AC 2007-1561: ENGINEERING SUSTAINABILITY?!

Roger Hadgraft, The University of Melbourne

ROGER HADGRAFT is Director of the Engineering Learning Unit in the Faculty of Engineering at the University of Melbourne. He has been working on problem-based learning issues since 1991 and has implemented significant curriculum change using project-based learning at both Monash and RMIT Universities. He is a civil engineer with interests in hydrologic modelling, knowledge management and engineering education. He has recently moved to the University of Melbourne to assist in the implementation of the Melbourne Model.

Jenni Goricanec, RMIT University

Jenni Goricanec has 25+ years of experience in telecommunications. She is completing a PhD on "A Philosophy of Engineering Practice for the 21st century, including sustainable futures".

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Engineering Sustainability?!

Introduction

Our world faces many challenges – climate change, drought, flooding, poverty, urban slums, water shortages, severe pollution, substance abuse, homelessness, profligate resource use, megacities, peak oil, land salinity, AIDS, malaria, and so on. It is already acknowledged that we are consuming the earth's resources faster than natural systems can recycle them [1] and that we are "putting such a strain on the natural functions of the Earth that the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted" [2].

Also, scientists now recognise that we are seeing human-induced climate change [3] and even the economists are starting to recognise the risks: "The scientific evidence is now overwhelming: climate change presents very serious global risks, and it demands an urgent global response" [4].

The further industrialisation of China, India and elsewhere is creating huge demands on already stretched ecosystems. Much of this industrialisation is to feed the affluent nations' needs for consumer goods, quite apart from the growing consuming class in the developing world [5].

It is clear that the sorts of problems facing the globe will need creative engineering solutions during this century. If this is the case, what sorts of engineers do we need to be educating for the 21st century? What capabilities will they need? What will be their focus? As this paper is for an ASEE conference, we have concentrated our attention on engineering practitioners but we provide an example from broader professional education in the Master of Sustainable Practice.

Reviews of Engineering Education

The last ten years has seen a series of reviews of engineering education. From these reviews has come an *outcomes focus* in engineering accreditation. The reviews continue to describe engineers as *primarily technical problem solvers*, e.g. the National Academy of Engineering's "Engineer of 2020" [6]:

- strong analytical skills (science, mathematics, discovery and design),
- practical ingenuity, creativity,
- communication, business and management,
- leadership, high ethical standards, professionalism,
- dynamism, agility, resilience, flexibility,
- lifelong learners.

Engineers Australia lists its required graduate attributes as follows [7] – the **emphasis** is ours:

a) ability to apply knowledge of **basic science and engineering fundamentals**;
b) ability to **communicate** effectively, not only with engineers but also with the community at large;
c) in-depth **technical competence** in at least one engineering discipline;
d) ability to undertake **problem identification, formulation and solutio**n;
e) ability to utilise a **systems approach** to design and operational performance;

f) ability to function effectively as an individual and in multi-disciplinary and multi-cultural **teams**, with the capacity to be a leader or manager as well as an effective team member;
g) understanding of the **social, cultural, global and environmental responsibilities** of the professional engineer, and the need for sustainable development;
h) understanding of the principles of **sustainable design and development**;
i) understanding of **professional and ethical responsibilities** and commitment to them; and
j) expectation of the need to undertake **lifelong learning**, and capacity to do so.

These are similar to those proposed by ABET [8], EURACE [9], ASCE [10] and IChemE [11].

A new focus (not just the technical)

These are all important attributes. However, we need a new *focus* for engineering, recognising that solving technical problems is no longer enough. In fact, many of the *predicaments* we now face will not be solved by technical means, but by social means. If engineers are to play a role in these issues, they will need much more than technical skills.

Consider water shortages in our major cities. In the 20th century, the solution was to build a new dam to satisfy growing demand. Increasingly, there are no new dam sites available or governments are reluctant to build on those that are available for fear of the environmental consequences (and the electoral backlash that may result). *Demand management* is the solution. This can be done in a number of ways, for example, through pricing, education and regulation. Increasing the price of water can change an industry's usage, where a small investment can lead to substantial changes in total water use, with consequential cost savings. Pricing has little effect on domestic consumption. Education (advertising) encourages domestic users to take shorter showers, install water efficient devices, check for leaks, install rainwater tanks, etc. Regulation can restrict water use through limiting outside water use such as watering gardens, washing cars, filling pools, etc.

Thus, engineers must be skilled in four areas of expertise – the triple bottom line (economic, social and environmental) plus the technical, for they will often be running the organisations that provide water, remove wastewater, provide electricity, public transport, telecommunications, etc. Solutions come from the economic (pricing), social (education, regulation), environmental (changing garden plants to use less water) and the technical (more dams, fewer leaks, recycling, desalination). Engineers must now be skilled in all these areas, not just the technical.

How is engineering done?

If we look in more detail at how an engineer solves problems, she might use a process like this:
- Meet the Client (the Client brief is the input)
- Plan to undertake the work
- Research to understand the problem (leading to) the Problem definition and scope
- Identify Alternative solutions and Selection criteria
- Analyse the options against the criteria and Decide which is preferred
- Recommend a solution and Document

The Mindmap (Figure 1) shows this process in more detail [12]. This is not new. Similar processes have been published in project management texts for decades. Software engineers, in particular, have their own versions, e.g. the venerable waterfall model. However, it seems rare to start with this process with first year students. Instead, we begin with lectures in statics, dynamics, computer programming, mathematics, physics, chemistry and so on.

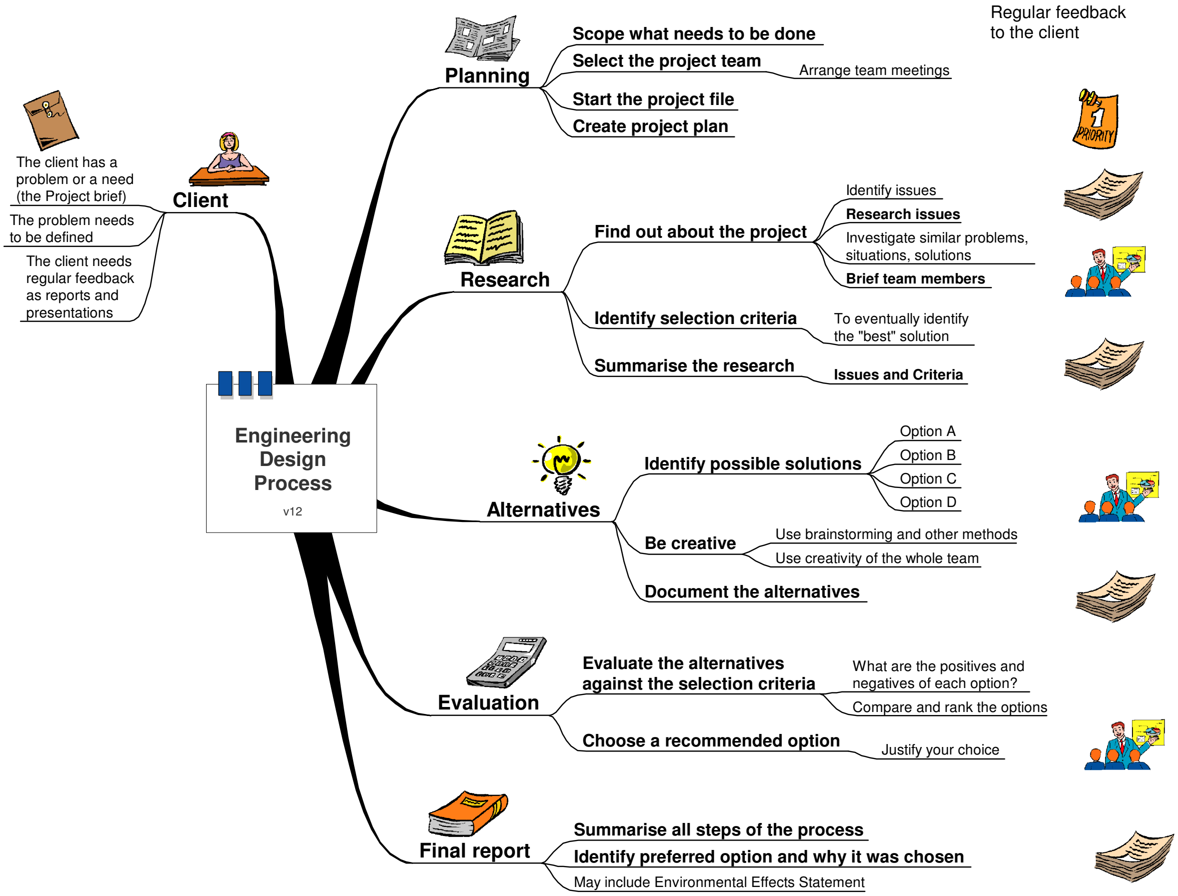

Figure 1 - the Engineering Design Process (mindmap)

So, if this is the basic process that engineers use to solve problems, what are the *basics*? They would seem to be skills in planning, research, problem definition, creative alternative generation, identifying selection criteria (using sustainability principles), modelling and analysis, decision-making and report writing. These are the *new basics*.

Compare this list with the *old basics*, which includes mathematics, physics, chemistry, applied mechanics, fluid mechanics, thermodynamics, etc. These map onto the new basics through the *analysis* phase (Figure 2). It is clearly time to rethink how we practise engineering education. Yet, the temptation remains to continue with the basic sciences through years one and two, with some engineering design being introduced in the third or final years.

Of course, the accrediting bodies have been saying this for sometime now (above). The outcomes based approach requires the development of both the new basics (process skills) and the old basics (technical skills), though the old basics usually taught first and are generally considered the most important.

The challenge is to enact these processes in our classrooms. Only through this process will we educate engineers who understand the sustainability challenges of the future.

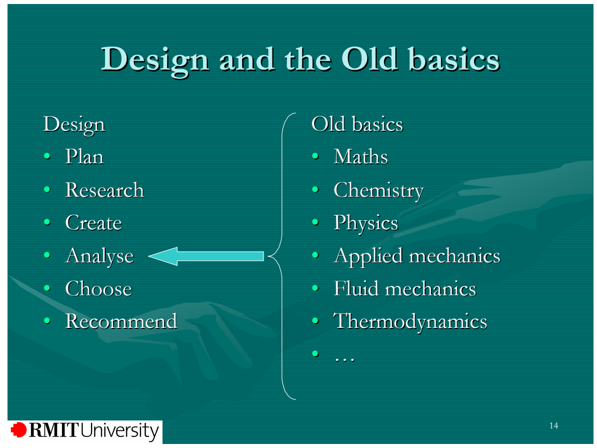

Figure 2 - Design and the Old Basics

Rearranging the curriculum

Traditionally, engineering education has been comprised of a process like this – a long sequence of technical courses followed by a capstone design course (Figure 3).

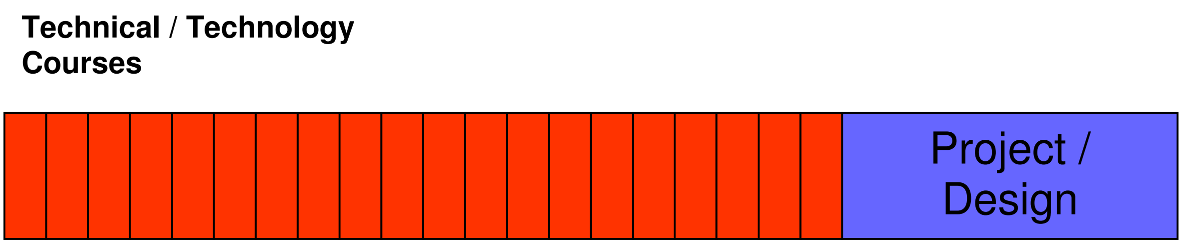

Figure 3 - Traditional engineering curriculum

At RMIT, where the authors worked until the end of 2006, more integrated curricula have been developed, which bring technical and process skills together in each semester [13]. This is sometimes called a project-oriented or project-based curriculum, e.g. [14].

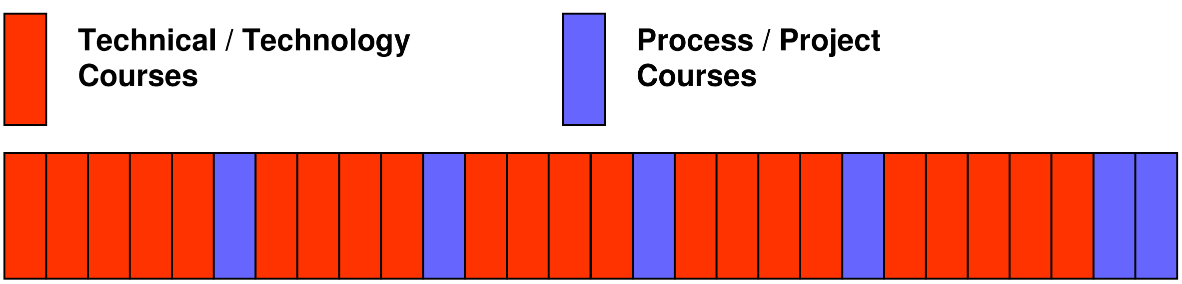

Figure 4 - Project-oriented engineering curriculum

In first year at RMIT, students do two project courses, which develop their conceptual design skills and help them understand the engineering design process (above). These projects are an opportunity to improve skills in project management, teamwork, written communication, oral presentation, debating, research and computing.

The later year projects give students opportunity *each semester* to integrate their practice of their technical skills. The choice of project is frequently technical, so students are (unfortunately) trained to see themselves as technical problem solvers. For example, second year projects include the structural design of steel-framed and concrete-framed buildings. In third year, students take a sustainable infrastructure design course, using sustainability concepts to develop a green design. In final year, students design a suburb or small town, integrating all the technical elements of civil and infrastructure engineering.

The authors believe that it is important to dissolve the distinction between process and technical skills, since they must be complementary. In this arrangement, the curriculum would start with the predicaments (more complex scenarios than *problems*) – Figure 5. Students uncover the technical skills as they engage with the predicaments. To make sure that they "cover" all the important "topics" a curriculum checklist could be used. This would be a problem-based rather than just a project based curriculum, e.g. [15].

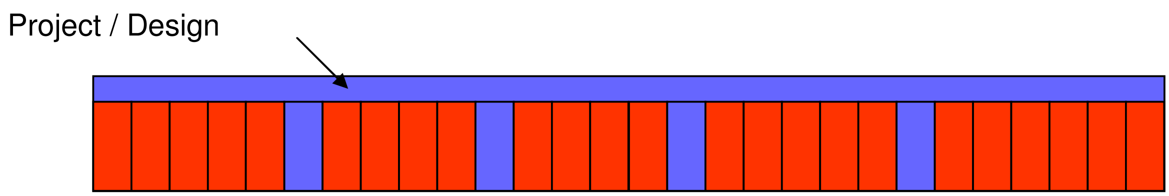

Figure 5 - Project-based engineering curriculum

An example of this approach in action was a computing elective taught in the final year of civil engineering at Monash University in Melbourne [16]. Students nominated their own scope of work for the semester. This was documented in a learning contract (by week 3). Most students wanted to learn AutoCAD skills. Their projects included a 3D model of a guitar, a formula 1 racing car, a bicycle, various buildings and the Humber Bridge (suspension bridge, UK).

The learning process included introductory lectures, online tutorials (from UNSW [17]), student seminars to teach the class and recommend learning resources, a final seminar to demonstrate what was achieved, a final report, learning journal and reflections on the process.

As students got started on their projects, they quickly exceeded their limited knowledge base, so they switched from using their technical skills back into learning mode. Their learning resources included the whole range of resources identified by the class, e.g. books and websites. However, most quickly realised that the most valuable learning resource they had was their fellow classmates. Once they had a learning issue under control, they switched back into "doing" mode.

A representation of this switching from doing to learning to doing to learning is captured below (Figure 6). In this model, students move from process skills to technical skills and back again, as the need requires. This is a curriculum for the 21st century, where students seek what they need to know. This is the process they will use as graduate engineers and they need to become masters of each skill.

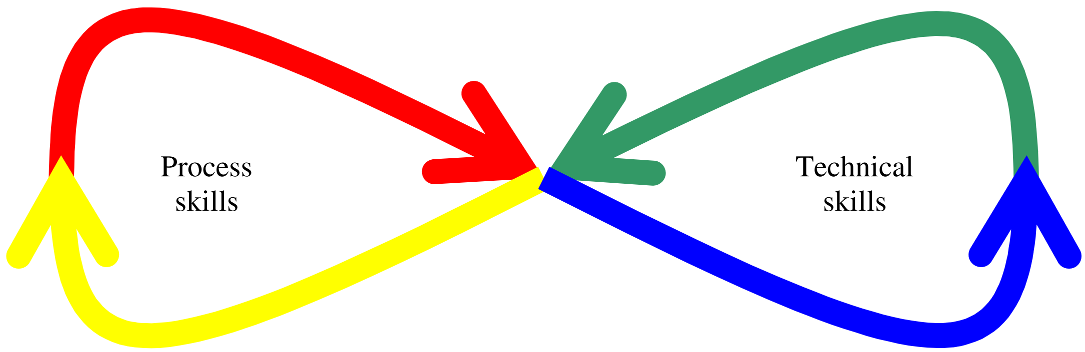

Figure 6 - Moving from process skills to technical skills (and back again)

In terms of the curriculum, it becomes an interweaving or blending of technical and process skills and knowledge (Figure 7). The challenge is to create a curriculum that implements these goals, where the preferred model is to divide the curriculum into narrow areas of expertise – applied mechanics, thermodynamics, fluid mechanics, structural engineering, groundwater, hydraulics, etc.

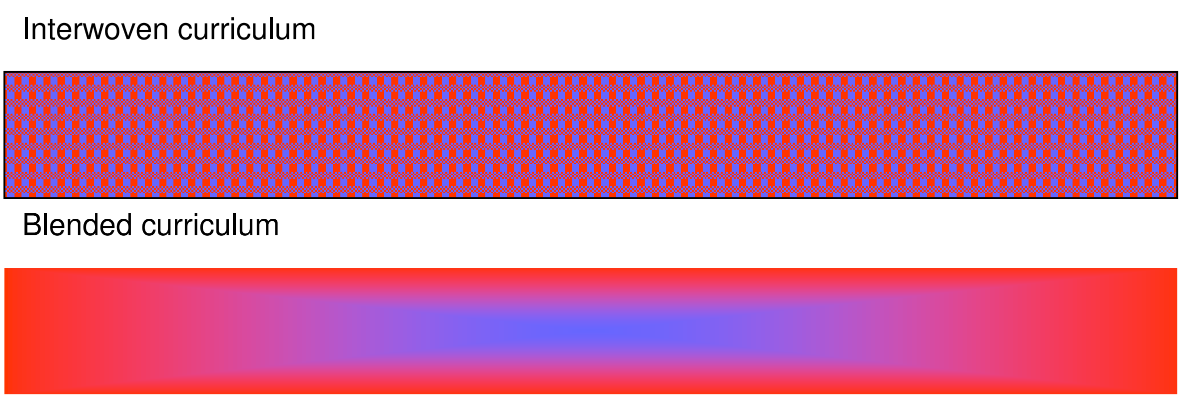

Figure 7 - Interwoven and Blended curricula

To develop the new basics, we need to model engineering education on engineering practice. This means that students must spend much of their time in complex problem solving rather than exercise solving. This is problem based learning (PBL) [18].

For the staff, it means change within a complex socio-technical system (the university) that is organised to optimise research rather than teaching. What insights are available from the literature of socio-technical systems to aid this process?

Implementing change

In a previous paper [19], the authors show how Latour's model of Actor Networks (Figure 8) presents a model for implementing socio-technical change of this kind [20]. Latour describes five key processes that require attention:

1. Mobilising
2. Autonomising
3. Building Alliances
4. Creating Public Representation
5. Linking and Knotting

1. Mobilising (logistics)

This stage defines *how* things happen. This requires a movement towards the world – in the physical sciences, it implies physical instruments, in anthropology, expeditions, in sociology, surveys and questionnaires. It includes the fabulous resources available on the Internet.

It also means articulating the argument. This process involves plans, project management, and finances, including funding. It includes resources such as teaching spaces, laboratories, field trips and technology organisations like Australian National Science and Technology Organisation and CSIRO.

Better use of these resources need to be considered in a redeveloped curriculum.

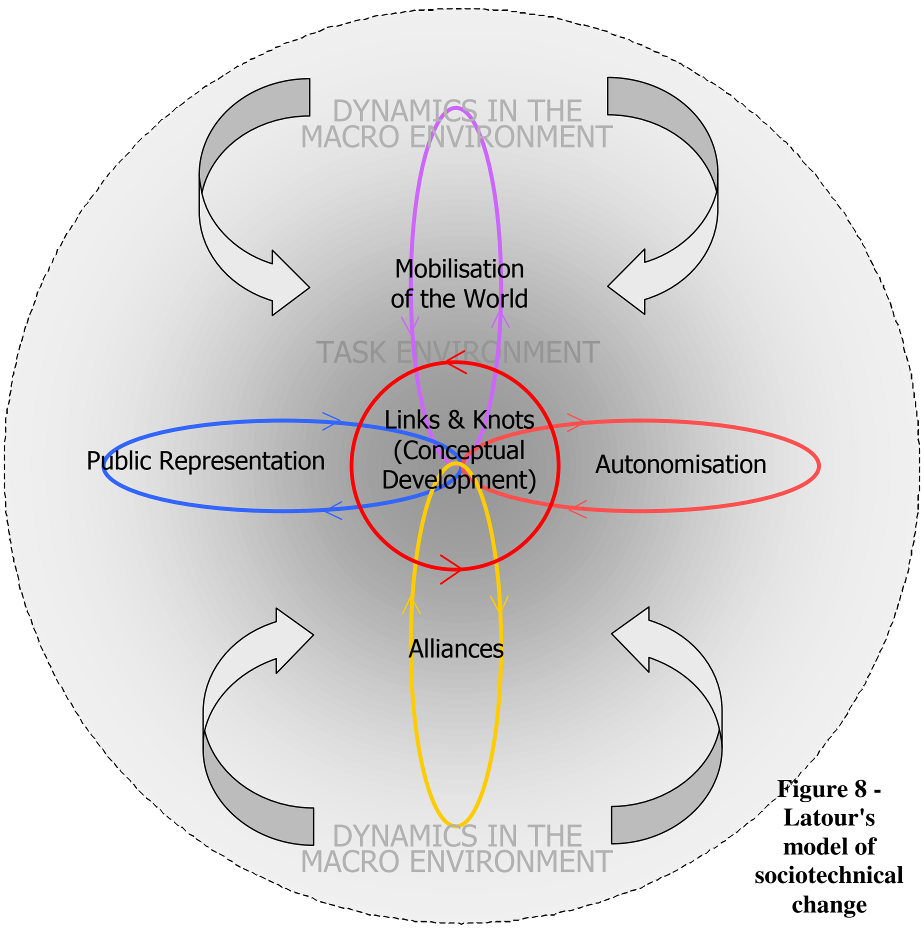

Figure 8 - Latour's model of sociotechnical change

2. Autonomising (peers)

This is the process of finding and engaging colleagues in the project. This loop: "Concerns the way in which a discipline, a profession, a clique, or an "invisible college" becomes independent and forms its own criteria of evaluation and relevance." p. 102 [20] This step requires building links with peers, both academic (teaching and research peers) and other engineers, engineering institutions, as well as administrative and technical staff. It means building links with service teachers in other departments and teachers in other programs and in other parts of the university. For example, developing the criteria to evaluate and determine relevance for the new discipline of sustainable practice (maybe, an accreditation body).

3. Alliances

This loop is about forming alliances to embed the development or innovation in the broader social, economic and political context. Alliances extend beyond the university. These deal with the broader social, economic and political context of the change. They include the government, companies, librarians, national and international organisations and others.

4. Public representation

This process deals with public perceptions of the functional, political, national or aesthetic value of a potential development or project. This includes influencing potential students and employers' perceptions of the new curriculum changes and ensuring that accreditation occurs.

5. Links and Knots

These processes bind together the other processes and make them work. They include the pedagogy and the technical content. What sorts of engineers are we producing?

These five processes form a hub and four -bladed propeller to drive change forward (just like the Spitfire aircraft of WW2 – Figure 9).

Note also that all the activities in Figure 8 take place within the "dynamics in the macro environment". It is one thing to develop, articulate and establish a project within a relatively stable, albeit competitive environment; it is quite another to do the same thing within a turbulent environment, for example, one where climate change means massive regional and global climatic, environmental and socio-economic consequences.

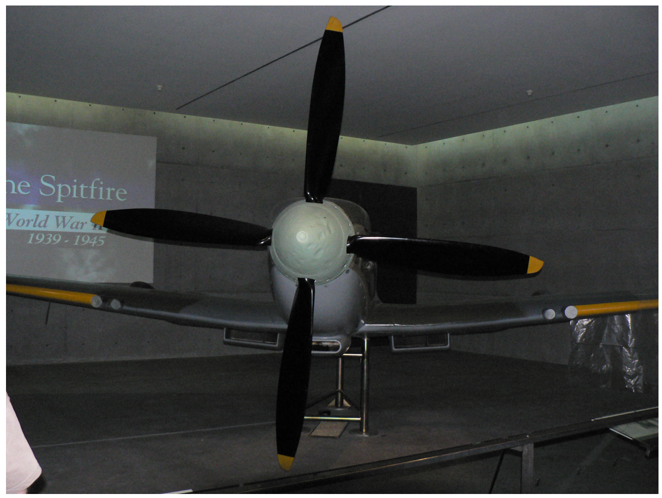

Figure 9 - Four-bladed Spitfire

As we can expect, there are strong feedbacks between the 'loops' of interactions – a supporting social trend (like "small is beautiful") primes the public for supporting messages which, in turn, facilitates the formation of alliances and attracts funding and other instruments of power.

Levels, Views, Scale – Course, Program, School, Student

By way of example, we will show how these processes can operate at various levels or scale within an academic environment – for both staff and students.

Our first example is changing at a **course or subject level**. This is the easiest change to make, but also the most constrained, as there is a limit to what one individual can achieve via changes within a single course. At this level, the five processes look like this:

- Logistics (mobilising) – teaching spaces, field trips, assessment tools, laboratories, teaching assistants, teaching materials
- Peers – other course leaders, the program team, staff developers

- Alliances – industry/companies, lecturers at other universities, engineering education society
- Public representation – internal and external publications about the changes, award applications
- Links and Knots – pedagogical strategy, technical content

These five categories of action provide a framework for making change successful and embedding it within a course (subject).

At a **program level**, there is more scope for change and each of the processes can yield more extensive opportunities for change:

- Logistics (mobilising) – business cases for new programs need to be developed, project plans for building new capabilities need to be enacted, including the hiring of additional staff, teaching spaces could be refurbished or created (e.g., to support group-oriented problem-based learning), online environments need to be created;
- Peers – leaders of other programs throughout the university, service departments, staff developers to work on strategic change, other engineers and professionals, engineering institutions including the local engineering education society;
- Alliances – industry/companies, similar program leaders at other universities;
- Public representation – to governments, industry, defence forces, social security, through internal and external publications about the changes, award applications, marketing materials for the new program to attract better students, school visits, papers for conferences;
- Links and Knots – what capabilities are we going to develop? And how? Including pedagogical strategy, technical content, how do courses and programs fit together? How does this fit into the university's systems? Are we going to change the environment within which it sits?

At a **school (department) level,** supporting several programs, each of these processes could be magnified further, allowing for greater engagement with logistics (e.g. plans for a program of change including the relationship between programs, better facilities and utilisation of staff across programs), peers (a wider circle of influence within the university and with engineering peers), alliances (a wider circle of influence and assistance beyond the university including integrated approaches to developing these), public representation (a stronger presentation of an alternative educational strategy to attract new students and a clearer perception for prospective employers) and linkages (a clearer sense of pedagogical process).

Students also can use Latour's model to make their own change (learning) effective. For them, the processes become:

- Logistics (mobilising) – teaching materials – print, electronic; laboratory and field exercises; projects – information and organisational skills required here
- Peers – other students; academic staff – group and communication skills required here
- Alliances – industry/companies who might provide work experience; engineering society
- Public representation – exhibition of student work (connecting with industry, parents)
- Links and Knots – process skills (described above)

Case Studies

1 – New undergraduate programs in civil & infrastructure engineering, chemical engineering and environmental engineering

The undergraduate programs in the School of Civil, Environmental and Chemical Engineering were renewed beginning in 2002, with introduction of the new programs in 2004 and 2005. Details can be found elsewhere [13, 21, 22]. A key change in each of the three programs was the introduction of project-based courses in *each semester* of the program (mentioned earlier and represented in Figure 4). For example, in civil and infrastructure engineering, projects include:

- Year1: An environmental impact assessment of a tourist development adjacent to the Yarra River in the central business district of Melbourne plus an own choice project (as a group), e.g. new airport train, airport terminals, ski lift, wind farm, water conservation strategy, urban subdevelopment, etc
- Year 2: Structural design of steel framed building and similar design in concrete. This project could be extended, to include foundation design, excavation for underground parking, economic analysis, construction scheduling, etc.
- Year 3: Sustainable design – "green" home or "green" apartment. Small structural projects are also included, e.g. cable-stayed footbridge and slab design for building designed in second year.
- Year 4: Investigation Project and Design Project as usual, the latter was of a new town of 6,000 people.

These projects provide the opportunity for students to develop their process skills explicitly, beginning in first year, and to integrate these with their technical skills (Figure 6).

This form of curriculum is relatively easy to introduce because it does not require all staff to be able to teach in a problem-oriented way. Neither does it require the reconceptualisation of the curriculum as in a true problem/project-based curriculum (Figure 5). As staff gain more confidence in a project-oriented environment, projects can play a larger role in integrating the curriculum across a semester and across the program.

2 – The Master of Sustainable Practice at RMIT

A more ambitious curriculum is the Master of Sustainable Practice (MSP) at RMIT University [23] – a multidisciplinary coursework program that admits those with a keen interest in sustainability and at least three years of work experience. At RMIT, any new program must articulate the *capabilities* that will be developed within its graduates. For the MSP, these are:

- Communicating coherently across disciplines and with the broader community;
- Identifying and defining sustainability problems;
- Researching;
- Developing proposals, including generating alternative solutions and analysing them against agreed criteria;
- Leading, managing and participating effectively in change processes;
- Evaluating activities undertaken for efficacy; and
- Being aware of self, others and processes used.

These capabilities present a high-level view of the sustainable practitioner. They must be strong in communication with affected communities; they must be able to articulate the problems and predicaments they face; they must be capable of constantly learning; they must be able to use their creative and analytical skills; they must be able to lead and manage change, evaluate that change and be constantly aware of themselves and others in the process.

It was clear to the RMIT authors that traditional teaching methods (pedagogy) would not achieve the sort of personal transformation that we believed would be necessary within the MSP. Considerable experience by the authors in problem-based and project-based learning provided a model for a more participatory and adult form of learning (andragogy). Smith [24], for instance, describes adult learners with these characteristics (reproduced from *the encyclopaedia of informal education* at http://www.infed.org):

1. **Self-concept**: As a person matures their self concept moves from one of being a dependent personality toward one of being a self-directed human being
2. **Experience**: As a person matures, they accumulate a growing reservoir of experience that becomes an increasing resource for learning.
3. **Readiness to learn**. As a person matures, their readiness to learn becomes oriented increasingly to the developmental tasks of their social roles.
4. **Orientation to learning**. As a person matures, their time perspective changes from one of postponed application of knowledge to immediacy of application, and accordingly their orientation toward learning shifts from one of subject-centredness to one of problem centredness.
5. **Motivation to learn**: As a person matures, the motivation to learn is internal [25].

We were keen to develop a program that would immerse its participants (both students and staff) in predicaments and problems that participants would bring with them from their workplaces, or other aspects of their lives. The notion of workplace projects as a vehicle for research and learning is similar to the Master of Education by Project at RMIT [26].

Progress in the capabilities is achieved and demonstrated through what we call the 7 P's of assessment [27] – quotes from these participant guidelines are provided below:

- **Personal Journal** – "… because we have chosen to run this program as primarily about 'learning in action', the day-to-day capturing of notes regarding your (and others') actions, your questions, your concerns, your insights, your thoughts, feelings and your learning is critical to your assessment. We intend that you will be increasingly mindful, capturing your thinking and feelings from your experiences in all aspects of your life – your project, at work, at home, your chosen electives, with your mentor, in the core courses, your reading and researching."
- **Project** – "The primary purpose of the project is to provide you a vehicle for the changes that you want/need to bring about, and thus a context within which to 'act' on issues of sustainability, and thus to 'improve' your practice to make it a more sustainable practice."
- **Project Mentoring** – "The Project Mentor's task is providing guidance in relation to your project. Note that the project work is intended as 'guided research' and that the whole Master of Sustainable Practice program has been designed around this concept (among others)." Each participant is assigned a mentor within the university who is able to provide some expert guidance (a little like a research supervisor) around their project.
- **Portfolios** – "Your portfolio is a primary source for assessment and evaluation in this program. It is both a container of evidence of your skills and a portrait of your development throughout the program. It is a purposeful collection of work that exhibits your efforts, progress and achievements in all areas being studied. The collection will include evidence of the choices you made in the selection of material, the criteria for selection, the criteria for judging and evidence of your self-reflection."

- **Personal Learning Contract** – "a contract with yourself to become mindful and articulate about your learning."
- **Personal Learning Mentoring** – one of the program teaching staff who provides "guidance to the learner to connect across the various learning activities".
- **Program Exegesis** – "One of the main roles of the exegesis is articulating and critically reflecting on your journey through the program and more specifically the change in you that has emerged (or is emerging or continues to emerge), at least in part, through your actions and reflections. The exegesis can also be seen as a "gathering-up" or "pulling-together" of the acting and thinking that you have undergone during the program (the various learning contract versions, the accumulation of six semesters' project work and reflections, your work with your writing cluster, the gathered material in your portfolio, performance reviews,…"

In the development of this program, we have used Latour's processes as follows:

- **Logistics** (mobilising) – we use group-oriented classrooms to support group-oriented problem-based learning; we use an online environment (BlackBoard) to provide documents and to support discussion between classes and as a prototype knowledge management system – a place to share knowledge with the class/group; we have sought staff who have the requisite facilitation skills to implement the andragogical approach
- **Peers** – we have engaged with staff across the university, in many Schools in the development and implementation of the program
- **Alliances** – we are building alliances with environmental groups, government departments and other universities
- **Public representation** – we actively market the program through organisational newsletters, including environmental groups
- **Links and Knots** – the andragogical strategy is described above.

Conclusions

We suggest that it is time that we begin to educate engineers within a new frame of reference – engineering for a sustainable world. While we continue to build them from the bottom up (years of training in the basic sciences), we risk hardwiring an approach to problem solving that only acknowledges technical issues. It is clear that the problems and predicaments of the future already require solutions that include the economic, social and environmental as well as the technical.

At RMIT, students are immersed in general project work from week one of semester one, with an introduction to sustainability principles. Each semester requires additional project work where students must see the project in its full perspective, with technical, economic, environmental and social criteria that must be satisfied. Through this process, we are beginning to educate the engineers we will need for the challenges ahead.

The Master of Sustainable Practice takes these ideas further, requiring students to use their project work to uncover what it is they need to know and be able to do. Students work as a learning community, learning from each other and from the program facilitators. With the explosion of information so readily availably via the Internet, this represents the future of engineering education.

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