Bringing the Outside, Inside - Engineering for Sustainable Futures

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Abstract: *This paper offers a new paradigm for engineering education and therefore for engineering. This paper proposes a future for engineering where sustainability is deeply embedded in the things that engineering produces (i.e. its outcomes), in the way engineering is practiced (i.e. its operational processes and structures), and in the way engineers and engineering learn (i.e. its evolutionary processes). Further, this paper proceeds on the assumption that the core elements of the engineers' role in modern society are project management, problem solving and solution development.*

We will begin by examining the concept of sustainable engineering outcomes, in an environment which is fundamentally problematic, and then move on to examine the necessary prerequisites for sustainable engineering practice, which, in turn, will require us to explicate the necessary adaptations in engineering education and institutional arrangements.

Keywords*: Sustainability of Engineering Education; Sustainability of Engineering Outcomes; Sustainability of Engineering Practices*

Introduction

To commence, a quote from Rosalind Williams (2002), reflecting on September 11th, 2001

> *"The other thing that is left when the material part of technology collapses is humanity. We always knew that technological systems are composed of both material and social elements, but, as the saying goes, now we get it. That is why the technological catastrophe was also a human catastrophe. People died because all the interlocking systems – aviation, military, safety, health, information – were crawling with humanity: passengers on airplanes, emergency workers in streets, knowledge workers at desks, medics in ambulances, security checkers in airports, mail sorters, postal carriers. They were men and women of all colors, nationalities, languages, and levels of education, only a few of whom could be called engineers. All of them had their lives bound up with the creation, the maintenance, and the use of technological systems……In short, disaster revealed the core truth of*

> *technology and science studies: that technoscience is embedded in human history and human society."*

The quote focuses on the "embededness" of technological artifacts, and this is the key theme of the paper that follows. When one talks about "sustainability" of engineering and its products, we are really talking about the sustainability of the people systems within which a given product of engineering is deeply nested, and whose ends it serves.

This paper proposes a future for engineering where sustainability is deeply embedded in the things that engineering produces (i.e. its outcomes), in the way engineering is practiced (i.e. its operational processes and structures), and in the way engineers and engineering learn (i.e. its evolutionary processes). Further, this paper proceeds on the assumption that the core elements of the engineers' role in modern society are project management, problem solving and solution development.

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Sustainable Engineering Outcomes in a Dynamic Environment

William Wulff, the President of the U.S. National Academy of Engineering, in his paper "The Urgency of Engineering Education Reform" (1998) makes the following point:

> *"Engineering is synthetic - it strives to create what can be. My favorite operational definition of engineering is "design under constraint." Engineering is creating, designing what can be, but it is constrained by nature, by cost, by concerns of safety, reliability, environmental impact, manufacturability, maintainability, and many other such "ilities." Engineering is not "applied science." To be sure, our understanding of nature is one of the constraints we work under, but it is far from the only one, it is seldom the hardest one, and almost never the limiting one.....the practice of engineering is changing. Indeed, those changes are what underlie the urgency I feel for a new approach to engineering education. Growing global competition and the subsequent restructuring of industry, the shift from defense to civilian work, the use of new materials and biological processes, and the explosion of information technology - both as part of the process of engineering and as part of its product - have dramatically and irreversibly changed how engineers work. If anything, the pace of this change is accelerating."*

In this paper we too argue that engineered outcomes and the projects that produce them must, of necessity, be informed by the characteristics of their context. However, we would extend Wulff's argument to put the stress very firmly on the dynamic characteristics of the context – in other words, on the way in which the context, and its constituent components, are changing. By doing this, we are changing the nature of the task, from "fitting in" to "adaptation with".

Traditionally, when learning how to construct buildings, students learn that what lies beneath the building (i.e. the context for the foundations) is integral to successful construction. When learning how to design or choose a computer system, students learn that the design, or choice, has to include consideration of the connections the system has across the whole organisation, and with our global communications infrastructure. Environmental engineering ensures that students, at least, confront the physical and energy links that artifacts are embedded within, and the so-called "unintended" outcomes (e.g. pollution, waste, resource depletion) of all engineering activities. These incremental expansions in the definition of what constitutes engineering have, to all intents and purposes, achieved the status of "common practice".

If one were to trace the trajectory of modern engineering practice, it is possible to discern a gradual move outward, from the object being engineered, to the environment within which it is nested. However, this movement has been piecemeal, driven by specific relationships with specific sub-parts of the overall environment (e.g. the foundations, the waste disposal system, the global "web"). This paper argues that the dynamic environment needs to be brought into the picture in two ways – first, the dynamics which are focused on the specific project in question, and second, the dynamics which any project would have to adapt with – essentially the dynamics which characterise a turbulent environment.

Fred Emery, the Australian Open Systems thinker and researcher, argues that one needs to understand 4 kinds of relations in order to define and achieve a sustainable future for the system (and its projects) you are interested in, where "L" stands for "Lawful Relationship", "1" stands for a system, and "2" stands for its environment. The diagram below portrays these relationships topologically:

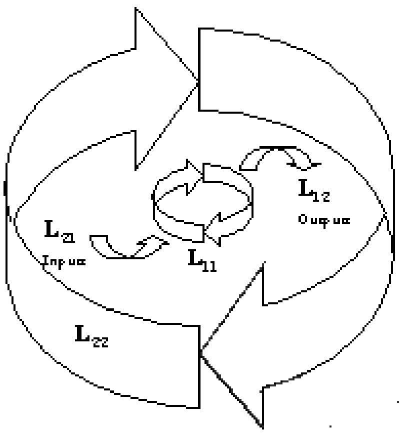

Diagram 1: Topological Representation of System-Environment Relationships

1. L_{11}; relationships within the system/organisation and its projects (eg relationships between project members, structure of steering committees, internal power structure, skill distribution, disciplines involved etc)
2. L_{12}; relationships from the system/organisation and its projects to its environment (what are often labeled as "outputs" - eg prototypes, finished products, new concepts, waste, recommendations for future actions etc).
3. L_{21}; relationships from the environment to the system/organisation and its projects, the conditions that the specific focus of our interest (ie the firm, the project in question) must adapt with (what are often labeled as "inputs" - eg standards, raw materials, available skills, professional expectations/culture, formal project tender specifications, informal client expectations, etc)

4. L_{22}; relationships within the environment, the conditions that **all** systems/organisations, and projects, which share the environment must adapt with. For example,
   - increasing application of technologies to all aspects of life and work,
   - increasing penetration by women into all social economic and political arenas of Western societies,
   - increasing resistance to, and conflict over, the extreme laissez-faire position taken by many governments, and institutions (eg WTO, IMF) globally,
   - increasing homogeneity of global culture and increasing conflict over this trend.

Whereas the core metaphor of traditional engineering is the stable, literally "rock solid" bridges, aqueducts, and buildings of classical civilisation, and the modernist metaphor is the clock-work machine, what we are going to call "*active adaptive engineering*" draws its inspiration from a biological metaphor. The 'project-and-its-tangible product(s)' is but one sub-system of a living, open system, and it is this open system which has to be sustained. The appropriate method for engineering a living, open system is active adaptive planning, using foresight to create a **desirable and feasible** future (or outcomes) for the system as a whole (if this approach had been applied to the Snowy River Scheme, aiming to sustain the Snowy River system, **and** its ability to sustain profitable water resources for agriculture, drinking and power generation over the long-term, the engineered solution would certainly have produced different outcomes to the environmental crisis we've created).

Environmental Types

The most important emergent property of the environment, today, has been the phase change into a "turbulent" (Emery and Trist, 1965) environment. The formal characteristics of turbulence are revealed below, in the classification of environmental types. These types should not be understood as simple graduations on a linear scale, but as qualitatively distinct levels of dynamics and organisation/complexity of the environment, each requiring a different class of adaptive response.

1. **Placid, Random Environment:** Goals and noxients (things to avoid) are unchanging and randomly distributed. In this type of environment, like the economists' "classical market", there is no distinction between tactics and strategy – the optimal strategy is just attempting to do one's best on a purely local basis. Furthermore, the best tactics can be learned by trial and error - the only transactional relations required are L_{11}. Under these (purely theoretical) conditions organisations would exist adaptively as single and rather small units.
2. **Placid, Clustered Environment:** The environment is still relatively static, but goals and noxients exhibit a degree of clustering. It corresponds to the economists' "imperfect competition". Strategy can now be distinguished from tactics – what the organisation knows about its environment becomes crucial for survival - both L_{11} and L_{12} are required for adaptation e.g. a positional strategy, as exhibited in the development of hill-top city states, controlling access, water resources, and arable land immediately below. Further, attempts to achieve an objective may lead into areas of danger, while avoiding a difficult issue may lead away from potentially rewarding areas. This is the class of environment within which human beings first emerged, and within which they have experienced most of their history (around 75-100 thousand years).
3. **Disturbed, Reactive Environment:** In this 3rd type, the environment becomes dynamic. It corresponds to the economists' "oligopoly". It is a level 2 environment within which there are a number of similar, competing, organisations, and this becomes the dominant characteristic of the field. Each organisation has to consider that what it knows can also

be known by the other organisations. Where the organisation wants to move, in the long run, is also where the others will move. Each organisation will wish to improve its own chances by hindering the others, and each will know that the others, not only wish to do likewise, but also know that each knows this.

The organisational response is that of an operation - a planned series of tactical initiatives, calculated reactions by others, and counteractions (ie now, L_{11}, L_{12} and L_{21} are required). It is now more important to define the organisational objective in terms of the ability to make and meet competitive challenges, ie. not focusing so much on location, but on the capacity or power to move, more or less, at will. The causal texture is then determined by the expectations and intentions that guide the moves and counter moves. This is the kind of environment which most organisations today are designed for.

4. **Turbulent Environment:** The dynamics now emerge, not only from the interactions of identifiable component systems, but also from the environment itself. The 'ground' is set in motion. Three trends contribute to the emergence of these dynamic field forces:
   - ♦ The growth of organisations, and linked sets of organisations, to meet level 3 conditions; are so large that their actions are both persistent, and strong enough, to induce "autochthonous" processes in the environment. (like the wooden bridge which will, itself, resonate as a consequence of soldiers marching over it in step). For example:
     - Growth of multinational oligopolies in the19th and 20th Centuries, and further development of their global reach during the 21st Century.
     - Growth of large scale competitive organisations (including NGO's and groups like Trade Unions)
     - Global agricultural "production" and the growth of monocultures, within vertically integrated food companies
     - Intellectual/knowledge "production" and the growth of "heaps of knowledge"
     - All linked through:
       - Oil and other natural resource networks
       - Physical transport networks (land, sea, air, space)
       - Electronic information networks (internet, data, fax, phone, telegraph)
       - Water, gas, electricity networks and the increasing interdependence of these networks with electronic and physical transport networks
   - ♦ The deepening interdependence between economic and social goals - to the point where economic considerations can come to dominate decision making, and some would claim "there is no such thing as society – only the economy" and, concomitantly, that one should strive for continual economic growth at the expense of all other considerations. Economic cycles have a wider impact and a more intensive impact.
     - Outcomes which have no economic value, are assumed to have no value
     - The social consequences of economic behaviour are downgraded
   - ♦ The increasing reliance on research and development to achieve the capacity to meet competitive challenge. This leads to a situation in which a change gradient is continuously present in the environmental field.
     - Amplification of all the other underlying trends; technology increases both the rate of change and the scale of change
     - Technological development increasingly wedded to political, military and economic goals (increases the rate of development, designed for purpose, not cost)

The resulting increased complexity, and the unexpected directionality of these causal interconnections, produces increased **relevant** uncertainty about the requirements for adaptation. Individual organisations, and projects, no matter how powerful, cannot expect to adapt successfully simply through their own direct actions. Now, all four possible relations (L_{11}, L_{12}, L_{21} and L_{22}) must be planned for as a prerequisite for adaptation. What is required in a turbulent environment, over and above tactics, strategy and operations is Active Adaptive Planning, based on an understanding of serial system-environment interactions.

To summarise, in this section we have argued that active adaptive engineering is the appropriate engineering paradigm for the 21st century. We have based our argument on the following facts:

1. Sustaining an engineered solution requires a sustainable ecosystem (system and environment) within which the solution is embedded.
2. The environment has to be understood as more than a collection of things and the relationships between them (i.e. more than its structure) – it also has to be understood as a dynamic whole
3. The current environment is turbulent – introducing a new level of dynamics and complexity into the engineering equation and, concomitantly, a new level of **relevant** uncertainty. This is why the engineering of large projects today is inherently problematic, and unanticipated consequences are the rule rather than the exception.

Sustainable Engineering Practices

Now, engineering practitioners need to learn about the other connections that engineered solutions have – for example with users and other stakeholders, with resources, with public perceptions of utility, with prevailing cultural assumptions etc. The diagram overleaf (Latour, 1999, p110) indicates the 4 main classes of interactions that determine the (potential) sustainability of a (potential) engineered solution are with:

- Logistical activities – what has traditionally been the focus of project management (e.g. the project plan(s) , the business plan, the marketing plan, the IT plan)
- Colleagues - forming coalitions across functional and/or disciplinary boundaries (e.g. with production, marketing or sales functions on the one hand or, with the disciplines that support engineering, on the other) to ensure that the process of designing and developing the (potential) solution is successfully integrated within the organisation, and with respect to, the appropriate reference groups (e.g. professional bodies).
- Potential and existing allies – forming alliances to actually market and sustain the solution (e.g. clients and other stakeholders, like governments, environmental or community groups)
- The public – that is, public perceptions of the functional or aesthetic value of a potential engineered solution.

These processes of planning, designing and researching an engineered solution are highly interdependent, and deeply embedded within a broader set of relationships. For example:

- Linking individual solutions to the complex and interdependent networks of people, resources and technologies which actually co-produce the solution (e.g. attempts to develop alternatives to the traditional automobile have to face the fact that they are not **only** up against "the auto industry", they are up against an alliance of powerful players in the automotive, liquid fuels, plastics, aluminium, rubber, steel, electronics, advertising, road building, motor vehicle maintenance/spare parts and service industries, as well as individuated drivers, the driver education industry and governments reliant on roads and petrol related revenues)

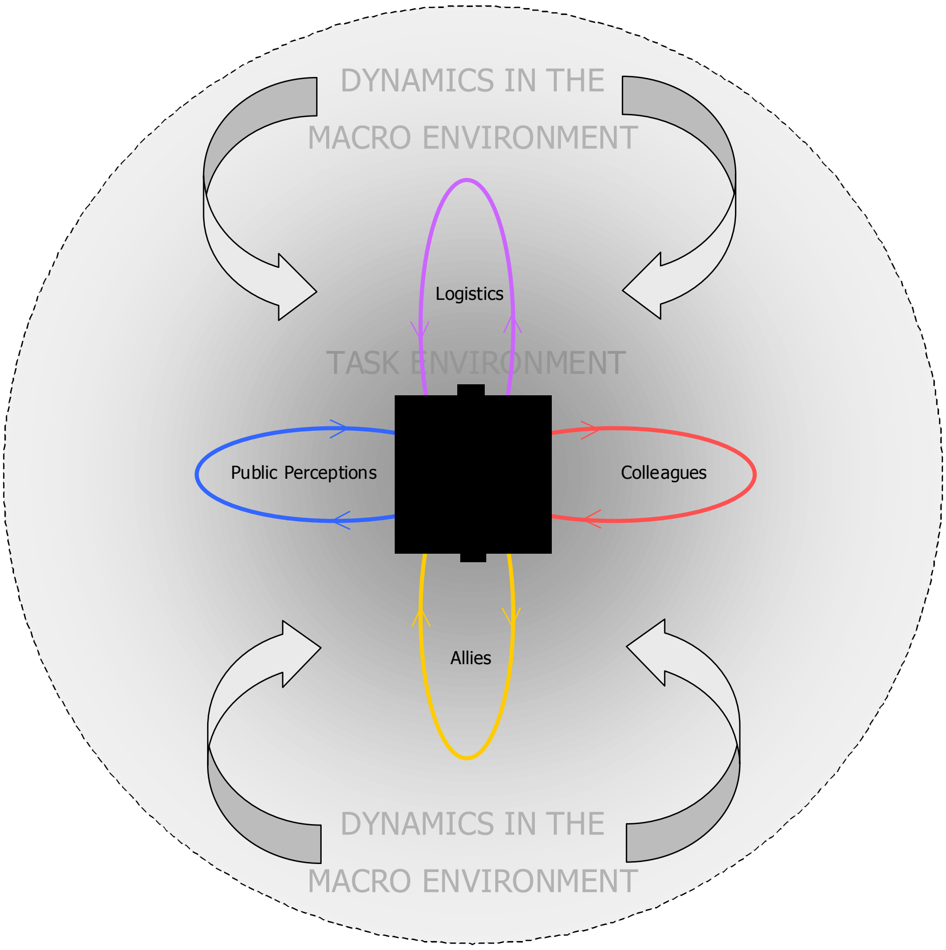

Diagram 2: Sustainable Engineering

- Identifying the right mix of skills, knowledge and tools for a given phase of a project, even for the same kind of artifact. For example, while it can be argued that "a bridge is a bridge, is a bridge", in fact, planning and designing a new bridge over the Burdekin river in far North Queensland, as opposed to the Hindmarsh Island bridge, or the Brisbane foot and bike bridge will require a different mix of skills/knowledge/ tools, because of the relationships these 3 bridges have with the broader social, political, technical and economic task environment they are embedded within. This, essentially, requires a full understanding of the role the solution will play within the whole eco-system it is a part of.
- Discriminating between non-linear projects (ie "wicked" problems, that 'meander' into the world along extended, dynamic and complex networks of people and technologies) and linear projects that can be managed with traditional project management techniques, like the "waterfall" method.(Conklin EJ, 1998)
- Identifying and applying appropriate research techniques to produce reliable answers to the questions arising from the project (eg not only technical research, but also social research, like, which stakeholders will salute, and which ones will give it the "thumbs down" or environmental research, like, an environmental impact assessment of the whole system within which the artifact will play its role).

However, all of these interactions in the so called "task environment", take place within a broader and, increasingly turbulent, macro environment, where, for example, the influence of social, economic and political trends can have a "make-or-break" effect on the responses of potential allies, on access to resources (logistics), on public perceptions, and on the readiness or capacity of colleagues to actively support what they may well see as a "courageous" project.

In a turbulent environment, active adaptive planning is a 3 stage process:

- Institutionalisation of a matrix of systems (Emery 1973, p77) – the building and sustaining of a set of mutually supportive relationships between all the key players in the design, development and delivery of the engineered solution. The relationships between the players need to made robust and predictable if the project, and the engineered solution, are to be sustainable.
- Project strategic planning (Emery 1973, p77) employing the Search Conference (Emery & Emery, 1974) methodology to bring all the key members of the matrix together and define a desirable and feasible future for the project, and the engineered solution
- Project design based on multi-functional project teams (Emery 1973, p77) employing the Participative Design Workshop (Emery & Emery, 1974)

In a turbulent environment these steps have to precede the more detailed project activities summarised in the previous section, or the project, while having a comprehensively adaptive relationship with its immediate task environment, may well be comprehensively maladaptive when it has to proceed within a turbulent environment (some possible examples include; 3G mobile telephony; the Mitcham-Frankston Freeway in Melbourne's south-eastern suburbs; high-rise public housing; the, so called, "dot.com revolution"; most recent IT projects eg RMIT's AMS and many recent intensive tourist developments in Indonesia).

Sustainable Engineering Education (of undergraduates, practising engineers and educators)

The task for engineering education must, increasingly, be the development of a culture of engineering that will enable engineers to deal adaptively with the "progressive composition of a common world" (Latour 2001). The key question then becomes one of organisation – in particular, **how to organise a sustainable technological world** – and by sustainable we must, increasingly, mean a world we can live in. From this perspective the relationships required to develop a sustainable solution can be summarised by "no sustainable innovation without representation"(Latour 2001). In the 3-stage process mentioned in the previous section, the theme that stands-out is the level of participation together with the level of democratic process involved.

To achieve this outcome, engineering and engineering education must become broader, more trans-disciplinary and, at the same time, it must allow itself to dissolve - to give up its assertive, clearly articulated and autonomous professional identity (cut off from the "outsiders" in politics, social inquiry and management).

The following is an outline of the range of subject material which will produce a sustainable engineering practice – through the acquisition of knowledge and skills that link engineering to the ecosystems within which it is practiced. Knowledge is extracted from the context, as appropriate to the task at hand rather than revealed as a series of content "blobs" from which students are expected to make abstractions. Skills in active adaptive engineering are learnt through acting in the context with an appropriate level of understanding of the dynamics of the context.

Some key elements of active adaptive engineering education are

- Focal Engineering, which Moriarty, 2000 defines as adding Knowing Why to the Knowing What and Knowing How of modernist engineering,
- Developing an eco-systemic perspective, that moves beyond the Traditional perspectives of engineering success,
- Pulling the Planning, Research and Design pieces together as an ongoing cycle (Action Research) as in Checkland, 1998,
- Understanding the nature of the "problem", expanding beyond the technical into traditional Socio-Technical and systems thinking,
- Solution development – embedding the solution in the task environment, embedding the solution in the macro environment; ensuring the Innovation is sustainable and using a truly trans-disciplinary approach in Socio-Technical Ensembles (Latour, 1999)
- Understanding the nature of the project to be managed
    - – is the project linear or non-linear?;
    - the extension of Socio-Technical thinking as applied to the Knowledge Industry;
    - "Wicked" problems or saturated interdependency (Conklin)

A Call to use Active Adaptive Engineering to Re-conceptualize Engineering

The world we live in, in the 21st Century, is turbulent. To deal with this environment we must learn to actively adapt with the environment, we need our solutions, to the problems and puzzles which we face, to be sustainable.

This a vastly different paradigm for engineers than the traditional stable, and literally "rock solid" bridges, aqueducts and buildings but also from the modernist metaphor of the "clock-work machine". We need to produce sustainable *outcomes*, to do this we need to practice "active adaptive engineering", and we need engineers and engineering to learn and therefore to evolve.

We need to shift the ground and re-conceptualize engineering and engineering education. To do this, in this turbulent environment, we need to apply the 3 stage process of active adaptive planning:

- Develop an institutionalisation of a matrix of systems. Build and sustain a set of mutually supportive relationships between all the key players in the design, development and delivery of the engineered solution. (a re-conceptualisation of engineering and engineering education). The relationships between the players will need to made robust and predictable if the project, and the engineered solution, are to be sustainable.
- Employ project strategic planning using the Search Conference methodology to bring all the key members of the matrix together and define a desirable and feasible future for the project, and the engineered solution
- design the project based on multi-functional project teams employing the Participative Design Workshop

Following the application of active adaptive planning principles, engineering practice can then move on to apply the comprehensive project management framework outlined in the previous sections. By approaching the engineers' task in this way, one builds sustainability in from the ground up, rather than adding it on to standard practice, like any other baroque variation.

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