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Concept Maps for Evaluating Learning of Sustainable Development

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Abstract

Concept maps are used to assess student and cohort learning of sustainable development. The concept maps of 732 first-year engineering students were individually analyzed to detect patterns of learning and areas that were not well understood. Students were given 20 minutes each to prepare a concept map of at least 20 concepts using paper and pen. The maps were then analyzed using three different methods. The first method considers only the structure of the map by quantifying its features. The second method considers the content and comprehensiveness of the map by classifying every concept included using a new taxonomy. The third method scores the maps against a rubric that considers the correctness of the maps' propositions as well as the maps' comprehensiveness and complexity. The results show that concept maps are a useful tool in assessing the knowledge and understanding of sustainable development concepts and that the students surveyed have a good awareness about the technical, social and environmental aspects of the domain. They did not include many concepts relating to equity and economic impact of sustainable development policies.

Keywords: Sustainable development, sustainability, education, cognitive mapping, concept maps, training

INTRODUCTION

Over the last two decades, there has been a growing recognition within the engineering education community of the importance of incorporating sustainable development into the engineering curricula. Accreditation bodies, such as Accreditation Board for Engineering and Technology (ABET) (2011) in the US

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and Engineers Australia (2008), as well as discipline-specific bodies, such as the Institution of Chemical Engineers (IChemE) (2012), all note the importance of including sustainability in any programme that they accredit. However, they all remain silent as to the most appropriate way to achieve this end.

In May 2007, the IChemE, a member-driven organization, released a document that looked at the future of the chemical engineering profession, 'A Roadmap for the 21st Century Chemical Engineering' (Institution of Chemical Engineers, 2007). The document was prepared after wide consultation among its members around the world. The IChemE noted that the '…education of future generations of chemical engineers and realignment of the current generation with sustainability objectives is a vital component of the process of sustainable development'. They observed that a re-examination of how sustainable development is taught at universities today parallels the re-examination of safety education in chemical engineering programmes in the United Kingdom following the 1974 industrial accident at Flixborough that killed 28 people (Khan & Abbasi, 1999; Mannan, 2005; Venart, 2007). An update on the IChemE's view of the future of chemical engineering profession in 2012, 'Chemical Engineering Matters' (Institution of Chemical Engineers, 2013), restated the importance of sustainable energy, water, food and societal health and well-being.

In 2010, the United States National Academy of Engineering (2010) published a list of 14 grand challenges for the engineering profession in the coming century. Five of these challenges are directly related to sustainable development and living—making solar energy economical, providing energy from fusion, developing carbon sequestration methods, managing the nitrogen cycle and providing access to clean water. The challenge is how the concepts of sustainable development should best be incorporated into the curriculum and how the competencies of graduating students may best be assessed.

Sustainable development can be incorporated into university engineering programmes in many different ways:

1. Through the use of stand-alone subjects with content that is delivered and assessed independently of all other content in the programme;
2. Through an integrated approach in which concepts of sustainable development are threaded throughout the entire programme starting with raising awareness in the first year and culminating in the application of sustainable development principles in some form of capstone project; or
3. Through a culture of sustainable development that pervades the entire fabric of the learning environment at the institution.

While the debate continues as to the best way to develop the competencies around sustainable development among engineering students, there remains the significant challenge of adequately assessing the learning and understanding of individual students and the cohort as a whole about the topic. While it is possible to assess student competencies in some technical applications of engineering science, such as the calculation of wind loads on tall structures or the separation efficiency of distillation columns, it can be more difficult to assess the competencies around sustainable development. A significant aspect of sustainable development as taught at universities today is in design philosophy. As such, it can be more difficult and time-consuming to assess. This study considers the use of concept maps to assess student and cohort learning of sustainable development.

CONCEPT MAPS

In recent years, concept or cognitive maps have been used in teaching and to assess student learning around a range of topics, from nursing education (Daley & Torre, 2010; Hsu & Hsieh, 2005) through accounting (Chiou, Lee & Liu, 2012) to engineering design (Shallcross, Buskes & Dagastine, 2011) and engineering safety case studies (Shallcross, 2013a, 2013b). Developed in the 1970s by Novak and co-workers, concept maps are a way to diagrammatically represent one's knowledge and understanding of a particular topic or domain (Cañas et al., 2004). A concept map consists of a group of concepts that are related either to the central domain of the map (e.g., sustainable development) or to one another. The individual concepts shown in the map are linked together using lines labelled with joining words or phrases which form propositions. The proposition formed by linking two different concepts together represents some aspect of knowledge or understanding that the map's author has about the topic. The way in which the elements of a concept map are interconnected reflects the way in which the subject's knowledge is structured. Generating a concept map requires the subjects to organize their knowledge. They need to analyze, synthesize and evaluate the information they have in order to generate a coherent map, which is in itself a non-trivial task (Besterfield-Sacre, Gerchak, Lyons, Shuman & Wolfe, 2004).

The task of constructing a concept map in the classroom may be framed in several different ways (Ruiz-Primo & Shavelson, 1996). For a given domain, students may be asked to:

- Construct a map from scratch, supplying all the concepts and linking words;
- Construct a map working with concepts drawn exclusively from a supplied list, but with the linking words provided by the student (Yin, Ruiz-Primo, Ayala & Shavelson, 2005);
- Construct a map using a supplied list of joining words, but with the concepts provided by the student;
- Fill in a pre-structured map with concepts and linking words supplied by the student.

In preparing the maps, the students might do so individually, in pairs or as part of a larger team. They might be asked to concentrate on preparing a more hierarchical map or one that features many examples. They might also be required to justify the elements of the map using some supporting documentation. Having surveyed a range of concept map studies, Ruiz-Primo and Shavelson (1996) conclude that the fill-in-the-blank tasks are inappropriate for measuring students' knowledge structures as the task itself too severely restricts the representation of the knowledge domain. They also concluded that imposing a hierarchical structure on some domains is inappropriate.

MAP ANALYSIS

Concept maps, no matter how they are generated, may be scored in a number of different ways depending on what the assessor is trying to evaluate. Depending on the method used, maps may be assessed to provide feedback on the understanding and knowledge of individual students or of the student cohort as a whole.

Several studies have been presented in which concept maps have been applied to the domain of sustainable development (Åhlberg, 2004; Lourdel, Gondran, Laforest & Brodhag, 2005; Lourdel, Gondran, Laforest, Debray & Brodhag, 2007; McClure & Bell, 1990; Segalàs, Ferrer-Balas & Mulder, 2008). The present study builds upon their work to develop a robust and reliable method for analyzing the content and structure of concept maps built around sustainable development as the central theme.

As noted by Shallcross (2013a), concept maps developed by students may be analyzed in several fundamentally different ways to determine the understanding around the domain or topic:

1. The structure of the map may be characterized by counting the total number of concepts included in the map, the number of propositions, the number of pathways leading away from the domain and the maximum number of generations that any concept is removed from the central domain. The work of Ifenthaler (2010) is an example of this type of structural analysis.
2. The content and comprehensiveness of the map may be assessed by classifying every concept included in the map into one of the several categories according to some taxonomy. Examples of this type of content analysis include the works by McClure and Bell (1990), Lourdel et al. (2007), Segalàs et al. (2008) and Shallcross et al. (2011).
3. The quality of the map may be characterized against a set of rubrics. Besterfield-Sacre (2004) proposed scoring maps in a subject manner against their comprehensiveness, correctness and complexity of structure.
4. The quality of a map may be compared to the map prepared by an expert in the domain topic (Taricani & Clariana, 2006).
5. All valid elements of a map, such as propositions, cross-links between different branches and sub-branches and examples, are counted and assigned different weightings to obtain an overall score for the map. Examples of the application of this type of scoring technique include the works by Daley and Torre (2010), McClure et al. (1999), West, Park, Pomeroy and Sandoval (2002), Hsu and Hsieh (2005) and Kwon and Cifuentes (2009).

In this study, the maps are analyzed using the first three methods. The fourth method, comparing each map to an expert map, is not used as the topic of sustainable development is very broad and open-ended, and this particular method has been used in the past to analyze maps of more concise domains. The fifth method is not used because of the subjective nature of the weightings that must be assigned to the different types of elements.

Using the first method of analysis, the following features of each map are characterized:

- Total number of concepts other than the domain;
- Total number of propositions;
- Number of pathways leading out of the domain;
- Maximum number of generations that any concept is away from the central domain.

The number of propositions in any concept map will always be equal to or greater than the number of concepts other than the domain. The difference between the number of propositions and the number of concepts other than the domain is equal to the number of links between different branches and sub-branches. Links between different branches and/or sub-branches move the structure of the map away from a strictly hierarchical one to one featuring more loops and interconnections.

In the second method of map characterization, each concept included in a map is classified into one of the several categories. Lourdel et al. (2007) proposed a method of analyzing concept maps for the domain of sustainable development that classifies each of the concepts in the map into one of the six categories (Table 1):

1. Environmental
2. Social, cultural
3. Multidimensional approaches

Table 1 Taxonomy of Sustainable Development Categories Used in This and Earlier Studies

Lourdel et al. (2007)	**Categories Segalàs et al. (2008)**	**This Study**
1. Environmental	1. Environmental	1. Environmental aspects
	2. Resources scarcity	2. Resources scarcity
2. Social cultural	3. Social impact	3. Social impacts and values
	4. Values	
3. Multidimensional approaches	5. Future generations (temporal)	4. Intragenerational and intergenerational equity
	6. Unbalances (spatial)	
4. Economic, scientific, technological	7. Technology	5. Technology
	8. Economy	6. Economic aspects
5. Procedural and political approaches	9. Education	7. Education
6. Actors and stakeholders	10. Actors and stakeholders	8. Actors and stakeholders

Source: Shallcross (2010).

4. Economic, scientific, technological
5. Procedural and political approaches
6. Actors and stakeholders.

By looking at both the distribution of the map concepts across the six categories and the number of propositions that are present between concepts of different categories, they found it possible to identify gaps in the knowledge and understanding of students towards sustainable development.

Later, Segalàs et al. (2008) expanded the number of categories to 10 by splitting several of Lourdel's categories. They added 'resource scarcity' and 'education' and replaced 'multidimensional analysis' with 'future generations' and 'unbalances'. The former accounts for intergeneration equity considerations and the latter accounts for intragenerational equity aspects, including poverty and wealth distribution.

The classification of concepts requires considerable subjective judgement on the part of the person performing the analysis. Depending on the context, including the linking words and the surrounding concepts, single-word concepts, such as 'justice', 'water' and 'jobs', might well be classified into one of several categories. The more categories there are within a taxonomy, the greater the likelihood for classification errors. However, fewer categories yield less useful data. In this study, eight was chosen as the number of categories as being an appropriate balance between gaining a useful insight into the distribution of the concepts among the categories and the need to reduce the number of subjective decisions that must necessarily be made when the concepts are classified.

In the present study, an eight-category taxonomy is proposed that maps onto the earlier work of Lourdel et al. (2007) and Segalàs et al. (2008, 2010) as shown in Table 1. The eight categories are:

Category 1: Environmental aspects—All aspects of the natural environment including living things, climate and geographical features.

Category 2: Resources scarcity—All non-renewable material and energy sources.

Category 3: Social impacts and values—Relating to quality of life, values and ethics of societal groups as well as actions that society can take.

Category 4: Intragenerational and intergenerational equity—Impact on opportunities across the generations and within the same generation but across regional and national boundaries.

Category 5: Technology—All aspects of the built environment including human-made artefacts, products, processes and systems.

Category 6: Economic aspects—All aspects of the economic environment including local and international economies and trade.

Category 7: Education—Relating to education and public awareness.

Category 8: Actors and stakeholders—People and institutions including companies, governments and nongovernmental organizations.

Examples of concepts for the eight categories are presented in Table 2.

Table 2 Example Concepts for Each of the Eight Categories

Category	Example concepts
1. Environmental aspects	Global warming, drought, plants, animals, energy, waste, carbon dioxide, pollution, climate change, deforestation
2. Resources scarcity	Non-renewable energy sources, non-renewable material, coal
3. Social impacts and values	Ethics, safety, laws, needs, wants, shelter, food, recycling, jobs and actions such as less power usage, reduce deforestation
4. Intragenerational and intergenerational equity	Future generation, equity, poverty, the future, living standards, quality of life, justice
5. Technology	Recycling, research, efficient design, machinery, fuel cells, wind power, life cycle assessment, wind turbine, desalination
6. Economic aspects	Profit, carbon tax, carbon trading, energy cost, material cost, economic growth, fair trade
7. Education	Public awareness programmes, training
8. Actors and stakeholders	Community, consumers, countries, engineers, government, politicians

Source: Author's own.

Where a concept did not clearly fit into one of the eight categories, it was assigned to the one closest to it in meaning or in intent. Occasionally, it was necessary to classify the concepts by studying the surrounding concepts and propositions. As Lourdel et al. (2007) note, there is always some level of subjectivity in classifying any concept into a classification system.

The third method to characterize the concept maps employs a scoring rubric adapted by Shallcross (2013b) from the work of Besterfield-Sacre et al. (2004). In this method, each map is scored either 0 or 1 or 2 against four dimensions (Table 3):

- Comprehensiveness: An ability to define the domain and the knowledge in terms of both the depth and the breadth of the topic area.
- Correctness: An ability to present concepts relating to the domain with accuracy and without the presence of misconceptions.
- Structure: An ability to arrange the concepts systemically, including links, where appropriate, between concepts on different branches and different levels.
- Map elements: An ability to prepare a properly constructed concept map that contains all the information necessary to allow the reader to properly interpret it.

Again, there is a subjective element to the application of the rubric. However, of the three methods used to assess the maps, this is the only one that addresses the correctness of the maps.

Table 3 Concept Map Scoring Rubric Considering the Four Dimensions of Concept Map Construction

Scoring Rubric	0	1	2
Comprehensiveness A student's ability to define the domain and the knowledge in terms of both depth and breadth of the topic area.	The map is incomplete, missing many key concepts indicating a lack of knowledge or understanding of the map's domain. The map barely covers some of the key aspects of the domain.	The map contains concepts representing the key aspects of the domain which would be expected to be found in the map.	The map's concepts taken together define the domain well indicating an awareness of nearly all the key aspects of the domain.
Correctness An ability to present concepts relating to the domain with accuracy and without the presence of misconceptions.	The map contains many errors or inappropriate concepts and/or links indicating a poor or naïve understanding of the topic.	The map contains some inappropriate concepts or links but most are fundamentally sound.	The map contains no, or very few, errors. All concepts and links included in the map are appropriate and sufficient indicating a sound understanding of the topic.
Structure An ability to systematically arrange the concepts presented with appropriate links between concepts across the entire map between different branches levels.	The map is strictly hierarchical with few, if any, links between different branches. The thinking behind the map development is linear. Obvious links between concepts are not included.	The map is well structured with appropriate links across the map between different branches and sub-braches. All obvious links between the concepts are made.	The key concepts are systematically arranged with well-defined links at all levels. The map also includes sophisticated branch structures.
Map Elements An ability to prepare a properly constituted concept map.	Propositions linking the concepts are absent and the directions of the links are missing. The domain is not clearly defined. The reader is unable to follow the map, and its meaning must be inferred.	Propositions or directions are not indicated on the links between concepts. Concepts and propositions may not be clearly distinguished. Some interpretation by the reader is required.	The map contains all the elements of a proper concept map including a clearly defined domain. The meanings of all propositions are clear and unambiguous.

Source: Shallcross (2013b) adapted from Besterfield-Sacre et al. (2004).

DISCUSSION

The topics of sustainable development, life cycle analysis and the role of engineers in addressing these issues are presented to first-year engineering students at the University of Melbourne. All students seeking to complete an engineering systems major within the Bachelor of Science degree are required to complete two first-year engineering subjects, Engineering Systems Design 1 and 2. Engineering Systems Design 1 is completed in the first semester of their study at the university. The subject introduces students to the engineering profession, engineering problem solving and engineering design as well as topics on safety, sustainability and professional ethics. Each week in the subject, students have three lectures and one 3-hour interactive and collaborative workshop. In the second week of the semester, students are given three 50-minute lectures introducing them to sustainable development and the roles and responsibilities of engineers in ensuring it. In the third week, they are given a lecture on concepts maps and in the following workshop, they are given several exercises in preparing concept maps.

In the first semester of 2009, 750 students enrolled in Engineering Systems Design 1 were asked to prepare concept maps based around the domain 'sustainable development' in the fourth week of the semester. They were each given an A4-sized sheet of paper with the domain written in its centre and were asked to hand-write their concept maps in 20 minutes. Of the maps submitted, 732 were found to be valid and were analyzed—approximately 80 per cent of the cohorts were male and 20 per cent were females. Approximately 30 per cent of the student cohort did not have English as their first language.

To illustrate the range of concept maps developed, the concepts maps prepared by three students are presented in Figures 1–3. The map of student 1 (Figure 1) contains 22 concepts linked by 23 propositions and is typical of a map that is hierarchical in nature, having just one linkage between two different branches. The map has four pathways out from the central domain and no concept is more than three propositions away from the domain. The map includes four or five concepts from five of the categories but has no concepts from 'resource scarcity', 'education' or 'actors and stakeholders'. On the subjective scales, the map scores '1' for 'comprehensiveness' as the map content does not include concepts from all key aspects but, instead, has a significant number of examples; '1' for 'correctness' as the propositions are fundamentally sound; '0' for 'structure' as the map is fundamentally hierarchical in structure with some obvious linkages missing; and '2' for 'map elements' as all the required map elements are present.

The map presented in Figure 2 also contains 22 concepts but has 43 propositions. This map has six pathways out from the central domain and no concept is more than three propositions away from the domain. This map includes nine concepts which may be categorized as 'environmental aspects' and includes six that may be classified under 'economic aspects'. Only two categories, 'resource scarcity' and 'education', have no representative concepts. The map scores '2' for all four subjective scales.

The third student map (Figure 3) contains 38 concepts and 53 propositions. Interpretation of the map is made more difficult as there are no linking words to generate the propositions between the concepts. Instead, the reader must infer the linkages. However, because the student has indicated the direction of the

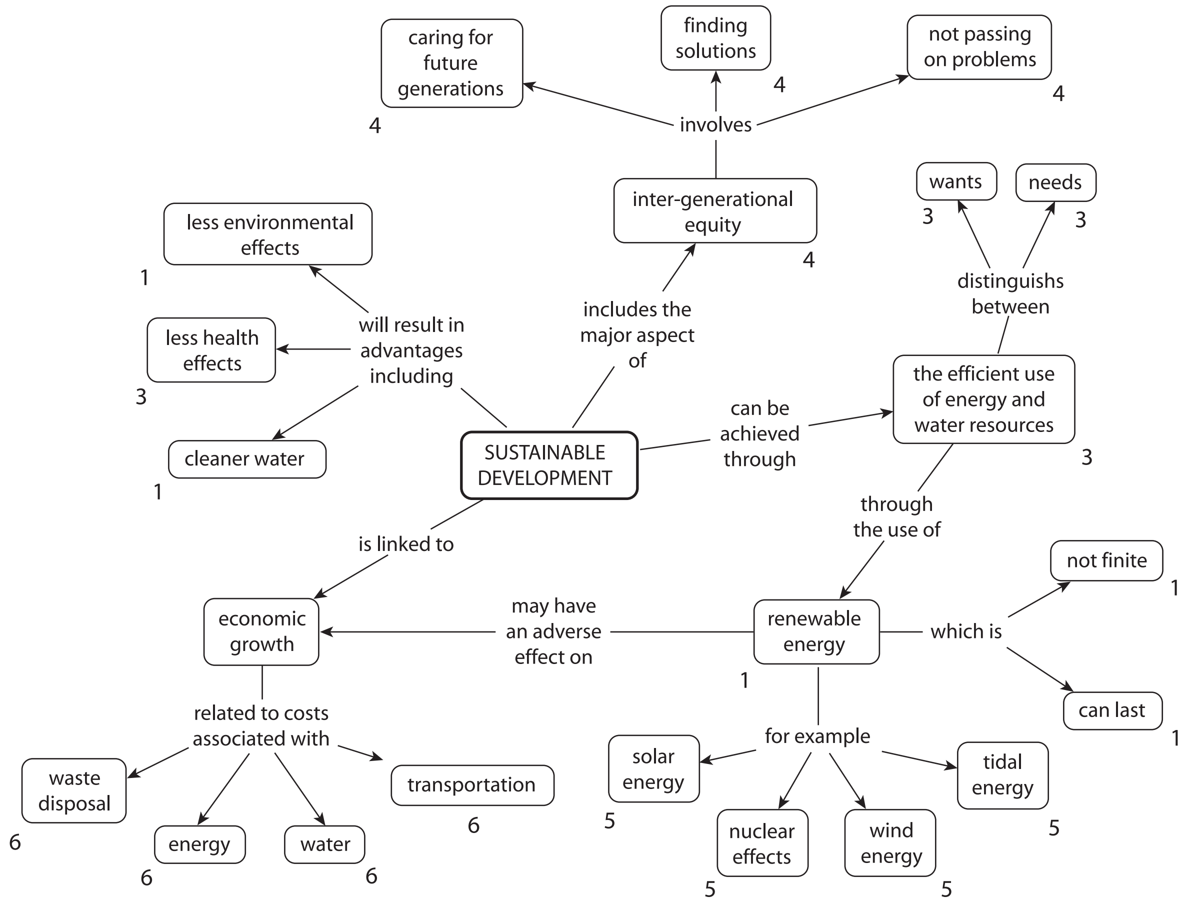

Figure 1 Concept Map of 22 Concepts and 23 Propositions Prepared by a First-year Student (student 1)

Note: The hand-drawn map has been redrawn by the author for legibility while preserving the structures, features and spelling of the original map. Each concept is labelled with a number indicating the concept category as listed in Table 2.

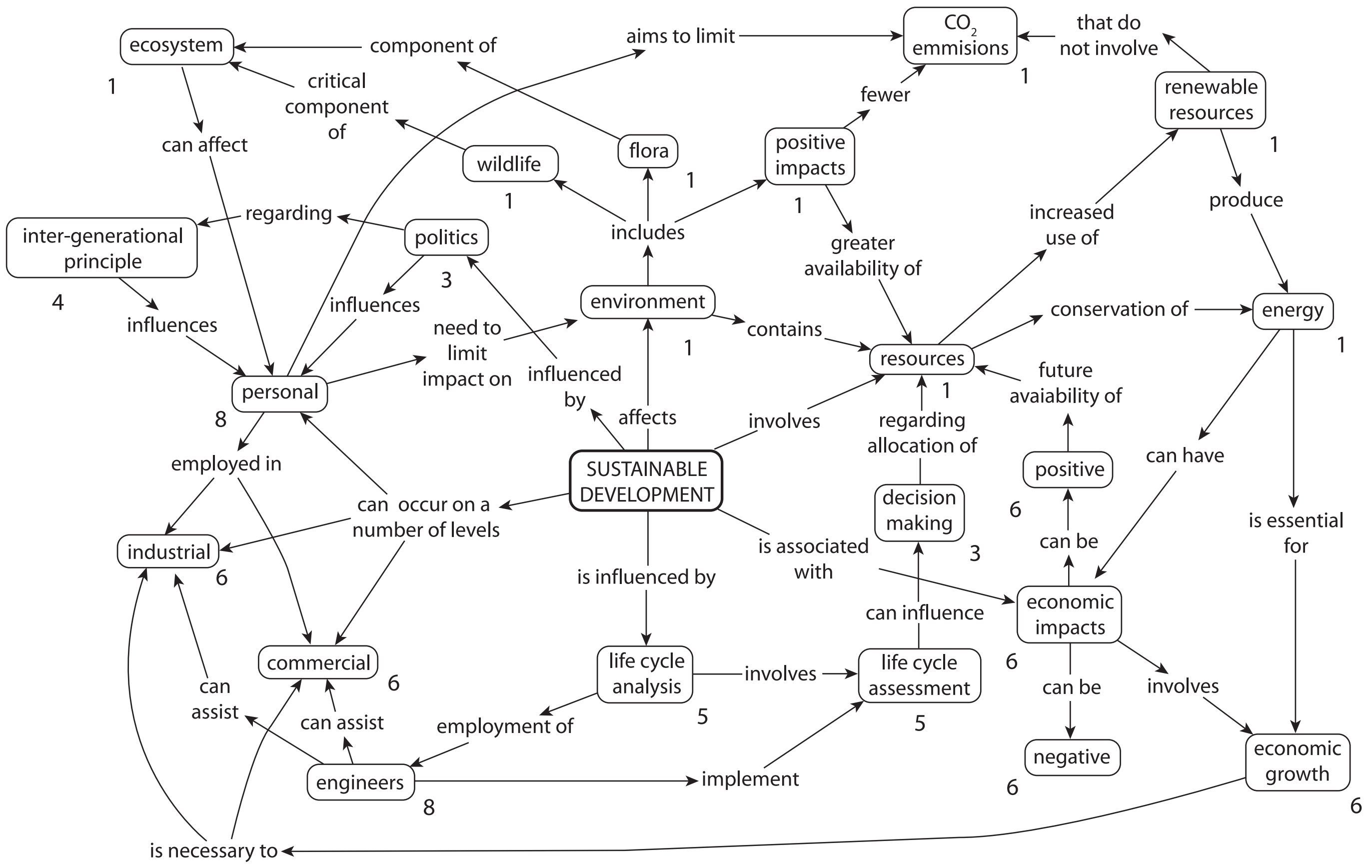

Figure 2 Concept Map of 22 Concepts and 43 Propositions Prepared by a First-year Student (student 2)

Note: The hand-drawn map has been redrawn by the author for legibility while preserving the structures, features and spelling of the original map.

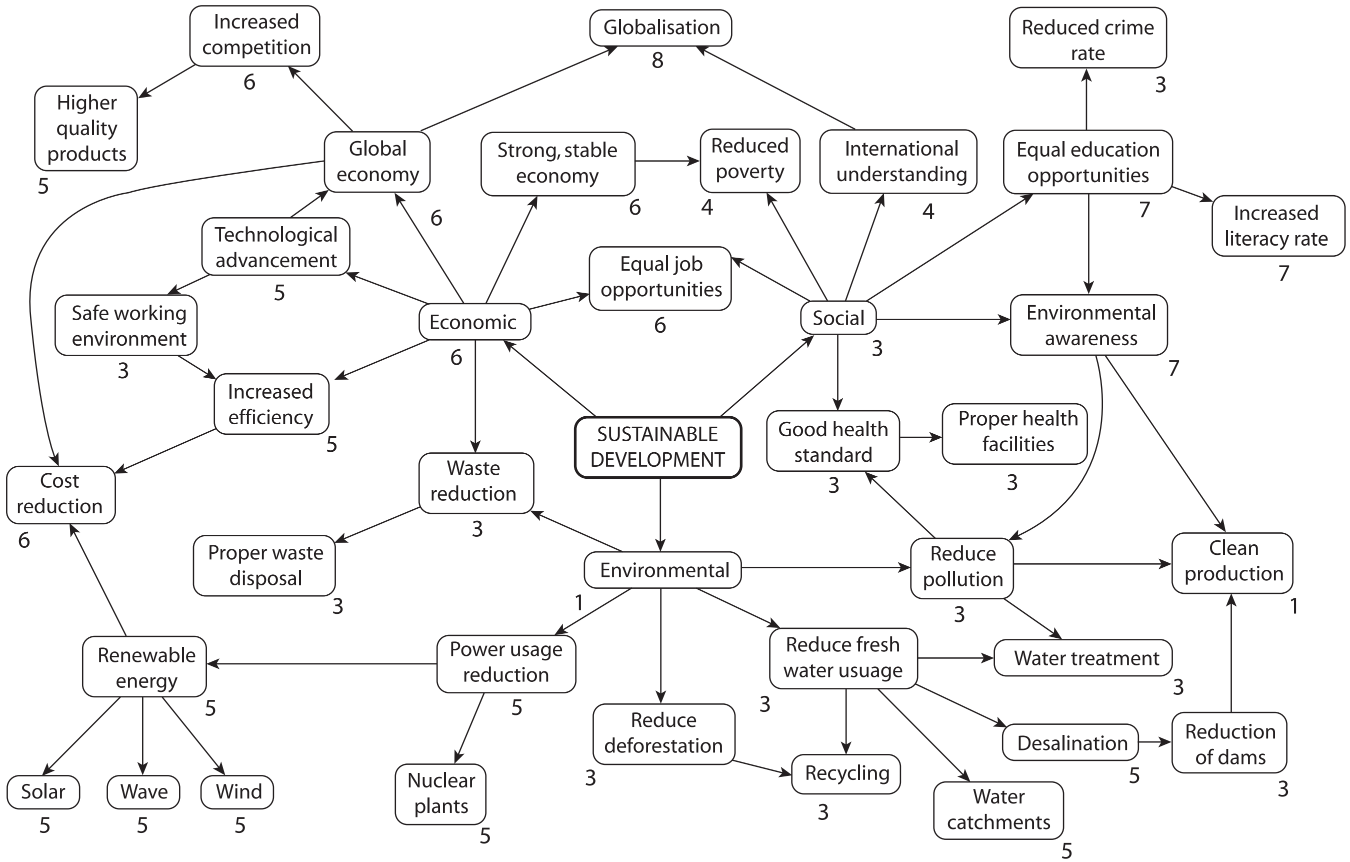

Figure 3 Concept Map of 38 Concepts and 53 Propositions Prepared by a First-year Student (student 3)

Note: The hand-drawn map has been redrawn by the author for legibility while preserving the structures, features and spelling of the original map.

proposition, it is possible to infer the intention of the map's author. The concepts presented, taken as a whole, comprehensively cover the topic of sustainable development and so the map may be scored '2' for 'comprehensiveness'. Similarly, notwithstanding the lack of joining words, the map may be scored '2' for 'correctness' and 'structure' but only '1' for 'map elements' due to the absence of the propositions.

The 732 valid concept maps were analyzed and found to contain an average of 29.7 concepts and 39.0 propositions, indicating that there were an average of 9.3 links between different branches or sub-branches. The maps were analyzed by the author alone, with a random selection representing 10 per cent being analyzed a second time, again by the author, to assess the reliability of the method. The assignment of each concept to a particular category is, by its nature, subjective. Most maps only contained one or two concepts whose categories were different between the first and second analysis. Given that each map contained on average 30 concepts, around 95 per cent of the concepts were consistently classified. The differences in classifications between the first and second analyses did not significantly impact the distribution of concept categories. Similarly, there were very few differences in the assignment of the four subject scores based upon the rubric of Table 3 between the first and second analyses. While there were some differences in the scores for individual maps, there was no significant impact on overall distribution of the rubric scores across the entire cohort.

The distribution of concepts across the eight categories is presented in Figure 4. This indicates that the students concentrated more on the technical, social and

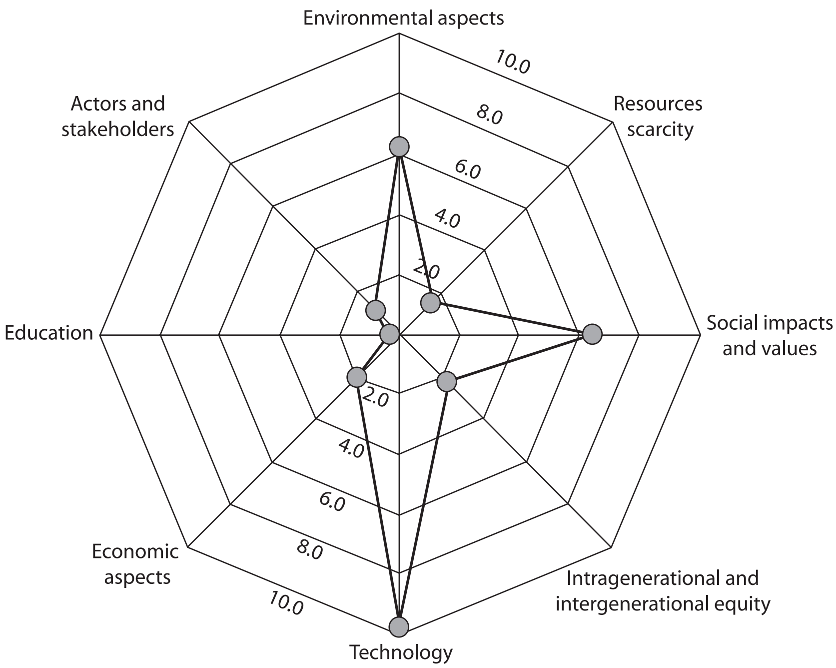

Figure 4 Distribution of Average Number of Concepts in Each of the Eight Categories for 732 Concept Maps

environmental aspects of the topic rather than the other categories. These three categories between them accounted for over three-quarters of the concepts presented in the maps. Eight students submitted maps with 10 or fewer concepts, while five students had maps incorporating 70 or more concepts. Only 15 maps (2 per cent of the entire cohort) had concepts from all eight categories, while 5.5 was the average number of categories represented across all the maps; 36 maps (5 per cent of the total number) were strictly hierarchical without any cross-links between different branches or sub-branches.

Almost every map contained propositions joining concepts from different categories (Figure 5). While it is natural to assume that the most number of links would exist between the three most popular categories, an analysis of the data suggests that the distribution of interlinks between concepts of different categories is not based solely on the relative frequencies of the eight categories. The number of links between 'social impacts and values' and 'actors and stakeholders' is more than 2.5 times higher than would be expected if the number of interlinks was distributed based solely on the frequency of these two categories. Other linkages are relatively under-represented such as those between 'technology' and 'education'.

An analysis of the concepts deemed by the students to be important enough to be included in their maps indicates that, as a whole, the cohort of engineering students

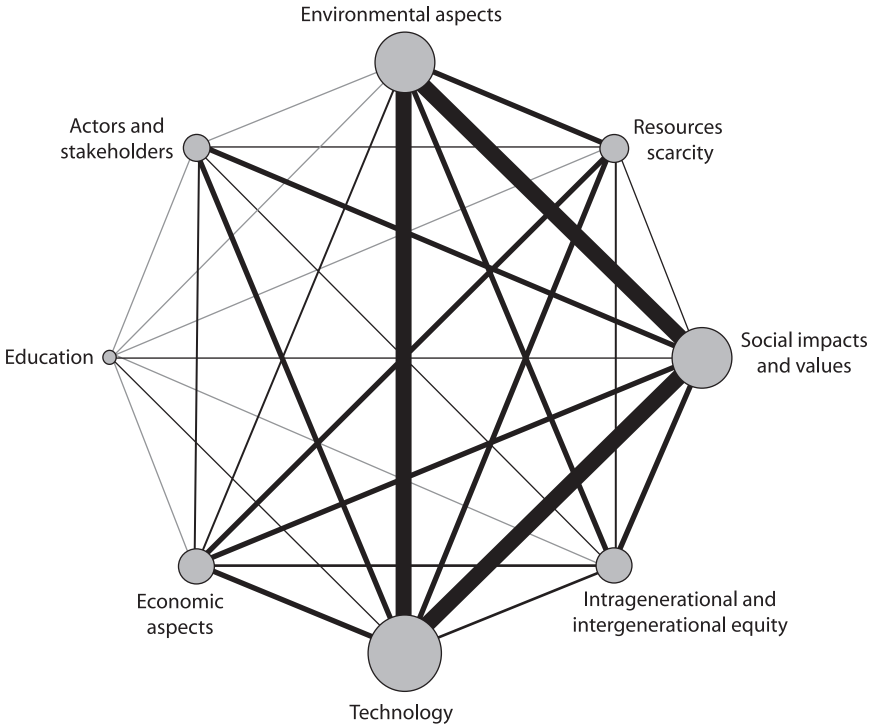

Figure 5 Network Diagram Showing the Interlinks between the Eight Concept Categories Averaged Overall 732 Valid Concept Maps

saw an important role for technology to respond to the challenges of sustainable development. Popular concepts included in this category were power generation technology including examples from the nuclear, fossil fuels and renewable sectors. Generally, where one of these power-generating concepts were included, then three to five different types of power generation technologies were included. The students understood many of the environmental aspects and also had a sound understanding of the social impacts. Further, the students tended to understand reasonably well the broader definition of sustainable development that looks at equity issues around poverty, living standards, quality of life and social justice. Economic aspects, such as tax, trade and economic growth, were understood but often in isolation from other concepts. Few students saw concepts relating to education worthy of inclusion. There were, on the whole, surprisingly very few links between actors and stakeholders and environmental issues, such as global warming, drought, pollution and climate change, despite what many might see as obvious linkages.

Figure 6 presents the distribution of scores for the four subjective dimensions of 'comprehensiveness', 'correctness', 'structure' and 'map elements' as presented in Table 3. From this data, we are able to conclude that less than a quarter of the class were unable to prepare a map which displayed a sound understanding of the domain, their maps lacking many key aspects. When the scores for each of the four dimensions are added, a total score for each map may be derived. While it may be argued that the four individual components should not be equally weighted with greater emphasis being given to the dimensions of 'comprehensiveness' and 'correctness', for the purposes of this application the four constitutive scores may be considered equally. The number of students who scored 0 across all four dimensions was 18 (2.5 per cent of the student cohort), while 17 students scored the maximum of 8.

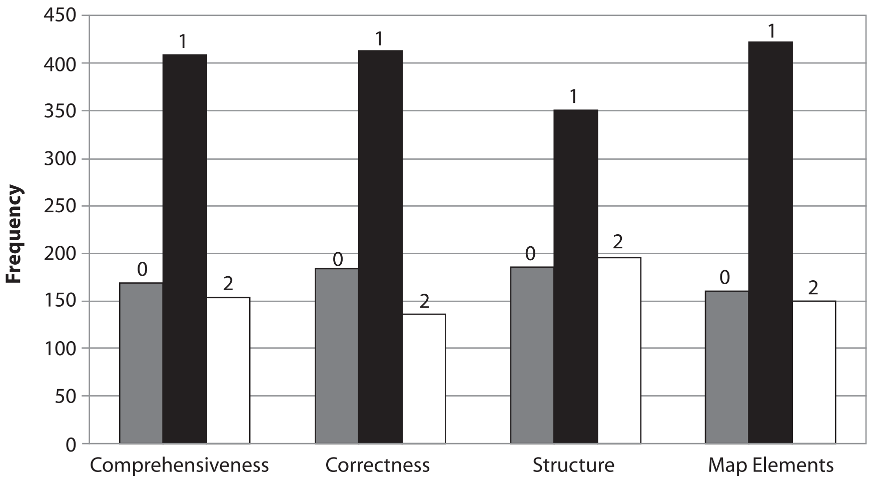

Figure 6 Distribution of Scores across the Four Dimensions of Comprehensiveness, Correctness, Organization and Map Elements

CONCLUDING REMARKS

If students are experienced in preparing concept maps, then they can become a useful tool in assessing student and cohort learning. In preparing their maps, students are required to identify the 20–30 most important concepts that they deem worthy of inclusion in their maps. When a scoring rubric is used that considers the completeness and correctness of the map content as well as its structure and elements, then a numerical grade may be assigned to each concept map. When the maps are analyzed by assigning each concept to a particular category, then a different type of picture may be built up of the cohort's understanding and learning of the domain. This type of analysis allows us to identify which areas of sustainable development were well understood and which areas were less understood.

Concept maps are also easier and faster to mark than a comparable essay. Misconceptions that might exist in the minds of the students can be readily identified by inspection of the maps. In preparing the concept maps, students are essentially required to identify the 20–30 most important concepts associated with the domain and then asked to form propositions linking them. These are then easier to identify in a map than they would be in an essay of 300–500 words.

The analysis of the 732 valid maps prepared by the cohort of first-year engineering students suggests that they have an appreciation of the concepts around environmental and technical aspects as well as social impacts and values. It is perhaps not surprising that engineering students would think about technical solutions to the challenges of sustainable development over economic aspects or education. Nonetheless, the engineering students had a sound grasp of the importance of many key societal challenges including poverty, lifestyle, wealth, health and equity, both between generations and across the current generation. An interesting follow-up study would be to conduct a similar survey with students studying business and economics; it might be supposed that a different distribution of concepts would emerge.

The results of this study suggest that in the later years of their undergraduate degrees, engineering students should be exposed more to the intragenerational and intergenerational aspects of sustainable development. They should learn more about the economic impacts of living sustainably on both the individual and the society as a whole. Further, despite the prominence given to some aspects of the sustainable development debate underway in the society around their educational institution, students are yet to recognize the importance of education in all its forms on the topic of sustainable development.

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