Chapter 2
Are Engineers Makers or Thinkers?

2.1 Do Engineers Have an Identity Crisis?

The notion of 'identity' is in vogue today. In some cases it has to do with individual identity: captured in the question "Who am I?" In others it has to do with group identity—references are made to 'post-colonial identity' or 'African-American identity'. We have an identity crisis when we are not sure about who we are or what we are doing. Thoughtful or reflective engineers could be suffering from an identity crisis regarding their collective engineering identity; and there are at least three reasons why (Dias 2013).

First, there is a crisis regarding the engineer's *influence*. There was a time when engineering was synonymous with the progress and uplifting of humanity. The great 19th century bridge builder Isambard Kingdom Brunel was second only to Winston Churchill in a poll, held at the turn of the millennium, to determine the greatest Briton of all time. Today however, we have an environmental crisis brought about by rapid industrialization; and a society that has become 'individualized' because people are more focused on their 'technological gadgets' (e.g. 'smart phones') than on relating to each other. Since engineers are at the forefront of industry and technology, there arises the question as to whether *engineers are doing more harm than good* through their actions. The study of such actions, their motivations, and impacts is that branch of philosophy called *ethics*.

Next, there is a crisis regarding the engineer's *role*. Most students who enroll in engineering undergraduate programs have a strong background and interest in science. They are good at analysis. Practising engineers on the other hand have to produce something or make things happen. That involves combining products and processes; getting people to either work with you or accept what you are doing; and achieving all this within a limited budget and time frame. In other words, they must be good at management and synthesis. The question then arises as to whether *engineers are scientists or managers*. Genuine scientists and capable managers are both valued in most societies, but engineers run the risk of becoming neither in trying to be both. In some cases engineering graduates move on to become managers; while

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others opt for academic careers as engineering scientists. The study of roles within the wider study of 'being' is that branch of philosophy called *ontology*.

Finally, there is a crisis regarding engineering *knowledge*, which overlaps the one regarding role. Most university programs in engineering are filled with theoretical subjects that are largely 'mathematics in disguise'. Engineering practice on the other hand is predominantly practical in nature, with great reliance placed on established procedures (or 'rules of thumb'), specified guidelines (or 'codes of practice'), and that indefinable element called 'engineering judgement'. Therefore, we can ask whether *engineering knowledge is theoretical or practical*. In some situations, engineers have difficulty in explaining how their knowledge differs from that of a technician or even craftsman, because of this reliance on rules of thumb. The study of knowledge is that branch of philosophy called *epistemology*.

The above questions are valid for engineers in most if not all societies. It is the duality ('or') posed in the questions that creates the discomfort or *angst*—a German word that is loosely understood as *anxiety* in English. This may not be the everyday experience of engineers, but if they are not confident about the answers to these questions, they could experience doubts about their self-worth or social value—and hence their identity crisis. Ethics, ontology and epistemology are well established branches of philosophy. So the engineer's identity crisis is a philosophical one, and highlights the importance of philosophy for engineering.

Usually however, technology and philosophy are seen as being poles apart (see Fig. 2.1), the latter focused on *thinking* and the former on *doing*. This tension is conveyed by the double-headed horizontal arrows in Fig. 2.1. This figure shows other entities that flow from technology and philosophy (in single headed vertical arrows), and there could be such tensions at these levels too. For example, while engineering is considered by some to be 'nothing but applied science', others would say that science is merely one of the tools at the disposal of a sophisticated engineer. While some would say that practice is based on theory, others may say that it is practice that generates the very concepts required for theory. Figure 2.1 cannot capture all

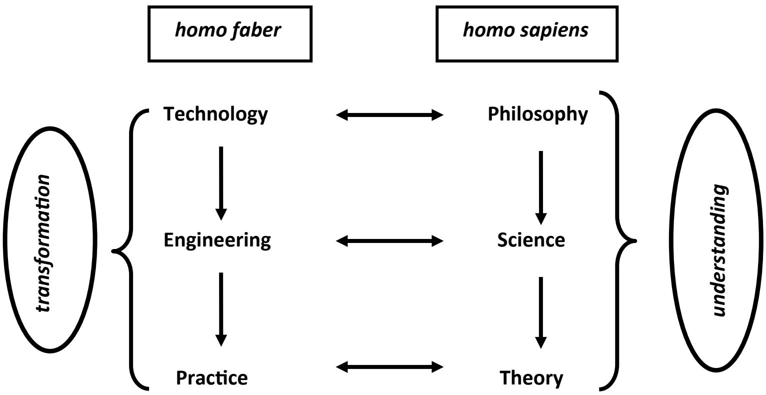


Fig. 2.1 Transformation versus Understanding (from Dias 2013)

the intricate relationships between the entities portrayed, but it serves to guide the discussion in this chapter. It is interesting that the entities on the right hand side are concerned with *understanding* (which is the goal of *homo sapiens* or 'the wise man'), while those on the left hand side with *transformation* (which is the goal of *homo faber* or 'man the maker'). Recall Karl Marx's comment, i.e. "philosophers have tried to understand the world; the point however, is to change it". All three identity crisis questions raised above can be related to the question of whether an engineer is a maker (*homo faber*) or a thinker (*homo sapiens*).

2.2 The Engineer's Influence: More Harm Than Good?

We answer this question in the context of the tension between philosophy and technology, given that engineers are the main agents of technology. Some 20th century philosophers (Ellul 1948; Heidegger 1977) have charged technology with being a harmful influence, quite in contrast to the 'humanizing' influence of philosophy and other liberal arts. The ill effects of technology can be categorized into at least four aspects (Dias 2003). The most obvious is the hazardous nature of some technologies, the prime example being nuclear technology. In addition, technology can promote injustice, for instance through infrastructure projects where social costs are borne by the poor and the benefits reaped by the rich. Technology can have adverse sociological impacts too—consider the way in which visual screens (whether televisions or computers) tend to destroy family conversation and interaction. Finally, and most subtly, it can have undesirable psychological impacts. Has technology created a society where 'technique' is all important, as opposed to understanding (of phenomena) or even genuineness (in relationships), reflected in the growing number of 'how to' books? Heidegger (1977) claims that man has been 'enframed' by his own technology. We shall consider more of this in Chap. 6.

The American engineer Samuel Florman (1994) however refutes these charges, and also points to the benefits bestowed upon the world by technology, in areas such as transportation and health, and by general improvements in the standard of living. In other words, 'humanization' can be seen, not so much as an enjoyment of the arts (which in most societies is enjoyed only by a relatively few), but rather as the liberation from 'slavery' brought about through technology, as described below by Karl Popper (1999, p. 104), himself a philosopher of science who we shall meet in Chap. 3. We must remember while reading this however that many parts of the world have not yet been liberated from such drudgery.

> Perhaps even more important, morally, was the great liberation of domestic slaves (also known as maids), which became possible largely through household mechanization. This tremendous revolution, and the emancipation that all but the very richest women experienced at that time, is today remarkably little remembered, even though it was a liberation from heart-rending slavery. Who today has any idea what it meant when all water had to be fetched and carried, when coal had to be brought in for heating, when all washing had to be done by hand, and when there were still oil lamps with wicks?

Florman (1994) also argues that the engineer's activity of making things and engaging in work is a way of experiencing his humanness, relating to the earth and producing what he calls 'existential joy'. He does admit however, that the work of engineers may lead to unforeseen negative consequences, but applauds them for trying to improve the world. Florman asks engineers to take courage from Sisyphus, the character from Greek mythology who was condemned to keep rolling a stone up a hill, only to have it falling back as he approached the summit. Florman sees Sisyphus as heroic—someone who refuses to give up even though his work is undone from time to time. In this context, it is interesting to note that modern initiatives against some of the ill-effects of technology want to use technology itself to cure those ills (Feenberg 1999). For example, technology intensive underground sequestering of carbon dioxide is being considered for reducing the consequences of burning fossil fuels; and it is the 'high-tech' internet that is used for getting greater access to knowledge and to communicate, by people who feel they are marginalized and alienated by technocrats.

The anti-technology attitude does not arise only because of technology's rather recent negative effects. For many centuries university education was seen primarily as a process for creating better human beings, through the dissemination and discovery of knowledge that was not directly 'useful'. In Ancient Greece for instance, 'pure speculation' (by 'thinkers') was considered to be a more noble activity than the doing or making of useful things (by 'workers'). Although Aristotle (2000) recognized and appreciated the importance of practical wisdom for action (*phronesis*), he concludes nevertheless by giving pride of place to theoretical wisdom (*sophia*). Consider also the following description of Archimedes given by Plutarch (Blockley 1981):

> Yet Archimedes possessed so high a spirit, so profound a soul, and such treasures of scientific knowledge, that though these inventions had now obtained him the renown of more than human sagacity, he would not deign to leave behind him any commentary or writing on such subjects; but, repudiating as sordid and ignoble the whole trade of engineering, and every sort of art that lends itself to mere use and profit, he placed his whole affection and ambition in those purer speculations where there can be no reference to the vulgar needs of life.

Florman (1994) says that this mind-set, together with the Biblical New Testament emphasis on the spiritual as opposed to the material, has given technology a bad image or low status in western culture. In eastern cultures too, the role of the sage (or 'guru') has been exalted over that of the worker, with the strict caste system in India, for example, perpetuating social barriers for generations. Blockley (1981) says "We must break the chains of Ancient Greece"; but how? Florman (1994) suggests, as least for western culture, that engineers dig deeper into their heritage for evidence that 'making' is indeed a noble pursuit, e.g., into the Old Testament, where the ability to perform various skilled crafts is ascribed to the indwelling of the Spirit of God; also into the pre-Socratic era, where craftsmanship was held in high esteem by Homer, who gives great technical detail regarding the making of Odysseus' raft and Achilles' shield, covering both tools and materials.

Meanwhile, a vast expansion of university education has taken place in the past century; with research and innovation directed towards wealth creation and problem solving. Science and engineering faculties were well funded; while humanities faculties, other than in the most prestigious universities, experienced gradual decline in both funding levels and student numbers. Technologists now use the term 'soft' to undervalue what goes on in arts faculties; while those in the humanities complain that human values are submerged by a technological mindset. At the end of the day however, in many societies an 'educated' person (or 'intellectual') is considered to be one who has knowledge of literature and culture, rather than one who can describe an internal combustion engine or an integrated circuit. As we shall see later on (Chaps. 6 and 7), Martin Heidegger is probably a good 'patron' philosopher for engineers. On the one hand, his view of what he called the 'human way of being' could be called an 'instrumentalist' one—we 'are' and 'do' before we 'think' (Dias 2006). On the other, he was suspicious of technology where it destroyed the rich diversity of the world and human interaction with it (Dias 2003).

So, are engineers doing more harm than good? Whatever accusations are made against engineers, those who level such charges would probably not want to live in a world without technology and engineering influence. Where the capacity for humanization is concerned, technology has credentials that can rival those of philosophy, as articulated above by Popper. Furthermore, as emphasized by Florman, engineers can be proud that they are men and women of action—being *makers* in other words—rather than merely engaging in 'pure speculation'. Engineers may feel inferior about their intellectual status however, i.e. their place on the scale of *thinkers*, and we deal with this at the next level of the framework (Fig. 2.1), which considers the tensions between engineering (very much a part of technology) and science (a development of philosophy).

2.3 The Engineer's Role: Scientist or Manager?

In order to shed light on the role of an engineer, we consider engineering design, which is a good reflection of engineering practice as a whole. We could view (engineering) science as the core or kernel of engineering design knowledge; a core however that is contained within outer layers of knowledge such as engineering idealization, margins of safety, design philosophy, design context and engineering process—see Fig. 2.2. Before using engineering science theories, we have to adopt a particular design philosophy, decide on margins of safety, and idealize the real world into a model to which scientific or mathematical theories can be applied; this has to be done within a design context that would be defined by the location and people (clients, customers) concerned. All of the above is enveloped in an engineering process that will involve collaboration and communication, not least with those who will fabricate, maintain and use the designed artefact.

Let us use the simple structural engineering assembly of a reinforced concrete beam supported between two columns in Fig. 2.3 as an example. It is the idealized beam that is analyzed using engineering science (to find, say, the design bending moment at midspan). However, is the beam best idealized as a simply supported

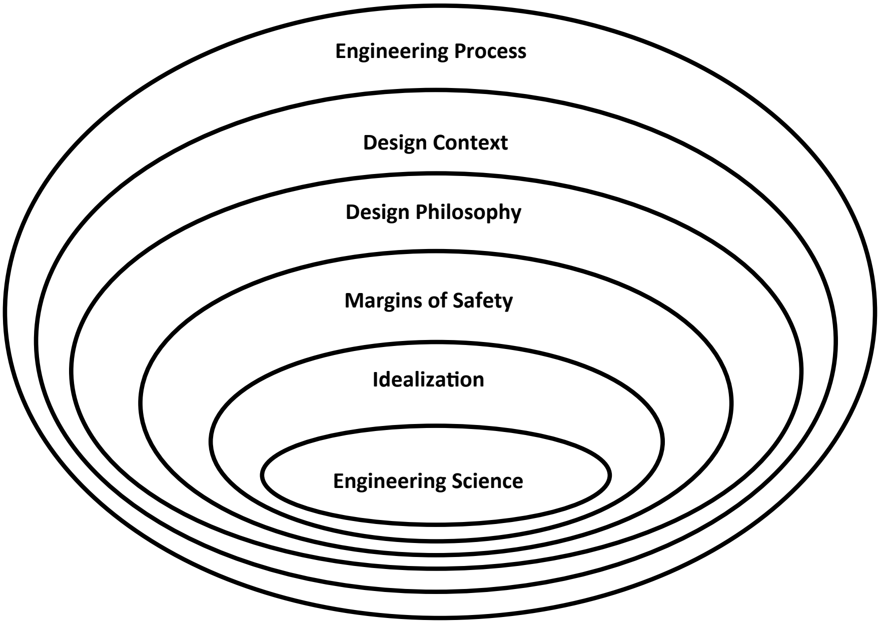
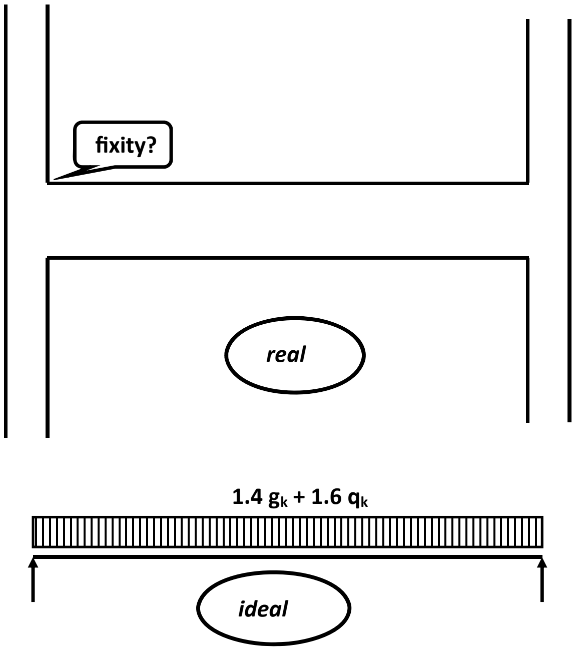


Fig. 2.2 Engineering design knowledge (after Dias 2013)

Fig. 2.3 Idealization of a real structural element (from Dias 2013)



beam (free to rotate on the column supports at its ends) or as a fixed ended beam (where rotation at supports is prevented by fixity to the columns)? The former is true in most situations, since the beams are stiffer than the columns. We also need to apply appropriate safety factors to the load that is anticipated. For example, we assume in most cases that the loads are distributed uniformly. However, the expected loads are increased by factors, in order to ensure a margin of safety; in this example the 'permanent' loads are factored by 1.4 and the 'imposed' ones by 1.6. We also have to adopt some design philosophy to make allowance for the restraining moments at the column supports, where the fixity is not known precisely. Another established structural engineering design philosophy is that structural elements are designed to be 'ductile'—in other words, while they are designed not to fail under the anticipated loading, if they do (say due to overloading), they should fail in a way that is gradual and ductile (as opposed to sudden and brittle). Blockley and Henderson (1980) use the term "calculation procedure model" to describe this entire process; it is not confined to calculations alone, but incorporates all the other decision making procedures.

All of the above occurs within a design context too. There is a 'narrow' design context, which could refer to the advantages and drawbacks of say the proposed construction site itself. For example, even if the column size required in Fig. 2.3 is smaller than that of the beam, we would make it larger in an earthquake zone, because we want to avoid the catastrophic consequences of failure in the columns. Broader than this however, are the ever present contexts of time, cost and politics within which all engineering has to be carried out. This context dependency or *contingency* means that engineering solutions will never be exact. As Goldman (2017) says, the rationality of engineering is one of 'compromised exactness'—the compromises being due to the overall process and especially the context. He presents such a rationality as being highly sophisticated and eminently suitable for social and economic decision making as well.

We can finally think about the process through which everything above has to be carried out. Within an engineering design office there will be senior engineers supervising younger colleagues. The latter will probably be responsible for carrying out the detailed calculations; or using computers for that purpose. However, the senior engineers will need to check the work of their juniors without spending too much of their precious time; they will need to decide what to check and where, in the structure or other artefact. Process also involves liaising with other professionals, which for structural engineers would mean architects and services engineers; and also the construction engineers. Such liaising could involve making compromises in their design solutions, or being able to negotiate for their own preferences by using persuasive arguments. There is also the notion of design for constructability—e.g. when specifying the steel reinforcement bars for the elements in Fig. 2.3, we should ensure that the sizes and spacing chosen allow concrete to be vibrated through them.

The message of Fig. 2.2 is that *engineering is broader and richer that science*. This breadth and richness create complexity that has to be managed for practical problem solving. It should be noted that the term 'complex' is used to denote richness in structure (whereas the term 'complicated' denotes abundance of detail). It is this structural richness that constitutes the intellectual challenge of engineering.

Another complexity is the uncertainty associated with engineering; this uncertainty has been classified (Blockley and Godfrey 2000) as Fuzziness, Incompleteness and Randomness (FIR). *Randomness* describes the variations to be expected in loading and material strength; we typically use statistics to tackle it. In order to be safe, we try to use in our calculations material strengths *below* which not more than 5% are expected, and loads *above* which not more than 5% have been known to occur in the past. *Fuzziness* relates to the imprecision in assigning states to an entity—for example, the judgement as to whether the beam in Fig. 2.3 is fixed ended or simply supported (hinged). Attempts to deal with fuzziness range from fuzzy set theory (Blockley 1980) to simple approaches such as designing for the worst effects of both fixed and hinged end conditions. *Incompleteness* has to do with the lack of knowledge about possible future scenarios, for instance the question as to whether the beam will be overloaded at any time during its design life, and by how much. Design approaches such as using the 'worst credible load' or designing for ductility (so that there is warning even if failure occurs) can be used. Interval probability theory is a more sophisticated approach (Blockley 2013).

Yet another type of complexity is that engineering problem solving often requires *abductive* reasoning, where a cause has to be posited, given an effect (observed or desired) and a known set of rules (Dias 2010). For engineering design this means that a solution (of which there could be many) has to be proposed for a desired performance, given the established rules of structural mechanics (and other associated heuristics). The fact that there will inevitably be more than one solution that can deliver the required performance is what constitutes the challenge. This is also called the solution to an 'inverse problem'. Apart from all of this, the 'calculation procedure model' has to make allowance for human error (or even malice) and accidents as well. So the engineering role is that of managing a process that involves people, procedures and products to deliver quality, including both safety and economy.

So, are engineers managers or scientists? From the above discussion we must conclude that engineers act more like holistic managers than specialized scientists, although their practice is grounded in science. This emphasizes yet again that the engineer is a *maker*—not only in the narrow sense of making things, but also in the broader sense of 'making it happen'. However, the complexity that (s)he has to tackle requires a particular kind of knowledge, understanding and even wisdom, thus making it appropriate for the engineer to be very high on the scale of a *thinker* too. We are now ready to consider the tensions between practice and theory, the third level in the framework of Fig. 2.1.

2.4 The Engineer's Knowledge: Theoretical or Practical?

There are many dimensions to the theory versus practice debate. As stated at the start of this chapter, most engineering programs are dominated by theoretical subjects, not only to ground engineering students in the 'kernel' of science (Fig. 2.2); but also to justify the existence of engineering as a university discipline, which has to be characterized by a body of theoretical knowledge. Engineering graduates discover however, that 'rules of thumb', 'codes of practice' and 'engineering judgement' dominate the actual practice of engineering. We can say therefore that engineering knowledge is largely practical, although it has to be based on theory.

Heidegger's (1962) example of a carpenter hammering a nail is very insightful for resolving this practice-theory tension. The 'primordial' (or immediate) experience of the carpenter is a seamless web of activity without any deliberate rationality on his part. He just picks up a hammer and drives a nail into a wall without analyzing what he is doing; he is practiced at doing so, being something natural for him. However, when there is a 'breakdown' in this 'everyday' experience, say when the hammer is too heavy, the carpenter will have to resort to 'mentality' and consider properties such as the weight of the hammer object; the notion of 'weight' becomes important. Again, if the head comes off the handle, once again he will have to give careful attention to solve the problem, and concepts such as 'jointing' will surface in his mind. In fact, Heidegger considered that scientific observation and reflection originated from such breakdowns in everyday activity or practice. So it is practice that gives rise to theory and not the other way around.

However, this illustration also underlines the necessity of theoretical training for engineers. Although they may be using mostly practical intelligence (e.g. 'rules of thumb') in their routine work, they will need a bedrock of theoretical knowledge to fall back on when faced with problems that intrude into their practice. Many professional engineering organizations, in the process of admitting engineers to full membership after a period of work-based training, are interested in finding out about problems encountered during the engineer's work, and how engineering 'first principles' were used to overcome them (Dias 2006). Heidegger's carpenter is a very important 'parable' for engineers. We return to it in Chap. 7.

There are other aspects of the interaction between theory and practice also worth looking at. For example, most engineering academics would say that the 'theory' components of a course should be taught before introducing students to 'practical applications'. In an overall sense, an engineering graduate would be seen as putting into practice the theory learnt at university. However, Patrick Nuttgens (1980), an architecture professor at York University who became the founding director of Leeds Polytechnic in the U.K. in the early 1970s, argues that children first learn about the world by practice before they acquire a theoretical framework; and that technical education should reflect this. Some 'sandwich' courses in engineering programs embody this to an extent. Students are exposed to practical experience during their period of study; and in some rare cases at the start of it.

Also, practice itself is now considered to be a rich source for theory, especially theories regarding engineering design; and the process of engineering design has been equated to theory building (Monarch et al. 1997). There are echoes here of 'grounded theory' (Glaser and Strauss 1967) used mostly by sociologists, where 'theory' is derived from the analysis of documents and transcripts of unstructured interviews. A broad philosophy of practice has been promoted for some time now (e.g. Goranzon 1995), with contributions from philosophers, engineers, craftsmen and actors; parallels have been drawn between actors and engineers. The attempt is to show that knowledge is very often acquired from practice (perhaps under apprenticeship), rather than from theory alone. Donald Schon (1983) wrote a very influential book called *The Reflective Practitioner*, which was subtitled *How professionals think in action*. The main theme of the book is that 'reflective practice', i.e. reflection on one's professional practice, generates practice based knowledge that is invaluable and very different from the theoretical knowledge that is embedded in 'technical rationality'. His ideas have been applied to engineering in general (Blockley 1992) and engineering design in particular (Dias and Blockley 1995; Dias 2002), for which it is argued that a combination of reflective practice and technical rationality is required.

We conclude this section by affirming that the knowledge used by engineers during their professional careers is mostly practical in nature, once again reinforcing the *'maker'* image of the engineer. We have shown however, that there is considerable interplay between theory and practice, and that many recent initiatives promote the intellectual status of practice. Despite this new focus on practice however, the greatest 'shortcoming' in practice-based knowledge is its lack of formalism. It is theoretical formalism that gives science its credibility and prestige in the academy and even in wider society. The practical knowledge of engineers is often perceived as 'just common sense'. In fact, even craftsmen and technicians are seen as having such knowledge, so that it is not valued as being intellectual. The place of the engineer among the ranks of *thinkers* is thus challenged. This challenge can be met through efforts to formalize practice.

2.5 Formalizing Practice

The formalization of engineering practice will strengthen the engineer's image as a *thinker*, while reinforcing his position as a *maker*—an agent of transformation. There are two levels at which formalization needs to evolve—at the conceptual level that deals with the engineering approach, and at the technical level that deals with practice-based knowledge. Systems approaches can be seen as providing a formalization at the conceptual level (Dias 2008). Formalization at this level is not easy, as best expressed by David Elms (2010):

> The systems approach is not easily systematised, so to speak, partly because of the breadth of the issues involved, but more generally because there is no narrow set of applications allowing development of an easily focused theory. Structural analysis, for example, has techniques fine-tuned to dealing with structures, but the systems approach can be applied to anything. It has no natural boundaries. What is needed is not so much a set of immediate techniques as general principles and overarching concepts for giving the approach its power and its constraints……The trap…to avoid [is] being so general as to be ineffective, hence specific guides and ideas are needed.

There have been many such frameworks proposed in the literature that interested readers can pursue. The reflective practice loop is one of them, consisting of the components reflection—action—world—perception—reflection (Blockley 1992). A development of this is the design—build—operate loops in the three spheres of purpose, process and people (Blockley 2010a). Senge (1992) has demonstrated that a number of management scenarios can be modeled with three basic elements—namely a reinforcing loop, balancing loop and process delay. Blockley (2010b) has proposed a framework that he calls 'new process', where a process is seen as a relationship between sub-processes of purpose (why) driving a set of attribute sub-processes (who, what, where, when) through a set of transformation sub-processes (how). All of these sub-processes also have their own sub-processes—they are a hierarchy of parts and wholes, or holons (Koestler 1967). Checkland and Scholes (1990) have proposed the CATWOE template for studying change management processes, the acronym covering the aspects of customers, actors, transformations, weltanschauung (worldview), owners and environment. They also argue that while the world is treated in hard systems as *systemic* and models of it as *systematic*, in soft systems the world is acknowledged as *chaotic* and models of it as *systemic*. The objective of soft systems models is not so much to *simulate* the world through systematic procedures, because such approaches will always be incomplete and lacking in real world richness; it is rather to *reflect on* the world in an integrated, systemic way, from the identification of problems to the implementation of change. In particular, such reflection could help to mitigate or even eliminate the unintended consequences associated with engineering projects.

Artificial Intelligence (AI) or more accurately knowledge processing can be used for or seen as providing a formalization for practice at a technical level. AI could then serve the systems approaches, in the way that mathematics has served the scientific method (Dias 2002). Both AI and mathematics are formalizations at a technical (rather than conceptual) level. Chapter 8 gives examples of how some AI techniques such as neural networks, case based reasoning, expert systems and interval probability theory can be used to capture, structure and process practitioner knowledge and experience. It also provides a philosophical grounding for practice based knowledge, drawing on two very diverse philosophers, namely Michael Polanyi and Martin Heidegger. The formalization of practice based knowledge could contribute significantly to endorsing, defending and uplifting the intellectual status of engineers.

2.6 Summary

– This study of the tensions associated with the technology versus philosophy, engineering versus science, and practice versus theory debates has helped to resolve some of the crises and answer some of the questions that engineers have in the areas of ethics, ontology and epistemology.
– In the face of the question as to whether they do more harm than good, engineers should remain proud of their contributions to society, but work at developing an acute awareness of technology's ill effects. They should also see themselves as agents of humanization as well as transformation.
– Regarding the question of whether they are managers or scientists, engineers should see themselves as holistic managers grounded in science. They should

see a whole to part relationship between engineering and science, in that engineering is richer and broader than science. The engineering role also demands a sophisticated and nuanced approach in order to deal with real world complexity.
- On the question concerning the nature of engineering knowledge, we have seen that engineers largely use practical knowledge, though they can always fall back on the theory they have been schooled in. They should however learn to see practice as being a type of theory formation too; and also work at developing some formal structures, both for the engineering approach itself and for practice based knowledge.
- The adoption of systems thinking frameworks could be useful for formalizing the engineering approach at the conceptual level. The use of knowledge processing tools such as AI may help to formalize practice based knowledge at the technical level.
- We can see that an engineer is primarily a maker (*homo faber*), a label of which to be proud, quite in contrast to Plutarch's reporting of Archimedes' views. However, strong arguments can be made as to why an engineer is very high on the scale of a thinker (*homo sapiens*) too.

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