# Towards a New Philosophy of Engineering

## Structuring the complex problems from the sustainability discourse

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A thesis presented for the Degree of

**Doctor of Philosophy**

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March 2008

## Contents

## Abstract

This dissertation considers three broad issues which emerge from the sustainability discourse. First is the nature of the discourse itself, particularly the underlying philosophical positions which are represented. Second, is the nature of the highly complex types of problem which the discourse exposes. And third is whether the engineering profession, as it is practised currently, is adequate to deal with such problems.

The sustainability discourse exposes two distinct, fundamentally irreconcilable philosophical positions. The first, "sustainable development", considers humanity to be privileged in relation to all other species and ecosystems. It is only incumbent upon us to look after the environment to the extent to which it is in our interests to do so. The second, "sustainability", sees humanity as having no special moral privilege and recognises the moral status of other species, ecosystems, and even wilderness areas. Thus, sustainability imposes upon us a moral obligation to take their status into account and not to degrade or to destroy them.

These two conflicting positions give rise to extremely complex problems. An innovative taxonomy of problem complexity has been developed which identifies three broad categories of problem. Of particular interest in this dissertation is the most complex of these, referred to here as the Type 3 problem. The Type 3 problem recognises the systemic complexity of the problem situation but also includes differences of the domain of interests as a fundamental, constituent part of the problem itself. Hence, established systems analysis techniques and reductionist approaches do not work. The domain of interests will typically have disparate ideas and positions, which may be entirely irreconcilable.

The dissertation explores the development of philosophy of science, particularly in the last 70 years. It is noted that, unlike the philosophy of science, the philosophy of engineering has not been influenced by developments of critical theory, cultural theory, and postmodernism, which have had significant impact in late 20th-century Western society. This is seen as a constraint on the practice of engineering. Thus, a set of philosophical principles for sustainable engineering practice is developed. Such a change

in the philosophy underlying the practice of engineering is seen as necessary if engineers are to engage with and contribute to the resolution of Type 3 problems.

Two particular challenges must be overcome, if Type 3 problems are to be satisfactorily resolved. First, issues of belief, values, and morals are central to this problem type and must be included in problem consideration. And second, the problem situation is usually so complex that it challenges the capacity of human cognition to deal with it. Consequently, extensive consideration is given to cognitive and behavioural psychology, in particular to choice, judgement and decision-making in uncertainty.

A novel problem-structuring approach is developed on three levels. A set philosophical foundation is established; a theoretical framework, based on general systems theory and established behavioural and cognitive psychological theory, is devised; and a set of tools is proposed to model Type 3 complex problems as a dynamic systems. The approach is different to other systems approaches, in that it enables qualitative exploration of the system to plausible, hypothetical disturbances.

The problem-structuring approach is applied in a case study, which relates to the development of a water subsystem for a major metropolis (Sydney, Australia). The technique is also used to critique existing infrastructure planning processes and to propose an alternative approach.

This dissertation is dedicated to

Sandra

and to James and Alexander

## Acknowledgements

The original motivation behind this thesis lay largely in a desire, for the first time, to engage in a subject deeply and comprehensively. Entering middle age, it seemed like a sensible thing to do! I did not imagine how immensely rewarding and rich an experience the following five years would turn out to be. It is wonderful to have the opportunity to meander down paths where your curiosity takes you, with enough time to think and to reflect – after nearly 30 years of working in the corporate world this was a luxury indeed. It took a couple of years of perusing the literature to really determine the direction to take and another couple of years for the concepts to gain substance. Then, of course, the challenge of the case study and, finally, writing the wretched thing up! But it was all extraordinarily satisfying.

I have been particularly fortunate to have had Jim Petrie as my supervisor. Jim has encouraged, stimulated, and supported my research programme to the fullest extent imaginable. From his initial encouragement and kind offer to supervise my candidature, his patience as I immersed myself in the literature, to the stimulating conversations and questions, to his generous sponsorship of my attendance at conferences in Scotland, Iceland, and Auckland to present various aspects of our work, Jim has been not just a supervisor but a true friend. Jim has the unique capacity to encourage, finely balanced with a sense of when to advise caution when confidence might be running ahead of substance!

At the outset, Jim suggested I meet Bruin Christensen, a philosopher with an interest in sustainability. What a wonderful suggestion! I don't think I had met a professional philosopher before and for a first encounter you couldn't want for anyone other than Bruin. I don't believe I could have come to terms with the philosophical issues (at least, to the extent to which I hope I have) without the lengthy conversations with Bruin and his tolerance of my asking much the same question more than once. Bruin's involvement in the Metropolitan Water Options project at the Warren Centre, not necessarily part of the associate supervisor's responsibility, brought wonderful insights both to the project and to my dissertation.

Two participants in the Warren Centre project whose enthusiasm and contribution was truly magnificent were Sandy Booth and Faith Thomas. Many thanks to both for their commitment to the project and their generosity in taking substantial private time to prepare the narratives. Thanks also to Hugh Ralston, Don White, and Robert M. Mitchell for their work on the Warren Centre project and their patience and contribution to development of the problem-structuring approach.

I would also like to thank old friends and colleagues in the School of Chemical and Biomolecular Engineering at the University of Sydney for their encouragement (and, at times, I suspect, their bemusement) as I plodded through my PhD. Many thanks to Brian Haynes, Rolf Prince, Geoff Barton, and Tim Langrish.

Last, and most important, my wonderful family. My two sons, James and Alex and, most particularly, my wife Sandra, have put up with my distraction over countless weekends and evenings, my ramblings on philosophy of science and engineering and have done so with great encouragement and with scarcely a complaint! From the bottom of my heart, thank you!

# Preface

The work presented in this dissertation is that of the author alone and is the result of extensive reading and thought in the areas of sustainability, philosophy of science and engineering, operational research, and psychology. Where the work of others is referred to, it has been cited explicitly. My supervisor, Emeritus Professor Jim Petrie, and associate supervisor, Dr Carlton Christensen, have contributed greatly to this work through their thorough questioning and critique.

In addition, the theoretical material was applied practically in a project managed by the Warren Centre for Advanced Engineering at the University of Sydney. This project, "Metropolitan Water Options", related to the sustainable development of Sydney's water system. Where case study material has been referred to directly in the thesis, written permission was obtained from the contributors.

A number of conference papers have been presented, which relate to the research as it developed:

Hector, D., Christensen, C., Petrie, J., Problem Structuring for Complex Sustainability Decisions: the case of Sydney's water supply, *World Congress of Chemical Engineering*, 10-14 July 2005, Glasgow, Scotland

Hector, D., Christensen, C., Petrie, J., The Role of Narratives in Problem Structuring Methods for Sustainable Urban Water Systems, *International Society for Industrial Ecology Conference 2007*, 17 June 2007, Toronto, Canada

Hector, D., Petrie, J., Structuring Complex Problems: the use of maps and narratives, *MCDM 2008, 19th International Conference on Multiple Criteria Decision Making*, 7-12 January 2008, Auckland, New Zealand

To date, one peer-reviewed paper has been accepted for publication, relating to the knowledge developed in this dissertation:

# Chapter 1 : Introduction

## *1.1 Sustainability and the challenges to engineering practice*

During the so-called modern era of the last 400 years, Western civilisation has flourished in virtually all areas. The Renaissance ushered in an era of philosophical, institutional, social, technological, and economic development unparalleled in human history. However, in the last 50 years, there has been increasing concern as to whether the current system is sustainable in the long-term, particularly as industrialisation extends to the 80% or so of the world's population currently largely untouched by this phenomenon. For nearly 200 years, the engineering profession has been a key participant in the industrialisation of Western society. In the latter half of the 19th century and early 20th century, respect for engineers grew as the social benefits of industrialisation brought prosperity to so many. More recently though, engineers seem to have lost this leadership role and the community respect in which they had been held, as scepticism about the benefits of progress has become established in most developed societies. The role of the expert has been challenged, as communities have had to deal with the results of misapplied or misunderstood technology.

This thesis seeks to respond to the increasing concern about the sustainability of modern society and a growing scepticism about technology and experts. On one hand, the dissertation seeks to understand better the underlying issues of sustainability – that is, the underlying philosophical frames and the nature of the immense complexity of the problems which sustainability presents. On the other, it seeks to identify ways in which engineers can better relate to the needs and aspirations of the broader community and once again take a major leadership role in providing a sustainable future for humanity, without compromising the well-being of the greater ecosystem.

Both these matters are challenging – in the first instance, there are significant philosophical issues underlying sustainability which span a broad spectrum of interests and which are influenced by very a diverse range of beliefs and values. And, in addition, the sustainability discourse throws up problems of immense complexity, which can only be regarded as "systems", that is, as a "whole" which may respond exponentially to disturbances, where complex interrelationships exist between aspects of the problem, and where small changes in one part of the system may cause dramatic changes in another.

These two facets of problem complexity make decision-making extremely difficult. Typical of these problems are decisions such as major infrastructure development (water, electricity and so on) and resources developments (such as mining, oil etc). In many cases, to do nothing is not an option – a decision has to be made. Established decision-making tools such as multi-criteria decision analysis (MCDA), for example, are valuable but require the problem to be *structured* for their full worth to be realised[1]. A major purpose of this dissertation is to develop such a *problem-structuring* approach, so as to complement and facilitate later application of *problem-analysis* techniques, thereby improving the quality of the ultimate solution (or set of solutions) identified.

The second issue – consideration of the principles of engineering practice – is also extremely important in the sustainability discourse. From the 1820s, when engineering became established as a profession, it made a significant contribution to the development of human well-being but in the last few decades, there seems to have been some divergence between the paradigm which guides engineering practice and societal expectations. Engineering is a key discipline for the resolution of many of the problems of sustainability and it is argued here that to identify some principles of 21st-century sustainable engineering practice is of great importance. Many of these issues span a broad spectrum of interests and are influenced by a very diverse range of values and beliefs. This dimension of the issue is one with which engineers are unfamiliar because, traditionally, they have taken a reductionist, analytical approach to solving problems. This approach needs considerable extension if the diversity of interests is adequately to be taken into account. These issues will be touched upon in this introduction, followed by an outline of the research approach.

## *1.2 Sustainability*

In the late 18th century, Malthus (1798) raised the concern that a linearly increasing capacity to produce food would soon create a problem for an exponentially growing population. For nearly 200 years Malthus' concerns did not materialise – food production increased at a greater rate than population growth. In their report to the Club of Rome in 1972, Meadows and Meadows (1972) raised far broader concerns than those of Malthus, suggesting that a population can prosper for a relatively long time (in human terms) by using non-renewable resources. Ultimately however, the population is

[1] Some argue that MCDA can be considered to be a problem-structuring approach in itself.

doomed to collapse as resource becomes more scarce and difficult to utilise. Although the Club of Rome Report has been dismissed in some circles because many of its predictions (for example, resource scarcity and cost) did not eventuate, one result was a greater awareness that the current pattern of consumption and resource utilisation is likely to be unsustainable in the long-term. Awareness of this has spread through the activities of non-government organisations and the United Nations. In 1984, the UN appointed Gro Brundtland, the Norwegian Prime Minister, to chair the World Commission on Economic Development, to give broader consideration to the issue.

In 1987, the Brundtland Commission published its report "Our Common Future", making what was then a radical connection between eliminating developing-world poverty and protecting the environment. Subsequent to the Brundtland report, there has been major United Nations activity on sustainable development and climate change. The United Nations Conference on Environment and Development held in Rio de Janeiro in 1992 resulted in "Agenda 21", which identified a range of initiatives for environmental protection, combating poverty, changing consumption patterns, and promoting human well-being. The Rio Summit also saw the formation of the United Nations Framework Convention on Climate Change (UNFCCC), which, in 1998, led to the Kyoto Protocol being adopted by most nations in the world (at the time, the USA and Australia being notable exceptions) to limit greenhouse gas emissions. A further United Nations conference on sustainable development was held in Johannesburg in 2002 to review progress of Agenda 21. Progress has been mixed – on one hand, the sceptics argue that the issues have been exaggerated; on the other, others argue that time is running out and that urgent action is essential[2].

Although the most widely recognised issue of sustainable development in recent years has been climate change (now generally agreed to be a consequence of anthropogenic greenhouse gas emissions), the issues are much broader than this. Habitat loss, the rate of extinction of species, water supply, sustainable agriculture, fishery depletion, energy use, resource extraction, urbanisation, deforestation have all provided a range of often interrelated challenges representing different facets of a highly complex, global

[2] Typical of the "for" and "against" positions are Lomborg (2001) "The Skeptical Environmentalist" and a documentary movie, "An Inconvenient Truth" (2006), narrated by former vice-president of the USA, Al Gore.

ecosystem, overlaid by just as complex a social system representing great diversity in worldview and belief.

Yet the increased concern stimulated by the Club of Rome report and the Brundtland Commission report is not unprecedented. The problems of modernisation were recognised as early as the middle of the 18th century when the opening of the maritime trade routes and the demand for timber for shipbuilding led, first, to major deforestation in Europe and, later, in colonial outposts along the trade routes, causing major environmental damage. In the 19th century, the impact of the Industrial Revolution first in Britain, then later in Europe and the United States, stimulated noticeable value shifts in terms of appreciation of nature and wilderness, and a recognition of the substantial negative consequences of uncontrolled industrialisation. This awareness spanned the pressing issues of health and sanitation in the rapidly expanding industrial cities to a more spiritual concern regarding the loss of wilderness and the damage to nature. The seeds of concern for sustainability grew out of, on one hand, immediate social worries about the squalor and intensity of modern industrial life and, on the other, early concern for the long-term well-being of the environment.

It will be argued here that this led to two distinct positions relating to sustainability. One, fundamentally a "deep ecology" approach, which might be simply referred to as "sustainability", is framed around an underlying philosophical position that humanity is in no way "special" – rather humankind is simply another species in a highly complex ecosystem. Hence, it should enjoy no special privileges in relation to other species and, arguably, due to our ability to reason, reflect and influence, we have additional obligations beyond those of other species not to interfere or encroach upon their well-being. Underlying the second position, which is generally referred to as the "sustainable development" approach, is the idea that humanity is in some way "special", that is, humanity alone is morally considerable. That is to say, the approach of sustainable development places human interests above all others. According to this development approach, there can be only one reason for protecting other species and ecosystems: it is in our interests to do so, so that present and future generations of human beings are not disadvantaged. Although there is some common ground between these two philosophical positions, there will be many instances where they conflict and the differences will be difficult, if not impossible, to reconcile.

Generally, the practice of engineering has been anthropocentric – it evolved to improve the well-being of mankind – so generally, it is identified with the position of sustainable development. If engineering is to be relevant to the challenges of both positions, that is of sustainable development *and* sustainability, consideration needs to be given to the way in which engineering practice has evolved, its underlying philosophy, and the types of problems which sustainability and sustainable development are likely to present in the 21st century.

## *1.3 Engineering practice*

Although the practice of engineering became established in the 18th century, it was not until the early 19th century that an "engineering profession" began with the foundation of the Institution of Civil Engineers in Britain in 1818. Although the concept of the "learned institution" was well established – the Royal Society of London, established in 1662, was already over 150 years old – the Institution of Civil Engineers differentiated itself from the other societies in that it was a "professional body". Until that time, learned institutions had been societies where people met simply to explore issues of common theoretical and practical interest, rather than attempting to address issues of common concern[3]. As the momentum of industrialisation increased in Britain, Europe, and then the United States, other professional engineering institutions were founded (e.g., the Institution of Mechanical Engineers (UK) in 1847, the American Society of Civil Engineers in 1852, and the American Society of Mechanical Engineers in 1880), reflecting the proliferation of professional bodies which occurred at that time.

In the second half of the 19th century and early 20th century, in the rapidly industrialising countries, the engineering profession was responsible for great improvement in human well-being. The construction of sewerage and sanitary water systems in major cities, development of energy and communications utilities, provision of infrastructure such as bridges, railways, buildings, and roads, and the technological advances underpinning industrialisation of Western society and the modern industrial economy. However, in the second half of the 20th century considerable disquiet arose.

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[3] It might be argued that formation of these professional institutions, many of which were created in the 19th and early 20th centuries, brought together conceptions of the learned institution and its interest in developing knowledge, and the craft-based organisation such as the guild, which had existed for several centuries. The distinction between learned institutions, professional bodies, and Guilds is a complex issue which undoubtedly includes issues of social and cultural history which lie beyond the scope of this dissertation.

The effect had on the environment by large-scale industrialisation (based largely on consumption-led economic growth), particularly in the US and Europe, was becoming noticeable, with air and water pollution being areas of major concern. The size and impact of industry was increasing dramatically – what were once local problems were becoming regional, and then, quite suddenly, global. Realisation was emerging of the global nature of industrialisation and that its impact might be far reaching and irreversible. Engineers (and other technologists) were increasingly identified as the cause of, rather than the solution to, the negative consequences of over a century of intense industrialisation.

The important point here is that during this period of the 19th to mid-20th centuries, engineering was primarily *technological* in its nature – it revolved largely around the application of the scientific method to what previously were considered to be industrial "arts". As this approach evolved and effective solutions were identified for many of the major problems associated with industrialisation and urbanisation, engineers largely were seen in a positive light. They were leading development and making available a vastly improved technical capability to provide the means for social progress and improved living standards. However, in the late 20th century, in modern industrial societies, engineers have become caught between a clash of values as confidence in progress was lost and there was a rise in scepticism towards technology and technologists – described by Beck (1992) as the emergence of the "risk society". The reason why this divergence has occurred can be understood if the underlying philosophy of late 20th-century engineering practice is examined.

### 1.3.1 Engineering practice and problem complexity

Until 70 years ago, the underlying practical philosophical principles upon which engineering was based were grounded primarily in the philosophy of science which, at the time, was largely positivist. However in the period since the 1940s, the debate within philosophy of science has led to the purely positivist approach being challenged and largely displaced and the influence of individual and societal values, cultural and sociological issues on the scientific method has been recognised. However, engineering has remained largely untouched by these developments and, consequently, has remained, for the most part, positivist in its approach. Engineering has taken a limited view of itself, being concerned only with the technical aspects of issues and has deliberately excluded consideration of broader, non-technical issues such as values, interests, and a more general worldview. It maintains the positivist perspective of an independent observer, detached from engagement in the problem itself. This was an effective way of dealing with early problems which were of a relatively simple nature. Here, problem complexity can be represented as an aggregate of simpler, smaller problems and that by identifying solutions to these small problems, a solution to the larger problem can be synthesised. But not all problems can be described and addressed in this way. By the middle of the 20th century, new ways were found to consider problem complexity, not as problems consisting of discrete elements which behave aggregatively, but as "systems", which behave holistically (von Bertalanffy (1950)). That is to say, the elements of the system interact dynamically with one another causing the system to behave as a whole not simply as the sum of the behaviours of each of the elements.

This paradigm is also largely effective in dealing with quite complex technological problem situations. The engineering profession was quick to recognise the significance of dealing with increasingly complex technological problems in this way and has moved well beyond purely reductionist methods. Analytical techniques, such as systems analysis, were developed to deal with the systemic nature of a broad range of technological problems as diverse as the integrated control of large petrochemical complexes, power generation systems, and highly complex mechanical equipment, to the sophisticated control of aerodynamically unstable supersonic aircraft. But engineers have only considered problem complexity in one dimension, that which relates largely to the interrelationships between the physical elements within the problem system in order for a solution to be identified. This approach does not pose any particular challenge to the underlying paradigm embodied in the positivist perspective of the independent, detached observer. However, when problem complexity is extended to another dimension so as to include the *domain of interests* represented in consideration of the problem, extending this beyond the purely technological – and this second dimension is placed orthogonally against the first – a new type of problem complexity can be identified.

The complex problem now has issues such as values, interests, beliefs, and culture which are *intrinsic to the system*. This is the case with techno-social systems, which span areas such as the development of water, energy, and transportation infrastructure, the provision of health and education infrastructure and services, and the development of major resources, such as mining projects, oil exploration, and agricultural development. Adopting this approach to consideration of problem complexity identifies three broad types of problem with increasing complexity. Type 1 problems are those which relate to relatively simple problems which can be attacked using the reductionist approach and where the domain of interests is of one mind regarding resolution of the problem. Type 2 problems are those which are systemic in nature, thereby requiring a systems approach and may have differences of opinion within the domain of interests – nonetheless there is a common desire to resolve the issue. The Type 3 problem emerges when a highly complex technological problem sits within a social system in which there is a diverse range of beliefs and worldviews. In such cases, there may be no common agreement as to the nature of the problem, much less a shared determination or approach to its solution. The current engineering paradigm readily deals with the Type 1 problem and can engage and resolve many Type 2 problems. But with Type 3 problems, the established engineering approach is inadequate in two ways. First, the reductionist engineering approach, although capable of addressing challenges within the technological subsystem, is insufficient to adequately deal with the full social system response, inclusive of issues of values, beliefs, and non-technologically-oriented worldviews. And second, the assumption of the detached, independent expert is no longer valid – the engineer becomes part of the system itself and must engage in the problem recognizing the influence of their own beliefs and values. Of course, the domain of interests is not confined to those of humans. In the case of sustainability and sustainable development, there are almost always interests beyond those of humanity, such as non-human species, ecosystems and so on, which need to be recognised and taken into account. The extent to which these are included within the problem and the extent to which their moral interests are acknowledged is an important consideration in determining the boundary of the problem system and contributes to its complexity. This characterisation places the problems of sustainability and sustainable development within the domain of Type 3 problems.

At the heart of resolving Type 3 problems there are two fundamental challenges: first, the presence and influence of such an array of beliefs and values indicates deep philosophical differences among the parties involved in the problems; and second, the very complexity of the issues and the relationships between problem elements can go well beyond the limits of human cognition. This suggests that for a problem-structuring approach for Type 3 problems to be effective, attention needs to be given to two areas in particular. There must be a clearly defined set of practical, philosophical principles to accommodate the broad range of interests represented in the problem. Furthermore, consideration has to be given to ways in which humans approach problem complexity, that is, the way in which they inform their judgements, identify choices, and make decisions when confronted with the Type 3 problem. Hence, in this dissertation, two key themes will be explored: the development of a set of practical, philosophical principles for 21st-century engineering practice to replace, or at least, to enhance the existing paradigm; and consideration of human psychology so as to develop an approach to the Type 3 problem which is consistent with and aligns with established theories of human cognition.

## *1.4 Philosophical principles for sustainable engineering practice*

As proposed above, late 20th-century engineering practice is not well placed to deal with the Type 3 problems of the sustainability discourse that face society in the 21st century. A new set of philosophical principles for the practice of engineering must be developed to meet these challenges and development of such a set of principles is undertaken here. Starting with the critique of philosophy of science which took place in the mid-20th century, implications are drawn regarding the practice of engineering, with particular emphasis being given to the "critical approach" which was so influential in the development of philosophy of science in the last 70 years. A set of practical philosophical principles for the practice of engineering in the 21st century is developed which accept the existence of a mind-independent reality, recognise the systemic nature of the universe, and give consideration to notions of truth and how we determine truth. In providing some insight into "the way the world is". These philosophical principles allow easier engagement with issues around behavioural and cognitive psychology which are important in coming to grips with Type 3 problems. Problem complexity and human cognition will now be considered.

## *1.5 Problem complexity and human cognition*

### 1.5.1 Problem complexity

The identification of the Type 3 complex problem described above as a particular problem type adds a new dimension of complexity which is particularly challenging. This new problem typology develops further the notion of the complex socio-techno-problem which was identified in the 1970s and 1980s as a particular problem type in the operational research field (being referred to as "messes" or "swamps") (for example, Churchman (1970), Ackoff (1979), Rosenhead and Mingers (2001)). Such problems were recognised as often being unique, values-laden, and dynamic. They often represent systems, with interaction between problem elements and aspects of potential solutions. Complete information about the problem rarely exists and there is often overwhelming amounts of problem information and competing views among decision-makers and other stakeholders. As noted above, this gives rise to complexity in two dimensions. On one hand, are the things we know or need to know in order to describe the structure of the problem (recognizing there are some things we cannot know due to the complexity of the system). On the other, is the complexity which arises due to differences in beliefs, values, interests and so on. Thus, the Type 3 problem taxonomy recognises that resolving the purely technological aspects of the problem is inadequate. Both the definition and resolution of the Type 3 problem include the additional dimension of deeply entangled aspects of economics, politics, ethics, morality and aesthetics. This requires a greater awareness by the problem-solver (or decision-maker) of the important philosophical differences outlined above. Furthermore, consideration must be given to the limitations of human cognition, which are likely to be encountered as the problem is both defined and resolved, and the need to engage within the problem at a much more fundamental level.

### 1.5.2 Behavioural and cognitive psychology

Since the 1940s, there have been three major theoretical approaches to the way in which people form judgements and make decisions when faced with complex situations. The first of these was framed around the concept of the human mind being similar to a computer: that is, the mind evaluates an immense number of alternatives rationally and then makes a decision. By the mid-1950s, it was clear that there were substantial differences between what a "rational" decision-maker would be expected to choose and the decisions of real decision-makers. This exposes a dilemma: either real decision-makers do not behave rationally; or there is a flaw in this conception of what is rational decision-making. This led to another approach, according to which the decision-maker reaches judgements based on rational evaluation of a limited amount of information, or, as Simon (1983) called it, "bounded rationality". At about this time, other limitations in cognition were explored by psychologists such as Tversky and Kahneman (1974), who identified a number of biases and so called "heuristics" which characterise human decision-making. This work in behavioural psychology has impacted a wide range of fields, from economics to urban planning. Subsequently, a third approach to cognitive psychology, which has been called "naturalistic" decision-making theory, or the second wave of behavioural psychology (for example, Beach and Connolly (2005)) was developed. This third approach, unlike the other two, attempts to explain the way in which people actually make decisions, rather than to formulate an abstract model, only to find a substantial gap between real and ideal decision-making behaviour. Thus, the dilemma noted above is avoided.

The characteristics of human cognition, in particular those exposed by the first two approaches noted above, have been interpreted both as deficiencies – severe limitations which impinge upon the human capacity for rational thought – and as advantages, which enable us quickly to make sense of highly complex situations and identify solutions which are largely effective. The position which will be argued in this dissertation is that the deficiencies in human cognition largely relate to *intuitive* thought and that through the other faculty which humans have developed – the capacity for *rational* analysis – in many situations provides us with the best of both worlds, that is, the insights of intuition and capacity to undertake rational analysis to better understand complexity. To come to terms with this challenge, there needs to be some fundamental understanding of the way in which humans represent and structure information they encounter in the real world, and how they contextualise the resulting representations in relation to the three spatial dimensions and the fourth, temporal dimension of the real world. The three areas of particular interest here are the way in which we construct these mental representations, how they are organised into some form of "cognitive map" to enable us to spatially orientate our thinking, and how forms of narrative are used both to provide a temporal context and to confabulate so that we can make sense of a situation when important information is missing.

The important point that emerges from consideration of cognitive and behavioural psychology is that to structure highly complex problems in such a way that they align with human cognitive processes would be expected to be beneficial for the application of both intuitive and rational thought. Hence, the theoretical approaches to cognitive and behavioural psychology noted above form one of the building blocks of the problem-structuring approach developed in this thesis.

The avenues of exploration of this thesis lead to investigation of the way in which system theory, in combination with cognitive and behavioural psychology, might lead to new ways to consider the Type 3 problems, which emerge from the sustainability discourse. The approach is based on a newly-crafted set of practical philosophical principles for the practice of engineering. The aim is to find ways to engage in the Type 3 problem and to develop a problem-structuring approach such that greater engagement with the domain of interests involved in the problem situation is encouraged and where the subsequent application of established problem-solving methodologies can be more effective.

## *1.6 The research programme, approach, and thesis outline*

### 1.6.1 The research programme

This dissertation sets out to investigate the class of problems often referred to as "complex problems" (or here, Type 3 problems) found in the sustainability discourse and the way in which the engineering profession might better contribute to their solution. The aim is fourfold:

- to gain an understanding of the underlying philosophical issues of sustainability and sustainable development and how this might be used to find better ways to structure the major problems encountered in the sustainability discourse;
- to consider the types of problems and problem complexity encountered when considering issues of the sustainability discourse, in order to gain insight into how these might be structured to more readily facilitate resolution;
- to identify a new approach to structure major problems of sustainability and sustainable development, so that problem resolution might be more readily and effectively achieved using established decision-making techniques. This is achieved through consideration of the philosophy underlying the engineering discipline and the cognitive issues which need to be addressed if problem complexity is to be productively engaged; and
- to test and critically evaluate this approach through its application to a case study involving the water system for a large metropolitan area (Sydney, Australia).

The research programme is framed by investigating and answering the following questions:

1. What is the nature of the underlying philosophical issues of sustainability and sustainable development?
2. To what extent do these philosophical issues influence the approach to complex problems?
3. What is the nature of problem complexity and how might this be thought of so as to facilitate problem resolution?
4. What is the philosophical basis of existing problem-structuring methodologies and, in particular, the way in which the engineering profession engages in problem resolution?
5. To what extent do human cognitive limitations influence the structuring of complex problems and the way in which they are approached?
6. How might psychological theory be utilised as the foundation for a new problem-structuring approach?

…and then:

7. How might problems such as those typically encountered by engineers be structured better to accommodate different philosophical views, widely varying cognitive approaches and capacities, and facilitate problem resolution, without losing richness of information – that is, without being overly reductionist?

This dissertation investigates areas not commonly explored by engineers. An important initial consideration was the research paradigm to be used and this is outlined below.

### 1.6.2 The qualitative research approach

At the beginning of the 21st century there are four philosophical positions upon which research is generally based. These are “Positivist”, “Post-Positivist”, “Critical Theorist”, and “Constructivist” and their characteristics are summarised by Guba and Lincoln (1994) in Tables 1.1 and 1.2.

| | POSITIVIST | POSTPOSITIVIST | CRITICAL THEORIST | CONSTRUCTIVIST |
|---|---|---|---|---|
| ONTOLOGY | Naive realism – a real but apprehendable world. | Critical realism – a real world but only able to be apprehended imperfectly and probabilistically. | Historical realism – a view of reality shaped by social, political, cultural, economic, ethnic, and gender values which crystallised over time. | Relativism – local, specific constructed reality. |
| EPISTEMOLOGY | Dualist/objectivist. Findings are considered to be true. | Modified deals/objectivist. Findings are considered to be probably true once subject to critical evaluation | Transactional/ objectivist. Findings are value-mediated. | Transactional strokes objectivist. Findings are created. |
| METHODOLOGY | Experimental/ manipulative. Chiefly uses quantitative methods seeking to verify hypotheses. | Modified experimental/ manipulative. Critical multiplism, seeking to falsify hypotheses, possibly including qualitative methods. | Dialogic/dialectical. | Hermeneutical/ Dialectical. |
| from: Guba, E.G., Lincoln, Y.S., from Denzin, N.K., Lincoln, Y.S. (eds.), (1994), *Handbook of qualitative research*, Sage Publications, Thousand Oaks, CA, USA, p109. | | | | |

*Table 1.1 – Basic beliefs of paradigms of inquiry*

Whether or not these four positions are truly *paradigmatic* is debatable, nonetheless they do provide a useful framework for characterising research approaches. Within these four though, two research paradigms are clearly evident: the *quantitative* and the *qualitative*. Cresswell (1994) distinguishes between the two in this way: quantitative research (also known as traditional, positivist, experimental or empiricist research) has its philosophical roots in the ideas of Newton, Locke, Mill, and Durkheim. Quantitative research is framed around the ontological principle that reality is objective, singular, consistently follows underlying laws, and is cognitively accessible by an independent, value-free researcher. The epistemological assumption of quantitative research is that the researcher does not influence that which is being researched and the axiology is that the researcher is unbiased and values free. The rhetoric of quantitative research is objective, formal, impersonal (that is, value-free and disinterested), and is governed by a methodology of discovery, justification, and presentation. The methodology concentrates on deduction, analysis of cause-and-effect, and attempts to be independent of context. It is important to note that the use here of the term "quantitative" does not simply refer to the gathering and analysis of quantitative data. Rather, it has a broader meaning: an approach is understood to be quantitative if it looks for a mathematically

| | Positivist | Postpositivist | Critical Theorist | Constructivist |
|---|---|---|---|---|
| Aim of enquiry | Explanation: prediction and control. | | Critique and transformation; restitution and emancipation. | Understanding; reconstruction. |
| Nature of knowledge | Verified hypotheses establishes factual laws. | Non-falsified hypotheses that are probable factual laws. | Structural/ historical insights. | Individual reconstructions coalescing around consensus. |
| Knowledge accumulation | Accretion – "building blocks" adding to the edifice of knowledge; generalisations and cause/effect linkages. | | Historical revisionism; generalisation by similarity. | More informed and sophisticated reconstruction; vicarious experience. |
| "Goodness" or quality criteria | Conventional benchmarks of "rigour": internal and external validity, reliability and objectivity. | | Historical situatedness; erosion of ignorance; action stimulus. | Trustworthiness and authenticity and misapprehensions. |
| Values | Excluded – influence denied. | | Included – formative. | |
| Ethics | Extrinsic; tilt towards deception. | | Intrinsic; moral tilt towards revelation. | Intrinsic; process tilt towards revelation; special problems. |
| Voice | "Disinterested scientist" as informer of decision-makers, policymakers, and change agents. | | "Transformative intellectual" as advocate and activist. | "Passionate participant" as facilitator of multi-voice reconstruction. |
| Accommodation | Commensurable. | | Incommensurable. | |
| Hegemony | In control of publication, funding, promotion and tenure. | | Seeking recognition and input. | |
| from: Guba, E.G., Lincoln, Y.S., from Denzin, N.K., Lincoln, Y.S. (eds.), (1994), *Handbook of qualitative research*, Sage Publications, Thousand Oaks, CA, USA, p112 | | | | |

*Table 1.2 – Paradigms underlying practical research issues*

descriptive model of the problem situation based on and fundamentally representative of the key theories which are known to or at least thought to describe nature itself.

The structured epistemology of the quantitative approach in dealing with reality aligns with an ontology which regards a system's behaviour as a function of the behaviour of each of the system elements. Hence, by describing the behaviour of the system elements in abstraction from the system, the behaviour of the entire system can be synthesised. This explains why quantitative research tends to be reductionist and addresses only those issues which can be explored and validated. The quantitative research paradigm is generally considered appropriate when the problem can be placed within the context of existing theories. Consequently, quantitative research is of the form of what Kuhn (1962) referred to as "normal science". There are two reasons why most engineering research has been done within this quantitative paradigm. First, engineers are skilled in the mathematical and experimental techniques which are key to success of the quantitative methodology. And second, historically, most engineering problems have been problems of applied science, rather than new science, often making the quantitative approach the most appropriate because the problems exist within a domain which is relatively well understood and has been quantitatively characterised.

In contrast, in the last 50 years, a different paradigm has emerged. Qualitative research, also referred to as interpretive (or "hermeneutic"), or even postpositivist research, derives from the philosophy of Dilthey, Weber, and Kant (Cresswell (1994)). It emerged as a counter-position to positivism and has been influenced by critical theory and even by postmodernism. The qualitative paradigm is based on an ontology which assumes reality to be reflective of the multiple perspectives of participants. Epistemologically, qualitative research acknowledges the interaction between the researcher and the researched. The axiological assumption of qualitative research is that the bias and values of the researcher are unavoidable and influence both the definition and the outcome of the research. The rhetoric of qualitative research is informal, evolving, personal and accepts the subjective. The methodology is inductive, evolving, contextual, but verifiable. The qualitative research paradigm is found typically where there is no theoretical basis for the research and where research is exploratory in its nature.

There is an important point to make in relation to quantitative and qualitative research approaches. Because the qualitative approach recognises the interaction between the researcher and the researched, thereby introducing the researcher's values, some might construe it as "subjectivising" reality in some way. But this would be to misunderstand the issue. To reject the reductionist epistemology which underlies the quantitative approach described above is not to argue that subjective aspects of the problem (such as beliefs, values, interests and so on) cannot be objectively described. On the contrary, the position taken here is that they are considered to be objective features of reality.

This thesis uses a research approach which sits within the postpositivist and critical theorist positions, that is to say it developed based on the qualitative paradigm. This is because of the underlying philosophical issues at the heart of sustainability and sustainable development and the need identified here to base the problem-structuring approach on sound ontological, epistemological, axiological, and methodological foundations. A review of the literature suggests that such an approach, starting with sound philosophical foundations, recognising and accommodating human cognitive limitations, yet drawing upon existing engineering concepts and techniques has not yet been attempted and might be expected to yield substantive results.

### 1.6.3 Thesis outline

The thesis is presented in three parts. The first part investigates the underlying philosophical issues of sustainability, the nature of complex problems, and relevant issues from philosophy of science. It also surveys the way in which the decision sciences have identified and explored complex problems, and the means by which the study of human judgement and decision-making might interrelate with these issues. In the second part, a problem-structuring approach is developed and presented, founded on sound philosophical principles, adapting and integrating a number of existing approaches, while recognising and taking into account human cognitive limitations. And last, the third part presents a case study in order to test and explore the effectiveness of the problem-structuring approach. The following gives a more detail account of the structure of the dissertation.

***Chapter 1 – Introduction***

***Part 1 – Framing the issues***
***Chapter 2 – Sustainability and Sustainable Development***

An overview of the general issues of sustainability is presented, arguing that there are two distinct philosophical positions which are popularly considered to be much the same, but in fact differ significantly at their most fundamental level. These two positions, referred to here as "sustainability" and "sustainable development", can lead to fundamentally irreconcilable positions within the domain of interests. It is important that this be recognised as a fundamental challenge in dealing with the problems the sustainability discourse exposes.

***Chapter 3 – Complex Problems and Approaches to Their Solution***

Consideration is given to the nature of complex problems relating problem complexity to the domain of interests. In considering problem complexity in this way an innovative problem taxonomy is developed, identifying three fundamental problem types. The "Type 3" problem is noted as being typical of the sustainability discourse. Consideration is given to two examples of the way in which particular disciplines concerned with decision-making under uncertainty (risk science and operational research) deal with problem complexity.

***Chapter 4 – Towards a Practical Philosophy of Engineering***

The first two chapters identify a number of significant philosophical issues which are explored in more depth in this chapter. In particular, the philosophy of science and its influence on the practice and application of technological sciences (such as engineering) and issues relating to uncertainty and problem complexity are explored. This exposes a number of philosophical deficiencies underlying the current practice of engineering and a set of philosophical principles are proposed to underpin 21st-century sustainable engineering practice.

***Chapter 5 – Cognition, Judgement, and Decision-Making in Uncertainty***

A review is presented of the developments in cognitive and behavioural psychology that have taken place in the last 70 years, in particular, the influence these have had on decision-making in the context of complex problem-solving. The aim of this chapter is to consider a number of theoretical "building blocks" upon which to develop the problem-structuring approach outlined in Part 2 of the dissertation.

***Part 2 – Development and application of the problem-structuring approach***
***Chapter 6 – Development of the Problem-Structuring Approach***

Starting with the philosophical framework developed in Chapter 4, and the cognitive and behavioural psychology considered in Chapter 5, a problem-structuring approach is developed. This represents the problem as a highly complex, dynamic system, utilising devices which are aligned with established human cognitive and behavioural decision-making processes. The problem-structuring approach developed in Chapter 6 provides a flexible, practical means of structuring problems to maximise stakeholder engagement and prepare for rigorous analytical treatment. The qualitative research approach to be used in the case study is also described.

***Part 3 – Research approach, case studies and outcome***
***Chapter 7 – Case Study : Sydney's Water System***

The case study has three aims. First is to establish that the Type 3 problem actually exists. Second is to demonstrate practical application of the problem-structuring approach. And third is to critically examine alternative approaches to determine whether the methodology developed in this dissertation has clearly identifiable advantages in relation to other problem-structuring and problem analysis methodologies. These three aims were achieved through structuring the case study in two parts: Part A establishes the existence of the Type 3 problem and demonstrates its practical application in structuring the problem for solution; and Part B achieves the third aim through critical examination of an existing urban planning approach, used by the New South Wales state government.

***Part A – The Sydney Metropolitan Water System analysis***

A major project was undertaken by the Warren Centre for Advanced Engineering at the University of Sydney (supported by Engineers Australia, the Australian Academy of Technological Sciences and Engineering, and the Nature Conservation Council of New South Wales), using the problem-structuring approach developed here as the framework underlying the project methodology. The approach develops a qualitative system model and associated narratives to allow a qualitative evaluation of system response to hypothetical disturbances. This results in information which can be directly or indirectly utilised in establishing values and objectives hierarchies in decision-making techniques such as multi-criteria decision-making.

***Part B – Critique of the Metropolitan Strategy and Metropolitan Water Plan***

In the period from 2004 to 2006 the New South Wales state government prepared a long-term strategic plan for the state of New South Wales, the major metropolis in the State (the Sydney metropolitan area), and the development of associated state infrastructure. The system model developed in Part A of the case study was used to inform a critical examination of the approach taken by the NSW government in developing these plans, identifying significant deficiencies in the traditional urban planning approach used by the NSW government.

***Chapter 8 – Discussion and Conclusions***

The final chapter draws together the arguments presented in the dissertation and identifies its contribution to knowledge. The important conclusions reached in this chapter are that there are *fundamental, often irreconcilable philosophical positions represented in "sustainability" and "sustainable development"*, the two principal positions found within the sustainability discourse and that these add a further dimension to problem complexity. This leads to the identification of a new problem typology, which maps the domain interests against inherent problem complexity and uncertainty, referred to here as the "Type 3" problem. The philosophical paradigm which underlies the practice of engineering in the late 20th and early 21st centuries is argued to be inadequate in dealing with the Type 3 problem and a *new set of practical philosophical principles is proposed, which align closely to those of late 20th- and early 21st-century society*.

Application of the problem-structuring approach in the case study demonstrates that the approach has both intrinsic and extrinsic value. Its intrinsic value is the insight which it provides to the particular Type 3 problem to which it is applied and the contribution it makes in structuring information to facilitate mapping problem information onto frameworks used in established problem decision-making approaches such as MCDM. Its extrinsic value is a framework against which a critique of other problem-structuring and problem analysis methodologies can be conducted.

The use of this approach by engineers as they engage in these highly complex, Type 3 problems will enable the engineering profession to contribute to these problems not just as independent, detached observers (as the current paradigm dictates) but rather as citizens. This issue is of great importance to the practice of engineering because the expertise of the engineering profession is critical in identifying and implementing solutions to Type 3 problems of sustainability.

## 1.7 Conclusion

This dissertation come to terms with four fundamental themes identified at the outset, namely:

- the philosophical issues embedded in the sustainability discourse;
- the nature of problem complexity exposed through consideration of the sustainability discourse;
- the importance of the engineering discipline and its underlying philosophical paradigm to evolve with changes in community values and expectations, to enable professional practice to represent system complexity in all its dimensions; and
- the importance of organising information so as to align both with the way in which human cognitive processes deal with problem complexity and uncertainty

and the structure required for use with established decision-making methodologies.

It is expected that this work will make contributions to decision science and engineering practice in a number of areas. Further work is anticipated in the structuring of information for its application in approaches such as multi-criteria decision-making. It provides a powerful tool for a wide range of strategic analysis techniques, generally grouped together and referred to as "scenario planning". Furthermore, there are significant opportunities to develop the conjoining of the theoretical approaches underlying cognitive mapping and narrative to provide more rigorous forms of both problem and methodology critique across all four space-time dimensions.

## *1.8 References*

Ackoff, R. L. (1979) The Future of Operational Research Is Past, *Journal of the Operational Research Society,* **30**, 2, 93-104.

Beach, L. R. & Connolly, T. (2005) *The Psychology of Decision Making: people in organisations (2nd edn.),* Thousand Oaks, CA, USA, Sage Publications, 8-12.

Beck, U. (1992) From industrial society to the risk society: questions of survival, social structure and ecological enlightenment, *Theory, Culture and Society,* **9**, 97-123.

Churchman, C. W. (1970) Operations Research as a Profession, *Management Science,* **17**, 2, Application Series, Educational Issues in the Management, Sciences and Operational Research, B37-B53.

Cresswell, J. W. (1994) *Research design: qualitative and quantitative approaches,* Thousand Oaks, CA, USA, Sage Publications, 4-12.

Guba, E. G. & Lincoln, Y. S. (1994) Competing paradigms in qualitative research. in Denzin, N. K. & Lincoln, Y. S. (Eds.) *Handbook of qualitative research,* Thousand Oaks, CA, USA, Sage Publications, 105-117.

Kuhn, T. S. (1962) *The Structure of Scientific Revolutions,* Chicago, Illinois, USA, University of Chicago Press, 23-34.

Malthus, T. (1798) *An Essay on the Principle of Population,* London, UK, J. Johnson.

Meadows, D. H. & Meadows, D. L. (1972) *The Limits to Growth,* New York, USA, Universe Books, 24.

Rosenhead, J. & Mingers, J. (2001) A new paradigm of analysis. in Rosenhead, J. & Mingers, J. (Eds.) *Rational Analysis for a Problematic World Revisited: Problem Structuring Methods for Complexity, Uncertainty and Conflict,* 2nd ed., Chichester, UK, John Wiley & Sons, 1-6.

Simon, H. A. (1983) Alternative visions of rationality. in Simon, H. A. (Ed.) *Reason in human affairs,* Oxford, UK, Blackwell Publishing Ltd.

Tversky, A. & Kahneman, D. (1974) Judgment under uncertainty: heuristics and biases, *Science, New Series,* **185**, 4157, 1124-1131.

von Bertalanffy, L. (1950) An Outline of General System Theory, *The British Journal for the Philosophy of Science,* **1**, 2, 134-165.