Effective Undergraduate Design-Build-Test Project Implementation: The Need for a Comprehensive Checklist of Self-Evaluation Criteria

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ABSTRACT

The basis of a checklist for Problem-Based Learning (PBL) type Design-Build-Test (DBT) experiences already exists in the form of the CDIO syllabus. Guidelines for effective implementation via a systematic approach to designing and operating such experiences have been defined within the CDIO community. However, a narrative review of conference papers in the CDIO knowledge base suggests low instances of disseminated DBT projects published that refer to a comprehensive range of CDIO syllabus outcomes, or make reference to an implementation methodology

Previous meta-analysis attempts to determine the efficacy of PBL in engineering education, outside of the CDIO community, have been hindered by variability in structure and implementation across different institutions. Consequently, the uncertainty of positive outcomes and the necessary paradigm shift in the approach to teaching required when switching to PBL have acted as inhibitors to the further development of best practice.

Based on the premise that checklists are a simple yet effective means of ensuring that best practice is followed, this paper sets out to promote the use of a self-evaluation checklist for effective PBL implementation, and for periodic review as part of a process of continual improvement. Widespread adoption of such a checklist would consequently bring greater standardization to the descriptions of DBT projects among CDIO collaborators (and others), so that further research into effective implementation might be enhanced. It is therefore proposed that the version 1.0 checklist presented here acts as a foundation that might further be utilized by communities of interested engineering education practitioners involved in DBT activities.

KEYWORDS

Checklist, PBL, DBT, CDIO Syllabus, CDIO Standard 5

INTRODUCTION

Problem Based Learning (PBL) advocates cite the development of a range of personal, interpersonal and professional skills in addition to the opportunity to apply disciplinary knowledge in an environment, which mimics professional practice, as being among the benefits of such an educational approach (Lamancusa *et al*, 2008; Edström & Kolmos, 2014). PBL students have been shown to find such problem based experiences challenging, motivating and enjoyable (Clavert & Laakso, 2013). Programs featuring significant amounts of

PBL also tend to benefit from higher retention rates (Kolmos, 2010). The skillsets developed in a PBL based curriculum are highly prized by industry, which also enhances students' employability prospects. In the context of engineering education, PBL is commonly realized through design implement experiences, which are a fundamental element of a CDIO curriculum and are defined by Standard 5 (Crawley *et al*, 2007).

Effective implementation of PBL however is not a simple matter and not always executed well. The formation and management of project groups can be difficult and students in dysfunctional groups have found the experience painful (Kjersdam, 1994). Faculty members often do not have experience of managing similar projects in an industrial setting (Lamancusa *et al*, 2008) and are also often unfamiliar and uncomfortable in the role of mentor or coach, which is considered preferable for PBL, compared to their normal role of lecturer (Elger *et al*, 2000; Malmqvist *et al*, 2004; Taylor *et al*, 2001). There are also infrastructural issues such as access to appropriate workspaces for the construction of prototypes. Indeed, some meta-analyses of PBL have found significant variation among implementations, negative effects where PBL was implemented poorly by non-expert tutors (Prince, 2004) and less knowledge acquired by students on PBL programs when tested by exams (Dochy *et al*, 2003); although significantly this knowledge was found to be retained better when retested at a later date. Such variations in implementation and hence uncertainty of positive outcomes, along with the necessary paradigm shift required in teaching approach and associated resources could all be factors inhibiting more widespread adoption of PBL.

Problem-Based Learning (PBL) has its origins in medical education of the early 1970's, initially introduced at McMaster University in response to bored students' dissatisfaction with being asked to remember vast amounts of information, which they perceived had little relevance to medical practice (Barrows, 1996). The methodology spread quickly as educators recognized benefits such as student motivation and stimulation which were subsequently confirmed by meta-analyses (Albanese and Mitchell, 1993; Vernon and Blake, 1993). Barrows (1996) noted that while implementations of PBL varied between institutions, the original six point core definition at McMaster worked well as a basic model for comparison:

1. Learning is student centered
2. Learning occurs in small groups
3. Teachers are facilitators or guides
4. Problems form the organizing focus and stimulus for learning
5. Problems are the vehicle for the development of [clinical] problem-solving skills
6. New information is acquired through self-directed learning

The authors contend that this definition from medical education applies equally well to PBL in an engineering context and that these six points should be considered as essential criteria on a checklist for determining if an activity is "authentic" PBL.

Inspired by the innovative approach being adopted in medical education, other disciplines started to adopt the PBL approach. An analysis of PBL in engineering conducted by an international panel, described by Kjersdam (1994), examined 20 years of the "Aalborg experiment" and found that half of graduates quoted the PBL work as the main source of relevant professional knowledge and concluded that the emphasis on synthesis and group culture produced a graduate more readily adaptable, and therefore employable, than the graduates of a more traditional education.

A later meta-analysis of medical education PBL, conducted by Dochy *et al*. (2003), found a robust positive influence of PBL on students' ability to apply knowledge, but a negative tendency in so much that PBL students acquire slightly less knowledge than those on a traditional course, yet significantly retained more of this acquired knowledge. In a study examining the effectiveness of active learning in engineering education by Prince (2004), it was observed that there were many different approaches at different institutions, which made comparison difficult. Previous attempts to quantify the impact of PBL in medical education had typically looked at the effect size in relation to the mean performance of a population before and after an intervention. Within engineering education however, the variation among implementations led Prince (2004) to comment that no consistent results are likely to emerge from meta-studies as "*the signal from the common elements of PBL would have to be greater than the noise produced by the differences in implementation of both PBL and the traditional curricula*".

Based on the premise that checklists are a simple yet effective means of ensuring that gross errors or oversights are avoided and that best practice is followed (Gawande, 2010), the objective of this paper is to develop a single-page checklist that practitioners of DBT projects could complete, either to assist when designing an experience, as part of self-evaluation of existing DBTs, or when writing a paper describing such projects as an addition to the knowledgebase for the CDIO community.

RESEARCH APPROACH

As stated, significant differences in implementation are typical of PBL at different locations. Such variety was also found to be prevalent among the published descriptions of Design-Build experiences in conference papers within the Knowledge Library on the CDIO Initiative's website (www.cdio.org). In order to visualize and identify trends of current PBL-DBT practice, a narrative review methodology was used to compare these conference papers from the CDIO Knowledge Library. At the outset, it was recognized that this approach has known limitations, not least of which being the subjective nature of the "expert" interpretation of what has been written by the various authors of these papers. In this instance, the authors of this paper each have over 10 years' experience of designing and delivering DBT projects in a CDIO based curriculum.

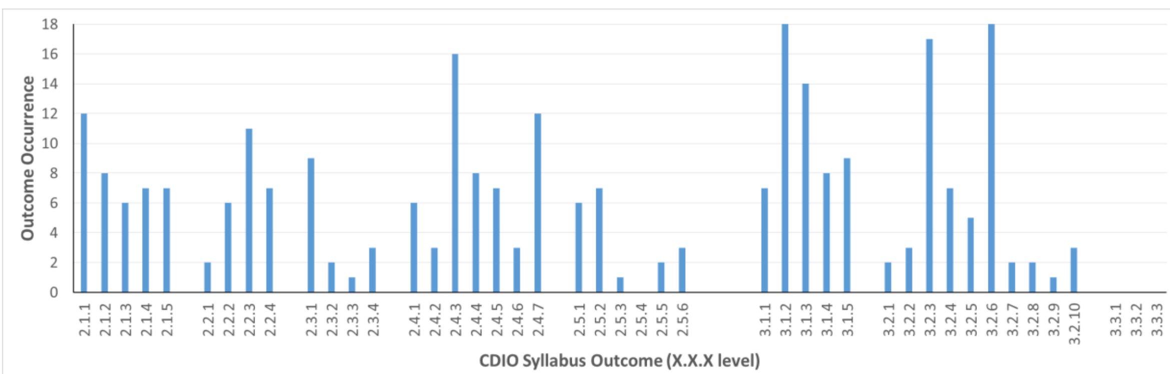
41 papers were found in the CDIO website archive using the search strings "Design Build Test" and "capstone". Of these, 26 were selected for inclusion in the review (Appendix 1), with papers describing introductory courses and those with no build-element being excluded. In total, papers with contributors from 19 different institutions are represented in the study.

The purpose of the review was to quantify which CDIO syllabus items at the X.X.X level were described as learning outcome objectives in the description of the DBT activities. No attempt was made to judge how successful the implementations had been, simply whether their CDIO syllabus outcomes were included as objectives of the projects in their descriptions. Further limitations to this approach are recognized in so much that it is likely many of the papers' descriptions do not fully cover all of the intended outcomes, as these may not have been the main focus of the papers. There will also be DBT activities taking place throughout the CDIO community, which have not been written up and presented as conference papers. Additionally, more experienced CDIO collaborators may well have progressed from "show and tell" type papers to something with more of an Engineering Education Research (EER) emphasis and might not have contributed papers on their practice in this area, which may well be excellent and could be a valuable resource for others.

FINDINGS FROM THE NARRATIVE REVIEW

The CDIO syllabus items most commonly described (n > 10) as learning objectives in the reviewed papers, as illustrated in figure 1, were:

- 2.1.1 Problem Identification and Formulation
- 2.2.3 Experimental Inquiry
- 2.4.3 Creative Thinking
- 2.4.7 Time and Resource Management
- 3.1.2 Team Operation
- 3.1.3 Team Growth and Evolution
- 3.2.3 Written Communication
- 3.2.6 Oral Presentation
- 4.4.1 The Design Process
- 4.4.3 Utilization of Knowledge in Design
- 4.4.4 Disciplinary Design



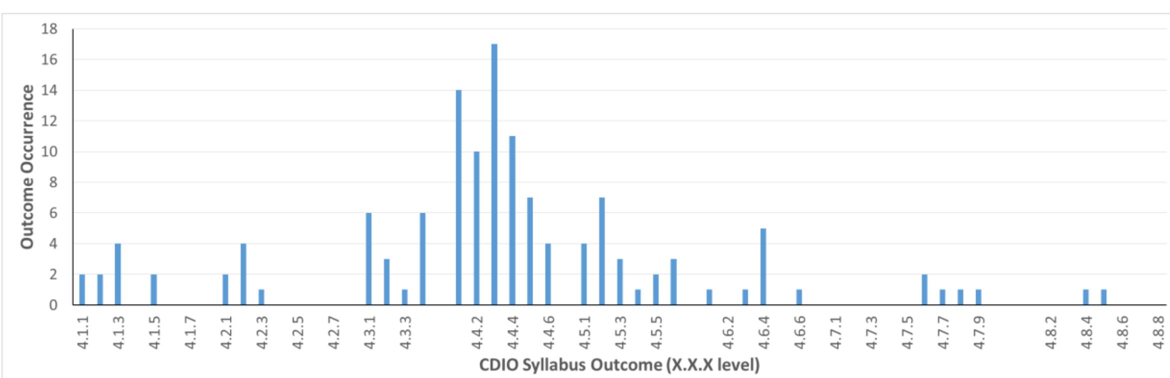


Figure 1. Frequency of CDIO Syllabus Learning Objectives in DBT Project Descriptions

The other most recurring themes identified by the narrative review of papers, which did not map conveniently to CDIO syllabus items, were designated as DBT operational considerations.

In descending order of frequency these were, facilitator skills,industry links, motivation, workspaces and competition. These are shown in figure 2.

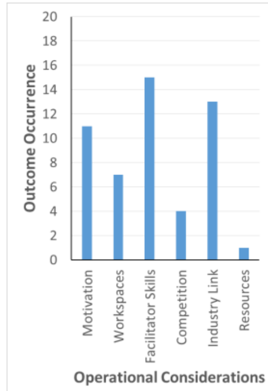


Figure 2. Frequency of CDIO Syllabus Learning Objectives in DBT Project Descriptions

CHECKLIST DEVELOPMENT

A table of essential and desirable attributes of Design-Implement experiences is presented in Chapter 5 of the CDIO book (Crawley *et al*, 2007, p107) and is derived from the Andersson *et al.* (2005) paper. Together with the PBL essentials from the original definition for medical PBL at McMaster (Barrows, 1996), and the findings of the narrative review of DBT practice undertaken in this study, the authors have developed a new, more comprehensive checklist (Appendix 2) with 3 major sections:

A. PBL Essentials
B. CDIO Syllabus Learning Objectives
C. Operational Considerations

Table 1 shows how the Andersson *et al.* (2005) essential and desirable attributes have been remapped on to the relevant sections of the new CDIO-PBL-DBT checklist.

Table 1 – Remapping of essential and desirable attributes to DBT checklist sections

Andersson *et al.* (2005) Essential Attributes	**Checklist Remapping**
provide product or systems design and implementation skills	Syllabus 4.4.1-4, 4.5.2-5
include elements of conception, design, implementation and operation	Syllabus 2.4.3&4, 4.3.1&2, 4.4.1,3&4, 4.5.2/3/4, 4.6.1
enable testing and evaluation during the operation phase	Syllabus 4.5.5, 4.6.4
focus on learning outcomes rather than the product to be designed	Operational consideration
provide many alternative number of paths to the solution	Operational consideration
be fully integrated with the curricular activities	PBL Essentials (CDIO Standard 3)
include adequate training in use of equipment	Operational consideration
provide all students with similar opportunities to develop their skills	Operational consideration
increase students' motivation for engineering	Operational consideration
reward students fairly for their contribution to the task	Operational consideration
Andersson *et al.* (2005) Desirable Attributes	
provide a platform for training of professional competencies	Operational consideration

reinforce disciplinary knowledge	Syllabus 4.4.3
be cross-disciplinary	Syllabus 4.4.5
develop teamwork and build community	Syllabus 3.1.2, 3.1.3
allow students to build and operate small, medium and large systems	Syllabus 4.3.1-4, 4.4.1-3, 4.5.5, 4.6.4
allow general prototype fabrication, test and redesign	Operational consideration, Syllabus 4.5.2, 4.5.5, 4.6.4
develop written, oral and graphical communication skills	Syllabus 3.2.3-6

The methodology defined by Andersson *et al* (2005) for designing DBT experiences in a CDIO context includes consideration of the level to which each of the CDIO syllabus learning outcomes are to be implemented. Items which are merely introduced (I) to the students need not be assessed, whereas items, which are either taught (T) or utilized (U) should be assessed. To preserve this practice a column in section B of the new checklist has been included into which one or more of the I,T,U letters should be entered.

It is intended that items in section A of the checklist (PBL Essentials) should be present in all CDIO-DBT experiences. Section C (Operational Considerations) should be treated as optional elements.

DISCUSSION

The CDIO Syllabus and Standards offer a framework which is somewhat unique among engineering education communities. They act as a shared set of objectives against which collaborators can self-assess and structure improvement of their degree pathways. In order to maximize the potential for the CDIO community to help and learn from each other, the version 1.0 checklist developed here is presented as a means both of self-assessment of DBT practice and also as a means of more conveniently comparing disparate DBT implementations. If all DBT related papers included a completed checklist as an appendix then it would be possible to catalog these so that they could be sorted and filtered.

Version 1.0 of the checklist presented herein includes a number of blank rows at the end of section B. This is in recognition that further CDIO syllabus learning outcomes might be part of other, as yet unpublished, implementations. As best practice develops it is proposed that the CDIO community could revise items in section B through collaboration at workshops or roundtable discussions at the annual conference, or as activities carried out by the regional groupings. Subsequent versions will be enhanced by future collaborative discussion.

Regular curricular self-assessment is a healthy activity and much like the rubrics for the CDIO Standards, the checklist should be considered for DBT review.

CONCLUSIONS

The CDIO Knowledge Library does not provide evidence of rigorous development of DBT experiences in line with CDIO methodology. The variety of DBT implementations and how they are reported was found to make comparisons of efficacy difficult. The lack of a consistent structure or direct reference to the CDIO syllabus meant that in order to process the information contained therein the authors had to resort to using a narrative analysis to make educated guesses of the practitioners' intent. This methodology has inherent reliability issues, but does therefore also reinforce the need for a reliable and structured tool such as the checklist being proposed in this paper.

A version 1.0 DBT checklist has been developed, which is cognisant of PBL literature and which collates best practice guidelines and current practice.

The authors contend that in future this checklist should be used by those submitting PBL papers to CDIO conferences and that subsequently such papers should only be included in the CDIO archive if a checklist has been completed. This would further facilitate advancement in the understanding of the CDIO community and in progressing best practice in this area of curriculum delivery.

Authors of previously published work should also be encouraged to retrospectively review their papers and complete the checklist. This would facilitate the archive material to be better sorted and filtered by those seeking to conduct further research and development, or enhance their own teaching practice.

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APPENDIX 1 – Papers Included in the Narrative Review

2002 - Miller D.W. & Brodeur D.R.	The CDIO Capstone Course: An Innovation in Undergraduate Systems Engineering Education
2002 - Brodeur D.R., Young P.W., Blair K.B.	Problem-Based Learning in Engineering Education
2004 - Malmqvist J., Young P.W., Hallstrom S., KuttenkeulernJ., Svensson T.	Lessons Learned from Design-Build-Test-Based Project Courses
2005 - Surgenor B., Mechefske C., Wyss, U., Pelow J.	Capstone Design - Experience with Industry Based Projects
2005 - Armstrong P.J., Kee R.J., Kenny R.G., Cunningham G.	A CDIO Approach to the Final Year Capstone Project
2007 - Evertsson M., Bankel J., Enelund M., Eriksson A., Lindstedt P., Raisanen C.	Design-Implement Experience from the 2nd Year Capstone Course "Integrated Design and Manufacturing"
2010 - Van der Loos H.F.M., Croft E.A., Hodgson A., Mikkelsen J., Winkelman P.	Strategies to Engage Capstone Design Course Sponsors in High-Priority, Client-Focused Projects
2010 - Ting K.E., Cheah S.M.	Assessment of CDIO Skills for Student Final Year (Capstone) Projects of Different Genres
2011 - Escudeiro N., Escudeiro P., Barata A., Lobo C., Duarte M., Costa A.	Developing Undergraduate Projects in Multinational Teams to Enhance Employability
2011 - Fai S.K.	An Observational Study of Infusing Design Thinking into the CDIO Framework
2011 - Rudd K.W., Waters J.K., O'Mara D., Flaherty C.J., Janssen M.	Systems Engineering in Senior-Design Capstone Projects
2011 - Seidel R., Shahbazpour M., Walker D., Shekar A., Chambers C.	An Innovative Approach to Develop Students' Industrial Problem Solving Skills
2012 - Hellborg G.	Experiences from Design-Build-Test (DBT) Projects in Lighting Design
2012 - Bragos R., Camps A., Oliveras A., Alarcon E., Pegueroles J., Sayrol E.	Design of the Advanced Engineering Project Course for the Third Year of Electrical Engineering at Telecom BCN
2012 - Loc N.H. & Trung P.Q.	Integrated Learning Experiences in the Machine Design Course to Assess the Achievement of Intended Learning Outcomes
2013 - Alarcon E., Bou E., Camps A., Bragos R., Oliveras A. Pegueroles J., Sayrol E., Marques F.	Designing CDIO Capstone Projects: A Systems Thinking Approach
2014 - Nguyen H.L., Pham C.B.	Integration of Design Problems and Projects into Courses for Manufacturing Engineering Program
2014 - Tio F., Kong J., Lim R., Teo E.	Developing and Applying Rubrics for Comprehensive Capstone Project Assessment
2014 - Kulmala R., Luimula M., Roslof J.	Capstone Innovation Project - Pedagogical Model and Methods
2014 - Truong V.T., Le B.N., Nguyen M.D., Nguyen T.M.	Assessing the Maturity of Teamwork Capabilities Through CDIO Projects
2014 - Gonzalez L	In Embry-Riddle the Capstone Project Brings Closure to Structures
2014 - Oliveras A., Vallverdu F., Rodriguez-Fonollosa J.A., Bermejo S., Garcia-Hernandez M., Bragos R.	Electrical Engineering DesignBuild Project: Class-D Amplifier Design and Characterization
2015 - Khan R., Ercan M.F., Kristian N., Ying S.Y., Jung T.C.	Engineering and Design: An Integrated Course with Real World Projects
2015 - Guo X., Taajamaa V., Yang K., Westerlund T., Zheng L.R., Tenhunen H., Salakoski T.	Capstone Bootcamp Concept Catalyzing Problem-Based Learning
2016 - Hermon J.P.	Enhancing the Manufacturing Knowledge of Undergraduate Engineering Students: A Case Study of a Design-Build-Test Challenge
2016 - Kontio E., Lakanmaa R.L.	Design-Build Experiences - ICU Game Capstone Project

APPENDIX 2 – CDIO-PBL-DBT Checklist v1.0

A. PBL Essentials	☑
Learning is student centered	
Learning occurs in small groups	
Teachers are facilitators or guides	
Problems form the organizing focus and stimulus for learning	
Problems are the vehicle for the development of problem-solving skills	
New information is acquired through self-directed learning	
CDIO Standard 3 - Fully integrated with the curriculum	

B. CDIO Syllabus Learning Objectives	I / T / U
2.1.1 Problem Identification and Formulation	
2.2.3 Experimental Inquiry	
2.4.3 Creative Thinking	
2.4.4 Critical Thinking	
2.4.7 Time and Resource Management	
3.1.2 Team Operation	
3.1.3 Team Growth and Evolution	
3.2.3 Written Communication	
3.2.4 Electronic/Multimedia Communication	
3.2.5 Graphical Communications	
3.2.6 Oral Presentation	
4.3.1 Understanding Needs and Setting Goals	
4.3.2 Defining Function, Concept and Architecture	
4.3.3 System Engineering, Modeling and Interfaces	
4.3.4 Development Project Management	
4.4.1 The Design Process	
4.4.2 The Design Process Phasing and Approaches	
4.4.3 Utilization of Knowledge in Design	
4.4.4 Disciplinary Design	
4.4.5 Multidisciplinary Design	
4.5.2 Hardware Manufacturing Process	
4.5.3 Software Implementing Process	
4.5.4 Hardware Software Integration	
4.5.5 Test, Verification, Validation and Certification	
4.6.1 Designing and Optimizing Sustainable and Safe Operations	
4.6.4 System Improvement and Evolution	

C. Operational Considerations	☑
CDIO Standard 10 – Enhancement of faculty teaching competence (facilitator / mentor)	
Assessment focus on learning outcomes rather than the product to be designed	
Assessment should reward students fairly for their contribution to the task	
Provide alternative paths to the solution (open ended problem)	
Provide adequate workspaces for building and testing	
Include adequate training in use of equipment	
Increase students' motivation for engineering (through industry links / competition)	
Provide students with learning and assessment opportunities suited to a range learning style preferences	
Provide students with a platform for development of professional skills	
Timeframe which enables prototype fabrication, test and redesign	

BIOGRAPHICAL INFORMATION

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Charles D McCartan, is a Senior Lecturer (Education) in the School of Mechanical and Aerospace Engineering at Queen's University Belfast (QUB) and is Programme Coordinator for their Foundation degrees in Mechanical Engineering and Aerospace Engineering. A graduate Mechanical Engineer (MEng, QUB, 1991; PhD, QUB, 1995), he has previously worked as a research fellow at QUB, as a senior engineer and team leader for Caterpillar, and as a technical manager at Optimum Power Technology. In addition, he has 21 years consultancy experience in the automotive sector. He is a member of the Society of Automotive Engineers (SAE) and a Fellow of the Higher Education Academy (HEA).

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