coal gasification and CO_2 capture and sequestration, and public awareness and attitudes regarding environmental protection and sustainability are important for the first two examples. The perceived value of the time saved through better transport infrastructure, and its relative position in the ranking of the demands on personal finance, is a complex issue in the third example, and three recent tollway projects in Australia got the patronage estimates completely wrong [7].

In addition to the service requirements of the market, the Owner will have a set of requirements on the service related to ensuring the viability of the project or, conversely, related to reducing the *risk* and enhancing the *opportunities* arising from the relationship of the service to the principal's existing business and capabilities. This includes such features as the ability to easily modify aspects of the product in response to expected changes in the market (e.g. increasing disposable income) and the use of existing distribution arrangements.

In many cases there may be a complicating factor that is not related to the nature or type of the service, but to its timeliness; the market presents a *window of opportunity*. While this does not make the service in itself more complex, it results in a significant increase in the complexity of the engineering process, as we will discuss in Ch. C2.

In all the project locations, and perhaps particularly here in the service requirements, the complexity has two sides to it. On the one hand, there is the complexity at any given moment in time, as evidenced by the number of requirements and the number of relations between them. This is what we most immediately recognise as a complex situation. But, on the other hand, both the requirements and their relationships may change over the duration of the project, and this *dynamic complexity* can be much more difficult to recognise and to handle adequately. Due to the relationships between requirements, a change to one requirement may propagate throughout the set of requirements, and a structured and careful approach is needed in order to determine and document all the implications. What we are faced with here are two opposing timescales: the timescale for externally introduced changes, and the timescale for the process of determining and executing the response to the changes. If the latter becomes too long compared to the former, the project will not progress, but consist only of processing changes. Examples of this can be found in the defence area, where the service (or capability) requirements can change over a relatively short period due to changes in the threat assessment and also due to technological advances, whereas the time required to process a set of requirements through the bureaucratic sequence of RFP, tendering, tender evaluation, and contract negotiations can be equally long or even longer, and so the process starts all over again, with a new set of requirements.

C1.5.2 The Project Environment

An engineering project is executed within a certain *environment*; that is, all those non-technological factors that influence how the product is created and how it is operated to provide the service. These factors include:

- Legislation and regulations regarding how work is performed, such as OH&S regulations, environmental protection legislation and consent conditions, and contracting conditions.
- Government policies, reflected in such factors as subsidies and tariffs, land use (zoning), and taxation rulings.

- Community concerns regarding noise impact, visual impact, health risks (e.g. high voltage transmission lines) etc, generally known as NIMBY (not in my back yard), but also concerns about the environment and endangered species (e.g. resistance to mines and dams).
- Special interest groups (representing industry sectors, such as the building industry, or sectors of the workforce, in the form of unions).

These factors increase the complexity of a project not only by their existence and interactions, but also because they need to be managed, in the form of such activities as lobbying, public relations, and community consultation. In infrastructure projects it is not unusual for this management effort to amount to several percent of the total engineering effort.

C1.5.3 The Resource Base

Every engineering project consumes resources in the form of finances, labour, energy, and materials. The totality of the sources or pools of these resources that are available to a project and on which it might potentially draw is its resource base. From this base the engineers will then have to make a choice of which resources they actually employ in the project, and it is the existence of a great (and increasing) number of possible choices that provides a further dimension to the complexity of engineering projects. Some of the main aspects of this resource base are

- The changing technological resource base, including new materials, construction elements, and processes, and the retirement of existing items.
- Economic factors, including labour availability and cost, material cost (e.g. the fluctuating price of steel), transport cost, and the cost of funds (credit availability and interest rates).
- A variety of possible contracting strategies, as discussed in Sec. B3.3, and illustrated in [2] by a couple of examples from the power generating industry.

C1.5.4 The Knowledge Base

In Sec. B2.4 we introduced a knowledge base as one of the properties of a project, and defined it as the base from which the knowledge required in order to be able to apply the resources is drawn. It will now be useful to consider that knowledge base to consist of two parts; a *domain knowledge base* and a *technology knowledge base*. By the domain knowledge base we shall understand the knowledge required to understand and analyse the stakeholder requirements; the technology knowledge base is the knowledge required to develop a solution.

Even though the two knowledge bases may overlap to a great extent, this conceptual distinction is very important, and the reason was touched upon at the end of Sec. B3.1, where we mentioned the work of John Warfield [8] and the idea of a “problematique”, an extended view of the service required that encompasses the context in which the need is expressed. The knowledge required to fully develop and understand the "problematique" will often be considerably different to the knowledge base the engineer would utilise in developing a solution. From our point of view, in our current discussion of complexity in engineering projects, the distinction is important in that the sources of complexity contained within the two knowledge bases are also different.

In the case of the domain knowledge base, the complexity arises from the fact that the "problematique" may have numerous aspects, each involving different knowledge areas, from politics and government policies to individual beliefs and value judgements, and these aspects may interact in subtle ways. As a result, understanding the "problematique" may be a complex process, requiring both a structured approach (e.g. as advocated by Warfield) and the involvement of various specialists outside of engineering.

In the case of the technology knowledge base, the complexity arises mainly from the extent of the base, and the fact that the increase in knowledge leads unavoidably to greater specialisation. The result of this specialisation is that there are barriers to the information flow between disciplines, and we now have the situation that, due to the increase in knowledge, we have increasing specialisation and therefore more barriers, at the same time that engineering projects are becoming increasingly multidisciplinary. Achieving optimal outcomes means balancing performance parameters and costs across all disciplines (in addition to all the non-engineering aspects), and rather than as an issue of understanding, the complexity manifests itself in the difficulty of *selecting* a solution. And again, a structured approach is required in order to arrive at a solution reasonably close to the optimal one in an efficient manner.

C1.5.5 Quantifying the External Complexity

Quantifying the complexity introduced into a project through its relationship with its environment is a difficult and largely unsolved task. There are many approaches discussed in the literature, often under the heading of risk assessment [9], but in practice the uncertainty and subjectivity makes the results largely qualitative. In a general fashion, the complexity can be thought of as arising as a result of the relative *distance* between the object required to meet the stakeholder requirements and the totality of existing objects. The space in which this distance is measured is a multi-dimensional one, and while the number of dimensions and the definition of the individual coordinates are project-specific, the following coordinates will normally be present:

1. The extent of the domain knowledge base required to address the requirements, relative to the existing knowledge base.
2. The number of technologies (or disciplines) required to address the requirements.
3. The extent of each technology required to address the requirements, relative to its existing state. This is also called *technology maturity*, and is an area where quantitative methods are relatively well established [10].

4. The extent to which the same or similar objects have been realised (with an allowance for the success of the realisations). This is particularly important when it comes to the host of issues related to community acceptance.

The same coordinates are involved in assessing project risk, but complexity and risk are by no means identical. If risk is defined as the probability of failing to meet the performance requirements within the given time and budget constraints, multiplied by a measure of the consequences of that failure, then risk is clearly dependent on those two constraints (as is easily seen by the fact that if the budget and timeframe both go to infinity, the risk goes to zero, no matter how complex the project is). But furthermore, the risk is also dependent on the particular manner in which it is proposed to carry out the project, i.e. on the Project Plan, as will be discussed in the next section.

By “existing” in items 1 and 3 above we should understand “available to the project”. Both domain knowledge and technology may or may not be available within the initial project organisation, but if it exists and can be made available, it is simply a matter of the cost (and possibly the time frame) involved, which brings us to the complexity within the project, i.e. to the complexity of the work.

C1.6 Complexity within the Project

Having assessed the complexity of the project in terms of the external influences, and having developed a good understanding of what work has to be undertaken in order to handle this complexity, there now remains to determine how to carry out that work. In general it is true that the complexity of the external influences is reflected onto the project itself, i.e. onto the object that will satisfy the requirements and onto the body of work required to create that object. It was to address this internal complexity that systems engineering was initially developed. This approach, which effectively puts a barrier around the project in its earliest phase, was appropriate to defence projects in the Cold War, where commercial aspects and community influence were relatively unimportant. And this approach is still quite apparent in many of the processes that make up systems engineering, as will be discussed in the following chapter.

However, with the wider application of systems engineering to areas outside defence and aerospace, and also somewhat of a changing view of the military role, the system approach to the external complexity is taking on increasing importance, and is being integrated into many of the systems engineering processes. Consequently, although the characterisation of a source of complexity as external may still be useful in *understanding* its nature; when it comes to *handling* complexity in the process of engineering there is little benefit in making this distinction. An example that is probably well known to most readers is that of change management; it is required to handle change whether it arises from the dynamic nature of the development process (internal) or from changes to the requirements (external). The dynamic nature of the development process is again a result of the complexity of the service requirements, and so on. Our approach to handling complexity in engineering projects focuses on handling the manifestations of complexity, such as the number of disciplines involved, the number of requirements, their interdependencies, their dynamic nature, etc; trying to reduce the sources through such ideologies as a return to Nature *à la* Rousseau is outside the scope of engineering.

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6. There is a great deal of activity taking place in the area of adaptive systems and, perhaps in particular, in what is termed complex adaptive systems or CAS (although there is no definite boundary between the two). Besides the ubiquitous Wikipedia, a starting point might be the UCLA Adaptive Systems Laboratory, `http://asl.ucla.edu/`, or the Adaptive Systems Research Group at the university of Hertfordshire, `http://adapsys.feis.herts.ac.uk/`. A textbook that addresses computational models of social systems (which are a focal point of CAS) is Miller, J.H., Page, S.E.: Complex Adaptive Systems. Princeton University Press (2007)
7. Three road tunnel projects – Cross City Tunnel and Lane Cove Tunnel in Sydney, and the Clem 7 tunnel in Brisbane – have had initial patronage of only 30-40 % of that estimated, `http://www.bitre.gov.au/?publications/Oz/Files/BITRE_literature_review.pdf`
8. Warfield, J.N.: An Introduction to Systems Science. World Scientific Publishing (2006)

9. Complexity, risk, and uncertainty are bound together like the three corners of a triangle, and this triangle is itself an inseparable aspect of any human endeavour, with the relative importance shifting around in the triangle depending on the particular situation. Giving references to such a wide and divers topic is not very useful (Google "Complexity and Risk" and get about 40 million hits). ISO 31000:2009. Risk management – Principles and guidelines, is the international standard, and most engineering companies would have their own approaches to this topic. Quite a good little Excel-based tool for engineering projects is that developed by Public Works and Government Services Canada, PWGSC Project Complexity and Risk Assessment (PCRA) Tool and Manual, `http://www.tpsgc-ppwgsc.gc.ca/biens-property/sngp-npms/pcra-ecrp-outil-tool-eng.html`
10. Technology maturity, also called technology readiness level, has been particularly important to the military and to the aerospace industry, as major users of advanced technology, and both the US DoD and NASA have well-developed and documented approaches to this issue (as do other defence departments)