System Engineering the Engineering Education Process: A Gap Analysis

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Abstract

In Australia, the relevance of current approaches to engineering education is being questioned. Implementation of best-practice education needs to be adaptable and responsive to change. However, the rate of change and active reform within universities tends to be slow. We propose that systems-based thinking offers a pathway to identify and help optimise the delivery of engineering education. The systems approach is a systematic and logical approach to decision making whilst facing complexity. This paper provides an assessment of eight generic steps that could be used in engineering education. Potential gaps that may hinder a systems approach are identified. The most significant gaps are: 1) a clear mechanism to craft learning and teaching objectives into measureable criteria is not apparent, and 2) we lack forecasting models to predict the outcomes of education options on graduate attributes as well as to quantify the performance indicators needed to compare these options.

Keywords: engineering education reform; systems engineering; curricula delivery.

1 Introduction

Calls for the reform of engineering education (EE) in Australia are persistent. A review initiated by the Australian Council of Engineering Deans ACED (King, 2008) revealed major concerns about the ability to graduate increased numbers of engineers with the requisite skills for the future. A wide range of issues were identified including a concern that the balance of subjects within the current engineering curricula is mismatched with the needs of industry. Part of the proposed vision for EE in Australia is to have a system that is 'responsive and adaptive to technological, professional and societal needs".

This vision contrasts with the perception that universities are extremely slow in implementing change within their engineering programs (Desha, Hargroves & Smith, 2009). Change within educational organizations have tended to be piecemeal without producing desired outcomes (Menchaca, Bischoff & Dara-Abrams, 2003) largely ignoring calls to utilize a more systemic approach, notably by Banathy (1991).

To quote Dym (2004):"the engineering education system is an artifact, worthy of design" and some basic precepts from systems analysis could (and should) be applied to EE to improve outcomes and address the abovementioned concerns. However, there is very little evidence in the literature to suggest that design-based or systems thinking, as often taught to undergraduate engineering students, is being actively employed for curricula reform (Rompelman & De Graaff, 2006).

The application of engineering techniques to reform EE has tended to be fragmented and highly selective. Faulconbridge and Dowling (2010) describe an approach based on engineering lifecycle planning to design and deliver technical courses. Lifecycle models are imbedded in many engineering standards (ISO, 2008) and divide complex problems into defined stages such as decision, design, development and delivery. On a similar vein, principles fundamental to the engineering concept of Conceive-Design-Implement-Operate (CDIO) have been employed by Loyer et al. (2011) to redesign several programs at a Chilean university. This builds on proposals to rethink EE through the lens of CDIO by Crawley et al. (2007). Shelnutt and Buch (1996) employed total quality management principles to guide strategic planning and curriculum revision at the University of North Carolina.

What seems to be unrepresented in the literature is the application of optimization techniques that are applied to whole systems to direct EE change. These techniques have a broad use in engineering including water resource allocation and infrastructure planning (Biswas, 1976), development of catchment and natural resource management strategies (Bellamy, Walker, McDonald & Syme, 2001) and multidisciplinary system design optimization (MSDO) used in aerospace engineering (de Weck, Agte, Sobieszczanski-Sobieski, Arendsen, Morris & Spieck, 2007). Such optimization approaches offer a systematic and logical approach to decision making within complex systems.

The objective of this paper is to evaluate the feasibility of a systems approach to EE reform at an initial and broad level. This will be achieved by consideration of the main steps that generically characterize a systems approach with the view of ascertaining potential gaps that may hinder its adoption. It is hoped that further research could be directed at filling these gaps.

2 The Systems Approach

The system under consideration herein is a learning system that can be conceived as a 'complex integration of course structure and content, assessment methods, and teaching methods delivered in such a way as to facilitate the desired learning outcome in a group of students' (Faulconbridge & Dowling, 2010 adapted from Biggs, 1991).

The complexity of many engineering problems often necessitates a systematic approach to their solution. The same applies to the development of management strategies to address multi-objective issues requiring social, economic and environmental trade-offs. A 'systems approach' is drawn upon to provide a framework useful to resolve complexity and as noted by Dandy (2011) exhibits several features: 1) A clear identification of assumptions, objectives, criteria and constraints, 2) The need to understand the total system and its components is emphasized, 3) A large number of options is considered and evaluated, and 4) preferred options are selected based on explicit trade-offs between the various competing objectives.

The systems approach comes in various guises – for the purpose of this paper, the basic steps are as described by Dandy (2011) for use in water resource planning, built on earlier work by Biswas (1976).

1. *'Formulate the problem*
2. *Specify the objectives for the system*
3. *Translate the objectives into measurable criteria*
4. *Identify the constraints*
5. *Collect and interpret the relevant data*
6. *Identify a large number of alternative solutions to the problem*
7. *Evaluate the consequences of each alternative in terms of the criteria*
8. *Select the preferred alternative(s)'*

The eight steps listed above provide a framework to explore the gaps inherent in using a systems approach to EE. Each step will be considered sequentially in the next section.

3 A Gap Analysis

3.1 Step 1 - Formulating the Problem

The 'problem' of the limited capacity and performance to deliver quality engineering graduates has been outlined at a broad national level by the ACED Review (King, 2008). To engage in EE reform, each university would need to describe their EE 'problem' in the context of their organization. This is obviously an important step as it initiates the process, but no major gaps (i.e. barriers that may hinder this problem formulation) are anticipated.

3.2 Step 2 – Specifying the Objectives

Australian engineering graduate attributes, namely the Stage 1 Competency Standards have been recently updated (Engineers Australia, 2011). These standards are the reference point for universities in order to achieve accreditation from the professional body, Engineers Australia, and thus form a sound basis to specify the objectives.

For Professional Engineers, there are 16 elements of competency that must be demonstrated at graduation, covering the areas of base knowledge and skill, application of engineering methods and processes, and professional and personal attributes. These are written generically, but in some disciplines, a more detailed account of graduate competencies is available. An example is the work by Dowling and Hadgraft (2012) to define environmental engineers.

3.3 Step 3 – Translating the Objectives into Measurable Criteria

One common approach used to demonstrate successful outcomes is to "map" how the various graduate attributes are embedded in individual courses and programs. This typically requires developing individual course matrices, using information that should form part of the course outlines/synopses routinely provided to students. That information includes such things as statements about what the successful student is expected to achieve in the course and are thus aspirational, rather than demonstrated outcomes. Such matrices need to link learning outcomes with graduate outcomes using assessment methodology. Outcomes from individual courses would then normally be collated across each program and the overall outcome evaluated.

Waters (2003) reviewed the then current situation in Australia and the UK with respect to how various universities have produced mechanisms for students to map, track and assess the development and/or acquisition of graduate attributes during their studies. Many universities provide self-assessment or portfolio building tools for students while others have developed specific courses or skills programs to equip students with the desired attributes. Waters (2003) concluded that it would be unwise to invest in software or mechanisms that "merely mapped notional graduate attributes rather than those that students actually had achieved" and suggests that a more active process of translating graduate objectives into measurable criteria is still needed.

Engineering attributes, skills and knowledge may be fully mapped linking assessment, outcomes and graduate attributes in matrices developed in-house and this is a well established process carried out with variable success for EA accreditation purposes. To create such a matrix the course designer estimates to what extent each graduate attribute is addressed. Such an approach may be seen as being rather mechanical in nature and perhaps a somewhat imprecise measure of delivery (and not acquisition) of graduate attributes within a single course. However, when aggregated over all courses in a program, a reasonable estimate of relative delivery of attributes is obtained, albeit very little about the effectiveness of that delivery and the quality of the course and/or programs. Supplementing this mapping process with an effective and rigorous evaluation method, such as Program Logic (Brodie, Bullen & Jolly, 2012) provides not only a mechanism to clearly articulate the goals and objectives of each course in each program of study but also provides clear evidence of attainment of these goals or otherwise.

3.4 Step 4 – Identifying the Constraints

It is anticipated that constraints can be readily identified and specific to the university context. Constraints could be financial and resource limitations, but as noted by Dym (2004) may also include a fixed requirement to deliver fundamental sciences (mathematics, physics etc.) within the first two years of an engineering program. Obviously, the setting of excessive constraints will limit the number of feasible alternatives under analysis.

3.5 Step 5 - Collecting and Interpreting the Relevant Data

The development of alternatives, and their evaluation against criteria, is expected to require extensive amounts of data. Although data collection and interpretation may be resource intensive, no major gaps that preclude the general feasibility of this step are expected. Again Program Logic may be used. This provides an "ongoing systematic process to plan, implement and evaluate educational programs" (University of Wisconsin. *Planning a Program Evaluation.* 30 March 2011; Available from: www.uwex.edu/ces/pdande).

3.6 Step 6 – Identifying the Alternative Solutions

The systems approach encourages the (rapid) evaluation of numerous options, so not to artificially constrain the possible solutions on offer. It is anticipated that options involving different combinations of curriculums, teaching content, assessment, pedagogies etc would be able to be readily identified.

3.7 Evaluating Alternatives Against the Criteria

Alternatives could be trialled by introducing real programs to real students and then monitoring the outcomes. Apart from the lengthy evaluation timeframe (given that engineering programs run over 2 to 5 years) and the limitations to simultaneously running multiple options, the ethics of intentionally experimenting with an engineering degree offering is questionable. As a general comment, the time lag to enact reform in engineering curricula are extremely long, up to 15 to 20 years taking the introduction of sustainable development as one example (Desha, Hargroves & Smith, 2009).

In a system engineering context, evaluation of alternatives is generally carried out using a computer-based simulation model. These models are simplistic representations of reality but have the distinct advantage of the rapid assessment of numerous options. For a systems approach to be feasible, simulation modelling to forecast EE outcomes would be needed.

Conceptual models of engineering education are available (Hoffmann, 2005; Owens & Fortenberry, 2007) but these are constructs that provide a useful framework or guide for universities to define, enhance and implement engineering programs.

Simulation models that are specifically devised to predict or forecast the outcomes of options (such as engineering coursework alternatives) appear not to be readily available. Frick, Thompson and Koh (2006) outline a predictive model for education systems that is under development. The model PESO is intended to assess the likely effects of school management change and is not specifically directed at graduate attributes. The lack of EE simulation models is a significant gap in the systems approach.

A suitable model is needed to predict graduate attribute outcomes or indicators of performance that can be gauged against the Step 3 criteria. The development of such a model is not intractable as much can be drawn from decision support models used in complex, highly uncertain situations (such as predicting ecological outcomes to management strategies). It is beyond the scope of this paper to identify how this model gap may be filled, but possible candidates include:

- Multi-Criteria Decision Analysis (MCDA) whereby alternatives are scored in terms of achievement against each objective. Scores aggregated and weighted to show overall performance. A useful starting point is the work of Anestis, Grigoroudis, Krassadaki, Matsatsinis and Siskos (2006) who developed MCDA-based software, Skills Evaluator, for the accreditation of Information and Communication Technology qualifications and skills.
- Bayesian techniques offer a way to incorporate prior knowledge into data-intensive analysis and are used extensively in probability assessment. It has promising applications in education management and has been used to predict future student academic performance (Bekele & Menzel, 2005; Nghe, Janecek & Haddaway, 2007).

Other model option ideas which are largely untested are:

- A 'virtual student' modelling approach such that how a student may navigate through the engineering program (the so-called student journey) is tracked and the accumulation of graduate attributes along the way is quantified.
- A stochastic version of the above approach using Monte Carlo simulation (many different student journeys are evaluated with multiple outcomes) and coming up with an average graduate attribute outcome or some other statistical measure of performance.

3.8 Selecting the Preferred Alternative

Educational institutions are typically established to service the needs of its local community and as such it provides its graduates with attributes to allow them to contribute to local society (Bullen & Silverstein, 2005). This is done within the context of some larger national accreditation standards. In addition there is increasing pressure to graduates to be 'global citizens' with skills that are transferable to the international market place. Agreements like the Washington Accord provide a framework that "recognises the substantial equivalency of program and a recommends that graduates of accredited programs in any of the signatory countries be recognised by the other countries has having met the academic requirements for entry to the practice of engineering" (Washington Accord Secretariat, 2004).

In selecting the preferred alternative, institutions have to have a very clear idea of not only what attributes, skills and knowledge are important in their context but also establish a priority which is reasonable for a graduate engineer e.g. are practical skills or transferable skills a higher priority than high level theoretical mathematics?

In addition, as with any systems approach, there needs to be a thorough and ongoing evaluation. Curriculum (design and content), teaching methodology, assessment strategies and the learning environment all impact on desired and designed outcomes. Further interventions may need to be made and their effect carefully monitored within a rigorous framework.

A suitable framework which can be used, in addition to the Program Logic strategy, is the Realist Evaluation proposed by Pawson and Tilley (1997). Realist Evaluation stresses the linked concepts of mechanism, context and outcome for understanding and explaining programs (Pawson & Tilley 2004). Mechanisms describe what it is about programs that bring about outcomes. The process of how participants act and react to resources and processes in a program is known as the mechanism. Whilst identifying critical mechanisms is a step in the evaluation it must be recognised that these mechanisms work differently in different contexts. Context should not be confused with location but rather refers to circumstances. Context describes the features of the conditions in which programs operate. Outcomes covers the consequences of programs both intended and unintended which result from the interaction of contexts and mechanisms (Pawson and Tilley 2004). It does not make hard and fast distinctions about the success or otherwise of a program but a good evaluation can explain a complex set of interactions and outcomes and tests these conjectures empirically (Mark, Henry & Julnes, 2002).

4 Conclusion

An engineering systems approach may provide a sound basis for curriculum design, especially if backed up by rigorous and continuous evaluations. To some extent, curriculum changes and implementations need to be seen as social practices (Saunders, Trowler & Bamber, 2011). However empirically derived outcomes, rather than impressions, assumptions or responding quickly to the latest educational fad provide a solid basis to ensure a robust curriculum design to deliver required learning outcomes. This is where a systems approach to engineering education is considered beneficial. A gap analysis indicates that establishing learning and teaching objectives into measurable criteria and then having a forecasting capability to predict and evaluate the outcomes of EE delivery options against these criteria are two areas that warrant further research.

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