Reforming Engineering Education
- A feasibility analysis of Models for Innovation

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INTRODUCTION

A challenge in engineering education is to educate engineers who thoroughly understand how to apply their knowledge and skills to design products and processes that have not existed before [1, 2]. It is a fundamental aim of academia to provide industry, the public sector and society with engineers who can do engineering [3, 4] and innovation [5]. Engineering education provides an academic foundation for the industrial and technological pressures faced by future engineers that aims to influence technological advances and enhance the quality of life in society [2, 6, 7] and improve ways of learning and educating future engineers [8].

The continuous need for updates that characterizes today's expectancies on engineering professionals has pushed accredited engineering programmes to repeatedly call for reform in the pedagogical approach to engineering education [4, 9]. To catalyze the change initiatives needed, Graham [10] states that successful change in engineering education is not typically triggered by pedagogical evidence, rather evidence show that diffusion of good practice from 'champions' are mostly limited and lack long-term implications. Due to the often short-term efforts induced by 'champions' sustainable change and persistence seem to fade due to incapability to allocate reasonable resources.

The purpose of this paper is to scrutinize several approaches to making changes in engineering education. These approaches have been structured differently and have had different purposes. The goal of the paper is to develop a model for assessing change approaches in order to get support for selecting the suitable approaches regarding the goal of the change and resources available.

The paper will be structured so that relevant literature from adjacent areas will be presented in a background section, followed by descriptions of the cases representing the approaches of changing engineering education focused in this paper. Finally these cases will be discussed in relation to the purpose of this paper.

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1 BACKGROUND

1.1 Engineering knowledge

We maintain that it is important to realise that “it is erroneous to consider technology as being an applied science” as pointed out by Skolimowski [11] in his essay “The Structure of Thinking in Technology”. Skolimowski summarizes the difference as “science concerns itself what *is*, technology with what *is to be*”. This is precisely what we pointed out in the introduction when we mentioned the need to educate engineers that have knowledge and the skill to be innovative and able to “design products and processes that have not existed before”. Hence the nature of knowledge in engineering is different from that in science [12, 13].

However, it is not uncommon that STEM-educational research (Science Technology Engineering Mathematics) is lumped together into one undifferentiated category or see the theoretical framework in engineering research as based on the “traditional scientific paradigm” [14]. Lavelle [12] points out that engineering work with real entities and artefacts and not the idealized and isolated objects of science, is poly-paradigmatic, is pragmatic and value efficiency and practical usefulness. In a similar vein Bucciarelli [15] argue against thinking that miss the uncertainty and ambiguity in engineering and stress that “designing is not lawlike or deterministic” and Schön [16] argues that “although some design products may be superior to others, there are *no unique right answers*”.

Bernhard [13] and Malmberg [17] suggest that a discussion about knowledge in engineering should take its point of departure in Aristotle´s five concepts of knowledge: *episteme*, *techne*, *phronesis*, *sophia* and *nous*. *Epistéme* is the knowledge of science based on general rules and structures, *téchne* is the knowledge of practice, *phrónesis* is the wisdom of practice (making good judgements) based on a persons own experience, *sóphia* is the wisdom of making good judgements using science and intelligence and finally *nous* is intelligence and the ability to make holistic judgements. It is stressed that an engineer should be able to make good judgements in new and unknown situations [13, 17] and be innovative [5]. Borrego and Bernhard [3] identified that in the European didaktik-tradition “professional appropriateness”, formation of the individual as a whole and what (the knowledge and skills to be learned) and why questions are important. Hence the discussion of engineering knowledge is essential in any discussion about innovating, designing and implementing changes in engineering education can not be separated from a discussion about our goals, views and values.

We need also need to discuss how to achieve the desirable knowledge. The USEM-model [18, 19] provides a framework for analysing some aspects of educational innovations. According to this model understanding (U), skilled practice (S), personal qualities and efficacy beliefs (E) and metacognition (M) contributes to the employability of a graduate from higher education and their likeliness to be successful in their chosen occupation. We suggest that these components also contribute to an engineer’s ability to be creative and innovative and the USEM-model be used as an illuminating tool for analysing on which elements different curricula put emphasis on.

Taking a departure in, inter alia, Dewey’s essay “education as engineering” [20] Bernhard [13] suggest that engineers has specific skills and knowledge, especially design, that can be applied in designing (“engineering”) learning environment in engineering education. In this paper we will, as trained engineers, discuss reforming engineering education taking an innovation and change management perspective.

1.2 Change management

A desired outcome of change is of course achievement of goals set for the change and many times a specific desire is sustainable changes. The outcome of change is dependent on what is changed and how the change is performed [21]. Norrgren [22] describes that an efficient change is achieved if the solutions reach a certain *quality*, that people *understand* the reasons behind the change, and also *accept* the change. Understanding is necessary to prioritize changes, and acceptance is crucial to achieving sustainable changes. Regarding extent of change, Norrgren makes a distinction between renewals and improvements. Both types of changes are relevant, depending on the situation in an organisation. Further, competencies in performing both changes create flexibility in the organisation, which is required when conditions change rapidly in the surrounding world. Based on a review of research in organisational change, Porras and Robertsson [23] refer to improvements as a first order change, limited effect within the organization, and renewal as a second order change, takes place on several levels and in several dimensions. They further categorize change according to whether a change is planned by the organization or if it takes place as a reaction to the surrounding world, the latter a more ineffective change is a likely result as the change process benefit from a systematic approach. Further factors that are crucial for the result of a change is that it is directed from the management of an organization and in the same time is planned so that people in the organization is involved and strongly effect the concrete changes that relates to them [24]. Change is sometimes driven by champions who can achieve effective results, however often related to a change of first order in a part of an organization [25].

In the same way as competence in how to perform change is needed (see above), learning about how to learn is worth striving for. Argyris and Schön [26] call this deutero-learning. It is important to make the distinction between single-loop and double-loop learning. Single-loop learning is expressed in simple terms as a corrective action. It concerns how to change a certain action in order to achieve the goals that have been raised in the organisation, and how to perform defined tasks in an effective way. Errors are discovered and then corrected. Double-loop learning, on the other hand, assumes questioning the goals and the definition of tasks. Norms and strategies in organisations should be questioned in order to find new ways of achieving effective performance. Double-loop learning assumes people gain insight from their own experiences, reflect upon them, and find solutions on the basis of them. Both kinds of learning exist, and should exist in tandem.

Translated into engineering education single-loop learning correspond to university departments and instructors learning how to educate engineering students better within the present system, e.g. achieving higher pass rates on (existing) exams or lower drop out rates. Double-loop learning would correspond where the content, goals and (tacit) assumptions of existing curricula is questioned. For example we argue that higher engineering education academia need to learn how to educate more creative and innovative engineers. It is interesting to note that in the European “didaktik-tradition” [3] “*what* should be learned and *why* it should be learned is a core question”, whereas in the “curriculum studies-tradition” pre-dominant in the US “*how* a given topic is best taught is a core question”. The parallel to double- and single-loop learning is apparent.

1.3 Systematically changing engineering education

Models for reforming engineering education based on scholarly research has recently received much interest manifested in for example the rapid growth of the field of engineering education research (EER) and the transformation of engineering education journals [3, 27]. It is beyond the scope of this paper to review the whole field of EER. Instead our focus is on a feasibility analysis for different models of reforming engineering education towards a larger inclusion of innovation skills. There has recently been an increased interest in the transferability and diffusion of research-based curricula in engineering education. According to Graham and Crawley [28] the transfer of educational innovations to other settings are usually difficult problem since innovations originally seem to be developed by “champions”. Hence, there is a need to find feasible ways to systemic change in engineering education [10]. Based on work by Henderson et al. [29] who identified four categories of change strategies Borrego et al. [30] have developed a model with eight change strategies and used it in an investigation of the use of evidence-based teaching in STEM higher education. The categories are (strategies within each category in parenthesis): 1. Disseminating curriculum and pedagogy (Diffusion, implementation), 2. Developing reflective teachers (Scholarly teaching, teacher learning communities), 3. Enacting policy (Quality assurance, organizational development), and 4. Developing shared vision (Learning organisations, complexity leadership). Taking a different approach Edström and Kolmos [31] has compared CDIO and PBL as models for engineering education development.

Table 2. Educational change matrix

	Narrow context (course level)	*Wide context (programme level)*
Top-down	Managed/driven by hierarchal structures	Formal requirements and guidelines
Bottom-up	Locally driven change initiatives	Fundamental change impact initiatives

Taking a point of departure in change management and design literature and in the European didaktik-tradition we will focus more on the content of educational innovations, what elements of engineering education and learning are changed and why (i.e. underlying logic and ideals), strategy, actors and potential. We propose an educational change matrix in Table 2 and we use this and the USEM-model in discussing the cases that will be presented in the next chapter.

2 CASE DESCRIPTIONS

Descriptions of several approaches to changing engineering education have been collected for this paper. These approaches found a basis for analysing current practices and will be scrutinized in order to identify aims with and resources used in the approaches, what results and effects that have been gained and also possible deficiencies. The analysis of the approaches will contribute to a discussion of critical actions taken when changing engineering education.

2.1 Integrated Product Development

The first approach described is a development of a new course on advanced level which today is part of a master track, Integrated Product Development (IPD). The course contains a major project that constitutes three quarters of a year on half speed allowing time for practicing engineering and organization as well as reflection. Each project involves approximately 15 students, making complexity in both task and organization two leveraging factors. Students are given an assignment from an industrial partner and the project formed is signified by coordination and systematization of parallel development processes and activities in the creation of a functional prototype. The individual learning is centralized in the ongoing project processes and supported, i.e. ‘individualized’ by specific reflection assignments and portfolio summaries. The final prototype is central, yet the nature of organizing intra group activities that supports a finalization of actions and activities concerns an overarching learning objective that surpasses any outcome derived attention.

The development started 15 years back when a need for a new training in mechanical engineering was identified. It related strongly to research that highlighted the need to train engineers in the organizing of product development. Teachers developing this course were strongly driven by both bringing a specific content in to the education and a learning setting for the students. By the time the first project course was realised it was a result of an institutional shift to strive for a project-based learning format inspired by ‘best practices’ and it aimed to train specific skills as well as give the students a first experience of the challenges in real life product development. When initiated this change was run by individuals, comparable to champions and gave a first order change. As time has passed it has become a common way to work in most mechanical engineering cap stone course.

2.2 Product Innovation Engineering

The second approach is fundamentally different in its foundation. PIEp is a research and change program for increased innovation capability in people and organizations. PIEp works towards new businesses, products, processes and organizations and PIEp has worked according to logic that this is achieved through the development of people. A key principle for PIEp has been that in order to make a long term change in society concerning increased innovation capability a critical mechanism for this is making change in education in order to leverage the innovation capability of people leaving universities.

During the first phases of PIEp (2006-2010) Education was run as a specific area of development with the main purpose to integrate innovation into courses and programs at the five university partners. Typical environments involved were mechanical engineering where cap stone courses in product development was held, similar to IPD described above. PIEp organized networks meeting where issues as Defining Innovation, Creativity in Design Education, and Integrating Innovation in Education, were discussed and also taught to teachers. PIEp strived for inducing a change by inspiration and new knowledge that build on the responsibilities of engaged teachers. From a university perspective PIEp has worked bottom-up engaging people and the program has had as a bearing idea that innovation need to be integrated on a broad level curriculum wise (an ambition to reach a second order change). This means that though the approach was not to work on full programs, innovation should be integrated in many courses and not only given in a specific course. Results from the actions were a clear increase in knowledge and awareness of the need to teach in innovation within the network, changes in courses at several universities, specifically by new elements in teaching. At one university a new master program was started, partly due to PIEp Education, partly due to the program as a whole.

2.3 Conceptual Labs

The third approach is an example of a bottom-up course level work: the conceptual lab project [32, 33]. This "project" started around 1995 with the aim of developing labs that contributed to develop students' conceptual understanding and to develop students' ability to connect models and theories to the "real" world of objects and events [34, 35]. In the labs developed within this project sensor-computer-technology that collected and displayed experimental data in real-time has been combined with "hands-on" and a design of task structure based on theories of learning such as variation theory [36]. Very good results on instruments testing conceptual understanding has been achieved with normalised in the range of $g \approx 50\text{-}60\%$ and with effect sizes $d \approx 1.1$ [32, 37]. The project was originally inspired by the approaches used in the curricular projects RealTime Physics (RTP) [38, 39] and Workshop Physics [40, 41] from USA. However, the development of conceptual labs has extended beyond the domains developed for RTP, for example into advanced mechanics courses for engineering students [42] and into advanced electric circuit theory courses for engineering students [33, 43, 44].

2.4 Analysing change approaches

The approaches to change briefly described above are summarised in table 3 with some of the characteristics of the approaches.

Table 3. Analysing some approaches to educational change.

Approach	*Aim/Driving force*	*Way of procedure*	*Change characteristics*	*Result*
Cap Stone Course IPD	Specific skills in product development organization/Research driving need of new skills in engineering	Initiated by teachers; Small resources for developing courses; Benchmarking concerning content and form	Locally driven change initiative	Successful course for a long period of time, local effect
Program for Innovation PIEp	Specific skills in innovation/Society and research driving need of new skills in engineering	Initiated by research program; Small resources for developing teachers; Based on research studies in innovation	Locally driven change initiatives striving for fundamental change	Smaller changes in several courses, larger effects lacking
Conceptual Lab	Good conceptual understanding of fundamental concepts is important for the development of skills in engineering	Initiated by teachers; Small resources for developing teachers; Based on research in pedagogy	Locally driven change initiative	Very successful in the courses there the approach is implemented. Implementation by other teachers lacking

3 DISCUSSION

The paper assesses approaches to changes that provide improvements to a narrow context, i.e. course level. On the other hand Problem-based-learning (PBL) and CDIO is described as a systems approach [31] to engineering education. The ideology behind full-scale implementations of PBL is that the skills students' need in their coming professional lives is best learned and developed when working together with other students solving complex, often interdisciplinary, practical real-world problems. It is worth noting that, to our understanding, full-scale implementations of PBL has mainly been made when starting a new university (i.e. the case in Aalborg) or when starting a new programme (i.e. computer engineering at Linköping University) and not as a transformation of an existing educational programme. Graham and Crawley [28] report that PBL can also be problematic to implement in programmes with a large student body and may require a higher student – teacher ratio. The higher demand on resources may reduce the transferability of PBL as is often the case in programmatic changes [22]. The approaches analysed here may have a less wide result than many times desired, however, they have also required low resources.

Applying the USEM-model [19] mentioned earlier the conceptual labs focus on the development of understanding (U) and metacognition (M). It is more or less hypothesized that this will contribute to better skills. As a comparison PBL focus on the development of skilled practice (S) and personal qualities and efficacy beliefs (E). The resulting development in U and M is more or less assumed in PBL. This difference in emphasis can be seen in the data reported in the literature: Compared to more traditional educational approaches it seems that PBL results in significantly better development of skills, but that the achievements in learning basic knowledge and conceptual understanding is approximately on the same level [45, 46]. On the other hand for conceptual labs (and similar approaches) there is strong evidence for the development of good understanding but the evidence for development of skills are lacking. The challenge is to develop approaches that develop good skills as well as a good understanding.

A common feature that stand out in presented cases are that Graham’s [10] notion of champion driven initiatives dominate, yet a problem to this is that the implication and sustainability get weakened. Notably, to establish more than a mere shallow effect, sustainable effort are according to the cases presented incapable to relate other than to a limited “narrow” context. Porras and Robertsson [23] arguments set these initiatives in a first order change, with mere limited effect as a result. This put distinct change efforts as indicators of improvements made and a way to instrumentally reproduce a mantra of accepted beliefs that incorporate a change pattern. There is nothing wrong with this, however, what should be a concern is the wish for propagation of good practices that follows as part of the activities incorporated in the reform are easily forgotten. To capitalize on every attempt to change it should therefore be essential to have a balance between top-down government and bottom-up freedom to act. In this equilibrium we pose that most sustainable change efforts are situated. Dimensions of change are affecting each other that through time allow saturation in one dimension changes to appear in either a lateral, i.e. a narrow or wide context or a hierarchical level, i.e. top-down or bottom-up.

4 CONCLUSION

Our cases and the literature points to problems with bottom-up course level as well as top-down program-level approaches. Sustainable change needs a balanced support when selecting the suitable approaches regarding the goals and desires attached to the change and resources available. Without explicit mapping to either the CDIO framework or PBL as a way of categorising attempts and steps taken, we mirror our results in these guiding approaches that span cross a “wide” context. To better prepare educational reform it is our belief that building good practices that can be supporting in each of the change dimension is essential. Even more so, being able to understanding current positioning in addressing change efforts allow a move to be made in to new dimensions, generating renewal within the organisation. Such moves benefit from the integration of perspectives from both change management and education in order to enable systematic changes tailored to the specific contexts of engineering and innovation.

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