PEDAGOGICAL APPROACHES TO DEVELOPING UNDERSTANDING OF SUSTAINABILITY IN STEM GRADUATES

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ABSTRACT

Developing the ability of graduates to think critically and creatively about sustainability issues is a goal now embedded in the ‘graduate attributes’ of many Universities. However, there is no consensus on the best pedagogical approach to develop this ability/capability. There is little evidence of success in terms of enhanced student learning in STEM disciplines, especially in engineering.

This paper reviews current approaches to developing the graduate attribute of sustainability in STEM graduates. It describes the evaluation methods that have been used and evidence collected on the success of these approaches. It presents results from research undertaken at RMIT University to assess the effectiveness of new approaches to teaching sustainability of engineering projects.

Approaches to teaching sustainability range from traditional lectures to community-oriented and constructive-learning pedagogies. Project based learning is a common approach in engineering education, but outcomes for students are highly variable. Understanding of sustainability was identified as a gap in work readiness of recent graduates. Furthermore, the evaluation of students learning in sustainability needs further development. However, there are few new approaches with evidence of success.

Results are presented on the development of breadth and complexity of student understanding of sustainability, comparing a second and final year course, over a number of years. A substantial increase in breadth and complexity of student knowledge was found after the introduction of a sophisticated and complex framework tool. Focus shifted from “technical” and “environmental” to “social”.

A cultural change is needed to move STEM academics away from using traditional approaches to teaching and learning that are ill suited to developing the attribute of sustainability in graduates. The role of STEM graduates in promoting sustainability thinking in their future careers is critical to reaching the tipping point.

Key words:

Pedagogy for sustainability, graduate attribute of sustainability, project based learning.
1 INTRODUCTION

Approaches to teaching sustainability in STEM programs range from traditional lectures to community-oriented and constructive-learning pedagogies [1, 2]. Problem or project based learning is a common approach in engineering education, but outcomes for students are highly variable, dependent on scope, context and learning approach [3,4]. A novel case study approach based on Bloom’s taxonomy has been developed recently [5]. Pappas and co-workers describe how their six-course design curriculum uses a developmental approach such that students move successively through six levels of Bloom’s Taxonomy.

However, despite numerous innovations in teaching sustainability, there is little evidence that graduates have achieved a skill level in understanding of sustainability necessary for the current world of work, where focus on sustainability is increasing. One study of work readiness of graduates who had undertaken a project based learning curriculum, found a gap in their understanding of sustainability and hence a limited ability to apply it in their employment [6].

Conventional methods of assessing student learning are unsuited to evaluating student learning in sustainability. Examinations are the most common approach, but these rarely test understanding, and are not suited to evaluation of group work. Project based learning (PjBL) is traditionally assessed using reports and presentations, but evaluation of student learning is dependent on the marker’s expertise. Other approaches to assessing student learning in sustainability include surveys, contextual references, the Structure of Observed Learning Outcomes (SOLO) taxonomy and ‘concept maps’ (Cmaps).

Surveys have been widely used in assessing students’ understanding of sustainability [7, 8, 9]. Surveys 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.

Contextual references is used to evaluate sustainability in the case study approach of [5]. Staff members selected for their expertise in each particular case study context marked students’ written responses. Each student wrote four responses per case study, for each sustainability ‘context’, namely, technical, economic, environmental and social. The expert marker counted the number of issues identified by the student, giving a maximum score of 3 for each context. This evaluation method gives some insight into breadth of student learning but not the depth. It requires the marker to have expertise in the case study. In addition, it does not provide direction for curriculum review.

The SOLO taxonomy is a qualitative tool used to analyse the sophistication of students’ writing on sustainability [8,10]. Responses may be characterised on a continuum from “pre-structural” (no understanding) through to “extended abstract” where the students demonstrate critical reflection. This gives useful insight into student learning but requires the marker to have expertise in qualitative assessment. In addition, it does not provide direction for curriculum review.

Cmaps are a quantitative tool that can be used to capture an individual’s or group’s thinking around any topic [11]. The map makers first identify concepts relevant to a central question and any interlinks between the concepts. Then they construct a Cmap showing the concepts and descriptive links. Cmaps were used in a large European study to evaluate engineering students’ learning in sustainability. Students in five Institutions created Cmaps at the start and conclusion of their relevant sustainability course. The Cmaps were analysing by measuring various metrics, including the number of concepts, the number of categories covered, and the interconnectedness of the concepts. Pre- and post-tests showed enhancement of student knowledge depended on pedagogical approach [1]. Cmaps are easy to use and capture the breadth and complexity of sustainability learning. Any gaps indicate where the curriculum should be improved.
In this study, Cmaps were used to evaluate student understanding of sustainability.

Chemical engineers at RMIT undertake a four year ‘single degree’ program or a five year ‘double degree’ program with a second major (business or science). They undertake a sequence of six PjBL core subjects during their programs, to develop design skills as well as research, teamwork and leadership skills [12]. Each subject has a different Project, and a team of staff teaching it. All the Chemical Engineering staff teach in one or more of the PjBL subjects. Students work in groups that are supervised (mentored) by one of the teaching team.

Sustainability is taught and assessed in all the PjBL subjects [13]. Students learn to evaluate alternative process plant designs using sustainability criteria. Outcomes from two subjects are compared in this paper, the 3rd and the 5th PjBL subject. Students work in groups of four to six students. In the two subjects in this paper, the staff co-ordinator develops a project brief concerning design of a chemical engineering process plant. The brief includes the product specification and market conditions. A second staff member guides the students in use of a management decision tool (GEMI) that aids selection of best process considering sustainability issues. Other staff members supervise each group.

GEMI The Metrics Navigator™ was chosen to evaluate the sustainability impacts of plant design. It is publicly available and suitable for use with small, simple or large and complex commercial projects. GEMI is a non-profit organization of leading chemical process and manufacturing 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 help analyse business issues in terms of TBL life cycles [14].

In each subject students choose sustainability issues relevant to their plant design from the United Nation Commission for Sustainable Development’s Agenda 21 checklist [15]. In the 3rd PjBL subject each group selects one issue and presents their research on the issue to the rest of the class. In the 5th PjBL subject each group also selects one issue but their research is used to develop relevant questions for a Community Forum attended by representatives from the Chemical Industry and from the plant neighbourhood community. Each group then critically evaluates responses of the Forum attendees on each issue to make their best process selection. Each group prepares a Report including literature review and justification of their choice of best process. A Cmap is included to illustrate their thinking on sustainability. In the final year students also sit a mid-semester test where they prepare a Cmap. A technical article on sustainability in the engineering sector is provided in the test: the Cmap should be based on this article. A summary of classes and assessment for each subject is shown in Table 1.

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**Table 1** Summary of sustainability classes and assessment

<table>
<thead>
<tr>
<th>Subject</th>
<th>Classes</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd PjBL subject</td>
<td>5 @ 1 hr lecture/workshops</td>
<td>Group Interim report with Cmap</td>
</tr>
</tbody>
</table>
| PROC2078 Process Principles | • How to write a critical literature review  
• UNCSD’s Agenda 21  
• GEMI sustainability framework  
• Risk matrices for business decisions  
• Group presentations on relevant Agenda 21 sustainability issues  
• How GEMI worksheets 1a, 1b, 2a, 2b should be filled out. | Group Final report  
Group Final presentation |
2 OBJECTIVES/METHODOLOGY

The objectives of the study reported in this paper were twofold:

- to compare sustainability learning outcomes in successive PjBL projects
- to compare sustainability learning outcomes for different student cohorts

Cmaps are used to measure sustainability learning outcomes of students working in groups. A sustainability Cmap is evaluated for three metrics: the number of concepts, the number or categories covered by the concepts, and the number of interlinks between concepts in different categories. The categories are based on the following taxonomy [16]: Environmental (Environment, Resource scarcity), Social (Social impact, Values, Future, Unbalances), and Economic (Technology, Economy) and Institutional (Education, Actors and Stakeholders). The complexity indicator (CO) and category relevance (CR) are calculated, normalised for group size. The method and calculations are described in detail in [17].

NC is the number of concepts per student. L_{CA} is the number of connections between concepts in different categories 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 average standard deviation for CO was calculated. The results for NC, L_{CA}, CO and CR are compared for students in different year levels, as well as students working as individuals or in groups.

3 RESULTS

The results for the two PjBL subjects are shown in Table 2. The results for complexity indicator (CO) are shown graphically in Figure 1.

Table 2 Comparison of Complexity Indicator (CO) for successive subjects

<table>
<thead>
<tr>
<th>Level</th>
<th>Year</th>
<th>Class size</th>
<th>NC</th>
<th>L_{CA}</th>
<th>CO</th>
<th>CO s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd PjBL subject</td>
<td>2013</td>
<td>84</td>
<td>5.1</td>
<td>0.3</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>60</td>
<td>6.3</td>
<td>0.3</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>5th PjBL subject</td>
<td>2013</td>
<td>84</td>
<td>8.3</td>
<td>0.5</td>
<td>3.8</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>63</td>
<td>9.1</td>
<td>0.6</td>
<td>6.0</td>
<td>5.4</td>
</tr>
<tr>
<td>Experts [18]</td>
<td>2008</td>
<td>19</td>
<td>19.8</td>
<td>1.25</td>
<td>24.8</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1 shows that the CO increased from the 3rd to 5th subject. The Cmaps contained more concepts (NC) as well as more links between concepts in different categories (L_{CA}). This shows student knowledge expanded in both breadth (number of concepts) and depth/complexity (number of links). The CO for the 5th subject is an average of 4.9, which is significantly higher than the CO for the 3rd subject (average 1.8). Overall this suggests that students are retaining and building on sustainability...
knowledge from earlier projects. Their knowledge and understanding is increasing in successive PjBL subjects.

The increases in CO compares with those reported by Segalas et al. [1] in the pan-European study of sustainability subjects taught in five Institutions. In that study CO values of Cmaps produced by students at the conclusion of each subject ranged from 1.7 (at Eindhoven University of Technology, NE) to a spectacular 26.8 (for an International short course at the Technical University of Catalonia, ESP). The average CO value was 10.7. No information is given on the standard deviation for the CO values. The CO values reported in this paper for the 5th PjBL subject are in the lower half of results the pan-European study: four of 10 results were less than 4.9, and six of 10 results were greater. This may be attributed to several factors. The portion of sustainability in the RMIT PjBL subjects are much less than the whole subject, compared to sustainability being the entire focus of the pan-European study subjects. The RMIT subjects are core subjects with large cohorts: most of the pan-European subjects were boutique electives. The RMIT students are undergraduate: many of the European students were Masters or PhD level, with a much higher starting level of sustainability knowledge. Unfortunately, Segalas does not include details of the class contact time, curriculum and assessment, although more detail can be found in [18].

Table 1 also shows the CO value for a benchmark group of experts. In the Segalas et al. study, as a benchmark, ‘several’ experts prepared a Cmap on sustainability, for which the average CO value was 24.8 [1].

Table 1 also shows the intra-cohort variation is high. The standard deviation of CO values from different groups in the same student cohort was 70% on average. This indicates the Cmaps varied widely in their complexity from group to group. This reflects different levels of motivation, ability and dynamics in different groups. This suggests care should be taken when drawing conclusions on teaching innovations introduced in a particular year: a longitudinal study should be undertaken to accurately assess the impact of a teaching innovation.

Table 1 also shows inter-cohort variation. The results for 2013 and 2014 for the 3rd PjBL subjects are very similar, suggesting little cohort variation. The curriculum, pedagogical approach and teaching team were similar for the two years. Interestingly for the 5th PjBL subject CO increased significantly, from 3.8 to 6.0, from 2013 to 2014. The standard deviation also increased significantly, from 1.3 to 5.4. This suggests wide cohort variation. The curriculum, pedagogical approach and teaching team were the same for the two years, except that timing of the three GEMI classes was changed from the first part of the semester to the last part. A similar increase in CO was observed for the 2014 cohort when they were undertaking the 3rd PjBL subject in 2012. This suggests this particular student cohort were a more capable cohort than average. This further suggests the utility of longitudinal studies to evaluate teaching innovations.

A longitudinal study is on-going to collect further data to evaluate this approach to teaching sustainability.

The results for complexity indicator are shown graphically in Figure 1. The increase in CO from the 3rd to the 5th subject is clearly seen. The difference in CO between the 5th subject and the experts is large. This indicates that while we are making progress, there is potential to achieve better learning outcomes for our final year students.
Results for Category Relevance (CR) are shown in Figure 2 and Figure 3 for the two PjBL subjects. Ideally there is an even spread of concepts across all categories, that is, each category should have a CR of 10%. However for engineering students there is generally a stronger focus on Technology than other aspects. A technology focus is reinforced by myriad influences in engineering. It reflects the dominance of technology issues in core subjects. These are taught by engineering staff members, who also have a dominant focus on technology. These same staff members supervise the groups, reinforcing the focus on technology at weekly group meetings. Literature on process plant design is also dominated by a technology focus, with scant mention of other aspects, except perhaps environmental. There is very little information on social aspects of plant design.

Figure 2 and Figure 3 show the main focus for students is Technology, as expected. However the focus weakens from the 3rd to the 5th PjBL course, from 37% to 27%, which suggests that the students learning about sustainability is broader and deeper in successive PjBL subjects.

Technology is not the only category with a CR greater than 10%. In the 3rd PjBL subject other prominent categories include Environmental and Economy, reflecting the wider availability of data on these two aspects in the literature. Social scored around 10%, which is good considering the dearth of information available on social aspects of plant design. This suggests that students’ learning outcomes in sustainability are broadening in response to the GEMI approach, as social aspects are not addressed elsewhere in the curriculum. There is some variation in categories between 2013 and 2014, again supporting the utility of longitudinal studies.

In the 5th PjBL subject the prominent categories were the same as in the 3rd PjBL subject, but all the Social categories increased (that is Social, Values, Future, Unbalances) as well as Education. Note ‘Unbalances’ indicates inequity between rich and poor. This further suggests that students’ learning outcomes in sustainability are broadening in successive PjBL subjects.
Figure 2 Category relevance (CR), 3rd PjBL subject

Figure 3 Category relevance (CR), 5th PjBL subject

Figure 2 and Figure 3 show that several categories have a CR of less than 10%. In terms of direction for improvement in the curriculum, this suggests a stronger focus is needed on those categories, especially Future and Unbalances. Changes to the curriculum to emphasise these areas is planned.
4 DISCUSSION

The sequence of PjBL design subjects in the RMIT Chemical Engineering programs offer scope for a systematic and detailed analysis of the sustainability of alternative process designs. Decision making against sustainability criteria is facilitated by use of a publicly available decision management tool – the GEMI The Metrics Navigator™ - developed by a consortium of large companies [14]. The tool helps organizations develop and implement metrics that provide insight into complex issues, support business strategy and contribute to business success. It can be used by junior and senior students to make better design decisions.

Students demonstrate their grasp of the richness and complexity of sustainability issues relevant to their design through concept maps (Cmaps) [11]. Cmaps are analysed for the number of concepts, their interconnectivity, and the distribution of concepts in various categories [17]. Student knowledge of sustainability increased significantly in successive PjBL subjects. Their knowledge expanded in both breadth (number of concepts) and depth/complexity (number of links). The focus on technology weakens, and focus on other categories, especially social, increases with successive projects, which suggests that the students learning about sustainability is broader and deeper. Students are retaining and building on sustainability knowledge from earlier projects in subsequent projects.

Inter and intra-cohort variation is marked, and indicates the need for a longitudinal study to accurately assess the impact of a teaching innovation.

Students have a dominant focus on technology. This is reinforced by many influences including:

- most core subjects have a technology focus
- most engineering staff members have a technology focus
- student group supervisors have a technology focus
- literature on plant design is dominated by a technology focus
- a dearth of information on social aspects of plant design.

The RMIT students failed to achieve a breadth and depth of understanding of sustainability similar to European experts or European engineering graduates [17]. This was partly attributed to the European subjects being boutique electives, at Masters or PhD level, where students started at a much higher level of sustainability knowledge [18]. Hence there is potential for further improvement in teaching approach, curriculum and assessment. Unfortunately there is very little information available on the curriculum and assessment of other sustainability subjects.

A longitudinal study is continuing to further evaluate this approach to teaching sustainability.

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6 REFERENCES


