Teaching and Assessing Systems Thinking in Engineering

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This paper presents research on undergraduate engineering students' perceptions of their learning about systems thinking.

Why is this important to engineering education?

Engineering faculties across Australia are experiencing substantial pressure from industry, the professional body and their own institutions to contextualise and embed generic graduate attributes in undergraduate programs (Engineers Australia, 1996; Engineers Australia, 2006; King, 2008). Similar pressure to reorient engineering education is evident in many other quarters (ASCE 2004; RAE 2006; ABET 2007; IMechE 2007). Responding to this pressure is proving challenging in Australia with three inter-related problems evident in the Australian engineering education literature: Innovative teaching of graduate attributes tends to be isolated and short-lived; rigorous evaluation of impact on student learning is rare; and contextualisation of institutional graduate attributes statements tends to be limited (Carew et al., 2007). In Australia and internationally, greater discourse, research and development are needed to embed engineering design-relevant meta-attributes (eg. reflective practice, creativity, social justice, systems thinking) in undergraduate engineering. The focus of this paper and our research is the teaching, learning and assessment of the meta-attribute *systems thinking*.

The Australian accreditation guidelines implicitly and explicitly mandate the teaching and learning of systems thinking relating to engineering design and operational environments as well as the broader context of engineering work (EA 2006: p7). Graduates require:

- … skills in the structured solution of complex and often ill defined problems;
- The ability to use a systems approach to complex problems…
- proficiency in the engineering design of components, systems and/or processes in accordance with specified and agreed performance criteria;
- skills in implementing and managing engineering projects within the bounds of time, budget, performance and quality assurance requirements;
- Skills in operating within a business environment…
- an ability to operate within a broad contextual framework accommodating social, cultural, ethical, legal, political, economic and environmental responsibilities and the principles of sustainable development and safety imperatives

An array of authors on the philosophy and future of engineering and engineering education represent systems thinking as key for competent engineering practice (eg. Nehdi and Rehan 2007; Radcliffe 2005; Carew and Mitchell 2002; Clift 1998); and engineering education researchers report that industry rank systems thinking as important for engineering design and management work (Hadgraft 2003; Maier and Rowan 2007; Spinks *et al.* 2006).

In summary, systems thinking skills are critical competencies for contemporary and future engineers for three compelling reasons (Therese, Carew and McCarthy, submitted):

- **Improved future practice:** The increasing complexity of systems created by engineers, and uncertainty and complexity associated with engineering work at the technology-society interface requires systemic understanding to map, predict, and, if possible, control or mitigate the nature and effects of engineering projects.
- **Continuing professional learning:** Systems thinking is an important meta-attribute in that systems awareness coheres with a range of related attributes important for reorientation of practice and continuing professional development in engineering (eg. lifelong learning; reflective practice; innovation; creativity; openness; social justice).
- **Philosophy of engineering practice:** Exposure to different approaches to system conceptualisation can highlight the new perspectives and insights offered by alternate approaches to modeling or metaphoric representation of systems. Hence development of systemic awareness offers engineers opportunities to improve understanding, design and steering of these systems.

Systems thinking is touted as a core engineering competence. It is a meta-attribute with value in all engineering disciplines and many non-engineering disciplines as well. Systems thinking is particularly important in disciplines such as chemical engineering and electrical engineering, where engineers are designing and implementing complex, interconnected systems of components. One would assume, therefore, that the development of systems thinking would be an important part of the curriculum in engineering disciplines. The study reported here addresses that assumption and begins to answer questions as to what the best teaching methods might be for developing this complex thinking skill.

Methodology and Data Collection

The research reported here was part of a broader study which used qualitative and quantitative measures (multi-method research design) to evaluate students' experiences of the teaching, learning and assessment of systems thinking in undergraduate engineering. In the broader study, we used three different data collection mechanisms to triangulate the findings:

- A **survey** instrument with six basic questions (Figure 1) and five demographic questions. The six basic questions followed the Phenomenographic approach by using second order questions aimed at eliciting the lived experience of the individual, reported from the individual's own perspective (Marton, 1986). Students were asked to rate the career usefulness of fourteen systems thinking skills (Figure 2), and how well they had learned and whether they had been assessed on these skills. A five point Likert Scale was used for student responses to questions 1, 2 and 4 where the word descriptions of rating 1, 3 and 5 were made explicit. Questions 3, 5, 6 were short answer (open-ended).
- Semi-structured **focus groups and interviews** with **students** using a question script.
- Semi-structured **interviews with academic staff** identified by the students identified in answering survey Question 3 and also from student focus group discussions.

1. How **useful** are the following systems thinking skills for your future career? (See Fig. 2 for skills list): **1** = Not useful (2= Somewhat useful) **3** = Moderately Useful (4 = Useful) **5** = Essential
2. How well have you **learned** about the following skills during your undergraduate degree? (same 14 skills) **1** = Not well (2 = Somewhat well) **3** = Moderately Well (4 = Well) **5** = Very well
3. Please give an example of teaching that helped you to learn one of the systems thinking skills (listed in Q2 above) **1** = Not at all (2 = Slightly) **3** = Moderately (4 = A lot) **5** = Thoroughly
4. Have you been **assessed** on the following skills during your undergraduate degree? (same 14 skills)
5. Please given an example of an assessment task that allowed you to adequately demonstrate one of your systems thinking skills (listed in Q4 above).
6. Do you have any further comments you would like to make?

Figure 1 - Overview of survey instrument

Findings

This paper primarily reports on the student survey research. We provide only a summary of the quantitative results as another paper (in preparation) focuses on full analysis of the quantitative data, and additional manuscripts are in preparation reporting the focus group and interview results. We collected data from students in both chemical engineering (strongly systems oriented) and civil engineering (arguably less systems oriented). We surveyed second year students (n=187) and final year students (n=122), providing some grounds for comment on possible development of capability over the intervening years (although these claims were necessarily circumspect given cohort issues). A summary of the demographic data is shown (Table 1).

An overview of the quantitative data generated from the survey is interesting (Table 2) and provides an introduction to the qualitative results. The percentages shown are the sum of those students who indicated a positive response (scores 4 and 5) on the usefulness, learning and assessment questions against the systems thinking skills listed in Figure 1. Note that 76.7% of students see the skills as useful for their future careers, with a slightly higher value for the final year civil engineering students. The focus on work related skills (Figure 2) is likely to have contributed to this. It is possible that students focussed on specific skills rather than these being examples of the use of systems thinking.

- Solving complex, ill-defined problems
- Using an holistic/systems approach for design
- Designing systems and/or processes according to specified criteria
- Developing and applying mathematical/physical conceptual models
- Documenting, analyzing and reflecting on engineering outcomes
- Ensuring occupational health and safety
- Communicating with others in engineering teams
- Managing engineering projects
- Operating professionally within a business environment
- Working with people from other disciplines and cultures
- Meeting legal, professional and ethical responsibilities
- Communicating with the wider community
- Meeting social and environmental responsibilities
- Working according to the principles of sustainable development

Figure 2 - Fourteen skills of systems thinking used in Q1, 2, 4 of the survey (derived from Engineers Australia Accreditation Guidelines, 2006)

Table 1 - Summary demographic data

Sex		**Age**		**Year**		**Major**		**Language at home**	
Female	118	<18	0	2nd	187	Chem	194	English	196
Male	186	18-20	123	4/5	122	Civil	115	Other	91
-	5	21-23	167					Both	19
		24-26	16					-	3
		-	3						
	309		**309**		**309**		**309**		**309**

Table 2 - Summary quantitative data

Program	**Year**	**Useful** (% positive response [scores 4 & 5])	**Learned**	**Assessed**
Chem	2nd	73.7±8.0	22.5±7.6	24.0±7.8
	4th/5th	75.7±9.5	45.8±11.0	43.9±10.9
Civil	2nd	77.6±9.6	30.2±10.6	29.8±10.6
	4th/5th	84.6±10.8	46.3±15.0	45.5±14.9
All	All	76.6±4.7	33.6±5.3	33.4±5.3

There was a significant difference[1] between students' scores on questions for 'useful' (question 1) and 'learned' (question 2) and 'assessed' (question 4). This suggested that systems thinking skills are perceived by students to be not as well learned or assessed as they should be, given the high proportion of students rating these skills as useful or essential for their future careers.

The learned and assessed scores were not significantly different across all years. As expected, final year students who indicated a positive response (proportion who answered 4 or 5) measured higher proportions on 'learned' and 'assessed' than second year students with students normally being exposed to more of these skills by final year where design and capstone experiences feature more prominently. However, only in the case of chemical engineering students did the scores differ significantly. In the case of civil engineering students the scores *appear* higher for fourth and fifth year students compared to second year students however the numbers in these groups were lower and so the error margin was greater.

At first glance, the similarity of the 'learned' and 'assessed' scores suggested that perhaps students answered in much the same way for both sets of questions. A chi squared test (χ^2) between the learned and assessed categories for all years (df=4) confirms this, with a χ^2 value of 0.09 indicating a significance value of p=0.999 suggesting no difference overall.

[1] Here, two scores were considered significant if the 95% confidence intervals of their proportions did not overlap.

The summary data shows that all groups of students saw the systems thinking skills as important (76.6% on average). There was a small year bias, suggesting there may be an improvement in perceived relevance and learning of systems thinking through both of the programs surveyed (Chemical and Civil Engineering), with final year students feeling more capable in these skill areas.

By learning process equipment, [the fourth year] design subject teaches in depth the skills to solve various problems that chemical engineers usually deal with (Chem Eng, Final Year Student).

The design of a mock mining town [was an example of teaching that helped me learn systems thinking skills] (Civ Eng, Final Year Student).

Given the quantitative results showed that students' perception of the usefulness of systems thinking did not match their experiences of being taught and assessed these skills, we now present the qualitative findings. These findings provide insights into how we might improve or increase students' experiences and perceptions of learning systems thinking.

Survey question 3 invited students to comment on 'teaching that helped you learn systems thinking'. The year 2 students surveyed showed differences between chemical engineering and civil engineering, with problem solving being the method most often nominated in chemical engineering while project work was most nominated by the civil engineering students (Table 3). In both cases, group work was mentioned as important in developing these skills. For example, a second year Chemical Engineering student, linking the learning of practical skills from group project work with learning to communicate with people from other cultures, commented that students are 'given more small projects to be done in groups rather than theory only…The group is set up by the teaching staffs [sic], so everyone could try to work with others regardless of culture differences.'

An example will be given, a complex tute problem to do (where the example done in class were a lot simpler [sic]) made us better problem solvers as we were pushed into not so familiar territory (Chem Eng, Second Year Student)

Working in groups for projects/assignments helps with the communication skills (Civ Eng, Second Year Student).

Table 3 - Teaching that helped learn systems thinking in Year 2

Chem	Year 2	Civil	Year 2
Tutorial problems	21	Group projects	17
Process eng	15	Labs	9
Group work	13	Math. Models	8
Labs	6	Management	7
Chem Process Analysis	5	Problem solving	5
OHS	4	Case studies	3
Maths	4	Lectures on Sust. Dev.	3
Management	3	Cultures	1
Intro Transport Processes	3	Self teaching	1
Lectures	3		

For the senior students, design projects were most often nominated by both disciplines (Table 4). For instance, several final year Chemical Engineering students identified group design projects as examples of teaching that helped them learn an holistic/systems approach to design:

Doing design work in final year design project [helped with using an holistic/systems approach to design (Chem Eng, Final Year Student).

The design project helps me to have a holistic view in designing the DME Plant (Chem Eng, Final Year Student).

Similarly, final year Civil Engineering undergraduates made the link between group design projects and the learning of systems thinking skills, such as communication and problem solving:

Design groups help communication skills (Civ Eng, Final Year Student).

Steel Design Week-Helped [with] working in a team [and] solving complex ill-defined problems (Civ Eng, Final Year Student).

Table 4 - Teaching that helped learning systems thinking - Seniors

Chem	Year 4/5	Civil	Year 4/5
Design project	15	Group projects/design	17
Process Engineering	9	Flow diagrams	4
Management	8	Complex problems/exams	4
Everything	5	Management	1
problem solving	3		
Group work	3		
Labs	3		

Question 5 (Please given an example of an assessment task that allowed you to adequately demonstrate one of your systems thinking skills [listed in Q4 above]) yielded similar results. This time, both civil and chemical students in year 2 nominated problem solving/tutorial problems most frequently as assessment tasks which allowed them to demonstrate specific systems thinking skills, as the following quotes illustrate:

> *Tutorials in Process Engineering where many problems were ill-defined but we were taught to solve them [allowed demonstration of systems thinking skills] (Chem Eng, Yr 2 Student).*

> *Introduction to Design tutorials that required us to work as a team to develop a solution for a specific problem, with typical procedures and team processes (Civ Eng, Yr 2 Student).*

Senior students in both disciplines predominantly nominated final year design projects as the most authentic assessment task, as the following open-ended responses make clear:

> *Process Engineering and final year design project which gives a tough scenario to work with (Chem Eng, Final Year Student).*

> *Doing our final year research project. We took on a project and did our own research (Chem Eng, Final Year Student).*

> *Mock mining town design with a group of students (Civ Eng, Final Year Student).*

> *Design of a town's water system and sewerage system (Civ Eng, Final Year Student).*

Questions 6 asked for further comments. Almost half of the comments were a request for a more practical education.

> *It would be great if we have practical base subject rather than theoretical base [sic] (Chem Eng, Final Year student).*

> *More practicals and more opportunities like design and projects would help us to put what we learn in practice rather than remain unsure of what is expected of us later in our careers (Chem Eng, Yr 2 Student).*

> *Perhaps more <u>real</u> industry exposure (real companies) during the course (Civ Eng, Yr 2, original emphasis)*

> *Not enough emphasis on case studies and real examples of engineering. Feels like I've spent 4 years solving desk problems with no real outcomes (Civ Eng, Final Year Student).*

Recommendations for engineering education

Surveyed students from both disciplines (Chemical and Civil Engineering) saw the development of a range of professional skills as useful to their future careers. They also noted that they were not getting enough teaching of these skills, nor were they getting enough authentic assessment opportunities to fully demonstrate mastery of these skills.

The surveyed students found a range of teaching methods useful to them in developing their capability in systems thinking, from traditional problem solving classes to complex design tasks. There were many requests for a *more practical curriculum* to take advantage of the projects, particularly group projects.

Future research plans

A companion paper that expands the discussion of the quantitative data is being prepared.

Follow-up research will examine systems thinking in other engineering disciplines. Further focus groups with students and interviews with staff will be used to explore what each group means by "systems thinking".

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References

Accreditation Board for Engineering and Technology (ABET) (2007) *Criteria for Accrediting Engineering Programs*. Engineering Accreditation Commission: Baltimore.

<http://www.abet.org/Linked%20DocumentsUPDATE/Criteria%20and%20PP/E001%2007-08%20EAC%20Criteria%2011-15-06.pdf>. (August 23rd, 2007).

American Society of Civil Engineers (ASCE) (2004) Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineer for the Future. BOK Committee for the Committee on Academic Prerequisites for Professional Practice. 12th January.http://www.asce.org/files/pdf/professional/bok_firstedition_jan2004.pdf> (August 30th, 2007).

Carew, A.L. and Mitchell, C.A. (2002) “Characterising Undergraduate Engineering Students’ Understanding of Sustainability.” *European Journal of Engineering Education* 27(4), 349-361.

Carew, A.L, Wickson, F. and Radcliffe, D.A. (2006) “Lessons from Transdisciplinarity Studies in the Design of Engineering Education Research,” 17th *Annual Conference of the Australasian Association for Engineering Education,* Auckland, New Zealand December.

Clift, R. (1998) “Engineering for the Environment: The New Model Engineer and her Role.” *Transactions of the Institution for Chemical Engineering,* 76 (B), 151-160.

Engineers Australia (2006) *Accreditation Criteria Summary.* Document S02. Accreditation Board Engineers Australia: Canberra.

Hadgraft, R. (2003) Defining Graduate Capabilities for Chemical Engineers at RMIT *14th Annual Conference of the Australasian Association for Engineering Education.* September, Melbourne.

Institution of Engineers, Australia (IEAust) (1996) *Changing the Culture: Engineering Education into the Future.* Review Report. Institution of Engineers, Australia: Canberra.

Institution of Mechanical Engineers (IMechE) (2007) *Summary of EC(UK) Output Statements General Learning Outcomes* IMechE and Engineering Council UK. < http://www.imeche.org/NR/rdonlyres/43E57C37-B58C-4315-8DC7-59A79DD38830/0/5AppendixAUKSPECGeneralOutcomes.pdf> (August 30, 2007).

King, R (2008) Addressing the Supply and Quality of Engineering Graduates for the New Century. Report on Engineering Education in Australia for the Carrick Institute for Teaching and Learning in Higher Education, Surry Hills, NSW, Australia.

Maier H.R and Rowan T.S.C. (2007) “Increasing student engagement with graduate attributes.” *Australasian Journal of Engineering Education* 13(1), 21-29.

Marton, F. (1986) Phenomenography – a research approach to investigating different understandings of reality, *Journal of Thought,* 21, 28-49.

Nehdi, M. and Rehan, R. (2007) “Raising the Bar for Civil Engineering Education: A System’s Thinking Approach.” *Journal of Professional Issues in Engineering Education and Practice*, 133, 116-125

Radcliffe, D. (2005) “Innovation as a Meta-Attribute for Graduate Engineers.” *International Journal of Engineering Education* 21(2), 194-199

Royal Academy of Engineering (RAE) (2006) *The Industry View.* <http://www.raeng.org.uk/news/releases/henley/pdf/Commentary.pdf> (August 30, 2007).

Spinks, N., Silburn, N. and Birchall, D. (2006) *The Industry View.* <http://www.raeng.org.uk/news/releases/henley/default.htm> (August 30, 2007).

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