# Evaluation of application of sustainability metrics across multiple undergraduate design projects

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## Abstract

This paper reports on an evaluation of an innovative approach to teaching sustainability introduced in undergraduate chemical engineering design projects across multiple year levels. The approach uses a sophisticated industry management tool to aid analysis of a design problem and to identify the best solution among a range of technology choices. The approach is compared with other methods of teaching sustainability, such as lectures or community based learning. Evaluation tools are compared, including concept maps (Cmaps) and a formal student survey.

The stream of project based learning subjects in the RMIT Chemical Engineering program offer scope for a systematic and detailed analysis of the sustainability of alternative designs. A sophisticated and complex framework tool – the GEMI Metrics Navigator™ - can be used by junior and senior students to make better design decisions when comparing alternative chemical manufacturing processes. Students demonstrate their grasp of the richness and complexity of sustainability concepts relevant to chemical engineering design using Cmaps. Students work in groups in design project subjects. Each group completes a Cmap on what sustainability concepts are relevant to the design problem both at the start and at the conclusion of the sustainability module. The Cmaps are evaluated for number and distribution of concepts against taxonomy of sustainability categories, as well as degree of connectivity. This study used a quasi-experimental pretest-posttest design. The results are compared between a 2nd and 4th year subjects.

The results show that the students' knowledge and ability to apply sustainability concepts to design problems increased significantly during their 2nd year subject, and increased further after their 4th year subject. The number of concepts and degree of connectivity of Cmaps increased after undertaking multiple projects. The distribution of concepts was poor, with categories (such as "technology" or "economy") overrepresented, and others (such as "future generations") underrepresented.

This longitudinal study will continue to evaluate the efficacy of this approach to teaching sustainability. Areas for future improvements include giving more support to lower performing groups as well as achieving a higher level of learning across all groups. The curriculum should be reviewed to focus more on the under- represented sustainability categories.

# 1 Introduction

Many universities struggle to develop the attribute of sustainability in their students. This study describes an innovative approach to teaching sustainability in design subjects as well as a methodology for evaluation. Both can be adopted by other Universities.

RMIT has a four year Chemical Engineering degree that has a blend of traditional courses and project based learning (PjBL) design courses from first to final year, one per semester. A recent study showed that while our PjBL graduates are "work ready" there are gaps in their understanding of sustainability issues. A new approach to teaching sustainability was adopted in several of the PjBL courses in 2011. This paper reports a longitudinal study of the efficacy of the new approach.

Project based learning (PjBL) is an educational approach well placed to develop generic skills (Mills & Treagust 2003). However few studies have looked specifically at how effective PjBL is at development of sustainability as a competency. This paper looks at outcomes for student learning in subjects when a sophisticated industry management tool, GEMI The Metrics Navigator™, is used to guide selection of criteria for making design choices. Student learning outcomes are evaluated by analysing concept maps drawn at the start and finish of learning modules.

# 2 Background

Chemical Engineering at RMIT University in Melbourne, Australia, is a four year program that is accredited at Masters level by the Institution of Chemical Engineers, UK. Each year of the program contains two semesters, with four subjects per semester. Of these, three subjects are taught with a traditional approach, and one with a project based learning (PjBL) approach. The PjBL subjects help students develop technical as well as generic skills. In these subjects, students work in small groups to design a chemical manufacturing plant. The project is different each year, to give a new challenge to students repeating the subject, to reduce plagiarism, and to bring in topical issues. In 1$^{st}$ and 2$^{nd}$ year PjBL subjects, lectures or workshops are delivered throughout the semester on relevant technology aspects or generic skills. In later years the scaffold of lectures gradually gives way to group meetings with a supervisor or industry consultant. Group work on the project is assessed through project reports and presentations, and individual technical knowledge is assessed with tests. The projects augment in complexity from first to final year, and repetition of the generic skills leads to mastery.

Our graduates are well regarded for their "work readiness", with high skill levels in project management and communication (Jollands *et al.,* 2012). However, no difference could be seen between these and graduates from a traditional program in terms of knowledge of sustainability. This was surprising, as constructive pedagogies have been shown to be a suitable method for teaching sustainability (Segalas *et al.* 2009, Mulder *et al.* 2012). The authors reviewed contemporary approaches to evaluating sustainability in industry and then implemented a new systematic approach to teaching sustainability across several projects in several year levels. This paper reports on a longitudinal study of outcomes from the new approach, comparing learning outcomes in sustainability for two PjBL subjects, one in 2$^{nd}$ year and one in 4$^{th}$ year.

# 3 Literature Review

*3.1 Approaches to teaching sustainability*

There are many approaches to teaching sustainability. A major pan-European study of sustainability subjects found that the pedagogical approach varied from traditional lectures to community based learning (Segalas *et al.*, 2009). The study found that community-oriented and constructive-learning pedagogies had superior learning outcomes, but no details are given on how the subjects were taught.

PBL is a common approach in engineering education. A number of studies have shown that PBL is an approach well placed to develop generic skills in engineering undergraduates (Mills & Treagust 2003, Litzinger *et al*. 2011). However, few studies have specifically evaluated efficacy of sustainability learning. The outcomes for students in PBL courses depend on what is taught and how the projects are run (Walker & Leary 2009). A recent study of work readiness of engineering graduates who had undertaken a predominantly PjBL program identified gaps in the graduates' understanding of sustainability issues (Jollands *et al.* 2012).

Community based projects are less common in engineering education, mainly due to the relatively high time and resource requirements to run the projects. One interesting example is described by Maxwell (2009), where a group of civil engineering students visited the construction site of a desalination plant, and met local actors who were both for and against the development.

*3.2 Approaches to evaluating learning outcomes in sustainability*

Several methods for evaluating student learning in sustainability have been developed in the last decade. These vary in ease of use, placement in the curriculum (embedded or add-on), and insight into areas of the curriculum that should be strengthened.

One approach is to use "concept maps' (Cmaps). Cmaps have been extensively developed by Novak (1998). Student identify concepts relevant to a central question and interlinks between the concepts, and construct a Cmap from these. The Cmap is analysed in terms of breadth and depth of knowledge across a range of categories, and the interconnectedness of the categories. In the Segalas study students were asked to draw a Cmap at the start and end of the subject. The differences were interpreted as enhancement of their knowledge from their learning in that subject (Segalas *et al*. 2009). This is an embedded approach that is easy to use, neatly captures the breadth and complexity of sustainability learning, and gives insight into where the curriculum should be strengthened.

Another approach is to apply an analytical framework such as the Structure of Observed Learning Outcomes (SOLO) taxonomy to student descriptions of sustainability (Carew & Mitchell 2002, Nicolaou & Conlon 2012). The framework is used to analyse student responses in terms of the level of conceptual sophistication , ranging from "pre-structural" (no understanding) through to "extended abstract" where the students demonstrate critical reflection. This is a qualitative approach that gives limited insight into the breadth of student learning or directions for curriculum review.

A last approach is a conventional survey. Such surveys have been developed by Azapagic *et al.*(2005) and Nicolaou & Conlon (2012). These can identify both depth and breadth of learning and directions for curriculum review, where the response rate is sufficiently high. Surveys can be administered with ease using on-line tools, but response rate may be low.

In this study, Cmaps were used to evaluate student learning. Cmaps are embedded in the curriculum, are efficient to analyse, and it is a useful tool for students to learn to use.

*3.2 Sustainability metrics used by industry*

Two management tools are available in the public domain to assess sustainability of chemical industry projects. The first is the IChemE's Sustainability Metrics (IChemE 2006). The metrics include checklists of triple bottom line indicators, such as employment and training. However, they have a number of limitations: the metrics don't identify the set of critical issues; stakeholders have no input to the indicators; the treatment of social issues is limited to health, education and income parity, and neglects equity and impact on future generations.

The second management tool is The Metrics Navigator™ developed by GEMI (2007). GEMI is a non-profit organization of leading companies dedicated to collaborative efforts to foster environmental, health and safety excellence and corporate citizenship. The tool helps organizations develop and implement metrics that provide insight into complex issues, support business strategy and contribute to business success. It provides an approach that assesses the materiality of issues. Input from internal and external stakeholders is used to analyse business success factors, business impacts, stakeholder concerns and the organization's perceived degree of control of each issue. Worksheets are used to systematically identify the business success factors, define the product and plant life cycles, and identify issues of critical relevance to the business and to external stakeholders.

The Metrics NavigatorTM is a more flexible, adaptable and systematic tool than the IChemE's Sustainability Metrics. It has a process to include external stakeholder input, helps identify key issues, and facilitates prioritisation. It has no limits on the range of issues to be considered. Hence it has been adopted as the sustainability evaluation tool in our PjBL subjects.

# 4 Methodology

Cmaps are graphical tools that are an easy and quick way for groups to represent their knowledge about a complex topic. A good Cmap has a high number of relevant concepts, a complex set of interlinks between the concepts, and an even distribution of concepts among ten categories. A suitable taxonomy is: environment, resource depletion, social, cultural, future generations, equity, technology, economic, education and stakeholders. The CMaps are analysed for complexity indicator (CO) and category relevance (CR). Calculations for CO and CR are per group member and per category. The method is described in detail in Segalas *et al.* (2008).

Students in PjBL subjects work in groups on a design project. Each group must submit an initial concept map, a draft and final report, and give a presentation. In the first tutorial, an icebreaker for the newly formed groups is to sketch an initial Cmap together. This is collected by the teacher, scanned and uploaded to the group's wiki electonically. At the conclusion of the sessions on sustainability, each group must develop a more polished final Cmap. This is included in the group's interim report. The study used a quasi-experimental pretest-posttest design by comparing the intial with the final Cmap.

# 5 Results and Discussions

Outcomes from two subjects are compared in this paper. The two subjects are a 2$^{nd}$ year subject, "Process Principles", and a 4$^{th}$ year subject, "Process Systems Integration". Each student chooses a group (in 2$^{nd}$ year) or is allocated to a group (in 4$^{th}$ year). The group size varies from four to six students. The subject co-ordinator develops a short project brief concerning design of a chemical engineering process on a commercial scale. The brief includes the product specification and market conditions. The whole class works together to draw up a list of issues that may be relevant to the design problem from the United Nation Commission for Sustainable Development's Agenda 21 checklist (FIDIC 2004). A shortlist of most important issues is agreed on by group vote. Each group is assigned an issue to research. In 2$^{nd}$ year each group then presents their research on the issue to the rest of the class. The presentations are used as a class resource. In the 4th year each group must develop questions on their issue. A community forum is then held with representatives of the proponent company and of the community stakeholders. Each group must ask questions on their issue on behalf of the whole group; all questions and answers become a class resource. This community forum is a key innovation in the teaching approach developed at RMIT.

The students then work through the GEMI worksheets, using their literature reviews as well as data from the presentations or community forum. The worksheets help the students identify the major issues, their risks and consequences. Selection of the best process to meet the project brief requirements is undertaken considering the performance of the various process choices against the list of major issues. In this way students select the most sustainable process from a shortlist of processes, after considering a broad range of sustainability issues, prioritising them in a systematic way using input from stakeholders.

The results for the 2nd year subject are shown in Table 1. NC is the number of concepts per student. $L_{CA}$ is the number of connections between concepts per student per category. CO is the complexity indicator, reflecting both the breadth of ideas and their connectivity, the product of NC and $L_{CA}$. The standard deviation for CO was quite high, 90% on average, indicating the maps varied widely in their complexity from group to group. This reflects different levels of motivation and ability of students in their self-selected groups.

There was a substantial increase in CO in 2nd year, when the results for "pre-test" and "post-test" are compared, which is pleasing. The post-test score is 5 to 10 times the pre-test score for CO. These increases compare favourably with those reported by Segalas *et al.* (2009) in the pan-European study of sustainability subjects taught in five universities, where increases ranged from as low as 1 (that is, no improvement) to 11 times the pre-test score for CO.

There is also a substantial increase in CO when the results for 2011 are compared with 2012 and 2013. This may be attributed to the teacher's experience teaching the subject for the second time, as well as the normal variation of student cohort from year to year. The 2012 cohort of 2nd years contained a critical mass of very high achieving students.

Table 1: Average Complexity index for 2nd year groups, 2011 - 2013

| Year | Class size | Test | NC | $L_{CA}$ | CO |
|---|---|---|---|---|---|
| 2011 | 85 | Pre-test | 1.6 | 0.1 | 0.1 |
| | | Post-test | 3.8 | 0.2 | 1.0 |
| 2012 | 50 | Pre-test | 3.3 | 0.3 | 1.3 |
| | | Post-test | 8.4 | 1.0 | 9.9 |
| 2013 | 84 | Pre-test | 2.6 | 0.3 | 1.0 |
| | 50 | Post-test | 5.2 | 0.7 | 5.0 |

The results for 4th year are shown in Table 2. The pre-test CO for 4th years in 2012 (4.2) is significantly higher than the pre-test CO for 2nd years (average, 0.8), which is pleasing: this suggests students are retaining and drawing on knowledge from earlier years, as well as having enhanced skill in drawing Cmaps. Pre-test data is not available for 2013 as the students undertook a slightly different curriculum. There was some increase in CO from pre-test to post-test in 2012, but the increase was not significant. This increase in CO was much smaller than in 2nd year, which reflects that the students started at a much higher level of understanding, closer to mastery. The 2013 4th year cohort out-performed the 2012 cohort. This may be attributed to again to year to year variation in student cohort, and increasing experience of the teaching staff.

The post-test CO was higher for 4th year (average, 8.0) than 2nd year (average 4.8), although the difference is less than one standard deviation. It suggests the pleasing result that learning outcomes after multiple projects are higher than after a single project, but more data is needed to make a firm conclusion. This longitudinal study will continue to collect data to evaluate this approach to teaching sustainability.

Table 2: Average Complexity index from 4th year 2012 - 2013

| | | | | | |
|---|---|---|---|---|---|
| 2012 | 50 | Pre-test | 5.1 | 0.6 | 4.2 |
| | | Post-test | 5.9 | 0.7 | 5.6 |
| 2013 | 84 | Post-test | 8.4 | 1.1 | 10.4 |

The trends are shown graphically in Figure 1. In the Segalas study, as a benchmark, a group of experts were also asked to prepare a Cmap, for which the CO value was 24.8 (Segalas *et al*. 2009). So there is clearly potential to achieve better learning outcomes for our final years. It will be interesting to see how the outstanding 2nd year class of 2012 performs in 4th year in 2014.

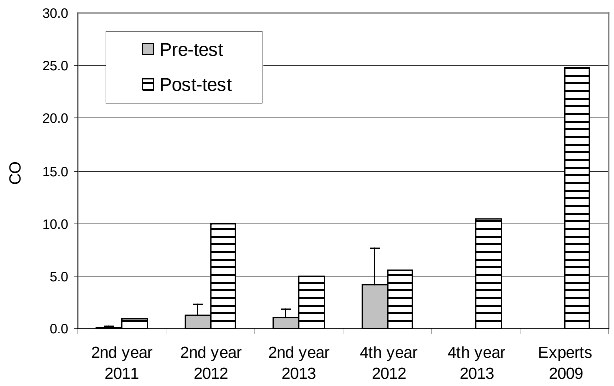
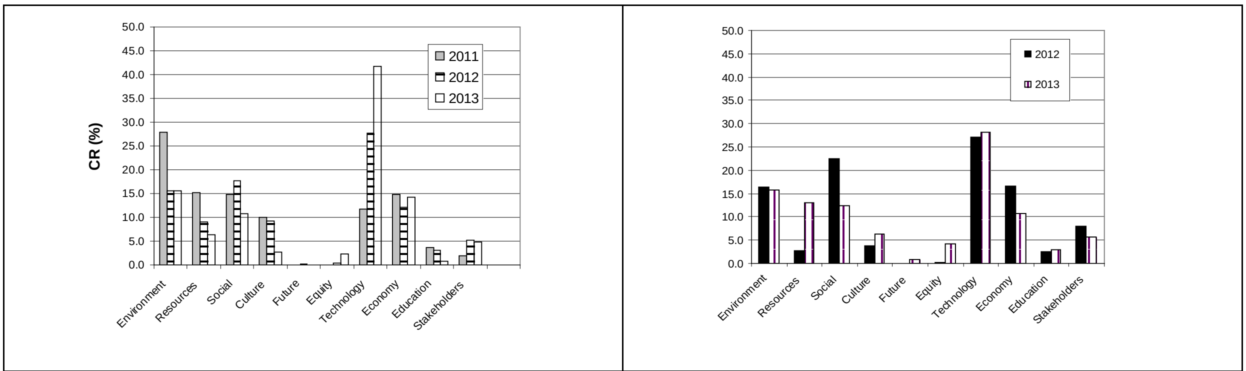



Figure 1: Complexity indicator (CO) by year level, pre- and post-test

Results for the average category relevance (CR) are shown in Figure 2 for the 2nd and 4th year subject. The aim is to have an even spread of concepts across all categories, so ideally each category should have a CR of 10%.

There are several categories with CR greater than 10%, indicating a dominant focus on these categories among the student cohort. CR for “Technology” is greater than 20% on average: this includes concepts related to plant design, product specification, and process efficiency. This high average CR value reflects a strong focus on technical matters – to be expected for engineering students. “Economy” and “Environmental” are prominent, reflecting the wider availability of data on these two aspects in the literature than on some other non-technical aspects. “Social” also consistently scores higher than 10%, which is pleasing, and suggests that students’ learning outcomes in sustainability are broadening in response to the PjBL subjects with GEMI, as social aspects are not addressed elsewhere.




| (a) 2nd year | (b) 4th year |
|---|---|

Figure 2: Category relevance (CR), 2nd and 4th year , post-test

It will be interesting to assess the reliability of the data over a longer period. The CR values for categories varied widely between groups, so the standard deviation is quite high (8 to 10%). The main focus varies from year to year: in 2nd year in 2011 the strongest focus was on “environment” but this changed to “technology” in 2012 and 2013. This reflects the different project contexts as well as stakeholder input on the priority issues.

The results also show there are many categories with a CR of less than 10%, reflecting lesser focus on those categories. Among both 2nd and 4th year cohorts there was less focus than desirable on education, inequity and future generations. This indicates we should consider changes to the curriculum to emphasise these areas.

# 6 Conclusions

The stream of project based learning subjects in the RMIT Chemical Engineering program offer scope for a systematic and detailed analysis of the sustainability of alternative designs. A sophisticated and complex framework tool – the GEMI The Metrics Navigator™ **-** can be used by junior and senior students to make better design decisions when comparing alternative chemical engineering processes. Students demonstrate their grasp of the richness and complexity of sustainability concepts relevant to chemical engineering design using concept maps (Cmaps). Cmaps are analysed for the number of concepts, the interconnectivity, and the distribution of concepts in various categories. Student knowledge of sustainability increased significantly in 2nd year and again in 4th year. There is potential for further improvement as the outcomes varied significantly from group to group, and no groups achieved mastery. This longitudinal study will be continued to further evaluate the approach to teaching sustainability. Use of the GEMI approach and evaluation with Cmaps is recommended for adoption in other Engineering programs.

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