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PBL and CDIO: complementary models for engineering education development

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This paper compares two models for reforming engineering education, problem/project-based learning (PBL), and conceive–design–implement–operate (CDIO), identifying and explaining similarities and differences. PBL and CDIO are defined and contrasted in terms of their history, community, definitions, curriculum design, relation to disciplines, engineering projects, and change strategy. The structured comparison is intended as an introduction for learning about any of these models. It also invites reflection to support the understanding and evolution of PBL and CDIO, and indicates specifically what the communities can learn from each other. It is noted that while the two approaches share many underlying values, they only partially overlap as strategies for educational reform. The conclusions are that practitioners have much to learn from each other's experiences through a dialogue between the communities, and that PBL and CDIO can play compatible and mutually reinforcing roles, and thus can be fruitfully combined to reform engineering education.

Keywords: CDIO; problem-based learning; project-based learning; PBL; educational development; curriculum development; change strategy

1. Introduction

1.1. *Background*

There are many strong drivers for curriculum change in higher engineering education, seeking to establish alternatives to traditional programmes consisting mostly of disciplinary theoretical courses (Sheppard et al. 2009). The background is a need to enhance quality and improve the processes and results of education, for instance to increase attractiveness to prospective students, decrease attrition, to improve preparation for professional practice, and better contribute to sustainable development, innovation, and job creation. In addition to drivers for change within universities, there is also political pressure and pressure from employers (National Academy of Engineering 2004; Royal Academy of Engineering 2007; Litzinger et al. 2011). The higher education environment in general has been significantly reformed in recent years, spurred on by

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for instance the Bologna process and the Accreditation Board for Engineering and Technology (ABET), both of which have been influential far beyond their formal scope. Changes include the structure of degrees and a switch to outcomes-based principles for curriculum, accreditation, and evaluation systems.

There is a great variety in how institutions go about the change (Graham 2012). Some projects are designed, carried out, and reported purely internally, while others are inspired by more established approaches, sharing and discussing the problem analyses, methodologies, and results in wider communities. There are several organisations, networks, and communities focused on curriculum change in higher engineering education worldwide. The aim of this paper is to analyse and compare two educational development approaches with organised international communities: problem/project-based learning (PBL) and conceive–design–implement–operate (CDIO). Our main questions are: What are the differences and similarities? How are the approaches related? What can they offer to engineering education development and to each other?

We see two reasons for making this comparison. The first is to offer a knowledge base for anyone wishing to learn about PBL or CDIO, in particular educators or institutions considering reform. The second is to invite reflection to support the understanding, critique, and evolution of PBL and CDIO, by its practitioners. As we need to constantly reflect on and develop our methods and their underpinning arguments, the aim is to provide a contrast conducive for better understanding also one's own familiar practices. In particular, this paper will make an effort to identify what one of the communities can potentially learn from experienced practitioners of the other, and areas with potential interest for future collaborations.

1.2. *Methodology*

The framework for the analysis was generated through an inductive, participatory, and iterative approach. The authors started with a dialogue to generate a gross list of relevant aspects to compare. To support the aims to invite learning and reflection, the comparison needed to examine the underlying ideas and how they are evident in practice. As PBL and CDIO represent *system approaches* to curriculum development, the comparison also emphasises the organisational and the curriculum level view. The resulting list of aspects was the basis for generating descriptions of PBL and CDIO through studies of the literature and documents, and drawing on our own experiences in PBL and CDIO, respectively. The first iterations of the comparison were discussed and gradually refined in three conference workshops with about 70 highly experienced practitioners (Kolmos and Edström 2011a, 2011b; Edström and Kolmos 2012). The workshop discussions indicated that points of comparison were the most salient and productive in generating insights by revealing similarities, differences, surprises, misconceptions, or unreflected assumptions. The resulting framework converged around the following core aspects: the history, community, definition, curriculum design, relation to disciplines, engineering projects, and change strategy. In the following, these aspects are examined and analysed for PBL and CDIO, respectively, then contrasted.

Describing CDIO and PBL in ways that enable comparisons is not a straightforward task, due to fundamental differences in their nature. Since there is much variation in PBL interpretation and implementation, there are multiple definitions and perspectives and the full diversity of PBL practice cannot be covered here. When the description had to be narrowed down, the approach practiced in engineering at Aalborg University was emphasised, but with an effort to demonstrate awareness of and sensibility to other traditions. Because of its more cohesive organisation, it was somewhat easier to define CDIO, at least sufficiently for the practical purpose of this paper. To invite further exploration beyond these short descriptions of PBL and CDIO, references are provided.

2. History

2.1. *PBL – histories*

The late 1960s and early 1970s were a period of experimentations and expansion in educational systems. When reform universities were established, inventing new educational models, the result was several forms of PBL. The problem-based learning model was implemented especially in health education at McMaster University (founded 1968) and Maastricht (founded 1972). The problem-based *and* project-organised models were practiced at Roskilde University (founded 1972) and Aalborg University (founded 1974), in a wide range of subject areas such as engineering, science, social science, and humanities (Illeris 1976; Neville and Norman 2007; Kolmos and de Graaff 2013). The pedagogy was developed from a critical stance in student movements, and added to a theory of learning with cognitive, emotional, and social dimensions (Illeris 2007). The PBL universities are well documented in all aspects of curriculum development, learning, and competence development (Schmidt and Moust 2000).

Nowadays, PBL is implemented all over the world. In health and law, the McMaster and the Maastricht models are often used, whereas the Aalborg model is applied in engineering and science (Graham 2009; Savin-Baden 2003). In the PBL curriculum, projects are the platform for students to achieve competences, and to relate disciplines to each other in analysis and identification of problems as well as the problem-solving process. Process skills such as self-directed learning, project management, collaboration, communication, and collaborative knowledge construction are taught in an integrated way by letting students reflect upon their practice. A fundamental principle is that the students are owners of the learning process and the facilitator guides the students by presenting several ideas, methods, and tools.

2.2. *CDIO – starting point*

CDIO started at Massachusetts Institute of Technology (MIT) in the late 1990s as a reaction to conventional engineering education, observing that in many institutions engineering science was replacing engineering practice as the dominant culture. Crawley (2001) summed it up: ‘Education of engineers had become disassociated from the practice of engineering.’ Ever fewer faculty members had professional engineering experience and values related to practice were weakened in the education – affecting graduate qualities. Industry feedback stated the need for change (Gordon 1984; Augustine 1994; The Boeing Company 1996) and similar requirements came from new outcomes-based accreditation standards emphasising a wider set of skills (ABET 1996).

This sparked an investigation into the question: ‘What is the full set of knowledge, skills, and attitudes that engineering students should possess as they graduate?’ The CDIO Syllabus (Crawley 2001; for version 2.0, see Crawley et al. 2011) lists and categorises desired qualities of engineering graduates, based on stakeholder input and validation. The acronym refers to engineering practice: *conceiving, designing, implementing,* and *operating* products, processes, and systems.

The early work at MIT struck a chord with Swedish educators and industrialists, and in 1999, the CDIO Initiative was formed by MIT, Chalmers, KTH Royal Institute of Technology, and Linköping University, with four years of funding from the Knut and Alice Wallenberg Foundation. They adopted the aim to educate students who:

- Master a deeper working knowledge of technical fundamentals.
- Lead in the creation and operation of new products, processes, and systems.
- Understand the importance and strategic impact of research and technological development on society.

The project partners set out together to develop pilot programmes at each university (Brodeur et al. 2002; Bankel et al. 2003), thereby creating, implementing, and documenting the CDIO approach, a methodology for engineering education reform.

2.3. *Comparing the history*

PBL and CDIO both advocate broader learning outcomes compared to traditional academic education, emphasising student development of skills and personal development, the process of *becoming* a professional. With its longer history, PBL should be recognised as a milestone for student-centred education, also preparing the ground for CDIO. A difference is that PBL emerged across disciplines, while CDIO was developed within engineering. Moreover, while PBL was an alternative pedagogy created in new reform universities, CDIO was designed by established institutions, for reforming existing programmes.

One fundamental difference is that the means/ends logic is almost the opposite. CDIO aims to align the intended learning *outcomes* with professional practice – and the focus on more appropriate processes for teaching and learning comes as a consequence of that. For PBL, it was the learning *process* that was aligned with professional practice, in a highly student-centred interpretation consistent with the social movements in the 1960s and 1970s. The CDIO Initiative was established much later and embodies more recent trends such as outcomes-based education, and explicitly uses references to external stakeholder interest to challenge traditions within the institutions. These differences can be attributed to the spirit of the times when respective approach was developed.

3. Communities

3.1. *PBL – organised communities*

The size of the community practicing PBL cannot be estimated, due to the different levels of implementation, ranging from individual instructors applying PBL in a single course and programmes where PBL is applied to some extent, to whole institutions built around the model, with researchers specialising in PBL evidence. There are several international networks for sharing experiences, none of them with a formal membership structure. Among the most established are:

- The UNESCO Chair in Problem-Based Learning in Engineering Education (UCPBL) runs the PBL Global Network with research symposia every second year. The UCPBL has declared a strong emphasis on research and is based on philosophy and learning principles across different PBL practices (Maastricht and Aalborg), derived from educational research and practice.
- The International PBL Symposium is organised by Republic Polytechnic, Singapore – the hub of an Asian community with an international symposium every second year.
- The Pan-American Network for Problem-based Learning – international conferences each second year.

There is a rich literature documenting PBL, including specialised journals such as the *Interdisciplinary Journal of Problem-Based Learning* and *Journal of PBL in Higher Education*. Plenty of the literature reviews indicate success (Dochy et al. 2003; Beddoes, Jesiek, and Borrego 2010). Results show that employers rank PBL education highly, stating that graduates are able to work from day one. Students from a PBL programme achieve a higher level of skills and competences, deeper learning, and increased motivation. Compared to traditional universities, the retention rates increase, students get higher grades and higher salary (Kolmos and de Graaff 2013). Some voices also warn about risks such as lack in disciplinary knowledge (Kirschner, Sweller, and Clark 2006).

3.2. *The CDIO Initiative*

Soon after the four founding institutions started developing a methodology for reforming programmes, other expressed an interest in participation. They were welcomed and presently the CDIO Initiative has grown to a large global organisation consisting of over 100 institutions as ‘CDIO Collaborators’. There is a formal structure where the CDIO Council grants the status as collaborator and controls key documents (CDIO Syllabus and CDIO Standards). From 2013, the council members are elected, replacing the original organisation where the first 10 collaborators had permanent seats.

Knowledge generated through the experience of developing engineering education is shared and disseminated within and outside the CDIO community. The annual international CDIO Conference started in 2005. Also annual and open is the worldwide working meeting. The early collaborators authored a book on the CDIO approach (Crawley et al. 2007, the second edition Crawley et al. 2014) and the CDIO website (cdio.org) contains resources and contact information as a starting point.

While some of the conference publications could arguably be categorised as educational research, and some are published in peer-reviewed journals, the majority of contributors are engineering faculty documenting their educational reform work and very few authors have a position as educational researchers. Lately, interest in educational research has increased, and peer-review of conference papers was introduced from 2009.

3.3. *Comparing the communities*

On the spectrum between a well-defined and centralised organisation, and an inclusive and decentralised community, it is safe to say that PBL consists of clusters of communities of practice that are open and inclusive, whereas the CDIO Initiative is an organisation with at least some control over defining documents and collaborator status.

CDIO is mainly an education development community where most participants are instructors and leaders of engineering education rather than educational researchers. Because of the longer history and the wider range of subjects, there are researchers focusing on PBL. Some networks are essentially research communities, and more research publications document the effect of PBL than of CDIO.

4. Definitions

4.1. *PBL definitions: three learning principles*

Since the first pioneering institutions, existing universities have adapted or partially adopted problem-based and/or project-based models (de Graaff and Kolmos 2003; Savin-Baden and Howell Major 2004) leading to a variety of implementations worldwide. PBL is applied in different cultural settings, subject areas and at different levels in the educational system ranging from schools to universities and continuing education. The scope of implementation ranges from the institutional, to programme and single course level. This diversity leads to a continuous debate on what should count as PBL (Savin-Baden 2003).

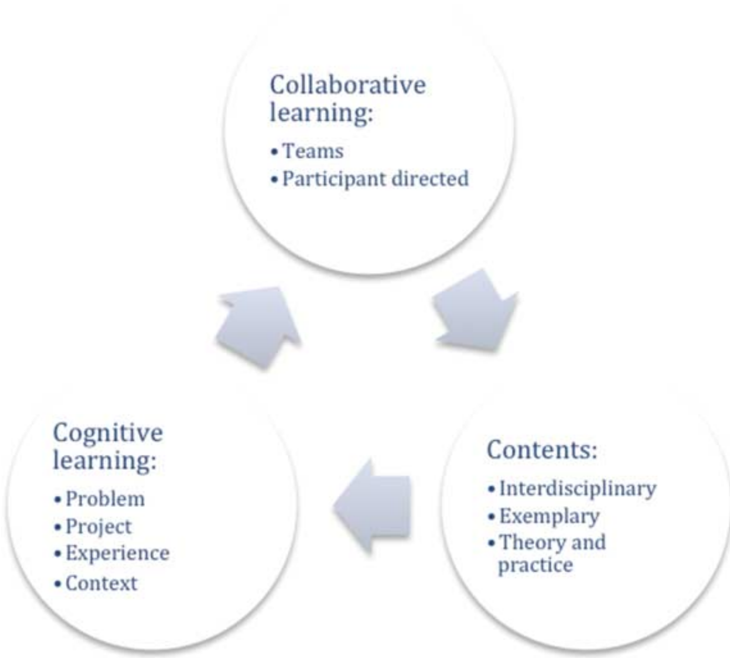

Figure 1. PBL learning principles (Kolmos, de Graaff, and Du 2009).

Local practices will, and should, constantly evolve with regards to content and educational methods. It is therefore short sighted to define PBL based only on practice – the concept should be dynamic and based on both theories and practices. The UCPBL also recognises cultural differences and has developed an understanding of PBL based on diverse practices and learning theories. The learning principles below (Figure 1) are intended to broadly guide practice, and are consistent with the McMaster/Maastricht and Aalborg models (de Graaff and Kolmos 2003).

The principles are related to the approach to cognitive, collaborative, and contents aspects (Barrows 1996; Illeris 2007). *Problem orientation* indicates that learning starts by analysing and defining problems, be they open and ill defined, or well defined. The choice of problems depends on the learning objectives – to learn methodologies will require open problems, and when the aim is to achieve specific methods, more narrow problems will be suitable. de Graaff and Kolmos (2003, 2007) call this the *cognitive learning* approach. Problems are the starting point for learning processes; they are placed in a context, and based on the learner's experience. If the course is also project-based, the task involves more complex and situated problem analyses and problem-solving strategies.

The interdisciplinary dimension and the theory–practice relation concern the *content in the curriculum*. Theory is used in analysis of problems and problem-solving methods. Interdisciplinary learning, and the fact that problems come mostly from practice, may create challenges for organisation of the curriculum. Another key aspect of the content approach is that problems, no matter how they are chosen, have to be *exemplary* to the overall learning outcomes and serve as the means for understanding at a deep level and to transfer methodologies to similar areas (Kolmos and de Graaff 2013).

Finally, the *social approach* is crucial. In team-based learning, the learning process is a social act where learning takes place through dialogue and communication. The students are not only learning from each other, but they also learn to share knowledge and organise the process of collaborative learning and collaborative knowledge construction. The social approach also covers the concept of participant-directed learning, which indicates a collective *ownership* of the learning process and, especially, the formulation of the problem. Ownership is key for students' motivation.

These principles should be regarded essential, so that any claim to run PBL should mean that the practice reflects all three learning principles. For instance, *individual* projects fall outside this definition – there must be a team aspect. The PBL curriculum is organised and designed differently, in, e.g. Maastricht and Aalborg. Maastricht students analyse cases and organise the learning process by seven steps procedures, whereas in Aalborg, they collaborate in teams and gradually learn project management skills. Also, the assessment systems are different. However, the three learning principles apply to both implementations.

4.2. *The CDIO Standards*

As the CDIO Initiative grew, a wider diversity of programmes and institutions were needed to be accommodated. At the same time, stakeholders sought clarification about the distinguishing features of CDIO programmes, and there was an apprehension that CDIO could lose meaning if 'anything goes'. What was chosen (in 2004) as the defining feature was the *educational reform process* (Crawley et al. 2007). After answering *what* students should learn (with the CDIO Syllabus), the next question must be: 'How can we do better at ensuring that students learn these skills?' The working definition of CDIO is 'how can we do better' captured in the 12 CDIO Standards (Table 1). The value or novelty lies not in any single standard on its own, but in defining a comprehensive and holistic approach, listing available drivers of change, and supporting the alignment of strategies. Seven standards are considered essential (with asterisks), describing a minimal approach for developing a CDIO programme.

The CDIO Standards were later equipped with rubrics for programme rating (CDIO 2010), thus indicating dimensions both for bringing about and systematically monitoring the development (Malmqvist et al. 2006; Kontio et al. 2012; Malmqvist 2012; Munkebo Hussman et al. 2012).

It is worth noting that the CDIO Syllabus is not a defining feature of CDIO. Each institution must formulate programme goals considering, e.g. stakeholder needs, national and institutional context, level and scope of programmes, and subject area. To accommodate diversity, the CDIO syllabus is offered as an instrument for specifying local programme goals by selecting topics and making appropriate additions in dialogue with stakeholders. As such, it has served as a reference for a multitude of engineering programmes and for diverse contexts and purposes (Bisagni et al. 2010; Edström et al. 2013).

4.3. *Comparing the definitions*

An obvious difference between CDIO and PBL is the degree to which their essentials can be defined at all. The PBL principles proposed here are evidence-based; they are known to be conducive to learning. However, a multitude of definitions exist for PBL, and there is arguably no forum where consensus could be established. On the other hand, the CDIO Standards express a more formal definition, codified and controlled by the CDIO Initiative, but with much room for variation in collaborating institutions' practice.

Another notable difference is the nature of what these working definitions set out to define. The PBL principles form a broad philosophy of teaching and learning focusing exclusively on the *learning process*, that is, *how* students should learn, and not on *what* they should learn. Therefore, the principles can be applied on course, programme, or institutional level, in different fields of education, and any level from school to university. Conversely, CDIO takes its starting point in the learning outcomes of higher engineering education, and how learning should be facilitated

Table 1. The CDIO Standards.

*Standard 1 – The context**	Adoption of the principle that product, process, and system lifecycle development and deployment – Conceiving, Designing, Implementing, and Operating – are the context for engineering education
*Standard 2 – Learning outcomes**	Specific, detailed learning outcomes for personal and interpersonal skills, and product, process, and system building skills, as well as disciplinary knowledge, consistent with programme goals and validated by programme stakeholders
*Standard 3 – Integrated curriculum**	A curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills
Standard 4 – Introduction to engineering	An introductory course that provides the framework for engineering practice in product, process, and system building, and introduces essential personal and interpersonal skills
*Standard 5 – Design–implement experiences**	A curriculum that includes two or more design–implement experiences, including one at a basic level and one at an advanced level
Standard 6 – Engineering workspaces	Engineering workspaces and laboratories that support and encourage hands-on learning of product, process, and system building, disciplinary knowledge, and social learning
*Standard 7 – Integrated learning experiences**	Integrated learning experiences that lead to the acquisition of disciplinary knowledge, as well as personal and interpersonal skills, and product, process, and system building skills
Standard 8 – Active learning	Teaching and learning based on active experiential learning methods
Standard 9 – Enhancement of faculty competence *****	Actions that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills
Standard 10 – Enhancement of faculty teaching competence	Actions that enhance faculty competence in providing integrated learning experiences, in using active experiential learning methods, and in assessing student learning
*Standard 11 – Learning assessment**	Assessment of student learning in personal and interpersonal skills, and product, process, and system building skills, as well as in disciplinary knowledge
Standard 12 – Programme evaluation	A system that evaluates programmes against these 12 standards, and provides feedback to students, faculty, and other stakeholders for the purposes of continuous improvement

is mainly a *consequence of what* students should learn. The CDIO Standards were developed to define the agenda for structured programme development in engineering. The methodology can also inspire educational development in other fields, e.g. in teaching professions (Fors et al. 2007).

Comparing the essentials has made it clear how CDIO and PBL overlap. CDIO Standard 5 prescribes a curriculum with at least two design – implement experiences of increasing levels of complexity. These learning activities are problem-based and project-organised, and students learn from authentic engineering practice. Thus, the introduction of a specific type of PBL elements in the curriculum is an essential feature of CDIO.

5. Curriculum design

5.1. *PBL – the Aalborg curriculum model*

There are many examples of curricula based on PBL in the world. One of the most complete and institution-wide implementations is the Aalborg model, see Figure 2. It is a hybrid model in the sense that students attend courses half their study time. Thus, the disciplines are mainly in taught courses.

The relationship between courses and projects can vary depending on the learning objectives. In some semesters, there is a tight coupling between courses and project: the disciplinary knowledge

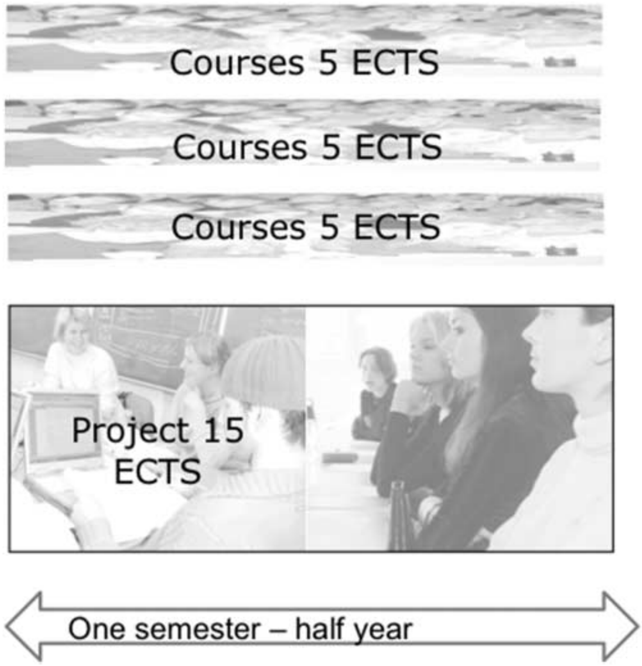

Figure 2. The Aalborg curriculum model in 2011.

is applied in the project. In other semesters, the project is more independent, and students use their learning from the courses only as needed for the project.

5.2. *CDIO – the integrated curriculum*

The CDIO Standards describe the process of designing an *integrated curriculum*, starting by establishing a vision of the graduates, informed by stakeholder needs, the context, and conditions (Standard 1). In the light of this vision, programme-level learning outcomes are formulated for both engineering skills and disciplinary knowledge, to be validated with stakeholders (Standard 2). After designing the curriculum structure, the programme learning outcomes are mapped with curriculum elements (Standard 3). This is a negotiation process where the intended learning outcomes serve as the 'currency' for defining the contribution of a course to the programme goals. Each course is thereby assigned an explicit function in the programme, and it is made clear which courses together carry the responsibility for each programme learning objective. Note the solution-independent approach: after the course learning outcomes are negotiated with the programme, the course design can be implemented in many different ways, because it is possible to address the same objectives through different teaching and assessment methods.

The principle is the same for reforming an existing programme – after any changes in the curriculum structure, the new course learning outcomes are negotiated. This methodology has been useful for reinforcing specific competences, see Figure 3. Examples include communication skills (Carlsson, Malmström, and Edström 2010), computational mathematics (Enelund, Larsson, and Malmqvist 2011), and sustainable development (Knutson Wedel et al. 2008; Enelund et al. 2012).

A tool to document the integrated curriculum in a structured way is the *integrated programme description* (Malmqvist, Östlund, and Edström 2006; Malmqvist and Arehag 2008), supporting faculty and other stakeholders to share their understanding of the programme design.

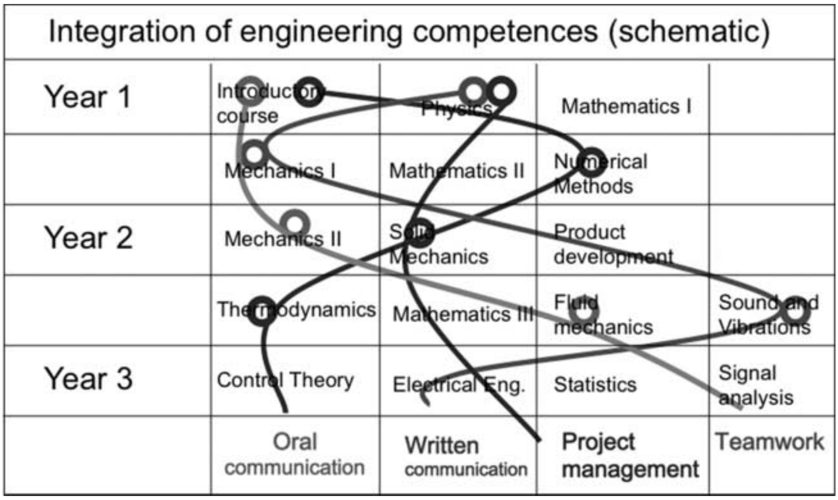

Figure 3. Systematic integration of specific competences.

The final stage is to develop the courses as *integrated learning experiences* (Standard 7), where students simultaneously develop disciplinary knowledge and professional engineering skills (Crawley et al. 2005, 2007). Since the intended learning outcomes address both disciplinary knowledge and professional skills, this should be reflected in the learning activities, and assessment system (Biggs and Tang 2011). The pedagogical principle is that integrated learning calls for integrated assessment (Standard 11) (Edström et al. 2005).

5.3. *Comparing curriculum design models*

CDIO is a concept for the curriculum level, a methodology for outcomes-based programme design making the coupling between programme and course level explicit. As CDIO is defined on the programme level, it is not applicable to say that a single course is a CDIO course, as we can say of a PBL course. CDIO is fully outcomes-based, and though active and experiential learning methods are emphasised, there is also a recognition that the same learning outcomes can be reached through different pedagogical methods. Taking its starting point in the learning process, PBL rather demonstrates that different learning outcomes can be reached using the same pedagogical philosophy based on projects and problems.

While CDIO essentially *is* a model for curriculum development, it is not so straightforward to say that PBL implies a curriculum model at all, given the wide diversity in PBL implementations, from course to institution level. Research evidence (Thomas 2000) suggests that PBL works best when it is implemented consistently across the curriculum, when everything from institutional support systems to buildings are aligned with the educational model. It is also possible to argue that it is better for the students to have a few instances of PBL in their education than none at all.

6. Relation to disciplines

6.1. *PBL and disciplines*

Kolmos, de Graaff, and Du (2009) defined elements of PBL curricula: objectives, types of problems and projects, progression, student learning, academic staff, space and organisation, and

Table 2. Dimensions of PBL curriculum elements (Kolmos, de Graaff, and Du 2009).

Curriculum element	Discipline and teacher-controlled approach	Innovative and learner-centred approach
Objectives and knowledge	• Traditional disciplinary objectives • Disciplinary knowledge	• PBL and methodological objectives • Interdisciplinary knowledge
Type of problems and projects	• Narrow • Well-defined problems • Disciplined projects • Study projects • Lectures determine the project	• Open • Ill-defined problems • Problem projects • Innovation projects • Lectures support the project
Progression, size, and duration	• No visible progression • Minor part of the curriculum	• Visible and clear progression • Major part of course/curriculum
Student learning	• Acquisition of knowledge	• Construction of knowledge
Academic staff and facilitation	• No training • Teacher-controlled supervision	• Training courses • Facilitator/process guide
Space and organisation	• Administration for traditional course and lecture-based curriculum • Traditional library structure • Lecture rooms	• Administration supports PBL curriculum • Library to support PBL • Physical space to facilitate teamwork
Assessment and evaluation	• Individual assessment • Summative course evaluation	• Group assessment • Formative evaluation

assessment. In principle, there are two extremes in interpreting and implementing these elements: a discipline and teacher-controlled approach, and an innovative and learner-centred approach. It is important to emphasise that there is no institution that practices a pure PBL curriculum, but rather a mix of traditionally taught courses and PBL. For instance, Aalborg University uses a hybrid model in the sense that the students attend courses half their study time. Table 2 illustrates the poles, and most PBL practices represent mixed or hybrid modes. The main point is to create awareness in the implementation of PBL – in a whole institution or a single course.

6.2. *Discipline-led learning in CDIO*

Recognising the need to educate for professional practice has not led the CDIO community to advocate a fully problem/project-based education. For sure, CDIO implies sharp criticism against poorly designed curricula, at worst consisting of disciplinary courses disconnected from each other, and as a whole, loosely coupled to espoused programme goals, professional practice, and student motivation. But *if and when they work well*, discipline-led courses provide conceptual understanding of systematically organised knowledge – a basis for solving real problems. Indeed, the *first* aim of CDIO is a *deeper working understanding* of disciplinary fundamentals. Strategies for improving student learning in discipline-based courses include active learning methods and assessment practices, conducive to conceptual understanding.

The fundamental idea of CDIO is the integrated curriculum, where discipline-led and problem/project-led learning are meaningfully combined. For existing programmes, it is often necessary to increase the share of PBL activities. But that is not sufficient; a curriculum is not integrated just because it contains both problem/project-led and discipline-led courses. The synergy comes from *integrated learning experiences*, where students simultaneously acquire disciplinary knowledge and professional engineering skills. Table 3 lists values from these complementary modes of learning, with potential synergies.

6.3. *Comparing the relations to disciplines*

Both PBL and CDIO represent curriculum models to support students in integrating and applying their disciplinary knowledge, and in developing the skills and working modes relevant for

Table 3. Contributions of discipline-led and problem/practice-led learning in the integrated curriculum.

Discipline-led learning	Problem/practice-led learning
• Well-structured knowledge base (content) • Knowing what is known and not • Understanding evidence/theory, model/reality • Methods to develop new knowledge, the scientific process • Interconnecting disciplines	• Integrating, applying, and synthesising knowledge • Open-ended problems, ambiguity, trade-offs, contexts, and conditions • Professional skills (work processes) • CDIO, or '*create the world that never has been*' (von Kármán) • Knowledge building of the practice
…connecting to problem/practice-led learning: • Deeper working understanding, i.e. conceptual understanding and functional knowledge • Knowledge with consideration for use • Embedded development of skills, e.g. communication and collaboration	*…connecting to discipline-led learning:* • Drawing on disciplinary knowledge, seeing through the lenses of problems • Reinforcing disciplinary understanding • Creating a motivational context for learning disciplinary fundamentals

professional practice. Therefore, both emphasise the problem-led component in education as alternatives to traditional purely discipline-stacking programmes. Note that in PBL, the problem-centred approach is the defining element, while it is the broader set of learning outcomes that leads CDIO to advocate better use of *both* discipline-led and practice-led learning activities.

7. Engineering projects

7.1. *PBL project types*

Based on the type of problems that students are working on and their relation to disciplinary learning outcomes, Kolmos (1996) defined three types of projects:

(1) *The assignment project* – relatively narrow learning outcomes and little freedom for the students to influence the learning process. Such projects are going on in laboratories at many universities and as they do not meet the learning principles they fall outside the definition of PBL.
(2) *The discipline project* – addressing disciplinary learning outcomes. Students are working on practical problems to apply theoretical knowledge. The discipline is the frame for raising problems and the project is limited to the discipline borders.
(3) *The problem project* – where the problem takes its departure in the contextual and societal dimension. The problem will determine the disciplines that are involved in analysis and solutions – both interdisciplinary and cross-disciplinary. The problem project normally starts with ill-structured problems with a certain level of complexity (Jonassen and Hung 2008).

These three types do not cover the full variety of projects and in the literature there are other taxonomies for problem types, for instance making the distinction between practical, empirical, and theoretical problems. Furthermore, there are typologies of projects, e.g. distinguishing analytical projects, where the aim is new knowledge on given problems, from design projects and construction projects aimed at new technological devices (Algreen-Ussing and Fruensgaard 1990).

7.2. *CDIO – the design–implement experience*

CDIO programmes contain various problem- and project-based learning activities, but the defining element is the *Design–Build Experience*, where students design and implement products, processes, or systems. Projects take different forms in various engineering fields, but the essential aim is to learn through near-authentic engineering tasks, in working modes that resemble professional practice. Standard 5 implies a *sequence* of design–implement experiences, with progression in several dimensions. Early in the education, smaller teams apply engineering knowledge of limited breadth and depth, while advanced project teams can involve over 10 students working over an academic year, drawing on a range of disciplinary knowledge and engineering skills. Projects concern increasingly complex and open-ended problems and later problems are ill defined and full of tensions, contextual factors, and stakeholder interests, resembling technical tasks new graduates might encounter in working life.

From a learning perspective, it is key that students bring their designs and solutions to an operationally testable state. To turn practical experiences into learning, students are continuously guided through reflection and feedback exercises supporting them to evaluate their work and identify potential improvement of results and processes. Furthermore, assessment and grading should reflect the quality of attained learning outcomes, rather than the product performance in itself (Edström et al. 2005).

7.3. *Comparing the engineering projects*

When comparing the project components, it is obvious that PBL comprises a broader scope of problems and projects, and that the PBL mode carries a greater part of the learning in the PBL curriculum. CDIO is born out of an engineering design environment and thus design projects and the near-professional engineering projects are important. But while CDIO proposes a curriculum with a sequence of project-based learning activities, it does not mean that the role of disciplinary courses is downplayed. In the projects, students reinforce their disciplinary understanding by applying the knowledge, and the practical experiences are intended to increase their motivation for learning theory. Furthermore, the problems will often prompt them to learn new theory just in time, as needed to create solutions – but in CDIO, the projects are not intended to replace discipline-led courses as the primary site to learn systematic disciplinary knowledge.

8. Change strategies

8.1. *PBL change strategies*

It is no coincidence that some of the most sustainable implementations of PBL were created when new universities were started around these principles. Organising learning around problems and stressing interdisciplinary learning often makes PBL perceived as challenging the traditions, and through its history it has provoked substantial resistance in institutions. As a consequence, the change management perspective is always present (de Graff and Kolmos 2007). An important legitimising strategy has been to provide research evidence for the positive effects of PBL, as the absence of evidence makes is difficult to defend investment in change.

8.2. *CDIO change strategies*

CDIO seeks legitimacy (Suchman 1995) as a cultural insider in engineering education institutions. The educational philosophy is dressed in engineering clothes – created by engineering faculty for engineering faculty, speaking the same language. Curriculum development resembles engineering design, with concrete pedagogical strategies adapted to engineering education. It is also part of the insider strategy to call for more appropriate contributions from discipline-led learning without fundamentally challenging the role of disciplines. Recognising that deep understanding of disciplinary fundamentals is crucial for engineering practice, the CDIO community proposes discipline-led courses for deeper and more relevant learning outcomes. This is also a pragmatic strategy – bringing about change by taking advantage of the strengths in the existing culture, not by being iconoclastic.

Another fundamental strategy for legitimacy is to involve stakeholders outside academia, e.g. professional organisations and employers, and students (Edström 2012; Edström et al. 2003). The wider dialogue can validate the goals with students, employers, and society. When other stakeholders are present, some arguments heard internally are easily exposed as self-serving or sub-optimising.

The CDIO community has had to challenge the assumption that CDIO programmes would require unreasonable resources. The main strategy in CDIO is to put existing resources (e.g. facilities, instructor and student time) to better use, not just adding new practices on top of the old. While a change project can often find extra temporary resources, the new ways of working that it establishes must be sustainable on normal funding. There is proof-of-concept for sustainable approaches, making even design–implement experiences cost-neutral in the steady state (Hallström, Kuttenkeuler, and Edström 2007; Edström, Hallström, and Kuttenkeuler 2011).

8.3. *Comparing the change strategies*

While evidence of effectiveness is seldom demanded from existing practices, the burden of proof seems to rest on those who want to introduce any change. Therefore, in both PBL and CDIO communities, strategies for making change legitimate, and thus possible, have been widely discussed. PBL, and to some extent CDIO, will partly challenge some academic traditions and identities. While problem-led learning aims to align with professional practice, discipline-led learning is better aligned with the organisation and structures of most institutions. Problem-led learning will therefore by its nature go against discipline-based organisational principles. We find the strategies for legitimacy somewhat different. CDIO conforms more to the culture of engineering and works (mostly) within the disciplinary structure of institutions and curriculum, while PBL makes appeals to academic culture first and foremost through research evidence of its positive impact.

9. Conclusions

The comparison has shown many similarities between PBL and CDIO. The two approaches for reforming engineering education share the main underlying values and goals – the emphasis on development of professional skills through learning processes that are similar to authentic practice. The difference is that PBL emerged from rethinking the process, while CDIO was developed from rethinking the outcomes. It is further shown that the implementation of CDIO and PBL is partly overlapping, as elements of PBL pedagogy are a defining feature of CDIO (design–implement experiences). Our first conclusion is therefore that PBL and CDIO practitioners should have much to learn from each other's experiences through a closer dialogue and exchange. Obvious areas of mutual interest include the pedagogy of problem-, project-, and design-based learning experiences and the lessons learned around organisational change strategies. Another area of mutual interest and collaboration is the emerging field of engineering education research, where the CDIO community can find much inspiration from the evidence produced around PBL.

The comparison also showed that PBL and CDIO are of quite different nature. While the PBL philosophy relates to the learning process in problem/project-based parts of the curriculum, CDIO contains a methodology to develop the whole curriculum including disciplinary courses. Our second conclusion is therefore that CDIO and PBL are not mutually exclusive, but complementary. For an institution that plans to create an innovative engineering curriculum, there is no need to make a choice between the two approaches as they can be productively combined. The CDIO approach supports a structured process of setting the high-level learning outcomes and systematically translating them into a curriculum, and any combination of CDIO and PBL pedagogy will support the development of appropriate learning experiences. The approaches should be seen as compatible and mutually reinforcing.

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