

# Systems and sustainability: sustainable development, civil engineering and the formation of the civil engineer

P. W. Jowitt

**Civil engineering is changing and needs to change more. This paper attempts to put the evolution of technology and the development of engineering into its historical context, and with it the emergence of problems whose solutions extend beyond technology alone if they are to achieve systems-level solutions. The balancing of economic, social and environmental objectives, both now and into the future, has become known as sustainable development and this is increasingly a key driver at a range of organisational and spatial scales. It is argued that sustainable development is now absolutely central to the practice of civil engineering and this needs to be reflected in the education and training of civil engineers. The outcomes from an Institution of Civil Engineers Task Group to address these issues are reported. A systems- and process-based approach is advocated which depends on the development of specific attitudes, systems skills and domain knowledge. Some of the barriers to such an approach are recognised and ways of overcoming them are suggested and discussed.**

## 1. INTRODUCTION

In December 2002 the Institution of Civil Engineers (ICE) Council met and received a report<sup>1</sup> from former President Tony Ridley following his attendance and participation at the Johannesburg Summit on Sustainable Development.<sup>2</sup> The discussion that followed marked a sea change and led to the clearest message being reported to the ICE membership at large through the columns of the *New Civil Engineer* (NCE) in January 2003: the Council had resolved that 'Sustainable Development is now absolutely central to Civil Engineering and we must organise ourselves accordingly.'<sup>3</sup>

While this was perhaps a defining moment, it did not spring from a vacuum. The ICE had already begun to recognise the changing agenda and act upon it. The ICE's Environment Panel had been established in 1995, becoming the Environment and Sustainability Board in 1999. That same year the Institution had awarded its Gold Medal to David Thom of New Zealand for his work on engineering achievement and the promotion of sustainability in the engineering profession across the world. In September 2002 the Council set up a Task Group to examine a 'cradle to grave approach to sustainable development in terms of Degree Accreditation, Professional Reviews and continuous professional development (CPD)'.<sup>4</sup>

Thom has been a pioneer in re-examining the needs and obligations of civil engineers and civil engineering through his work with the World Federation of Engineering Organisations and through his many publications.<sup>5,6</sup> In the course of his lecture to the ICE in 2000,<sup>7</sup> Thom identified a number of emerging and vivid issues, referred to collectively as 'Times Winged Chariots'. Just as engineers in New Zealand had been pioneers in earthquake engineering through the work of Park and Paulay, the work of Thom and others in New Zealand would rekindle a fire to redefine the nature of a civil engineer's education. As Tony Ridley had remarked in the debate at Council in December 2002: 'A 21st century civil engineer is not the one I was educated to be in the 20th century.'<sup>1</sup>

Of course, there have been others who have reminded us that the engineer's role goes beyond that of the executor of narrow technologies. As Donald Schön had written some years previously:<sup>8</sup>

'In the varied topography of professional practice, there is a high, hard ground overlooking a swamp. On the high ground, manageable problems lend themselves to solution through the application of research-based theory and technique. In the swampy lowland, messy, confusing problems defy technical solution. The irony of this situation is that the problems of the high ground tend to be relatively unimportant to individuals or society at large, however great their technical interest may be; while in the swamp lie the problems of greatest human concern.

The practitioner must choose. Shall s/he remain on the high ground where s/he can solve relatively unimportant problems according to prevailing standards or rigor, or shall s/he descend to the swamp of important problems and non-rigorous inquiry?'

In Schön's terminology, sustainable development has all the characteristics of a 'messy problem', but if it is to become a more central and explicit component of the civil engineering and engineering curriculum, the phrase 'non-rigorous inquiry' needs to be dealt with. Engineers are not comfortable—and rightly so—with the idea of a profession which eschews rigour. Does sustainability fall into this category, and did Schön really intend that engineers should act without rigour? It is a question that will be examined more fully later, but in the meantime it is simply noted that sustainability is not a technical discipline, at least not in the same sense as hydraulics or mechanics for example. It defines the context in which technical and other

disciplines are applied and the emergent properties that arise from their application. It is much more a way of thinking—a habit of mind—and to do with how problems should be addressed. It is about adopting a systems approach and it is about the engineering process. None of this absolves it from rigour.

Inevitably, there are sceptics. As a correspondent to the NCE in May 2003 commented:<sup>9</sup>

‘When I looked at the ICE news piece in NCE 17/24 April my first impression was of a page of meaningless jargon... I may have missed something in the 10 years since I retired, but I do not know what sustainability means or what a civil engineer can do to ensure it.’

The problem with sustainability and sustainable development is not a lack of definitions—there are very many. It is easy to see why some are so sceptical.

Nevertheless, the concepts of sustainability and sustainable development are not so difficult to grasp: they are simply about finding the right balance between economic well-being, the benefit of society and concern for the environment and its resources (which are all too often treated as free goods), together with a notion of intergenerational equity. An economist might argue that all these issues are amply catered for by a combination of the notions of supply and demand, the consumer’s willingness to pay and the time value of money/discounting methods. The latter are quite crude and simplistic, usually involving a time invariant discount rate, a perception of time that is uniform and a concept of value that is linearly additive. The flaws in the discounted utilitarianism approach to determining best investment/development paths have been widely noted. As Heal<sup>10</sup> has observed:

‘If one discounts present world GNP over 200 years at 5%, it is worth only a few hundred thousand dollars, the price of a good apartment. Discounted at 10%, it is equivalent to a used car. On the basis of such valuations, it is irrational to be concerned about global warming, nuclear waste, species extinction and other long run phenomena. Yet societies are worried about these issues, and are actively considering devoting very substantial resources to them.’

Some understanding of sustainable development is evident in those societies for whom it has been a part of their history and culture, for example the Aboriginal peoples of Australia, the Inuit of the North American Arctic, or the Maori of New Zealand (though it was the Maori who caused the extinction of the large flightless Moa bird, not the later arrival of the European Pakeha). In a more modern, economic and urbanised age, it was Jeremy Bentham<sup>11</sup> who espoused the imperative ‘the greatest good for the greatest number’ and then Gifford Pinchot,<sup>12</sup> the American politician and forester, who added to Bentham’s phrase the words ‘for the longest time’ to reinforce the idea of intergenerational equity. Or more recently, Rachel Carson in her seminal work: *Silent Spring*,<sup>13</sup> and Meadows *et al.* in their *Limits to Growth* report to the Club of Rome.<sup>14</sup>

There have also been societies that have perished by failing to balance their immediate personal well-being with the resources that sustain it (most notably, for example, the Easter Islanders). The modern world might also suffer the consequences of a

spendthrift attitude to the world’s resources and a lack of concern for the excluded members of society. We could all be Easter Islanders soon.

In case there is any doubt, it is useful to recall Thom and cite some of his Time’s Winged Chariots, and instructive to remind ourselves that these are almost wholly of our own making.

- (a) Water demand is doubling every 21 years.
- (b) Over 70% is used for irrigation.
- (c) Limits on irrigation lead to limits on food production.
- (d) Limits on food production in poor countries lead to imports, higher prices and political instability.
- (e) Water tables are falling (caused by excessive pumping and leading to permanent damage to aquifers).
- (f) Some rivers no longer reach the sea.

Nowhere are these issues more critical than in places such as the Middle East, where water supplies are on a tipping point and where equitable access to water is at the heart of the conflict between the nations and peoples of the region. It is no accident that addressing these water resources issues—in which civil engineers have a central role—is a key part of the road map to peace. Engineers need to be much more than the technical handmaidens and aides-de-camp of opposing politicians.

## 2. THE EMERGENT LANDSCAPE—AND HOW DID WE GET HERE?

Society has evolved through various phases of social, economic and technological innovation. The Austrian economist Schumpeter took the view that the patterns of economic growth and technical innovation are not uniform but have been necessarily episodic.<sup>15</sup> It is a view rather contrary to the ideas of steady economic growth and equilibrium to which politicians currently strive. In Schumpeter’s concept of ‘dynamic instability’, periods of technological innovation would always be followed by bursts of economic activity and exploitation, during which the process of innovation would subside in the maelstrom of its exploitation. At some point the economy would favour another period of innovation, and so the cycle would repeat itself (Fig. 1).

While Schumpeter’s cycles of innovation and economic activity are characterised by the dominant technologies, it is becoming increasingly clear that tomorrow’s underpinning drivers will be as much about lifestyle issues as they are about technological and economic development. And that interface between human/social demands and the application of technology is—as it always has been—the domain of the civil engineer. There are other, complementary views of development, which explicitly include this social dimension.

For example, Elms<sup>16</sup> offers a social perspective on technological development and which helps to explain the arrival of some of Thom’s Winged Chariots. Elms identifies four phases of technology: immediate, urban, rational and systems/holistic.

The first of these relates to primitive periods (at least, technologically) in which human needs were met individually and on a very immediate basis—people gathered or hunted and met their own needs for water, food, shelter and clothing.

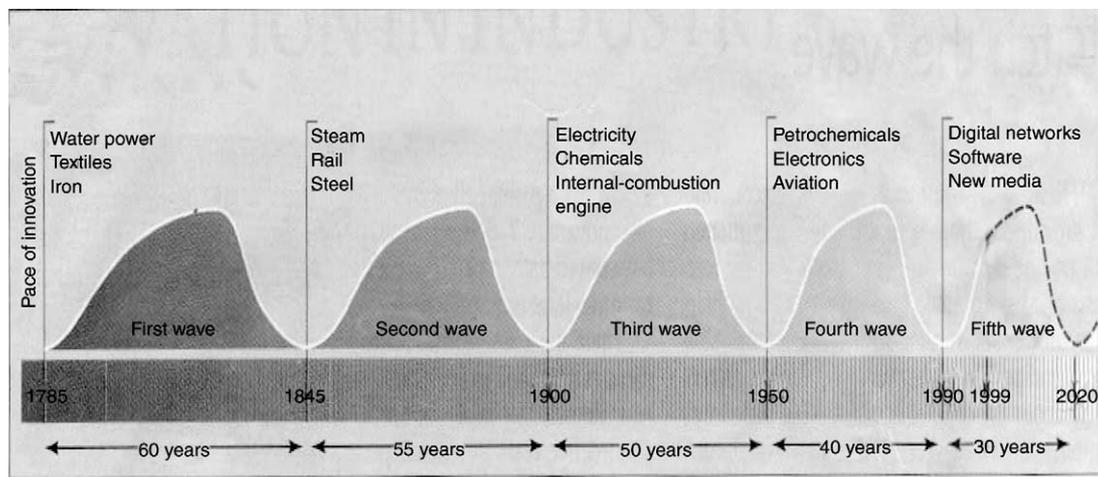


Fig. 1. Schumpeter's waves of innovation and economic activity

Technology in this *immediate phase* was simple and available to all and exemplified by short supply chains in which individuals largely fulfilled their own needs directly.

At some stage a more urban society emerged, with a social order in which people started to develop specialist skills, cooperate through trade, or organise such things as irrigation systems etc. Supply chains were lengthening. But within such societies, whatever knowledge was held was localised, empirical and experiential. The sharpness and temper of a cutting edge was based on experience and gauged by the colour of the heated metal, not by formal measurements of temperature, much less by what was then understood of the chemical properties of iron and carbon at the microscopic level and their translation into material properties at the macro level. Although such technology might be empirically repeatable, its artefacts and components were not particularly interchangeable. The technology of the *urban phase* broke the immediate link between individual needs and the means of their satisfaction, creating the systems for centralised administrative power, the cooperation of groups of individuals in trade and the emergence of specialist crafts based on empirical and heuristic skills. But they were not yet based on science or technical rationality.

These concepts would emerge in the age of enlightenment and with it the Industrial Revolution, in which engineering science would start to get behind empiricism and replace it with a rational explanation of physical behaviour at a range of spatial and temporal scales. The emergence of the Industrial Revolution and with it the era of *technical rationality* was now embedded in mathematics, material science, mechanics and engineering science. The skilled individual artisan began to be replaced by mass production, standardisation and component interchangeability. Supply chains were becoming ever longer—to the extent that few people would now have the skills or knowledge to supply all their own needs for food, shelter, power or the trappings that accompanied them. Increased efficiency and levels of production were achieved by mechanisation, powered by machines fed by fossil fuels. It appeared that anything seemed possible. In some ways it was. In the

realm of the civil engineer, Thomas Tredgold<sup>17</sup> was indeed able to say with confidence that 'Civil Engineering is the art of directing the great sources of Power in Nature for the use and convenience of man'.\*

And there were some immense achievements, perhaps most notably those associated with the countries of Europe and North America, where improvements in human health were brought about by the development of proper water supply and sanitation systems. When the nineteenth-century social reformer Ernest Chadwick wrote to Councillor John Shuttleworth of Manchester to say that 'For all purposes it would be of the greatest importance that you should get the advice of trustworthy engineers, of whom I am sorry to say there are marvellous few—a more ignorant and jobbing set of men... I have rarely met with', he would be confounded by such as Joseph Bazalgette and his construction of London's system of major intercepting sewers and with it the dramatic reduction in the incidence of cholera and other water-related diseases. But this same prize is still seemingly beyond the reach of millions in the developing world without such basic provision and without which the achievement of the UN Millennium

\*The full version of Tredgold's definition is as follows, which shows the strong interconnection between civil engineering and the economic cycle:

'Civil Engineering is the art of directing the great sources of Power in Nature for the use and convenience of man; being that practical application of the most important principles of natural Philosophy which has in a considerable degree realized the anticipations of Bacon, and changed the aspect and state of affairs in the whole world. The most important object of Civil Engineering is to improve the means of production and of traffic in states, both for external and internal Trade. This applied in the construction and management of Roads—Bridges—Rail Roads—Aqueducts—Canals—River Navigation—Docks, and Storehouses for the convenience of internal intercourse and exchange; and in the construction of Ports—Harbours—Moles—Breakwaters—and Lighthouses, and in the navigation by artificial Power for the purposes of commerce.'

Development Goals<sup>18</sup> might remain a dream.<sup>†</sup> Infrastructure might be the solution, but education might well be the key.

From the *rational phase* of technology sprang the canals, highways, railways and ports; the power systems; the water supply, sewerage and irrigation systems; the development of large-scale construction and the changing form of cities and towns. But from it also has sprung the problems of congestion, air pollution, damage to the environment, global warming, over-abstraction of watercourses, water pollution, urban blight and social injustice.

In the era of technical rationality—which has dominated the past two or three centuries or so—economic and technical progress has generally been embedded in narrow technical disciplines which, despite our scientific understanding, have not anticipated the wider physical and non-physical consequences at the *systems* level. No one foresaw that Henry Ford's production line of black Model Ts would lead inexorably to changes in urban form, large-scale urban congestion, air pollution (and its linkage to the higher incidence on child asthma), CO<sub>2</sub> emissions or global warming and climate change. The development of large-scale irrigation and hydropower schemes did not anticipate the loss of biodiversity, ecosystem damage, soil erosion and loss of soil fertility. There was an overriding economic imperative.

The behaviours of these large and complex systems was neither fully appreciated nor fully understood. It is now becoming clear that the earth is no longer a homeostat, no longer able to withstand and rebound from human activity. It has limits. To use an engineering analogy, parts of the world have gone beyond the elastic limit and entered the plastic range. This realisation marks the end of the era of technical rationality and the beginning of a more systems/holistic view of the world. In some quarters it is still taking time for the message to sink in.

### 3. DEALING WITH WICKED PROBLEMS—AND THE SYSTEMS/HOLISTIC APPROACH

Large-scale problems still tend to be focused on narrow technologies and technical fixes. Solutions tend towards dealing with complication (detail) rather than complexity (structure). Such problems have come to be known as 'wicked problems', and which are characterised and manifest themselves by crossing the boundaries between policy responsibilities.<sup>19</sup>

Historically, technical responses to social development might have involved elements of great complication internally and great engineering innovation and achievement in the short/immediate term, but they often took little account of their wider and longer-term effects. They were not aware of the internal and external complexities. They might have been

<sup>†</sup>The Millennium Development Goals were first set out during the 1990s, and later compiled and became known as the International Development Goals. The goals were recognised by the UN General Assembly as being part of the road map for implementing the UN's Millennium Declaration. There are eight overall goals (on poverty, education, gender, child mortality, maternal health, HIV/AIDS, environment, global partnership).

systematic, but they weren't *systemic*. But many emerging problems do not have narrow technical solutions and instead need solutions/concepts that take a systems view of the world, accounting for complexity and coupling inter-disciplinary understanding with a much broader concept of system performance. This defines Elms' fourth phase of technology that the world is now entering—the *systems/holistic phase*.

Technological innovation and economic development can thus be viewed historically as a sequence of linked but distinct phases. The start of the twenty-first century marks the end of one such phase—the era of technological rationalism—and the start of what is best described as the systems or holistic phase, where there are many technological drivers and in which corporate business is becoming increasingly internationalised. But what really defines this systems phase is the demand for sustainable development and with it the balancing of economic, environmental and social issues at all scales—political (local, regional, national, supranational) and spatial (urban, peri-urban, suburban/rural and land/coastal/marine-based). This brings with it the demand for greater stakeholder involvement and the need to resolve complex, less well-defined problems. The time has now come for solutions and dialogue which take a systems view of the world, which account for complexity and which couple scientific understanding with a much broader concept of system performance. The budding civil engineer needs to be aware of this from the start.

The role of the civil engineer was absolutely central to the rational phase. Civil engineers will be even more central to the systems/holistic phase, but they will need to adapt: Tredgold's definition might be usefully modified to read: 'Civil Engineering is the art of *working with* the great sources of Power in Nature for the use and *benefit of society*' (Fig. 2).

## 4. SYSTEMS AND RIGOUR

Two issues need to be addressed: can sustainable development be addressed with rigour, and if it involves a systems view of the world, what does that mean?

### 4.1. The concept of a 'system'

The foregoing has introduced the concept of a system. What does this mean? Is this yet another topic fraught with definitional difficulty. One definition of a system is as follows: 'A mental construct (model) of entities... a creation of the mind defined for some purpose.' The critic might think this has an in Alice in Wonderland quality: 'It means exactly what I want it to mean.' Actually, this might not be a bad attribute: it signifies purpose, not vagueness.

And, in terms engineers will well understand, and often work with effectively, it is simply about defining the most appropriate—and inclusive—control volume, and its technical, environmental, social and economic interactions with the world beyond that control volume.

Attempts to construct systems models of component aspects of the environment, transportation systems, organisations, etc. are now well-established. Examples exist from ancient history; for example, a clay tablet dating from about 2000 BC represents the early water resources and taxation systems of Mesopotamia.<sup>20</sup> In more recent times, the application of systems analysis to the



Civil Engineering is the art of **directing** the great sources of Power in Nature for the use and **convenience** of man

(a)



Civil Engineering is the art of **working with** the great sources of Power in Nature for the use and **benefit** of society

(b)

Fig. 2. (a) Thomas Tredgold's nineteenth-century definition of civil engineering; and (b) a twenty-first-century definition of civil engineering

estimation of the effective firepower of a navy or army was described by Lanchester's square law and provided the basis of Nelson's successful tactics at Trafalgar. In the 1920s, Hotelling wrote his seminal work using the calculus of variations on the optimal economic extraction rate of finite (e.g. minerals) and renewable (e.g. forestry, fisheries) resources.<sup>21</sup> In the field of operations research, 'hard systems' methods such as linear programming and dynamic programming (LP/DP), Game Theory<sup>‡</sup> and simulation models were developed in the 1940s for the more effective prosecution of war.

They quickly became tools for the systems modelling and management of peacetime activities, such as the design and operation of water resources (most notably in the Harvard Water Program<sup>22</sup>), production scheduling in manufacturing, construction management, and traffic management. By the 1970s and 1980s systems engineering along these lines had found its way—not always without difficulty—into various civil engineering curricula (e.g. at Imperial College, Bristol, Liverpool, Heriot Watt, and Cardiff in the UK; Canterbury in New Zealand; Manitoba, UBC, Calgary, Waterloo and St Johns in Canada; and Washington, Purdue, MIT, Johns Hopkins and many others in the USA).

The landmark 'systems' concepts were the notions of:

- (a) a systems *boundary*
- (b) a set of *state variables* within this boundary that characterise *the state of the system*

<sup>‡</sup>Game Theory and the 'Prisoner's Dilemma' have diverse civil engineering applications—from such as tendering strategy to planning; for example, 'it is in society's interest that a bridge/wind power installation should be built, but it might be in an individual's interests that someone else pays for it, and that it should be built somewhere else.'

- (c) a set of *external inputs* and *system outputs*
- (d) a set of *system/state equations* which define the interaction of the external inputs and the state variables and which *describe how the system will evolve*
- (e) a performance measure represented by an *objective function*.

So far, this systems view is still rooted in the mathematical language and calculus of the rational phase and appropriate to those classes of problem that are susceptible to technical determinism. This limitation began to emerge as problems arose which had much wider systems boundaries (to the extent that they overlapped other interacting systems—the wicked or messy systems problem) and which were more complex and multi-disciplinary in character, rather than being rooted in just one narrow technical discipline. Such 'hard systems' views are now being accompanied by 'soft systems' approaches (and not to be confused with 'easy'). Increasingly, these are the tools necessary to deal with the issues facing twenty-first-century societies: problems that are ill-defined and have complex and sometimes conflicting objectives.

The connection to Schön's 'messy problems' should not be lost. System complexities and system functions can be modelled conceptually by these so-called soft system tools such as mind/concept maps, cognitive mapping and influence diagrams. Some formal tools have been developed to explore the structural connectivity, relationships and hierarchies within such systems. Other soft system methods have been developed to assess 'system health' in terms of its balance, completeness, cohesion, consistency and discrimination.<sup>23,24</sup>

It is increasingly clear that even a systems view of the world is not tractable by equations alone. Opinions, ethics, and conflicts are not easily captured—and even less, calibrated—by mathematics. But a systems view is absolutely central to sustainable

development, which brings the discussion back to the need for rigour, so germane to the traditional view of civil engineering.

#### 4.2. Non-technical rigour

Even though engineering is based on rigour, the professional reputation of the civil engineer depends on judgement, informed opinion, compromise and the engineer's ability to draw together apparently incommensurate issues and concepts.

One of the first systems concepts a first-year engineering student is exposed to is that of balance and structural equilibrium. The structures involved are generally statically determinate and there is little consideration of displacements. Indeed, these are not even part of the analysis, though of course they become vitally important in design. For determinate structures, equilibrium involves an appreciation of only forces and loads.

Systems which are statically indeterminate—for which equilibrium considerations alone are insufficient to resolve the relationships between externally applied forces, reactions and internal forces—require additional considerations that involve entirely different concepts: namely those of displacement and, in particular, the compatibility of nodal displacements and member extensions and material strains. By themselves, these are problems of pure geometry and kinematics<sup>§</sup> and require no consideration of the causal loads or member forces and stresses.

Thus for a two-dimensional, pin-jointed structural frame (whether determinate or indeterminate) the equations of equilibrium can be stated as

|   |          |
|---|----------|
| 1 | $AF = P$ |
|---|----------|

where  $A$  is a matrix of geometric coefficients,  $F$  is the vector of member forces and  $P$  is the vector of the horizontal and vertical components of the nodal loads.

For the same structure, it transpires that by an appropriate (but logically consistent) notation/sign convention, the equations of kinematic compatibility can be independently represented by the following contragredient equations, despite the fact that there might be no cause-and-effect relationship between the forces and displacements so described.<sup>¶</sup>

|   |                  |
|---|------------------|
| 2 | $A^T \delta = A$ |
|---|------------------|

where  $\delta$  is the vector of horizontal and vertical nodal displacements,  $A$  is the vector of member extensions, and  $A^T$  is the transpose of the same matrix of geometric coefficients  $A$ .

<sup>§</sup>In the author's experience, students have far more difficulty getting to grips with kinematics than equilibrium, despite the fact that it is a more tactile and demonstrable concept through simple models/experiments/practical demonstrations.

<sup>¶</sup>The existence and significance of these contragredient relationships between a set of loads and an independent set of displacements often escapes the immediate comprehension of the typical undergraduate student—as it did the author when he was a student. It crops up later in that concept which many civil engineering students also find so initially baffling—virtual work.

The connection between *actual* displacements and the *actual* forces that cause them depends on the material constitutive law, for example Hooke's elastic stress–strain law

|   |          |
|---|----------|
| 3 | $CF = A$ |
|---|----------|

where  $C$  is the matrix of member stiffnesses.

These three sets of equations are sufficient to determine all reactions, internal forces/stresses, nodal displacements and member extensions/strains.

But what has this got to do with sustainability and rigour? Simply this: it shows how the engineer has reconciled concepts of force (with dimensions  $(ML/T^2)$ ) and displacement (with dimension  $L$ ), not just at the elemental level but also at the structural/systems level. The challenge to the engineer now (and to student engineers of the future) is to extend this ability to areas and systems which, if not so neatly described by sets of equations, are nonetheless characterised by sets of relationships between seemingly incommensurate objects. And if engineers cannot do this alone, they must learn how they can work in partnership with others to achieve common goals.

It is worthwhile returning to the work of Schön and Richards and the dilemma about choosing between technically manageable problems on the high ground or those messy and 'wicked' problems in the swamps that characterise the real world. As Schön says<sup>8</sup>

'This dilemma has two sources: first, the prevailing idea of rigorous professional knowledge, based on technical rationality, and second, awareness of indeterminate, swampy zones of practice that lie beyond its canons.'

And to that might be added: '...involving the exercise of judgement.'

4.2.1. *Technical and non-technical paradigms need to be applied with no loss of rigour.* In mechanics the engineer is fortunate: the apparently incommensurate objects of force and displacements are brought together through equilibrium, compatibility and the material properties—for example Hooke's law. But even without knowledge of Hooke's law, the engineer would realise there was some relationship between applied loads and displacement, even if such notions were only empirical. It is worth noting that although Galileo's understanding of simple beam theory was based on a false hypothesis, it still enabled him to make some predictions about the failure of beams that seemed to accord with experience.<sup>25</sup>

In Schön's realm of the messy problem, it is still possible for the engineer to develop an understanding of behaviour at the systems level. It might be inexact, but it can be described, gradually refined and increasingly understood. And one day, some of it might be verifiable by formal relationships. Perhaps nowhere in the technical repertoire of the civil engineer is this better demonstrated than in soil mechanics, where the behaviour of granular, spatially inconsistent, and often inhomogeneous and non-isotropic materials has been progressively understood and captured, sometimes treating the material as a

|    |   |
|----|---|
| A1 | Sustainable development is not a passing fancy—neither is it a soft woolly option or lacking in rigour.   |
| A2 | In definitional terms, we do not need to go through yet another debate about what sustainable development actually means or how it is measured before we start to do something about embedding it in engineering education.   |
| A3 | Civil Engineering, as practised, is changing—and needs to change more. Sustainable development is at the heart of it. <sup>30</sup>   |
| A4 | Civil engineering/sustainable development is increasingly about <i>managing complexity</i> —that is, things that are <i>rich in structure</i> —as opposed to things that which are <i>just complicated</i> —that is, <i>rich in detail</i> .*   |
| A5 | Civil engineering/sustainable development is increasingly <i>issues/process</i> driven, not <i>technique</i> driven. (Issues such as quality of life, health, safety; EU legislation, transport/travel, urban development, climate change.)   |
| A6 | In contrast, civil engineering education is still largely <i>technique</i> driven, not <i>issues/process</i> driven.  |
| A7 | If sustainable development is to be mainstreamed/embedded in engineering education/CPD then it needs to <ul style="list-style-type: none"> <li>● be generic, not prosaic</li> <li>● encourage a questioning of perceived wisdoms and a challenging of assumptions</li> <li>● be open-ended and encourage out-of-the-box thinking</li> <li>● be team-focused not individual-focused</li> <li>● involve a different learning/pedagogic approach.</li> </ul> <p>In short, it requires individuals to be equipped with an appropriate set of <i>attitudes, skills</i> and <i>knowledge</i>.</p> |
| A8 | The barriers to mainstreaming/embedding sustainable development in engineering education (undergraduate/postgraduate/CPD) include the limited experience and traditional teaching/learning styles of academic staff/chartered reviewers/the profession at large in sustainability issues—most of whom are the products of a technique-driven education and training.  |

\*'Urban regeneration is complex; Finite elements are complicated!'

Table 1. The eight assertions

continuum, sometimes treating the soil grains and the voids separately.

The same has happened with water, a compound whose microscopic properties at short temporal and small spatial scales are incongruous, unexpected and bizarre, but which at the engineering level can often be ignored, treating water quite differently as an isotropic continuum obeying simple laws of continuity, mass balance and so on. But even with water, the problems of emerging interest require a systems view of the world where large-scale heterogeneity predominates, and where some of the issues to be dealt with—for example, mechanisms of determining equity of distribution between different social/political groups—are not capable of reduction by solving complicated sets of equations.<sup>26,27</sup> Sometimes, it is necessary to rely on judgement, not numbers: 'Not everything that can be counted, counts... and not everything that counts can be counted.' (Albert Einstein)<sup>28</sup>

Engineers need to understand problems at the component level, but increasingly they are called upon to address emergent properties at the systems level. It just requires a more sophisticated calculus.

## 5. MAINSTREAMING SUSTAINABLE DEVELOPMENT INTO CIVIL ENGINEERING EDUCATION

The preceding sections of this paper have outlined the need for the civil engineer to engage in a wider view of the world, and to acquire skills that go beyond the traditional disciplines. Where does the engineer first acquire such skills, and how are they developed in practice?

In April 2002 the ICE issued *Society, Sustainability and Civil*

*Engineering—a sectoral sustainability strategy*.<sup>29</sup> The strategy was developed in consultation with over 200 leading engineers and other stakeholders. The accompanying action plan identified three main priority areas including, 'promoting cultural change and innovation in the civil engineering industry' under which fell the specific action to 'open discussion with the Joint Board of Moderators\*\* with regard to the sustainability content of undergraduate courses'.

In September 2002, the ICE Council established a Task Group<sup>††</sup> to 'drive implementation of sustainability principles into education, training and professional development'. The proposal to establish this group laid out a number of assertions, some of them quite contentious. These assertions are itemised in Table 1.

These assertions were accompanied by Four Questions, as listed in Table 2.

It was against these background assertions and questions that the Task Group was established to develop a 'cradle-to-grave' implementation of sustainability principles into education, training and professional development, including

\*\*The Joint Board of Moderators (JBM) is the ICE/IStructE Degree Accreditation Body.

††The membership of the Group was: Paul Jowitt (Chair), Roger Plank (Sheffield University, IStructE and JBM); Nicola Bowen (Warwickshire CC& ICE G&S), Fiona Geddes (Environment Agency and ICE G&S), David Foxley (RAEng), Andrew Crudginton (ICE), Sebastian Wood (Whitby Bird), Liam McGee (Environment Agency), Rachel Cowlshaw (Environment Agency), Quentin Leiper (Carillion and ICE Environment and Sustainability Board).

|    |  |
|----|--|
| Q1 | Who are we trying to attract to civil engineering and what qualities do we expect them to have and to develop?                     |
| Q2 | What are the personal and professional aspirations, values, drivers and motivations of those we seek to attract to the profession? |
| Q3 | Are we succeeding in attracting them to civil engineering and if not, why not?   |
| Q4 | What can we do about it?   |

Table 2. The Four Questions

- (a) input into current revision of the JBM environmental guidelines
- (b) input into scheduled revision of ICE's core objectives
- (c) liaison with key stakeholders to promote the importance of sustainability principles
- (d) assistance with implementation (within higher education, professional development and CPD).

The Group very quickly agreed on one overriding goal: they were determined to try to make a difference at the heart of the learning process rather than tinker at the fringes of the curriculum.

It was recognised (see Assertion No. 8) that there would be related implications for staff development and guidance within higher education and the professional review process and the associated methods of assessment. This reflected what was already being recognised and established independently by, for example, the Royal Academy of Engineering in its RAEng Visiting Professorship Scheme for Engineering Design for Sustainability.<sup>31</sup>

The experience of others in embedding design principles into engineering education and learning—required explicitly by the JBM—was noted, particularly the increasing involvement of engineers from practice to provide students with a direct link to those active in the design process. It was recognised too that within higher education academic staff in engineering are recruited more for their research potential (and usually focused within a particular technical discipline) rather than for their practical engineering or design experience, or their teaching skills and familiarity of process-based learning. There were strong parallels between the learning of design skills and sustainable development, and the tensions both could create with the more traditional, analytical and technique-based elements of the curriculum and their delivery.

A good knowledge of theory is a prerequisite for design—the young engineer really does need to know how to do some analysis and actually understand something. But there is a balance to be struck between a purely academic approach and formal analysis on the one hand, and the abilities to sketch out a design intuitively (if not these days on the back of a fag packet, then on the back of a restaurant serviette) and understand the practical issues of design on the other. It was a balance required in the education and training of Isambard Kingdom Brunel by his father Marc Isambard, who insisted that the habit of drawing (sketching) was as important to an engineer as a knowledge of the alphabet, and it led to both

father and son developing such extraordinarily acute powers of observation.<sup>32</sup> But in addition to his sketching, Brunel was studying Euclid's geometry from the age of 11, and later, in France, he augmented his skills in mathematics and sketching with an interest in Latin. *Tempora mutantur, nos et mutamur in illis!* (Times have indeed moved on.)

As with design, so it is with sustainable development. There is no single right answer, but there are many which are inappropriate. This can often represent uneasy ground for both student and lecturer, especially if their learning experience has been predominantly one in which each problem was expected to lead to a uniquely definitive solution. It is risky. Under such conditions the lecturer might feel it is safer to hang on the lectern rather than stray into parts of the solution domain with which there is less familiarity and certainty. This tendency inhibits the adoption of a more process/issues-based approach to explore the appropriateness of solutions and their boundaries. It can also lead to a more comfortable and predictable but ultimately less rewarding and stimulating learning experience for the student.

## 6. CONTENT AND PROCESS

The pressures on curriculum content are well known. To design, construction management, construction law and health and safety, now add sustainable development. The Task Group resolved early on that its focus would *not* be on the *content* of civil engineering education. It was not about trying to shove more material into an already overcrowded curriculum, but more about the *learning process* and the encouragement of a *systems view*. Just as with design, sustainable development is not just another technical 'subject'. If there were issues of additional content, they would be *pulled* naturally into the curriculum through need and as the student's learning developed.

Insofar as the Task Group's enquiry covered content, it would be confined to the development of appropriate levels of *Awareness/Attitudes, Skills and Knowledge*.

Let us now consider each of these in turn.

- (a) *Awareness/Attitudes*
  - (i) An overarching approach to engineering problems in the context of environmental, economic and social issues.
- (b) *Skills*
  - (i) The ability to work with complex/ill-defined problems.

- (ii) The development of teamwork and (two-way) communication skills.
- (iii) The ability to evaluate the merits and demerits of options.
- (c) *Knowledge*
  - (i) Broad and deep.
  - (ii) Technical.
  - (iii) Environmental.
  - (iv) Social processes.
  - (v) Legal.
  - (vi) Disciplined body of general knowledge.

As already indicated, the Task Group was more concerned with the *process* through which these issues might be drawn into the curriculum. In particular, and very much mirroring the process of civil engineering in practice, it was about the need for the learning process to be

- (a) amenable to the use of case studies
- (b) studio based
- (c) issue driven
- (d) process based
- (e) team based
- (f) design/delivery focused.

## 7. TASK GROUP OUTCOMES

The key outcomes are outlined in the following subsections.<sup>33</sup>

### 7.1. Input into current revision of JBM environmental guidelines

The JBM was already in the process of revising its accreditation guidance, including both its design and environmental guidelines, so the work of the Task Group was timely. The first tangible outcome of the Task Group was a draft set of sustainability guidelines for consideration by the JBM for incorporation in the accreditation requirements for civil and structural engineering BEng/MEng degree programmes. These were approved by the JBM in April 2003, and were linked strongly to the JBM's revised guidelines for design,<sup>34</sup> especially in their advocacy of an issues/process-based approach to learning.

Both sets of guidelines were written to improve the synergy between them, including the recommendation 'that the two sets of guidelines be considered together, especially in relation to teaching and learning methodology and assessment. In particular this will involve an increase in project work, preferably in a situation where they can interact with their fellow students and mentors.'

### 7.2. Input into the scheduled revision of core objectives

The process that the ICE set in train in October 2002 has moved rapidly into the mainstream of engineering education and

<sup>33</sup>The Design attributes of a competent engineer include:

- Ability to cope with a multitude of factors making up a design brief
- Ability to interact with clients and colleagues to develop a better understanding of the brief including social and economic objectives
- A knowledge of how to gather relevant information on environmental and planning issues.'

training requirements. In December 2003 the Engineering Council's UK SPEC for the first time included the requirement for chartered and incorporated engineers to have a specific competence to 'undertake engineering activities in a way that contributes to sustainable development'.<sup>34</sup> The Task Group was invited to present a summary of its outcomes at the Royal Academy of Engineering/Engineering Council workshop on 17 February 2004, aimed at sharing and developing best practice.<sup>35</sup> The Engineering Council's move reflects the demands of government, clients and society for technical professionals able to tackle the complex problems facing modern society and deliver a more sustainable future.

Mainstreaming sustainable development into civil engineering education and training will also impact on prospective engineering students—not least so that they might come to see engineering as a more attractive career option, and one which more vividly addresses their perceptions and aspirations of real-world issues in a more balanced way. The institutions therefore have an both an incentive and obligation to offer training and career paths that reflect their future members' values and the problems they will encounter in their working lives.

### 7.3. Assistance with implementation (both within higher education and CPD)

Having advocated a shift to a more issues/case study based approach to elements of the learning process, the Task Group has been working on providing assistance with implementation (in both higher education and CPD), for example with the RAEng and those involved in the RAEng Visiting Professor Scheme for Engineering Design for Sustainability. A key outcome of this collaboration has been the development of a model for a 'summer school' (scheduled for July 2004) for academics and reviewers in which they can be engaged with the sustainable development agenda and assisted to produce innovative approaches to teaching and learning to help them add value to and broaden out the teaching of their particular civil engineering specialism.

## 8. CONCLUSIONS AND DRIVERS

This paper traces the evolution of technology and the development of engineering through its various phases, from the immediate and urban technologies of the past, the period of technical rationality and enlightenment, through to the present time. It is argued that a more holistic/systems view of the world is now required—one in which engineers need to be more fully aware of the economic, social and environmental dimensions of their activities and more skilled in meeting their objectives. Collectively this defines the nature of sustainable development and it is at the heart of civil engineering.

Sustainable development has been shown to be consistent with adopting a systems approach to resolving real-world problems and capable of being addressed with wide-scale engineering rigour. The case has been argued for mainstreaming an appreciation of sustainable development into engineering education and training, and with it, the inculcation of an appropriate habit of mind, attitudes, systems skills and domains of knowledge to enable the engineers of the future to better contribute to society.

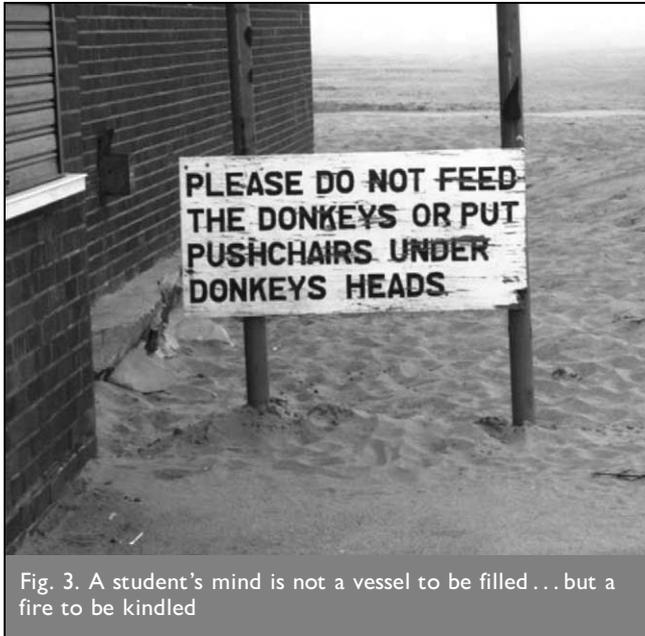


Fig. 3. A student's mind is not a vessel to be filled... but a fire to be kindled

The work of the ICE in achieving these objectives has been described, advocating a more process/issues-based approach to engineering education, in which the student's mind becomes a fire to be kindled, rather than a vessel to be filled by additional curriculum content in narrow subject-specific disciplines (Fig. 3). It is recognised that such an approach represents a challenge, especially for many of us who are the product—and therefore a reflection—of a different approach to engineering education and learning.

## 9. ACKNOWLEDGEMENTS

The author would like to acknowledge the contribution made by a number of friends and colleagues over many years to the views expressed in this paper. These include David Elms, David Thom, Colin Brown, the late John Munro, David Blockley, the late David Wilkinson, Tony Ridley, Mark Whitby, Adam Poole, Robin Nicholson, Gordon Baker, Peter Guthrie; colleagues at the Scottish Institute of Sustainable Technology and fellow Members of the ICE/IStructE Task Group and the Environment and Sustainability Board.

## REFERENCES

1. RIDLEY A. ■■■■■.
2. *Proceedings of the Johannesburg Summit on Sustainable Development*.
3. *New Civil Engineer*, 2003, Jan.
4. ICE COUNCIL.
5. THOM D. A. The need for 'environmental engineering education fundamentals'. In *The Environmentally, Educated Engineer: Focus on Fundamental*. (ELMS D. G. and WILKINSON D. (eds)). CAE Publications, Canterbury, NZ, 1995, ISBN 0-908993-08-0, pp. 25–37.
6. THOM D. A. Engineering education and the New Industrial Revolution. *International Journal of Engineering Education*, 1998, 14, 89–94.
7. THOM D. A. Can technology save the world? *Proceedings of an ICE Lecture*, London, 2000.
8. SCHÖN D. A. Preparing professionals for the demands of practice: the crisis of confidence in professional knowledge. In *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions*. Jossey-Bass Publishers, San Francisco, 1987, ch. 1, p. 376, ISBN 1-55542-220-9.
9. *New Civil Engineer*, 2003, 17, No. 24, May.
10. HEAL G. *Interpreting Sustainability*. Columbia Business School, 1996, working paper PW-95-24 (<http://www.columbia.edu/cu/business/wp/>, May 1996).
11. BENTHAM J. *Introduction to the Principles of Morals and Legislation*. 1789.
12. PINCHOT G. ■■■■■.
13. CARSON R. *Silent Spring*. Houghton Mifflin Company, Boston, 1962.
14. MEADOWS D. H., MEADOWS D. L., RANDERS J. and BEHRENS W. W. *The Limits to Growth*. A Report to The Club of Rome, Universe Books, New York, 1972.
15. SCHUMPETER J. A. The creative response in economic history. *Journal of Economic History*, 1947, 149–159.
16. ELMS D. G. 'Why are we here' In *The Environmentally, Educated Engineer: Focus on Fundamentals*. (ELMS D. G. and WILKINSON D. (eds)). CAE Publications, Canterbury, NZ, 1995, ISBN 0-908993-08-0, pp. 15–23.
17. TREGOLD T. ■■■■■.
18. BANYARD J. Water for the world—why it is so difficult? *Proceedings of the 5th Brunel International Lecture, ICE*, London, 2004.
19. RICHARDS S. *Wicked Problems and Clever Solutions: Sustainable Development and the Institutional Framework for UK Agricultural and Rural Policy*. Report to the UK Round Table on Sustainable Development, 1998.
20. DOOGE J. C. I. Concepts of the hydrological cycle ancient and modern. *Proceedings of a Seminar*, Heriot Watt University, 2000.
21. HOTELLING H. The economics of exhaustible resources. *Journal of Political Economy*, 1931, 39, 137–175.
22. HUFSCHMIDT M. A. The Harvard water program: a summing up. In *Water Research* (KNEESE A. V. and SMITH S. C. (eds)). Johns Hopkins, University Press, Baltimore, 1967.
23. ELMS D. G. Healthy Systems Criteria. Unpublished personal communication, 1997.
24. ELMS D. G. System health approach for risk management and design. *Proceedings of ICOSSAR Structural Safety and Reliability '97, Kyoto* (SHIRAIISHI, SHINOZUKA and WEN (eds)). Balkema, Rotterdam, 1998, pp. 271–277.
25. PETROSKI H. Galileo's confirmation of a false hypothesis: a paradigm of logical error in design. *Civil Engineering Systems*, 1992, 9, 251–263.
26. DOOGE J. C. I. The occurrence and movement of water. *Proceedings of a Conference, Conferring Lecture*, Politechnikakrakowska im Tadeusa Kosciuszki, Cracow, 2000.
27. JOWITT P. W. Sustainable water supplies—worth fighting for? *Proceedings of a Royal Society of New Zealand Conference: Fresh Water New Zealand: Problems, Processes and Priorities*, 2004 (in press).
28. EINSTEIN A. ■■■■■.
29. INSTITUTION OF CIVIL ENGINEERS *Society, Sustainability and Civil Engineering—a sectoral sustainability strategy*. ICE, London, 2002.
30. FORUM FOR THE FUTURE. *The Engineer of the 21st Century Inquiry: Change Challenges for Sustainability*. Forum for the Future, London, 2003.

31. THE ROYAL ACADEMY OF ENGINEERING. Available online at: <http://www.raeng.org.uk/education/vps/sustdev.htm>
32. VAUGHAN A. *Isambard Kingdom Brunel: Engineering Knight-Errant*. John Murray (Publishers) Ltd, 1999, ISBN 0-7195-5282-6.
33. CRUDGINGTON A. and JOWITT P. W. Sustainability in education training and continuous professional development (CPD)—results of an Institution of Civil Engineers/Institution of Structural Engineers Task Group. *Proceedings of an International Engineering Education Conference EE2004, Innovation, Good Practice and Research in Engineering Education*, University of Wolverhampton, 2004.
34. ENGINEERING COUNCIL UK. *UK Standard for Professional Engineering Competence*. Engineering Council UK, London, 2003.
35. *Proceedings of the Royal Academy of Engineering/Engineering Council Workshop*, 2004.

Please email, fax or post your discussion contributions to the secretary by 1 ???????? 2004: email: [emma.holder@ice.org.uk](mailto:emma.holder@ice.org.uk); fax: +44 (0)20 7665 2294; or post to Emma Holder, Journals Department, Institution of Civil Engineers, 1-7 Great George Street, London SW1P 3AA.

DRAFT