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A SYSTEMATIC APPROACH TO THE DESIGN AND IMPLEMENTATION OF DESIGN-BUILD-TEST PROJECT COURSES

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1. Introduction

Project courses in which students design, build and test a device on their own are increasingly being used in engineering education. The reasons include that such projects do not only train design skills, they also give an improved understanding of engineering science knowledge. From a learning point of view a design-build-test (DBT) experience might be invaluable. For engineering design practice, understanding of and abstraction from real situations are vital skills. The students need to learn the ability to confront the concrete details of real problems and to abstract a relevant understanding of them – to build ties between these problems and abstract concepts [1]. The project-based learning also results in further advantages such as having the project as a unique learning motivator as well as giving possibilities for planned reflection loops for experience-reflection-generalization [2]. Last but definitely not the least, the students practice non-technical competencies such as communication, teamwork etc., that are vital for their future role as engineers. However, it must be admitted that (DBT) experiences may also be costly, time-consuming, require new learning environments and different specialized faculty competence.

The proper set-up of a DBT educational experience generally requires consideration of a large number of factors - identifying goals, selecting projects, budgeting, and so on - that differ from those in traditional educational situations. We therefore see a need for a better understanding of DBT-based learning experiences, along with guidelines for their design. Scientific publications on the topic tend to describe a particular course or learning environment (confer, for example [3], [4]), though there are some investigations that summarize the experiences from a larger number of courses ([5], [6]). In literature, however, there is still a lack of systematic tools procedures and tools for the design of DBT learning experiences.

The presented work constitutes a part of the CDIO project [7], [8], an international initiative that aims to develop a new model for engineering education. The aim for this project is to develop a new model for engineering education, one which aims to bridge the gap between analysis and synthesis, between disciplinary focus and multidisciplinary considerations, and between engineering science knowledge and professional competencies such as communication and teamwork, issues which are crucial for engineering curriculum development. Here, we, and others, have noticed that there is an increasing stress between science-oriented goals such as analysis skills and practice-oriented skills such as synthesis. However, we suggest, the answer to effective curriculum development is not to make minor trade-offs between these two goals but rather to find a new model for engineering education that enables us to reach both.

Thus, the approach of the CDIO project is to develop a model which provides students with an education that stresses engineering fundamentals set in the context of Conceiving-Designing-Implementing-Operating (CDIO) real-world systems and products. This context is a generalized description of a complete product/system life cycle called in this project, *Conceive-Design-Implement-Operate*. The *Conceive* stage includes defining the need and technology, considering the enterprise strategy and regulations, developing the concept, architecture, and business case. The second stage, *Design*, focuses on creating the design, *i.e.*, the plans, drawings, and algorithms that describe what will be implemented. *Implement* refers to the transformation of the design into the product, including manufacturing, coding, test and validation. The final stage, *Operate*, uses the implemented product to deliver the intended value, including maintaining, evolving and retiring the system.

A CDIO-based education is characterized by that it aims to meet twelve standards, or principles [9]. The CDIO standards address program philosophy, curriculum development, design-build experiences and workspaces, methods of teaching and learning, faculty development, and assessment and evaluation. More specifically, these standards state requirements on the program to have a curriculum that is systematically designed to meet clearly stated learning objectives, a richness of design-build-test experiences, and feature integrated learning experiences where learning of professional competencies such as communication and teamwork are integrated into disciplinary courses and DBT experiences. Design-build-test projects thus are a key element of this educational model. The CDIO project has therefore been the framework for several smaller projects of which has resulted in a variety of knowledge on how to set up, run and assess project-based courses. This paper brings together these tools and discusses their application in relation to a particular course.

The aim of this work is to, in the first part of the paper, in general terms describe a procedure and set of tools and guidelines for designing and implementing DBT project courses, in order to provide guidance for teachers involved in such activities. The second part of the paper goes into more details on how these have been applied in a specific course. The DBT project used to demonstrate the procedure and tools is Formula Student [10], as implemented at Chalmers University of Technology. Formula Student is a small racing car DBT project competition for engineering students. The aim of this course is to give knowledge about and experiences of applied practical engineering work as well as prototype manufacturing. The course concerns a total car concept where the entire process from conceive and design to implement and operate is regarded. In the paper, this example is worked through the process of stating learning objectives, developing the teaching approach and selecting assessment procedures. For each step, tools developed in the CDIO project are applied.

2. Design-build-test project course development

In the CDIO model, design-build-test experiences are defined as learning events where the learning takes place through the creation of a product or system play a critical role. The product that is created in the learning event should be developed and implemented to a state where it is operationally testable by students in order to verify that it meets its requirements and to identify possible improvements. The product can be built of hardware, software, a combination or even a digital model. The media that the product will be built of needs to be carefully chosen but this does not mean that it has to be very close to final product status.

Table 1. Essential and desired features of a design-build-test experience

Essential	• provide product or systems design and implementation skills • include elements of conception, design, implementation and operation • enable testing and evaluation during the operation phase • focus on learning outcome rather than the product to be designed • provide many alternative number of paths to the solution • be fully integrated with the curricular activities • include adequate training in use of equipment • provide all students with similar opportunities to develop their skills • increase students' motivation for engineering • reward students fairly for their contribution to the task
Desirable	• provide a platform for training of professional competencies • reinforce disciplinary knowledge • be cross-disciplinary • develop teamwork and build community • allow students to build and operate small, medium and large systems • allow general prototype fabrication, test and redesign • develop written, oral and graphical communication skills

Depending on the level of the course it can be a simple functional model or a complex near production-status prototype as long as it meets the basic requirement of being operationally verifiable and thus providing direct feedback to the students. Essential and desired features of a DBT experience are summarized in Table 1.

It must be realized that developing a DBT course is different and more complex than traditional course development and teaching. This does not only need to relate to the learning environment or the project task, but to a combination thereof. The role of the teacher will be quite different and the amount of administration or work to find a suitable learning environment should not be underestimated. Nevertheless there are also a lot of similarities to traditional course development. All course development generally includes identifying and stating learning objectives, selecting teaching methods, selecting assessment methods, carrying out the course and evaluating and improving as shown in Figure 1.

Stating learning objectives for a DBT experience

The starting point for any educational design effort is the statement of the learning objectives, i.e. formulating what capabilities or competencies that the students should possess upon completing the course or program. When setting up learning objectives for a DBT course, an underlying assumption is that the learning objectives should be clear and assessable, similar to requirements made in engineering design as a discipline. Well written objectives will clearly state the learning outcomes, what the student will be able to accomplish as a result of the course. The learning objectives should be based on the essential and desired features listed in Table 1, and should emphasize elements of integrated learning, i.e. that students learn and practice non-technical personal, interpersonal, and product and system design and implementation competencies through the same processes in which technical knowledge is learned and assessed. In order to facilitate for teachers to state well-formulated learning objectives, a major effort has been made in the CDIO project to develop a generic goal statement for engineering education, called the CDIO syllabus [12]. In the project, the CDIO syllabus is used to drive development of new curricular content, devise teaching, learning and assessment methods as well as new learning environments.

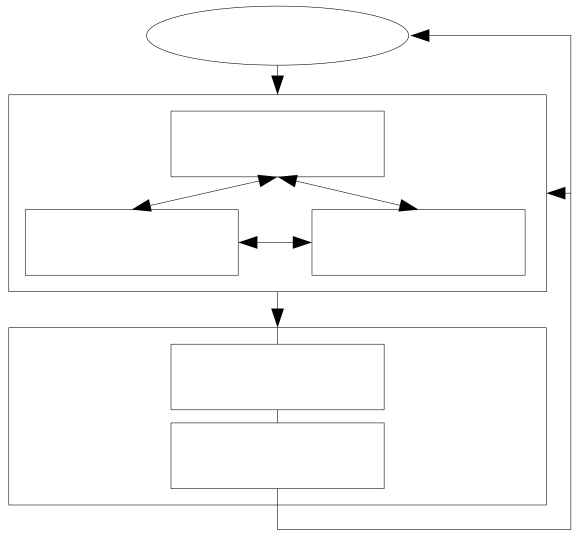

Figure 1. Generic course development and operation process.

The point of departure for the CDIO syllabus is a statement of what engineers do, and thus, the functions that a graduating student must be able to perform upon graduation*: "Graduating engineers should be able to conceive-design-implement-operate complex engineering systems in a modern team-based environment"*. From this overall need, a hierarchy of learning objectives has been derived. The requirements are classified in four basic categories:

1. Technical knowledge and reasoning
2. Personal and professional skills and attributes
3. Interpersonal skills and attributes and
4. Ability to conceive, design, implement and operate systems

The first category is program-specific. However, the last three are applicable to any engineering program. The main categories are decomposed until individual learning topics (cognitive objects or processes) are reached, such as or *"Statistical validity of data"* (under 2.2.4) or *"Customer needs"* (under 4.3.1). The full syllabus has four to five levels per category. Table 3 shows the first three levels. Assessable learning objectives can then be written by connecting a topic from the CDIO syllabus to a cognitive verb that indicates the desired proficiency level. Examples of such assessable learning objectives include *"Discuss the statistical validity of data"* and *"Elicit and interpret customer needs"*. This is done by first selecting a topic from the CDIO syllabus, then classifying the desired proficiency level according to a five-level scale and then, finally, connecting that level to levels and verbs chosen from Bloom's taxonomy [13] to formulate the learning objective. See Table 2.

Table 2. CDIO proficiency levels vs Bloom cognitive verbs.

CDIO proficiency level		**Bloom levels**	**Corresponding cognitive verbs (examples)**
1	To have experienced or been exposed to	-	
2	To be able to participate in and contribute to	Knowledge	Recognize, List, Describe, Match
3	To be able to understand and explain	Comprehension	Locate, Classify, Explain, Translate, Interpolate, Extrapolate
4	To be skilled in the practice or implementation of	Application, Analysis	Prepare, Use, Practice, Resolve, Analyze and Test, Categorize, Discrimate
5	To be able to lead or innovate	Synthesis, Evaluation	Plan, Create, Construct, Rearrange, Assess, Evaluate, Defend

Table 3. Condensed CDIO Syllabus, showing three levels of content detail [12].

1 TECHNICAL KNOWLEDGE AND REASONING
- 1.1 KNOWLEDGE OF UNDERLYING SCIENCES
- 1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE
- 1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES
- 2.1 ENGINEERING REASONING AND PROBLEM SOLVING
  - 2.1.1 Problem Identification and Formulation
  - 2.1.2 Modeling
  - 2.1.3 Estimation and Qualitative Analysis
  - 2.1.4 Analysis With Uncertainty
  - 2.1.5 Solution and Recommendation
- 2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY
  - 2.2.1 Hypothesis Formulation
  - 2.2.2 Survey of Print and Electronic Literature
  - 2.2.3 Experimental Inquiry
  - 2.2.4 Hypothesis Test, and Defense
- 2.3 SYSTEM THINKING
  - 2.3.1 Thinking Holistically
  - 2.3.2 Emergence and Interactions in Systems
  - 2.3.3 Prioritization and Focus
  - 2.3.4 Trade-offs, Judgment and Balance in Resolution
- 2.4 PERSONAL SKILLS AND ATTRIBUTES
  - 2.4.1 Initiative and Willingness to Take Risks
  - 2.4.2 Perseverance and Flexibility
  - 2.4.3 Creative Thinking
  - 2.4.4 Critical Thinking
  - 2.4.5 Awareness of One's Personal Knowledge, Skills, and Attitudes
  - 2.4.6 Curiosity and Lifelong Learning
  - 2.4.7 Time and Resource Management
- 2.5 PROFESSIONAL SKILLS AND ATTITUDES
  - 2.5.1 Professional Ethics, Integrity, Responsibility, and Accountability
  - 2.5.2 Professional Behavior
  - 2.5.3 Proactively Planning for One's Career
  - 2.5.4 Staying Current on World of Engineering

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION
- 3.1 TEAMWORK
  - 3.1.1 Forming Effective Teams
  - 3.1.2 Team Operation
  - 3.1.3 Team Growth and Evolution
  - 3.1.4 Leadership
  - 3.1.5 Technical Teaming
- 3.2 COMMUNICATIONS
  - 3.2.1 Communications Strategy
  - 3.2.2 Communications Structure
  - 3.2.3 Written Communication
  - 3.2.4 Electronic/Multimedia Communication
  - 3.2.5 Graphical Communication
  - 3.2.6 Oral Presentation and Inter-Personal Communications
- 3.3 COMMUNICATION IN FOREIGN LANGUAGES
  - 3.3.1 Communication in English
  - 3.3.2 Communication in Intra-EU Languages
  - 3.3.3 Communication in Extra-EU Languages

4 CONCEIVING, DESIGNING, IMPLEMENTING, AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT
- 4.1 EXTERNAL AND SOCIETAL CONTEXT
  - 4.1.1 Roles and Responsibility of Engineers
  - 4.1.2 The Impact of Engineering on Society
  - 4.1.3 Society's Regulation of Engineering
  - 4.1.4 The Historical and Cultural Context
  - 4.1.5 Contemporary Issues and Values
  - 4.1.6 Developing a Global Perspective
- 4.2 ENTERPRISE AND BUSINESS CONTEXT
  - 4.2.1 Appreciating Different Enterprise Cultures
  - 4.2.2 Enterprise Strategy, Goals, and Planning
  - 4.2.3 Technical Entrepreneurship
  - 4.2.4 Working Successfully in Organizations
- 4.3 CONCEIVING AND ENGINEERING SYSTEMS
  - 4.3.1 Setting System Goals and Requirements
  - 4.3.2 Defining Function, Concept and Architecture
  - 4.3.3 Modeling of System and Insuring Goals Can Be Met
  - 4.3.4 Development Project Management
- 4.4 DESIGNING
  - 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
  - 4.4.6 Multi-Objective Design (DFX)
- 4.5 IMPLEMENTING
  - 4.5.1 Designing the Implementation Process
  - 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
  - 4.5.6 Implementation Management
- 4.6 OPERATING
  - 4.6.1 Designing and Optimizing Operations
  - 4.6.2 Training and Operations
  - 4.6.3 Supporting the System Lifecycle
  - 4.6.4 System Improvement and Evolution
  - 4.6.5 Disposal and Life-End Issues
  - 4.6.6 Operations Management

Selection of teaching & learning methods for a DBT experience

"Deep learning is more likely when the student experiences a need to know something in order to carry out tasks which matter to them. Students need to be active rather than passive. Deep learning is associated with doing. If the learner is actively involved, then more connections will be made both with past learning and between new concepts. Doing is not sufficient for learning, however. Learning activities must be planned, reflected upon and processed, and related to abstract conceptions." [14]. Yes, a DBT course should result in deep learning, but a number of issues are needed to be dealt with in order to devise a teaching approach that makes this happen.

One is that the choice of project based DBT learning inherently brings along the selection or hunt for a suitable project task, an issue which is much more complicated for DBT tasks than in a traditional engineering science subject where exercises are limited in scope. The choice of a DBT task should correspond to the learning objectives, preferably be sponsored, and the task statement must leave room for alternative solutions. Faculty needs to realize that the role of the task might be seen by the students as the "real" learning objective, and failure in the task might be the same as failure in learning for them. Thus, a specific issue that needs to be considered is finding the adequate level of difficulty. A too difficult task may result in students as mere "implementers". A too simple task may on the other hand not promote motivation nor build the self-confidence that result from having met a challenge, which are two of the most significant benefits of DBT projects. The students' high involvement in the DBT task can also create problems with keeping time-balance to other courses.

It is not only the role of the project task that needs to be reflected upon: it is also necessary to realize that the teacher role will be different from being a mere transmitter of knowledge. It is known that in order to make student design projects a successful learning experience, it is essential that faculty shift their role from a traditional lecture or consulting role to a coaching role. For success the coaching role need to encompass three main responsibilities. You need to be mentor (providing support, being there), mediator (buffer to customer) as well as manager (guide in both team process and design process) [15]. A traditional series of lectures would probably not be the choice but a few selected lectures might be needed "to get started" in the beginning of the course or in order to start a specific phase of the project. To summarize, the course design would then typically be based on a limited number of (guest?-) lectures, and a high fraction of coaching. Further, some time needs to be spent on selection of learning environment. For a DBT experience it is important and the resultant locations show a large variation in purpose, facilities, equipment and investment [16].

For guidance in the choices above, the CDIO Initiative has developed a set of guidelines and resources. A basic first step is to analyze the preconditions for the courses based on a set of identified learning barriers and strategies to overcome those in project-based courses [17]. In this work, project-based courses were examined in order to identify general problems and associated strategies occurring in these kinds of courses. Barriers, recommendations and resources are, to facilitate for course design, in the report structured into six categories; course planning, course objectives, providing students with schedules and time management assistance, course management, team orchestration and assessment of student knowledge. For each barrier, a number of recommendations that provide possible solutions to addressing the barrier are listed. Some of the recommendations are accompanied by supporting tools such as checklists. Further, guidelines for DBT experiences [5] as well as workspace design and operations [16] can be considered for more details and inspiration in the choice of learning environment and project task as well as other choices. To carry on after this initial analysis, the CDIO Initiative has also developed a set of teaching and learning tools that are available on the website [8]. One example is the LIPS project model [11], a set of templates for project documentation such as requirements specification, Gantt charts, test specifications that enable students to use an industry-like working practices in their projects. Under development are also a set of on-line IRMs (Instructor Resource Modules). Each IRM offers resources, teaching suggestions, and assessment tools in self-contained packages for a specific CDIO skill area or topic. These teaching activities and resources are not intended to be courses unto themselves; they are to be integrated into existing engineering courses. Examples of IRMs include Communication (3.2), Ethics (2.5.1) and Setting System Goals and Requirements (4.3.1).

Selection of assessment method for a DBT experience

Assessment of student learning begins with the specification of course learning objectives, *i.e*., the knowledge, skills, and attitudes that students will develop as a result of DBT experiences. Just as different categories of learning objectives require different teaching methods and learning experiences, they also require different assessment methods in order to ensure reliability and validity of the assessments. Methods that assess student learning in DBT experiences include: rating scales, or rubrics, for judging student performance; reflective journals and portfolios of student work; assessments by instructors, peers, and employers; and, self-assessment by students.

Assessment of DBT experiences needs to address both the design/development process and the final product. A functionally excellent technical solution does not necessarily imply clear and detailed documentation of its development process. Likewise, systematic work does not necessarily result in a functional prototype or innovative product. The intended outcomes of the DBT experience need to be clear and explicit to instructors and students from the start. Oral questioning and interviews are useful methods to determine if students have developed a conceptual understanding of the DBT process and product, as well as the level and quality of their contributions to group projects.

When constructing a rubric to rate DBT processes and products:

1. Identify the key criteria, traits, or dimensions to be evaluated. The course learning objectives and the CDIO Syllabus are good sources. For example, if innovation or creative thinking is an important outcome, it should be listed as a key criterion.
2. Think about what an exemplary product or prototype would look like. What are its key characteristics? For example, what are the customer requirements? Sometimes, the key characteristics become clear when you think about what an *unacceptable* product or performance would look like.
3. Decide the number of scale points needed to discriminate among the full range of different degrees of quality. Usually three to five scale points are sufficient.
4. Decide if the identified criteria are of equal importance or will be weighted differently. For example, if meeting customer requirements is more important than finding an original solution to the problem, then the former criterion can be weighted more heavily than the latter in the overall assessment.

Trevisan et al. [18] describe the design and use of sound scoring criteria for assessing student performance. They include examples of useful rubrics. Table 4 is a template that can be used to assess a variety of student products or performances, whether they are used by instructors, peers, employers, or students themselves. Assessment in DBT courses should address the entire range of intended learning outcomes, using a variety of tools and methods.

Table 4. Template for a Rubric to Assess the Quality of a Product or Process

Weight	Criteria	Missing	Does not meet expectations	Meets expectations	Exceeds expectations

Comments:

Table 5. Definitions of Introduce, Teach and Utilize

	Learning objective	Teaching/learning activity	Assessment
Introduce	Probably not an explicit objective	Topic is included in an activity	Not explicitly assessed
Teach	Must be an explicit learning objective	Included in compulsory activity. Students get to practice and receive feedback	Students' performance is assessed. May influence grade.
Utilize	Can be related to a learning objective	Used to reach other objectives	Used to assess other objectives

As an example of the use of multiple methods of assessment, Gibson [19] assesses students' contributions to client meetings, oral presentations and reports, giving respective weights of 20%, 20%, and 60%. He also suggests detailed marking schemes for each of these areas and points out the problem of marking projects with a wide variation in the availability of reference material and expertise. Examples of assessment plans and marking schemes can be found also at the CDIO web site [8] in papers by Brodeur et al. [20], [21].

Alignment of learning objectives, teaching and learning approaches and assessment methods

Finally, a fundamental principle of course design is to ensure the alignment between the learning objectives, the teaching and learning approaches and the assessment: "What you assess is what you teach", as the truism goes. In the CDIO project, a matrix tool has been developed to keep track of the relations between these aspects. The rows of the matrix list each learning objective in topical form, chosen from the CDIO syllabus. For each relevant learning objective, the adequate level of teaching and learning is listed using a three-level scale, I (Introduce), T (Teach), U (Utilize). Teaching activities are categorized as I-Introduce, T-Teach or U-Utilise, based on intent, time spent, and linkage to learning objectives, assignments and assessment criteria. The formal definitions for Introduce, Teach and Utilise are shown in Table 5. The decision to make the distinction among Introduce, Teach and Utilise was made after it was observed that the word "teach" was used to describe a great number of varying activities occurring within courses. Finally, for each taught learning objective, the assessment method is listed. The resulting matrix is shown in template form in Table 6 and is exemplified in Table 8. The resulting course design matrix ensures that all learning objectives are systematically assessed. A similar tool has been developed for the curriculum level; linking program-level goals to the courses were they are taught.

Thus, to sum up this section, the CDIO Initiative has developed a set of new approaches to curriculum development, teaching and learning methods, learning assessment and student workspaces related to DBT experiences that facilitate adopting a systematic approach towards designing and operating DBT experiences. The resources are available on the CDIO Initiative Homepage [8]. Selected examples are listed in Table 7.

Table 6. Course design matrix template

Learning objective/opic		Teaching level	Assessment
1	**Technical knowledge and reasoning**		
1.1	Knowledge of underlying sciences	Introduce	
1.2	Core engineering fundamental knowledge	Teach	Assessment methd
1.3	Advanced engineering fundamental knowledge	Utilze	
1.4	Other subjects		
2	**Pesonal and professional knowledge, skills and attributes**		
2.1	Engineering reasoning and problem solving	I/T/U	
…	…	I/T/U	
2.5	Professional skills and attributes		
3	**Interpersonal knowledge and skills: Teamwork and commuincation**		
3.1	Teamwork		
3.2	Communication		
3.3	Communication in foreign language		
4	**Conceiving, design, implementing and operating systems**		
4.1	External and societal context		
4.2	Enterprise and business context		
4.3	Conceiving and engineering systems		
…	…		
4.6	Operating		

Table 7. Overview of selected CDIO resources.

Resource	Purpose	Description	Reference
CDIO syllabus	Facilitate the creation of clear, complete and communicable goal statements for engineering programs	A generic, customizable, goal statement (syllabus) template	[12]
Course design matrices	Facilitate systematic design of course to meet their learning objectives	Matrices that map learning objectives to the teaching and assessment approaches	[8]
Project-based learning barrier strategies	Help identify potential learning barriers in a particular course and strategies to address them	Structured list of barriers and associated strategies	[17]
Design-build-test guidelines	Support teachers in planning and running DBT experieces	Guidelines for DBT experience pre-course planning, task design and course execution	[5]
Student workspace guidelines	Provide assistance for development of student workspaces that enable DBT projects	Guidelines for workspace design, equipment and operations	[16]
Implementation Kits	Provide information, tools, models and templates to help programs adapt and implement CDIO	Guideines Papers & reports Tools Templates	[8]
Instructor resource modules	Develop sharable, modifiable teaching resources for faculty charged with teaching CDIO skills	On-line, multimedia, instructor guides containing teaching suggestions and assessment tools in self-oriented packages for specific CDIO skills areas	[8]

3. Case study: Formula Student project at Chalmers

The origin of the Formula Student competition [10] is the Formula SAE competition which has been held in the USA since the 1980's. It has from there spread to Europe, where it is called Formula Student, and to Australia, where it is called Formula SAE-Australasia. The purpose of the competition is for students to conceive, design, fabricate, and compete with small formula-style racing cars. The restrictions on the design of the car are few so that the knowledge and imagination of the students are challenged. Vehicles from colleges and universities throughout the world take part in the competition. The end result is a great opportunity for engineering students to take part in a realistic engineering project.

Chalmers first participated in the Formula Student competition in 2002. The first year was mostly a learning year, but it was believed that learning by doing was the best way to go. In 2003 this proved to be right since that years' team managed to design and build a very competitive car, which won several awards both in England and in Australia. During the first two years, the project was an extra-curricular student project, not a credited course, but at Chalmers it was then decided that the project was such a valuable learning opportunity that it should be developed into a formally credited design-build-test project course using the CDIO toolbox to support the development.

Learning objectives

As stated in the introduction of the paper, the aim of this course is to give knowledge about and experiences of applied practical engineering work as well as prototype manufacturing. The course concerns a total car concept where the entire process from conceive and design to implement and operate is regarded. As it is a large project, considering time (it takes almost one calendar year) as well as technology (many subsystems), system thinking, communication and teamwork are important topics.

More specific learning objectives were identified using the CDIO syllabus, Table 3, and then connected to suitable cognitive verbs (Table 2). As each learning objective amounts to a full sentence, a complete listing of the learning objectives including proficiency levels is beyond the spatial constraints of the paper. Some examples are listed below. They include that after the course the students shall be able to

- Use previously acquired knowledge, and search for whatever additional knowledge that is needed to design a part of the project (car). [Topic 1.4 – Advanced engineering fundamental knowledge and topic 4.4 - Designing]
- Use a project model, participate in defining the work (e.g. setting goals) and then be an actor in the project group, technically as well as socially. [Topic 3.1 - Teamwork]
- Plan the manufacturing of the designed part using appropriate methods. Topic 4.5.2 - Hardware manufacturing process]
- Test a part (both separately and together with other parts) for further development. [Topic 4.6.4 - System improvement and evolution]

When the learning objectives had been identified, they were graded according to the I (Introduce), T (Teach) and U (Utilize) scale depending on what previous knowledge the students have and how the course fits into the curriculum. Assessment methods for the taught (T) objectives were then selected, as shown in Table 8. The table further demonstrates that the learning objectives span across all major parts of the CDIO syllabus, highlighting the integrated teaching & learning nature of the course.

Table 8. Course design matrix for Formula Student course.

Learning objective/opic		Teaching level	Assessment
1	**Technical knowledge and reasoning**		
1.1	Knowledge of underlying sciences	U	
1.2	Core engineering fundamental knowledge	U	
1.3	Advanced engineering fundamental knowledge	T	Written/oral
1.4	Other subjects	U	
2	**Pesonal and professional knowledge, skills and attributes**		
2.1	Engineering reasoning and problem solving	T/U	Participation
2.2	Experimentation and knowledge discovery	I/T/U	Participation
2.3	System thinking	T/U	Participation
2.4	Personal skills and attributes	U	Participation
2.5	Professional skills and attributes	U	Participation
3	**Interpersonal knowledge and skills: Teamwork and commuincation**		
3.1	Teamwork	U	Reflective journal
3.2	Communication	T	Written/oral
3.3	Communication in foreign language	U	Written/oral
4	**Conceiving, design, implementing and operating systems**		
4.1	External and societal context	-	
4.2	Enterprise and business context	I	Participation
4.3	Conceiving and engineering systems		
4.3.1	Setting system goals and requirements	U	Written/oral
4.3.2	Defining function, concept and architecture	U	Written/oral
4.3.3	Modelling of system and insuring goals can be met	U	Written/oral
4.3.4	Development project management	U	Reflective journal
4.4	Designing		
4.4.1	The design process	T/U	Written/oral
4.4.2	The design process phasing and approaches	U	Reflective journal
4.4.3	Utilization of knowledge and design	U	Written/oral
4.4.4	Disciplinary design	T/U	Written/oral
4.4.5	Multidisciplinary design	T	Written/oral
4.4.6	Multi-objective design (DFX)	T	Written/oral
4.5	Implementing		
4.5.1	Designing the implementation process	U	Participation
4.5.2	Hardware manufacturing process	I/T/U	Written/oral
4.5.3	Software implementing process	U	Participation
4.5.4	Hardware software integration	U	Participation
4.5.5	Test, verification, validation and certification	U	Written/oral
4.5.6	Implementation management	U	Written/oral
4.6	Operating	I/T/U	Reflective journal Written/oral

Teaching approach

Calendar-wise, the course duration is a full school year, starting in September one year and ending at the Formula Student competition in July next year. Student workload-wise, it amounts to one quarter of the workload for the academic year. It is divided into four specific phases of about the same length. The first phase focuses implementing a project model where the different workgroups responsible for the subsystems of the car are established. Also, the milestones and tollgates are set. In setting this up, the team is expected to utilize the teamwork and project planning knowledge acquired during the first three years at Chalmers. A teaching assistant is the overall project leader but different students rotate in the role of deputy project leader. The teaching assistant (project leader) is typically a PhD student who has participated in a Formula Student competition during a previous year. With this organization the project outcome becomes less sensitive to project management performance which could happen if a student is appointed project leader, and then fails to meet the requirements for that position.

The students write four major technical reports, corresponding to different stages of the product development and manufacturing process. At the end of phase one the time schedule for the reminder of the project is fixed. In this phase, the technical report describes the conceptual layout of the car, and in some more details outlines the particular subsystem of the report writer. The following phases are about engineering design of the different subsystems (phase two), manufacturing of the parts and assembling these into a car (phase three), and testing and improvement (phase four). Thus, the technical reports are strongly aligned to the CDIO sequence. In addition, the students write two reports on the team's performance, one at the end of phase one with a reflection on how the forming of the groups was carried out and how each student would have done differently if performed a second time. Then, at the end of the project (approximately 30 weeks later) another reflection report is carried out.

The teachers' supervision in the course is mainly oriented towards the teamwork level, making sure that they follow their time schedule and to solve possible disputes: In advanced-level DBT projects like Formula Student, it is important that the students have time to make their own mistakes and to correct them. As they identify the problems of building a car they propose technical solutions, and some of these need rethinking. If we, as teachers, then would interfere and tell them that this is not a good solution we would be back to a standard course where the students do what they are told instead of thinking on their own. Having a project running for a whole year makes this possible.

The project-based learning barrier strategies [17] were then applied to identify and deal with potential difficulties in the course. A few of these are discussed below:

Project re-newal. The basic idea is that students should build a new car every year, starting from scratch. However, in reality, Formula Student is essentially a re-design project: an important feature of the project is to use the specification given in the rules to design a car and, since the rules are more or less the same year after year, the same car could be built every year with only a slight redesign or tuning of the previous year's car. This car would probably perform well but the learning experience for the new students would suffer. So, should students be allowed/encouraged/discouraged from re-using knowledge and solutions from previous years? The approach selected here was to ask previous year students to not give too detailed information to the next team but still to be available to discuss technical matters. Also, there is a possibility to prescribe that the new car should feature new certain features.

Varying pre-knowledge. The pre-knowledge amongst the students varies significantly more that in the typical design-build-test project. Some students taking this course have already worked with or even built a vehicle, whereas others take this as a first opportunity to learn how to work in a large project with a realistic product, but have no previous experience at all. The varying pre-knowledge and diversity in interests in the student group is handled by demanding that each student before start-up of the project writes a short summary describing them. With this information we (the teachers) try to find tasks/roles that make the project a suitable challenge to each one. Another aspect of varying pre-knowledge stems from that the students in the course come from different master-level specializations. Some specialize in the automotive area while others specialize in applied mechanics or materials science. Thus, there are no lectures decided beforehand, but the students can (and are encouraged to) suggest lectures or study visits themselves. Regarding project management skills, the students have, during their first three years of education at Chalmers, been lectured on these subjects and also practised them in smaller projects. So they are expected to know enough project management theory for this course, they "only" have to practice, and there are no dedicated lectures on project management. This, however, may be slightly problematic for students who have joined Chalmers at the master-level, and whose undergraduate programs have contained less of project management and also of communication's skills.

Combining a credited course with an extra-curricular activity. During the first two years, the Formula Student project at Chalmers was not a credited course, but instead it was an extracurricular car-building project performed by students for their pleasure but with support from the Mechanical engineering (M) program. The long-term intention was to incorporate the project into the curriculum but it was not sure to what extent. The idea was that if you wanted to do it just for fun that was OK but if you wanted to make it a formally credited part of your education that should also be possible. Now the project has become an elective DBT course in the curriculum of the M program. If someone wants to join the project without joining the course there is such a possibility but these persons then get minor roles. The major reason to arrange it this way is that it is difficult to have students who have formal requirements (like milestones reports) working together with students who do it on their spare time. Thus, the project is run by 10-20 registered students and a few extra-curriculars. Only students registered for the course will be assigned to the leading roles in the teams.

Resources. Design-build-test experiences require different learning environments, faculty competence and, sometimes, additional financial support. In order to provide a proper learning environment for this kind of projects, Chalmers has recently built a "prototype lab", a workshop where the students can manufacture most of their own parts. Then they realize that "that designing a system is one thing, designing a system that has to be built is a much more involved task" [22]. In connection to this, a major effort on faculty competence development has been launched and continues to date. Here, it is vital that several teachers are involved, to build critical mass, to reduce sensitivity and to enrich the dialogue during the course development process. The financial issue emerging from that a racecar may need to use expensive materials and components has been used as an opportunity to train an aspect of communication. The students have to acquire certain funding from external sources and in order to achieve that, they need to prepare and perform "sales" presentations.

Assessment methods

According to the CDIO model, assessment should take place when a topic is assigned Teach or Utilize (Table 5). In the course, two major groups of learning objectives were assessed.

Learning objectives relating to technical knowledge and to the CDIO process are relatively straightforward to assess. Progress towards these learning objectives is initially monitored through reading (and giving feedback to) technical reports and having seminars where the students present their work (conceptual models, design and calculations, manufacturing and operational experiences) to the other students working in the project and to invited teachers. Towards the end of the project, when the car is being built and tested, students receive concrete feedback on their solutions. An important part of the assessment takes part at the Formula Student competition where there are professionals who judge not only the performance of the car but also the design and the reasoning behind it, its manufacturability, the cost etc. The competition takes place after the course is finished so it does not influence the grades, but the feedback from the judges is still an important part of the learning process.

A more challenging aspect of the assessment in the course is to assess how the students have performed as team members. The basis is student reports in which they reflect on questions regarding project management, teamwork etc in general, as well as about the outcome of the project so far. This is carried out at two points in the project: one after establishing the team and creating the conceptual design of the car, and one at the end of the project. No formal peer assessment takes place, meaning that it is not requested from the students to hand in judgements of their teamwork colleagues, but the teaching assistant serving as project leader communicates to the participants throughout the project.

Overall, assessment in design-build-test projects remains a challenge. It is very different from having written exams with questions and calculation problems. However, in our view, the major problem is not so much the lack of appropriate methods but rather the training of faculty in the use available methods.

4. Conclusion

The procedure and the case used here demonstrates that it is possible to systematically design and implement design-build-test project courses, addressing issues such as stating learning objectives, selecting teaching methods and assessment procedures. In addition, important pre-conditions for the implementation of a design-build-test project are pointed out, such as dedicated workspaces and faculty competence development. Using the tools provided will make sure that these elements that fit together and help teachers avoid typical pitfalls. In the case studied, the use of the CDIO resources affected the course development in several ways, for example:

- The learning objectives were based on topics from the CDIO syllabus in connection with suitable cognitive verbs. This increased the quality of the learning objective statements, making the list of learning objectives more complete ands easier to communicate to the students as well as to other teachers and the program management.
- The relationships between the learning objectives and the applied assessment methods was analyzed by using the course design matrix, ensuring that all taught learning objectives were assessed.
- The learning barrier strategies were analyzed and a number of issues were identified and dealt with during the planning phase of the course.

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