1 The Engineer's Role in Environmental Protection

Our relationships with nature are complicated. On the one hand, we depend completely on functioning ecosystems for the provision of food and many other services, but on the other hand, our activities have impacts on natural systems, threatening the long-term prosperity of human society and the survival of other species. Engineers are key facilitators in these relationships, mechanising and optimising the flows of valuable resources into human society, and accelerating or moderating the damage done to nature. This realisation has driven various attempts by engineers and other professionals to employ sustainable development in practice.

In order for the urgent transition to sustainability to take place, all business activities, government policies and industrial projects need to be considered in terms of their potential impacts on different areas of the economy, society and nature. Very often, trade-offs will have to be managed, and this frequently involves negotiation between stakeholders, each with its own set of experiences, interests and values. In this context, what is the role of the engineer or applied scientist? This book deals with this question and provides some knowledge and tools. As we have worked with the water, materials, textiles, food, chemicals, waste management and regulatory sectors of the economy, much of this book is based on the needs of engineers and applied scientists (we use these terms interchangeably) who are employed in these sectors, but it will be relevant also to other engineers facing environmental management challenges connected with resource use and pollution.

1.1 The Concept of Sustainable Development

Since the 1970s, the concept of sustainable development has increasingly been used to describe the need to find new societal models that could keep generating economic growth, and thereby continue to increase welfare levels in the world while also protecting the environment. Some particular environmental issues became critical then because the size of human settlements and the scale of industrial production had developed dramatically over the previous 100 years. In particular, acid rain and persistent toxic pollutants were discussed at the time. In Scandinavia, for example, fish were dying in acidified lakes. The acidification was caused by emissions originating in other countries where coal burning was common. Meanwhile, predatory birds and marine mammals in the Great Lakes of North America and in the Baltic Sea in Northern Europe were suffering reproductive problems on account of persistent chemicals in their food chains. It was clear that environmental problems could not be solved on a national basis and that

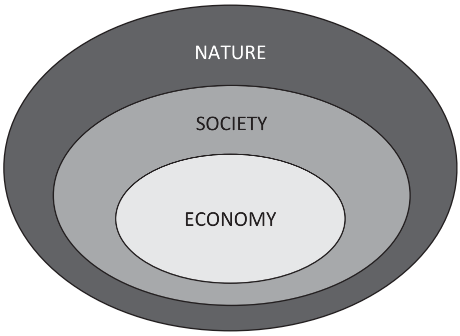

Figure 1.1 Sustainable development described as the consideration of three areas but where economy operates within society which in turn operates within the environment (nested dependencies model; after Doppelt, 2008), in contrast to models that separate the three areas and place them as partly overlapping circles

the global community needed to come together to create a common vision and find ways to cooperate to establish a more 'sustainable' kind of development.

The definition of sustainable development provided by the Brundtland Commission in its report 'Our Common Future' in 1987 is the most commonly quoted: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. At the heart of this definition is the fulfilment of human needs, now and in the future. However, we may also choose to introduce other values into this concept, such as the right of other species to thrive as well. In fact, discussions on sustainable development are often criticised as too anthropocentric, particularly by people with more Earth- or life-centred worldviews who see an inherent value in nature beyond its value in directly serving mankind via the provision of ecosystem services (discussed in Chapter 2). For more discussion of other worldviews, see Chapter 9. Common to different definitions of sustainability or sustainable development is that they all mention diverse dimensions of the world that need to be viewed simultaneously in a holistic way. With this perspective, different positive and negative impacts, as well as potential trade-offs, can become visible. Most commonly, we express this as a need to simultaneously consider environmental impacts, economic impacts and social impacts, and illustrate it by means of three overlapping circles or three pillars. However, more or fewer dimensions and other terms can occur in other conceptualisations of sustainable development. When the hard limits posed by the function of natural systems are emphasised over the softer limits of the man-made economic system, it is common to place economy and society within the realm of nature, as illustrated by the nested dependencies model in Figure 1.1 (see Doppelt, 2008). Today, the global dialogue on sustainable development and what it means in practice is perhaps best described by the 17 sustainable development goals; see Table 1.1.

1.2 Unique Skillsets and Perspectives of the Engineer

'Engineer' is an ancient word which acquired some qualifying prefixes in the 18th and 19th centuries, creating the branch terms we recognise today. Chemical

Table 1.1 The United Nations Sustainable Development Goals

Goal	Statement
1	End poverty in all its forms everywhere
2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3	Ensure healthy lives and promote well-being for all at all ages
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	Ensure availability and sustainable management of water and sanitation for all
7	Ensure access to affordable, reliable, sustainable and modern energy for all
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10	Reduce inequality within and among countries
11	Make cities and human settlements inclusive, safe, resilient and sustainable
12	Ensure sustainable consumption and production patterns
13	Take urgent action to combat climate change and its impacts
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

engineering deals in particular with the application of chemistry, mathematics, physics and biology to perform chemical processes on a commercial scale. Civil engineering is also a broad field but more concerned with applying mathematics, physics and material and environmental science to the development of infrastructure, including roads and buildings. In mechanical engineering, engineers typically use similar scientific concepts and thermodynamics in the design of automated mechanical systems. There are many other branches of engineering (electrical and electronic engineers are the most numerous), not to mention specialisations within the fields mentioned here, but the point is that they all use natural scientific knowledge and mathematics in their professions in a way that many other professions do not. Sometimes engineering is referred to as applied science, and it is therefore natural that the types of knowledge and paradigms that exist in science also exist in engineering, although complemented with a more pragmatic ontological stance as engineering is not only about the search for what is 'true' but also for what is effective and useful. Furthermore, engineering is not only about the function of the technology itself but also its use, management, policy, economy and various other aspects of technology.

What is the role of engineers in the context of *sustainable development*? What specific skillset and perspectives does engineering provide? How is this useful in complementing other skillsets and perspectives? What are the limitations of the skillsets and perspectives of engineers and what are the dangers of applying only an engineering perspective to problem-solving? This chapter explores these issues and provides some mental models and tools that are particularly useful in different engineering contexts – they were generated using an engineering perspective. Consequently, they may not represent and provide all the necessary information for different projects and must therefore be complemented with models and tools that represent other perspectives.

One important way in which engineering differs from many other fields is that it often deals with the quantitative modelling of various technologies. Engineers are often very skilled in mathematics and, based on analysis of various quantitative parameters of a technology or a technical system, engineers can often model and predict the expected behaviour. Systems analysis is a set of tools that are common in engineering and engineers often use systems analysis tools combined with their mathematical skills to describe fairly complex technical systems, such as factories, cars or computers. Predicting how complex systems will operate and the environmental impacts they will have is one of the important contributions of engineering science to sustainable development – without it policy makers may at worst be left with glib, simplistic ideas about sustainability, such as that more recycling is always better. An engineer can identify scenarios under which the energy used and pollution generated by a recycling system exceed the energy used and pollution generated by using raw materials to make the same product. Engineers can introduce quantitative information which would otherwise be missing in planning and policy debates.

When it comes to even more complex sociotechnical systems such as the behaviour of traffic or food provision for a whole city, engineering methods may be inadequate and only useful for some aspects and under certain conditions. The more complex the modelled system is, the less the modelling will represent reality, as uncertainties and complex interactions come into play. There is a danger in expecting that all important aspects of a system can be described in mathematical terms and its behaviour thereby predicted. In particular, when the studied systems are not purely technical but rather sociotechnical or even sociotechnoecological, such as for managing climate change, problem-solving becomes challenging and such problems are often referred to as *messy, ill-structured* or *wicked*, and they require other management approaches to complement the traditional engineering methods. Some approaches include attempts to use different perspectives in the same project (multidisciplinarity), to create new perspectives in which elements from several others are present (interdisciplinarity) or even go beyond disciplines to work together with society in problem formulation and attempting to find workable measures that will lessen a complex (and possibly even wicked) problem and lead to an overall improvement (transdisciplinarity). In some contexts, 'narrative approaches' that embrace qualitative and path-dependent information (Andersson et al., 2014; Boje, 2001) will have to be applied for describing the functioning of wicked systems.

Inherent in the tools that are predominant in engineering are certain epistemological and ontological perspectives. For example, *positivism* is a research philosophy that sees factual knowledge based on observation, including measurement, as trustworthy. The role of the researcher is to collect data and to use as objective an approach as possible in interpreting them. Positivism is based on an atomistic view of the world, which means that it assumes that the world can be divided into discrete, observable elements and events that interact in a determined and regular manner. Results from a study based on a positivist philosophy are typically observable and quantifiable and experiments can be copied and will generate similar results, providing managers and decision-makers with similar recommendations. As the saying goes, 'you cannot manage what you cannot measure.' But it goes without saying that there are systems and phenomena that may be relevant to the broad field of engineering that such approaches might fail to capture.

This is not to go to the extreme of proposing that facts do not exist outside of an observer or that the concept of sustainability is too wicked for use. Some facts regarding the relationships between systems can be established and measurable aspects of environmental systems can be considered *absolute* preconditions for sustainability (for example, where climate change results in a local wet-bulb temperature of 35℃, mammals will die of heat stress because dissipation of metabolic heat becomes thermodynamically impossible; see Sherwood and Huber, 2010). So there is great value in the work which engineers do to describe an environmental or technical process in mathematical terms, and to calculate optimal process settings for the variables we control, but there is a limit to what can be described in such terms. In short, there is sometimes a perception in science and in engineering of a dichotomy between quantitative and qualitative research when in fact, these are complementary and will answer different questions.

1.3 Sustainability as an Engineering Problem

Technological systems often require energy and materials both for the manufacturing of their technical components and for their operation. Therefore, the design and practical use of technology will often determine the energy and material throughput of modern society. Unfortunately, these energy and material flows can lead to severe problems of resource availability and pollution. The actions of engineers will therefore have a strong impact not only on the well-being of people whose needs they aim to fulfil but also on the environment. An engineer therefore needs a systems perspective to be able to understand the impacts of technology, for example from a life cycle perspective. Along the value chains that are generated as different industrial and societal actors get involved in the life cycle of a certain technology, there may also be social impacts on people that are affected, for example fashion retailers in Sweden influence workers in a Bangladeshi clothing factory, and electronics manufacturers in Asia influence workers in a mine in South Africa. Therefore, a holistic approach is also needed that considers various types of impacts in an integrated manner. This systems view is needed both for assessing current technologies, for understanding what needs to change and for understanding the potential impact of new designs and of scale-up of new technologies.

Within the broad framework of industrial ecology, there are various informational tools for assessing and optimising stocks and flows of material and energy resources. In this chapter of the book we focus on the broad framework and some examples of principles and systems-based models that engineers may employ. In later chapters, some of the information tools of industrial ecology are described, such as life cycle assessment and material flow analysis (Chapter 7) and multicriteria analysis (Chapter 9).

1.3.1 Industrial Ecology

'Industrial ecology' was first mentioned within the field of economic geography in the late 1940s, but has now become an established field of study, manifested primarily within engineering sciences. So although the term appeared earlier, it is generally said to have been coined in 1989 by Frosch and Gallopoulos (1989).

The term *industrial ecology* makes a metaphor between technological and natural systems, suggesting we need to mimic how energy and material flows are handled in nature, using basic laws of physical chemistry and thermodynamics in the analysis of energy and material flows. In an ecosystem, species feed on each other's wastes. Technological systems should thus be organised so as to facilitate circular flows of materials (Graedel, 1994). Circularity is thus a key concept in industrial ecology. Further, most of the energy input to ecosystems is solar energy, and when the 'producers' (the green plants) have tied up some of this energy in biomass, it can be accessed by 'consumers' and 'decomposers'. Thus, reliance on solar-based renewable energy is another key concept within industrial ecology. Another key aspect of ecosystems is the interaction between different types of organisms, with diversity as an important feature providing resilience (the ability to cope with change) to ecosystems.

When principles of industrial ecology are applied to industrial activities, in particular when it deals with the exchange of energy and material flows between different industrial facilities, this is often referred to as *industrial symbiosis*, another metaphor from ecology.

Inspired by the framework of industrial ecology and the traditional perspective of an engineer, several different sets of sustainability principles or sustainability criteria have been proposed. Some of these are described in what follows. There is a strong focus on energy and material flows caused by the production and use of technology in these principles and criteria, so other aspects may be missing. This is something that engineers need to pay attention to so that the whole breadth of relevant sustainability aspects is considered in practice.

1.3.2 Overall Sustainability Principles for Activities in the Earth System

1.3.2.1 Circular or Biobased Economy

As long-term visions and principles for the establishment of economic activities in society, the concepts of *circular economy* and *biobased economy* have become strong in the past 20 years, and they have been the basis for both development of national policies and other strategies and principles. Both circular and biobased economy are manifestations of industrial ecology thinking on a societal level. The two concepts often strongly overlap but also emphasise different aspects of energy and material flows.

Circular economy focusses primarily on the circulation of material flows and suggests that the economy should rely on activities that enable such circularity. In China's 11th five-year plan, starting in 2006, promoting a circular economy was identified as a national policy. A circular economy is the basis for the cradle-to-cradle framework developed by Braungart and McDonough. In 1995, they started a consultancy and later published a book that described their framework (McDonough & Braungart, 2002). Their framework emphasises the need for circularity and they suggest that all flows in society need to be designed to be part of either technical or biological recycling systems so that the flows can be seen as either technical nutrients or biological nutrients. They also stress that nature is not always efficient but it is effective, and our current focus on improving efficiency should be shifted to or at least complemented with a focus on effectiveness, that is, on doing the right things. They argue that if we are doing the wrong things, it does not matter how efficient we are in doing them.

Starting in 2010, the Ellen MacArthur Foundation picked up these ideas and developed them further. The Foundation's framework for circular economy (www.ellenmacarthurfoundation.org) is illustrated in Figure 1.2. The different strategies shown in Figure 1.2 speak clearly to industrial actors on what options they have to closing loops. The flows of renewables to the left in Figure 1.2 are the flows that McDonough and Braungart call biological nutrients, and the stock flows to the right are the technical nutrients.

In practice, the pursuit of a circular economy today often results in various reuse or recycling efforts and a rethinking of product design to allow for reuse or recycling. It is often emphasised in these types of frameworks that the best form of recycling is closed-loop recycling that avoids the down-cycling to products of lower quality, as this only delays disposal rather than provides true circularity to the societal metabolism.

The biobased economy (or bioeconomy) instead focusses on the need to move towards biobased production. This is a response to our dependence on finite fossil resources and the problem of climate change that results from the combustion of products and fuels made from them. The biobased economy is of course particularly attractive to countries and companies with considerable biomass resources (e.g. forests). Market interest in paper products is decreasing. So in Sweden and Finland, for example, the biobased economy is seen as an opportunity to strengthen the forest industry by means of value-added products from new technologies being introduced in existing pulp mills, or from new biorefineries using new combinations of technologies to produce a variety of products from wood or other biomass. In 2012, former US president Barack Obama announced a National Bioeconomy Blueprint, describing the bioeconomy as 'economic activity powered by research and innovation in the biosciences'.

The biobased economy is not necessarily something completely different to a circular economy. Going back to Figure 1.2, the biobased economy can be seen

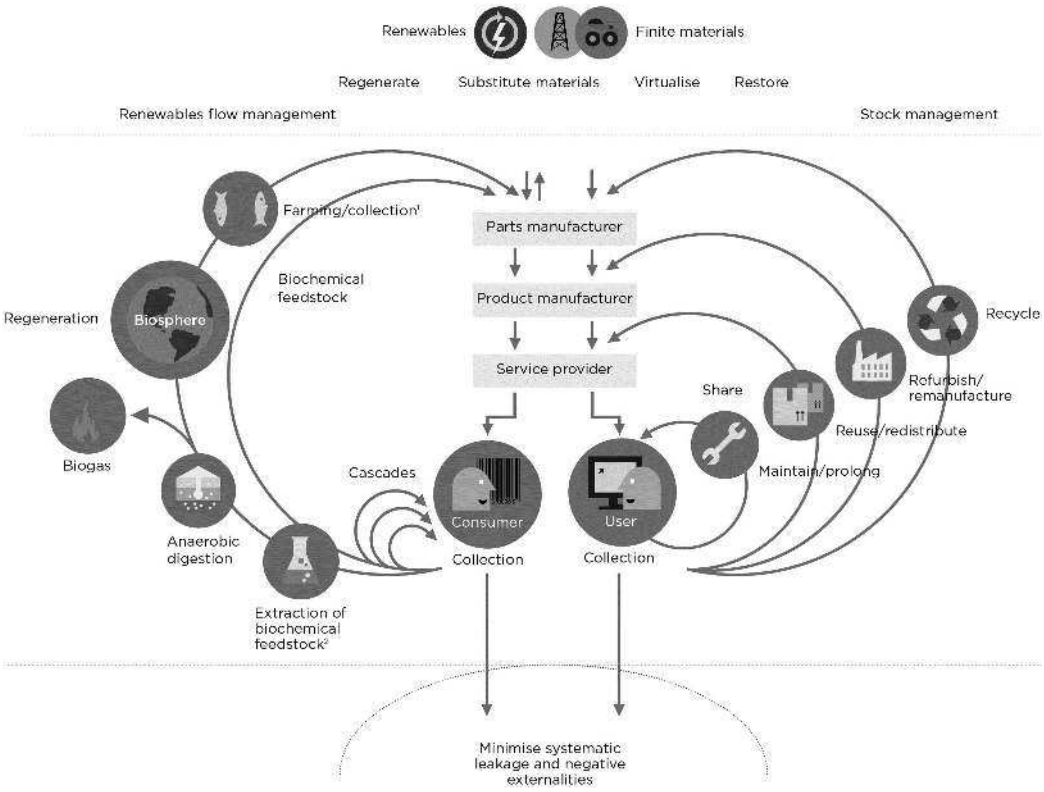

Figure 1.2 The circular economy framework as illustrated by the Ellen MacArthur Foundation (www.ellenmacarthurfoundation.org). Adapted with permission from the Ellen MacArthur Foundation

as the left-hand side that deals with biological nutrients and particularly in the sense that it relies on nature's ability to circulate carbon flows and nutrients such as nitrogen and phosphorus.

1.3.2.2 Four Principles for Sustainability

In the 1990s, a set of four principles (or 'system conditions') for sustainability was developed by the Swedish researchers John Holmberg, Karl-Henrik Robèrt and Karl-Erik Eriksson (Holmberg et al., 1995; Robèrt et al., 1997). They suggested there were basic scientific foundations on which such principles could be developed. In particular:

- Nothing disappears; mass and energy in the universe are conserved; mass and energy may be converted into different forms, but the total amount of energy in an isolated system remains constant (the principle of matter conservation and the first law of thermodynamics).
- Everything spreads; energy and matter tend to dissipate spontaneously (the second law of thermodynamics, or the law of entropy).

- There is value in structure; material quality lies in concentration and structure of the matter that makes up a material; what we consume are the qualities of matter rather than matter itself.
- Biological plants create structure and order by using energy from the sun; net increases in material quality on Earth are generated almost entirely by photosynthesis.

On the basis of these foundations, they proposed four principles. The original principles are reproduced here (with some explanatory parenthetics). In a sustainable society:

(1) Substances extracted from the lithosphere must not systematically accumulate in the ecosphere (for example fossil CO_2 and heavy metals).
(2) Society-produced substances must not systematically accumulate in the ecosphere (for example antibiotics and endocrine disruptors).
(3) The physical conditions for production and diversity within the ecosphere must not be systematically deteriorated (for example by deforestation and draining of groundwater tables).
(4) The use of resources must be effective and just with respect to meeting human needs.

The first three principles are inspired by a systems analysis of the Earth system, using the basic laws of energy and matter. Therefore, they are aligned with industrial ecology thinking and represent an engineering view of the world. The fourth principle, shown here in its original wording, was intended to reflect an engineering perspective on the existence of limits to global resources, but also the need to share these resources in order to fulfil normative goals concerning human needs and intra-generational equity within the sustainable development discourse.

The Swedish non-governmental organisation (NGO) The Natural Step (TNS) took on the role of promoting these principles internationally and today works with organisations all over the world to try to implement them in corporate practice. TNS presents these principles as a set of rules that any government or business activity will have to comply with in order to have a place in a sustainable world, thus making them a useful set of criteria for evaluating long-term strategic planning. TNS has also reworded the principles several times (for example using the grammatically better ‘degraded’ instead of ‘deteriorated’ in the third principle). Of the four, the last principle has been the subject of the most dispute and revision, shifting it further from the scientific towards the humanistic domain. The latest wording at the point of publication of this book says a sustainable society has ‘no structural obstacles to people’s health, influence, competence, impartiality and meaning’ (TNS, 2018).

1.3.3 Systems-Based Models Describing Causes or Cause-Effect Relationships

1.3.3.1 IMUP Equation

The environmental problems that became increasingly pressing in the 1970s were a direct result of the increasing production and consumption in society that was made possible by the technological and societal development we sometimes call *industrialisation*. The so-called IMUP equation illustrates the connection between industrialisation and environmental problems (Azar et al., 2002). It is a development of the so-called IPAT equation that Ehrlich and Holdren proposed in 1970 (Chertow, 2001). The IMUP equation reads:

$$I = i * m * u * p \qquad (1.1)$$

Where I is the total impact in some kind of quantitative impact unit, p is the human population of the considered region, u is the utility level for the region given in the number of 'functions' that are provided to each person (e.g. the number of km transported or kWh used per capita), m is the material and energy intensity given as mass and energy units per provided function, and i is the impact per mass and energy unit. (In the predecessor equation called IPAT, the i and m factors were combined into one technology factor.)

This decomposition of the total impact into four factors is an engineering model for illustrating the sustainability challenges and some available strategies. With a simple calculation example, this equation can help us to understand the magnitude of the challenges that we face. Many different assessments (see further descriptions in Section 2.5) indicate that the pressure on the environment needs to be greatly reduced. Depending on the type of impact, we might come up with many different estimates for how much the total impact needs to decrease, but let us consider the 2017 estimate by the Global Footprint Network of how much the global ecological footprint exceeds the carrying capacity of the Earth, in order to come up with a number. They estimate that we are using an area equivalent to the available area on 1.6 Earths. The total impact therefore needs to be reduced by almost 40% in order to prevent our consumption from exceeding the Earth's carrying capacity. At the same time, population is increasing. It is currently estimated that in 2050, the world population will be around 9.7 billion, an increase by about 1.9 billion compared to 2017, or almost 30%. We can also expect that consumption levels will increase as this is a global trend, and in particular in poor regions as these are experiencing economic growth. Let us assume that the global consumption level will triple until 2050, which is probably a low estimate, thus the utility level will increase to 300% of the present. If we are going to reduce the total impact to 2050 to the level stated earlier, with a simultaneous increase in global population and in consumption levels, we can calculate the need for changes in the i and m factors (the technology factors in the earlier IPAT equation) that are related to how much and what kind of material and energy we use for providing the utilities, i.e. changes that we need to make in industry in terms of efficiency, raw material base etcetera. The calculation shows that these two factors together need to be reduced to only about 16% of what they are today, i.e. the *eco-efficiency* needs to increase by more than a factor of 6 (see Chertow, 2001, for a description of the *Factor X* concept). The term *eco-efficiency* is commonly used also in other contexts to describe how many goods or how much value we can create out of each unit of resource or per environmental impact unit. Remember that the calculation presented earlier represents a low estimate for the challenges that lie ahead; various organisations have suggested factors between 4 and 50.

The IMUP equation also implicitly suggests the different possibilities we have for reducing the pressure on the environment. Looking at all four factors, we can reduce