EMBEDDING SUSTAINABILITY INTO CHEMICAL ENGINEERING EDUCATION: CONTENT DEVELOPMENT AND COMPETENCY MAPPING

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ABSTRACT

Sustainability has recently become an important component of chemical engineering educational practice and pedagogy. Recent evidence of this movement are the enhanced Engineers Australia (EA) competencies focussed in this area as well as changes in IChemE's McNab-Lacey student design prize selection criteria to emphasise sustainability. Over the past three years JCU Chemical Engineering, funded through a curriculum refresh program, has been trialing an approach to embed sustainability into the four year undergraduate chemical engineering degree program. Elements in the approach used by the authors have included aligned attribute definition, attribute mapping and content development. Parallel to these developments are facilitators of change that include research alignment and staff professional development. In this paper the authors describe briefly the development of generic sustainability attributes and the mapping of these attributes to the four year program, details of which are expanded on in Sheehan et al (2012). This paper describes the process of alignment of the JCU sustainability attributes to the newly developed Engineers Australia professional engineer stage 1 competencies, facilitated by the identification of sustainability related subject learning outcomes. A selection of newly developed content in a core chemical engineering subject (energy balances and introduction to design) and its alignment to the attributes will be described. This paper discusses methods used to identify gaps in current norms and brainstorm new content and skills for embedding within future chemical engineering programs.

INTRODUCTION

Over the past 10 years or more, sustainability and sustainable design have emerged as important features of chemical engineering higher education degrees. Academics, leading engineering professional organisations and accrediting bodies such as Engineers Australia and The Institution of Chemical Engineers have recognised the need for engineers to be cognisant in the emerging domain of sustainability. Whilst many higher education institutions have recognised this need and made moves to address it, the embedding of sustainability within degree programs as a contextual focus for engineering design and engineering development still remains a significant challenge. As brief background, it is worth outlining characteristics commonly attributed to sustainability within the chemical engineering higher education. Key elements of sustainability recognised across the spectrum of literature in this area include definitions of sustainability and sustainable design, an understanding of systems and the interactions between engineered and other (social and ecological) systems, usage of life cycle assessment/thinking and quantification of impacts using techniques such as sustainability metrics or triple bottom line approach. Additional elements that may also be aligned to sustainability have included safety and risk analysis as well as multi-disciplinary and cross-cultural understanding and awareness. In this paper we will advocate that teaching sustainability also requires that we more carefully consider and explain the contextual basis in parallel with teaching traditional chemical engineering concepts.

The accrediting bodies IChemE and Engineers Australia (EA) are important drivers of Australian undergraduate engineering curriculum renewal and they provide well defined professional standards and expectations for engineering graduates. Both of these institutions have recognised the need for renewal in this area and are encouraging higher education providers to embed sustainability throughout UG engineering education. The EA has recently updated its professional competencies list to predominately strengthen emphasis in the (sustainability) elements outlined above, including ethics, sustainability, systems approach, risk and safety and broadening contextual issues in engineering. Furthermore, the IChemE's McNab-Lacey student design prize has recently been modified and will now be awarded to the design project that best shows how chemical engineering practice can contribute to a more sustainable world. By aligning sustainability with a typical capstone design project the IChemE hope to "*extend the boundaries of conventional chemical engineering, and provide new "beginning of pipe" ideas rather than better "end of pipe" solutions*".

The specific objectives in this award are to:

- encourage students to think of sustainable development as a key element of their design projects
- Influence chemical engineering departments to position sustainable development at the heart of the curriculum
- Demonstrate that IchemE take sustainability very seriously

There are a few examples in the literature that describe methods and approaches to the embedding of sustainability into engineering education. Murphy et al (2009) and Allenby et al (2009) both provide details on the progress in embedding sustainability into both research and teaching areas in higher education institutions in the United States, with the latter paper providing an excellent philosophical treatise on the challenges and motivations in this endeavour. The University of Texas in Austin is an exemplar in this area. In Europe progress has been more limited (in contrast to accreditation driven reforms in both Australia and the USA) although progress at Delft University (see for example Mulder, (2006) and Segalàs et al (2009)) provides a good case study in this area. In Australia, recent changes to undergraduate chemical engineering program at James Cook University also makes an interesting case study (Sheehan et al, 2012). The dominant approach to date seems to have been for higher education institutions to create new postgraduate courses in "sustainable engineering" that lead to Masters level qualifications. However, the difficult and challenging task to embed sustainability within existing undergraduate programs has rarely been tackled, yet remains as a well-recognised goal in much of the literature.

There is a significant body of literature outlining the types of skills and techniques that loosely define the field of interest in relation to engineering sustainability and particularly green engineering design. Readers are referred to a review of these techniques and sustainability definitions by Garcia-Serna et al (2007). Another specific example of this would be the 12 principles of green engineering (Anastas & Zimmerman, 2003). More practical examples in the literature include those by Brennan (2009) which provides an excellent overview introducing the type of content required, categorises learning areas and provides some examples of supporting project based activities. In that paper Brennan briefly suggests that concepts and knowledge be taught early in the degree and then developed later in one or two concentrated courses. The breadth of tools and techniques in this area as well as the descriptors of criteria and objectives in sustainability are vast, and will certainly evolve and multiply as our familiarity and understanding of sustainability increases. As such there is acceptance that there is flexibility in how *awareness of sustainability* is developed. As a means to avoid being bogged down in the open ended spectrum of tools, techniques and criteria definitions, a more generic pedagogically driven approach is to emphasise the required *generic competencies* and *attributes* that lead to a student's *awareness of sustainability*. There are fewer examples in the literature that describe the development of engineering competencies in relation to sustainability. Segalàs et al (2009) compares the developed sustainability attributes at three European universities and classifies them under three broad descriptors of knowledge and understanding, skills and abilities, and attitudes.

The typical approach to embedding sustainability has been to introduce new content focussed on developing student's "knowledge of sustainability" in the early years of a degree program. This typically involves an introduction to definitions of sustainability, introduction to nutrient (N, P) and element cycles, including carbon and water, and discussion of climate change/energy constraints in engineered systems. More sophisticated and deeper levels of content which aim to develop students understanding of "complex systems" and lead ultimately to an ability to assess process impacts, has been to introduce Life Cycle Assessment and systems thinking. There are some excellent examples of LCA that can and have been incorporated into chemical engineering education. The examples provided by Evans et al (2008) include a LCA of different alternatives to hand washing (including air dried and paper towel dried) and an optimisation problem related to process plant location. Both these examples use CO_2 equivalents as the basis of comparison. Examples by O'Brien et al (2009) describe LCA of fly ash usage in cement manufacturing and are assessed in terms of CO_2 equivalents and water consumption. Other examples include those in a key sustainable design textbook by Azapagic and Perdan (2011) which contains a lengthy discussion of sustainability indicators and impacts as it relates to vinyl chloride monomer production. Much of the comparison in the latter example is cast in terms of safety and toxicity. Although there are good LCA and sustainability examples spread throughout journal and conference articles, there is a distinct lack of a fundamental chemical engineering textbook that has integrated these newer concepts into more traditional theory and problem solving examples.

In this paper we describe the process and methodology for embedding sustainability into the JCU chemical engineering program. In particular, our (i.e. the institution's) interpretation of a student's *awareness of sustainability* is defined. Mapping techniques are described as a means of identifying content location and sequencing of subject content. One of the subjects which plays a key role in developing students awareness is described and specific content examples are discussed, which link both to the overall methodology of curriculum renewal and to developing more refined mapping tools.

REVIEW OF APPROACH TO CURRICULUM RENEWAL

There are widely accepted and well-tested methodologies to follow in order to formulate an approach required to embed sustainability into undergraduate education programs. National and international case studies in this area have generally followed a similar process of renewal and include common characteristics. These characteristics can be conveniently classified using the term Rapid Curriculum Renewal for sustainability (Desha and Hargroves, 2011). The elements of this approach include:

- Awareness raising & developing a common understanding amongst staff
- Identifying graduate attributes
- Auditing and mapping each program against graduate attributes
- Embark on strategic content development & renewal
- Bridging & outreach with industry & education
- Integrating curriculum with campus & community opportunities

To this list we would suggest the following elements are added, in order to obtain a finer level of understanding of the specific content requirements involved in embedding sustainability into engineering programs:

- Identifying subject *learning objectives* and the depth of coverage
- Mapping the progression of *learning objectives* throughout program

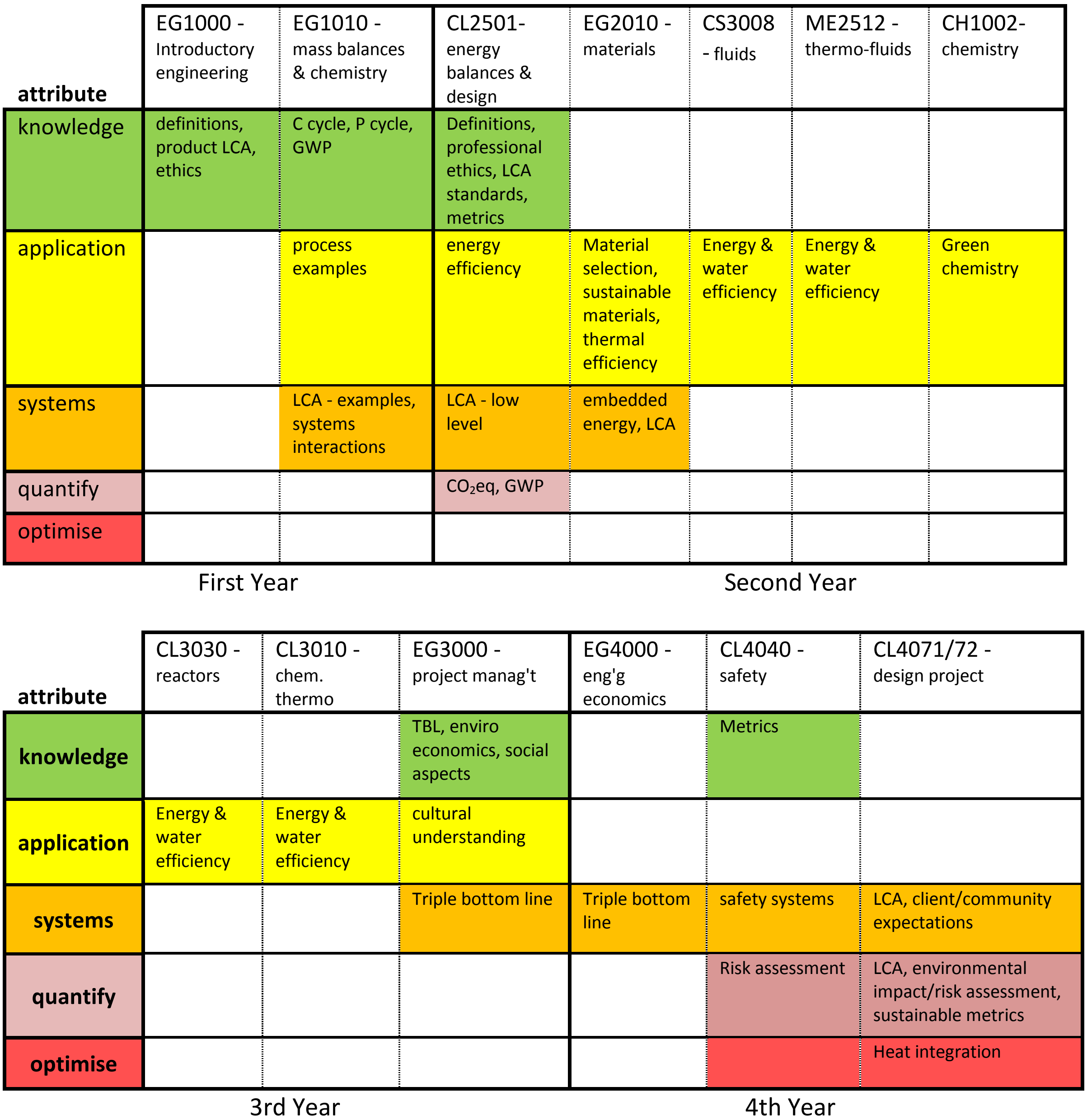
For the JCU - Chemical Engineering case study, specific details of the broad approach are outlined in Sheehan et al (2012). In this section of the paper we briefly draw attention to two of the key elements within this approach that were used to inform the process of developing specific subject content. These stages were the determination of sustainability attributes and program wide mapping to identify target subjects and broadly describe content within those subjects.

A workshop involving all engineering disciplines (chem., mech., civil, electrical) was utilised to identify common attributes that describe a student's "*awareness of sustainability*" and align with the teaching staff's understanding of sustainability (Table 1). Immediately prior to this component of the process is an appropriate time to provide staff with professional development opportunities, such as guest seminars and targeted conference attendance, in order to raise the general awareness of sustainability. The attributes are described in Table 1 and are deliberately multi-disciplinary in order to suit the integrated nature of teaching within the engineering program at JCU. However, multidisciplinary attributes also suit the desired characteristics of modern chemical engineers, who being fluent in sustainability, are able to transcend the traditional boundaries between disciplines. The final attribute in Table 1: optimise; is termed a stretch target and would not necessarily be achieved in an generalist undergraduate chemical engineering program but may be achieved by students completing a chemical engineering sustainability major or in a postgraduate degree. The inherent simplicity of the 5 stage attributes and the scaffolded nature of the attributes (i.e. knowledge generally precedes conceptualising systems which precedes quantifying impacts and benefits) works well in developing a preliminary program wide mapping strategy.

Graduate attribute description	**Capability keyword**
Knowledge of sustainability including definitions, discipline context, relevance and importance.	Knowledge
Discipline specific exposure to sustainability applications including examples of sustainable practice and design.	Applications
Ability to conceptualise complex systems and their interaction across ecological, social and environmental dimensions.	Systems
Ability to use tools to quantify sustainability of products, processes and designs.	Quantify
Ability to optimise engineering designs to trade off across the three dimensions of sustainability (environment, equity, economy)	*Optimise*

Tab. 1: Generic graduate attributes in sustainability

In a follow-up workshop amongst chemical engineering teaching staff only, the attributes were mapped into the existing chemical engineering program. Subjects deemed appropriate for incorporating sustainability content (i.e. existing content deemed to be aligned with the required attributes) were chosen. Approximately 12 subjects from 32 total program subjects were selected. The mapping process involved brainstorming what attributes would be addressed in each subject within the map. A preliminary attempt to define content specifics using keywords was also undertaken in an effort to guide the development of appropriate curriculum. Mapping was also informed by taking keywords from the Australian context presented within the IChemE roadmap: Energy and Water. The attribute map is illustrated in Figure 1. As this was the early stages of (mapping) content development and alignment, there was a reduced level of understanding amongst staff of what specific content was required and particularly how content can be integrated and scaffolded across the entire program. These deficiencies led to the requirement of a more targeted mapping process described in the next section of this paper.



attribute	EG1000 - Introductory engineering	EG1010 - mass balances & chemistry	CL2501- energy balances & design	EG2010 - materials	CS3008 - fluids	ME2512 - thermo-fluids	CH1002- chemistry
knowledge	definitions, product LCA, ethics	C cycle, P cycle, GWP	Definitions, professional ethics, LCA standards, metrics				
application		process examples	energy efficiency	Material selection, sustainable materials, thermal efficiency	Energy & water efficiency	Energy & water efficiency	Green chemistry
systems		LCA - examples, systems interactions	LCA - low level	embedded energy, LCA			
quantify			CO_2eq, GWP				
optimise							

First Year

Second Year

attribute	CL3030 - reactors	CL3010 - chem. thermo	EG3000 - project manag't	EG4000 - eng'g economics	CL4040 - safety	CL4071/72 - design project
knowledge			TBL, enviro economics, social aspects		Metrics	
application	Energy & water efficiency	Energy & water efficiency	cultural understanding			
systems			Triple bottom line	Triple bottom line	safety systems	LCA, client/community expectations
quantify					Risk assessment	LCA, environmental impact/risk assessment, sustainable metrics
optimise						Heat integration

3rd Year

4th Year

Fig.1: Generic sustainability graduate attribute program map. JCU Engineering is a small and highly integrated School with 25 staff offering a 4-year bachelor engineering degree

comprising 32 subjects (15 discipline, 17 multiple disciplines), with five discipline-major options (chemical, mechanical, civil, computer systems and electrical engineering). The School's intake comprises approximately 15-20 chemical engineering students per year.

It is important to recognise that rather than spread content evenly across all mapped subjects we have used a few key subjects to convey the majority of sustainability content. Particularly the content aligned with the attributes *knowledge*, *systems* and *quantify*. The target subjects for this content are a 2nd year course on energy balance and introduction to process design, a 3rd year engineering project management course, a 4th year safety course and a 4th year chemical process design (full year capstone subject) course. Other subjects in the map are primarily an avenue for presenting applications, reinforcing prior learning and gap filling, where necessary. Eventually it is anticipated that all subjects in a degree program would present material and examples that include sustainability as the context for technology selection, design and engineering analysis.

CONTENT DEVELOPMENT AND LEARNING OBJECTIVES

Following this mapping process and over a period of two years, a range of content renewal and content development was undertaken across most of these subjects. In some cases content was sourced from colleagues in other institutions or was facilitated through funding conference and workshop attendance or other resource requests (such as textbook or software purchases). It is worth noting that at this stage, the development of specific subject content, while guided by the attribute mapping, was largely left to the subject coordinators and as such was aligned with their own understanding of the subject and in many cases, their own research strengths and specialty knowledge areas. This is thought to be an appropriate starting point for content development and is assumed to lead to higher quality teaching though teacher-content familiarity than would be obtained by enforcing that specific content be taught. This approach also leads to capacity building amongst teaching staff. However it is essential in these early stages to encourage and support staff in professional development that expands their understanding and ability to interpret sustainability within their own field of expertise (teaching and research). There are limited text books in this area, particularly lacking are fundamental texts (such as a Himmelblau and Riggs (2004) or Felder and Rousseau (2000) equivalents) which incorporate sustainability as a context throughout the book. As such, developing content in this area can take chemical engineers a bit out of their "comfort zone" and readymade content is not easily obtained.

Program wide staff professional development is particularly important to the embedding of sustainability attribute "Applications" across a range of different subjects. Our interpretation of applications is that existing content be delivered to students using sustainability as the context for comparative assessment and analysis. Embedding this attribute requires teaching staff to align existing subject content and skills development within the new context of sustainability. Alignment of existing content and sustainability is best explained by way of examples:

- In an energy balance course (CL2501) introducing students to the use of psychrometric chart data, fundamental skills development can be gained through an example comparing traditional cooling tower design with newer technologies with reduced chemical, water and cost requirements, such as air cooled condensers. This leads to students developing complementary skills in quantifying and comparing impact (such as water use) and facilitates discussion of life cycle assessment as a means to compare process options and as a framework for process design selection criteria.

- Another example in the same energy balance course, where steam table usage and developing understanding of vapour pressure-temperature relationships are taught, is a comparison between single and multiple effect evaporation. Energy balances and steam table data can be used to calculate the resultant energy efficiency gains. This also leads to facilitating discussion of tradeoffs between capital and running costs.

As a result of the allowing staff to develop their own sustainability aligned content under limited specific constraints (ensuring ownership and academic confidence in the content) there remains potential for overlap and repetition. Furthermore, scaffolding of student learning outcomes and skills development may not be ensured in this way and learning may end up being disjointed. As such, a secondary mapping process is being trailed to consolidate content and facilitate the determination of new specific content and provide a theoretical basis to subject/program development. This mapping is intended to be a more focussed, pedagogically driven attempt to align the new content to accreditation guidelines and to identify gaps in the curriculum renewal across the entire program. A more thorough treatment is hoped will also ensure well designed assessment is being developed to reinforce student learning.

In this mapping process the specific student learning outcomes directly related to sustainability content and attributes were identified by each subject's teaching staff. As much as possible the learning objectives aimed to include the keywords from the 4 program-wide attributes. By way of example, the sustainability-related learning outcomes in a 2nd year course on energy balances and design are shown below, with generic attributes underlined:

LO1. To develop knowledge of the definitions of sustainability, sustainable design and the roles and responsibilities of engineers in sustainable development
LO2. To develop a broader knowledge of the environmental impacts and environmental sustainability performance measures of chemical processes
LO3. To develop knowledge of the life cycle assessment approach to product and process design and to use this knowledge to propose life cycle systems diagrams for products and chemical processes
LO4. To be able to understand and quantify engineering applications to enhance energy efficiency in chemical processes
LO5. To be able to quantify the impact of chemical processes in terms of $CO_{2\ eq}$ emissions

The process of defining the sustainability-related LO's is pedagogically valuable. It encourages teaching staff to formalise and clearly define what they are hoping students learn in their subject. Furthermore, it links to generic program-wide attributes through the use of underlined key words and it can also help to identify complementary learning objectives that may then be embedded in later courses. For an example of the latter, in learning objective 2, the subjects focus is on *environmental* impacts and measures. Following from the three pillars of sustainability (economy, environment, equity/society) it can be assumed that in latter courses related learning objectives should include "*economic* impacts and measures" and "*social* impacts and measures". Hence new specific learning outcomes required across the program can now be defined which makes it easier to allocated these LO's to specific subjects, or identify where they may be already covered. Likewise, a series of new learning objectives aligned with LO5 can also be identified, including:

To be able to quantify the impact of chemical processes in terms of [aquatic emissions/solid emissions/ airborne emissions....etc]

Specifying LO's also aligns well with requirements of engineering accreditation. Each LO can be mapped onto, for example, the EA stage 1 competency standards (Engineers Australia, 2011) for professional engineers as shown in Table 2. In light of the recent introduction of new competencies and strengthening of existing competencies, we have formatted the Table entries to identify these recent changes. It is interesting to note that most learning objectives address the strengthened EA competencies and only LO4, which is aligned with the *applications* attribute, addresses existing competencies. This works well with our intention that the *applications* attribute involve teaching staff interpreting their existing content within a new context: sustainability.

Learning objectives	EA professional engineer competencies					
LO1	1.5 (a)	1.6 (d)	*2.3 (b)*	*2.4 (f)*	3.1 (a)	**3.1 (c)**.
LO2	1.6 (d)	*1.6 (f)*	*2.1 (g)*	*2.3 (b)*	*3.3 (b)*	*3.4 (a)*.
LO3	*1.6 (f)*	*2.2 (e)*	*2.3 (c)*	*2.4 (e)*.		
LO4	2.1 (e)	3.3 (a).				
LO5	2.1 (e)	*2.3 (c)*	*3.3 (b)*.			

Tab.2: Sustainability learning objectives and their alignment to EA engineering competencies (Engineers Australia, 2011). **Bold** entries indicate a new competency expectation or major change and *Italic* entries indicate a strengthened emphasis.

To obtain a finer level of insight into the achievement of the stated learning outcomes and the depth of the student learning a Revised Blooms Taxonomy (described in Nightingale et al, 2007) is utilised (Table 3). It is hoped that using this technique will drive teaching staff to more carefully consider their subjects LO's and also to become more familiar with how the LO's relate to the type of learning (such as learning facts, concepts or procedures) and depth of learning (such as recalling facts, understanding in similar circumstances, applying to new scenarios...etc). This technique also helps to better understand what new content may be required by identifying, for example, LO's that are more procedural than factual. To explain this point further, consider stated LO3 which is clearly a key element in the development of students understanding of systems and life cycle assessment. Yet it is quite challenging to construct a step by step pathway of student progression in this area. Using Table 3 it can be assumed that future learning outcomes are required to address conceptual knowledge (evaluate and create) and procedural knowledge (understand, apply, evaluate and create) in this area. In this way, LO3 can be progressed in other subjects to populate these missing sections of the matrix and as such provides a recipe for content design predicated on a sound foundation of scaffolded learning experiences. However, it is worth also noting that it may not be necessary to meet all these objectives and each institution will endeavour to reach their own prescribed depth of learning.

Knowledge domain ↓ *type of learning*	Cognitive process domain → *depth of learning*				
	Remember	Understand	Apply	Evaluate	Create
Factual knowledge	LO1 (T,E) LO2 (T,E,F) LO4 (A,F) LO5 (T, A, E)	LO1 (T,F,E) LO5 (T)	LO5 (T,A)		
Conceptual knowledge	LO3 (T, E) LO4 (E)	LO3 (T) LO4 (A)	LO3 (T)		
Procedural knowledge	LO3 (E)				
Meta-cognitive knowledge					

Tab.3: Constructive alignment of sustainability learning objectives and subject assessment tasks (A: assignments, E: exams, T: tutorials, F: field trip/site visit)

CONCLUSIONS

Incorporating or embedding sustainability into chemical engineering undergraduate programs is an important change in engineering education that is becoming widely recognised by academics and professional accrediting boards. Examples in the literature describe the general approach to undertaking curriculum renewal but lack specific details in terms of mapping and content requirements. Graduate attribute mapping techniques are useful in broadly identifying both content areas as well program location. In order to condense and organise content, align with accreditation competencies, and identify new content, specific subject learning objectives aligned with the graduate attributes are valuable. An example of 5 learning outcomes in a 2nd year energy balance course illustrate some of these benefits. Stated learning outcomes and an pedagogical analysis of the type and depth of student learning (via Modified Blooms Taxonomy) can be used to determine new learning outcomes that facilitate the scaffolding of student learning as well as inform the determination of new learning outcomes related to sustainability.

REFERENCES

Allenby, B., Murphy, C.F., Allen, D. and Davidson, C. (2009) Sustainable engineering education in the United States, *Sustainability Science*, **4**(1), 7-15.

Anastas, P.T. and Zimmerman, J.B., (2003) Through the 12 principles - green engineering, *Envrionmental Science and Technology*, March 1, 95A-101A.

Australian Dept. Education, Employment and Workplace Relations. (2009-2011) Diversity & structural adjustment fund, JCU curriculum refresh project - Australia's University of the Tropics.

Azapagic, A. and Perdan, S., (2011) Sustainable Development in Practice: Case Studies for Engineers and Scientists, 2nd Edition, Wiley-Blackwell, United Kingdom.

Brennan, D., (2009). Education Priorities For Chemical Engineers in Green Process Engineering, in *Proceedings of the 2nd International Congress on Green Process Engineering*, Venice, Italy.

Desha, C. and Hargroves, K. (2011) Informing engineering education for sustainable development using a deliberative dynamic model for curriculum renewal in *Proceedings of the 2011 Research in Engineering Education Symposium*, Madrid, Spain.

Engineers Australia: Stage 1 Professional Engineer Competency Standards, (2011) http://www.engineersaustralia.org.au/sites/default/files/shado/Education/Program%20Accreditation/110318%20Stage%201%20Professional%20Engineer.pdf. (accessed 22/5/2012).

A Guide for University Departments and Assessors: Based on Learning Outcomes, IChemE.

Evans, G.M., Galvin, K.P. & Doroodchi, E., (2008). Introducing Quantitative Life Cycle Analysis into Chemical Engineering Curriculum, *Education for Chemical Engineers*, **3**(1), 57–65.

Felder , R.M. and Rousseau, R.W., (2000) *Elementary Principles of Chemical Processes*, 4th Edition, John Wiley and Sons, New York.

García-Serna, J., Pérez-Barrigón, L. and Cocero, M.J., (2007) New trends for design towards sustainability in chemical engineering: Green engineering, *Chemical Engineering Journal*, **133**, 7-30.

Himmelblau, D.M. and Riggs, J.B., (2004) Basic Principles and Calculations in Chemical Engineering, 7th Edition, Prentice Hall, New Jersey.

Nightingale, S., Carew, A. and Fung, J., (2007) Application of Constructive Alignment Principles to Engineering Education: Have we really changed?, in *Proceedings of the 2007 AaeE Conference*, Melbourne, Australia.

Mulder, K.F. (2006) Engineering curricula in sustainable development. An evaluation of changes at Delft University of Technology, *European Journal of Engineering Education*, **31**(2), 133-144.

Murphy, C.F., Allen, D., Allenby, B., Crittenden, J., Davidson, C., Hendrickson, C. and Matthews, H.S., (2009) Sustainability in engineering education and research at US universities, *Environmental Science and Technology*, **43**, 5558-5564.

O'Brien, K.R., Menache, J. and O'Moore, L.M. (2009) Impact of Fly Ash Content and Fly Ash Transportation Distance on Embodied Greenhouse Gas Emissions and Water Consumption in Concrete, *International Journal of Life Cycle Assessment*, **14**(7), 621-629.

Segalàs, J., Ferrer-Balas, D., Svanström, M., Lundqvist, U. and Mulder, K.F., (2009) What has to be learnt for sustainability? A comparison of bachelor engineering education competences at three European universities, *Sustainability Science*, **4**(1), 17-27.

Sheehan, M., Schneider, P., & Desha, C. (2012), Implementing a Systematic Process For Rapidly Embedding Sustainability within Chemical Engineering Education: A Case Study of James Cook University, Australia, *Chemistry Education and Practice*, **13**, 112-119.

Technical Strategy Roadmap: Progress Report (2008), *Driving in the right direction*, IChemE.