

CDIO: An international initiative for reforming engineering education

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ABSTRACT: With support from the Knut and Alice Wallenberg Foundation, the Royal Institute of Technology (KTH), Linköping University and Chalmers University of Technology of Sweden, and the Massachusetts Institute of Technology (MIT) of the USA, launched the CDIO Initiative to improve undergraduate engineering education in their countries and, eventually, worldwide. The Initiative is an open-architecture endeavour that is designed to be adaptable and adoptable by any undergraduate engineering programme. In 2002, the Technical University of Denmark joined the Initiative and, in 2003, other schools in Canada, South Africa, the United Kingdom and the USA were aligning themselves as well. CDIO is a closely coordinated programme with parallel efforts at participating schools. The Initiative's vision is to provide students with an education that stresses engineering fundamentals that are set in the context of Conceiving - Designing - Implementing - Operating (CDIO) real-world systems and products. The article describes the Initiative's launch, progress and impact.

INTRODUCTION

With support from the Knut and Alice Wallenberg Foundation of Sweden, four Swedish universities, namely Chalmers University of Technology (Chalmers), Göteborg, the Royal Institute of Technology (KTH), Stockholm, Linköping University (LiU), Linköping, as well as the Massachusetts Institute of Technology (MIT) in the USA, formed an international collaboration in October 2000 to improve undergraduate engineering education in Sweden, the USA and worldwide [1].

Three overall goals direct the alliance's endeavours. They are to educate students to:

- Master a deep working knowledge of technical fundamentals.
- Lead in the creation and operation of new products and systems.
- Understand the importance and strategic value of their future research work.

The project vision is to provide students with an education that stresses engineering fundamentals set in the context of Conceiving - Designing - Implementing - Operating (CDIO) real-world systems and products. Thus, the project became known as the CDIO Initiative.

The Initiative's strategy to implement CDIO has four themes:

- Curriculum reform to ensure that students have opportunities to develop the knowledge, skills and attitudes to conceive and design complex systems and products.
- Improved level of teaching and learning necessary for deep understanding of technical information and skills.

- Experiential learning environments provided by laboratories and workshops.
- Effective assessment methods to determine quality and improve the learning process.

From its start, the Initiative's product was designed as open architecture. It would be freely available to any and all schools that offer undergraduate engineering education, to take CDIO methodologies, products and templates, and readily adapt and adopt them to their own programmes. While the collaborating schools shared a common vision of an education set in the context of CDIO, and they would work in close cooperation on the four main themes, they chose to implement the Initiative in four different professional areas. Success in a variety of engineering education disciplines would help ensure CDIO's universality and adaptability. KTH is developing its programme in vehicle engineering, MIT in aerospace, Chalmers in mechanical engineering and LiU in applied physics and electronics.

Each participating school has an overall CDIO director and at least one representative on each of the four theme areas. Student representatives from each school participate in the four theme areas, as well as contribute as a separate student group.

The four original CDIO collaborators maintain a steering committee of engineering deans and industry representatives, which helps guide the Initiative and serves as liaison to the Wallenberg Foundation. An external review board evaluates the project biennially [2].

CDIO-based undergraduate engineering education features the following elements:

- A curriculum organised around the disciplines and interwoven with CDIO activities.

- Student projects complemented by internships in industry.
- Multidisciplinary instruction and active and experiential group learning.
- Networked classroom, workshop and laboratory settings.
- Robust assessment and evaluation processes.

The context for this undergraduate engineering education is a generalised description of a complete system lifecycle 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, that is the plans, drawings and algorithms that describe what will be implemented. *Implement* refers to the transformation of the design into a 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.

At the outset of the collaboration, each of the four theme areas identified specific tasks for joint investigation and development with parallel efforts at each school. *Curriculum* initiatives include defining and validating the outcomes of an engineering programme, early engineering experiences, disciplinary linkages, integrated design-build experiences and CDIO skills education. *Teaching and Learning* tasks are concrete (hands-on) learning, problem formulation, active learning, feedback and research into teaching and learning approaches. The *Laboratories and Workshops* group focuses on models for building and furnishing workshops and laboratories, as well as research into best practices in the use of laboratories for engineering education. *Assessment* reform includes the identification of clear goals and outcomes, CDIO skills assessment, creative skills assessment and programmatic evaluation.

Intended programme outcomes have been identified for each of the four themes at both programmatic and student experience levels (see Table 1).

CURRICULUM

New curriculum models and designs are based on an organised list of learning outcomes identified as critical in the education of new engineers. Each institution has conducted surveys of its faculty, students, alumni and industrial representatives to validate the importance of these outcomes [3]. This list, now called the CDIO Syllabus, may be found on the World Wide Web (WWW) at <http://www.cdio.org>.

The CDIO Curriculum theme proposed a curriculum model in which:

- Disciplines are the organising principle interwoven with design-build experiences.
- Design-build experiences motivate and reinforce learning and teach system building.
- Clear connections of learning to utility exist throughout the curriculum.
- Rigour and breadth of coverage are preserved.
- Students are well prepared to be leading engineers, as well as researchers, with a clear understanding of the strategic value of their area.

The integration of these features into existing and new curriculum is left to each institution. Three integration models are proposed for local adaptation. A *block* model fully integrates disciplinary content and CDIO skills into one or more courses. In a *linked* model, two or more subjects are taught separately and concurrently, eventually merging with CDIO skills as the main link. In an *umbrella* integration model, subjects and courses are taught separately and are connected by some coordinating CDIO activity.

In the design of new curriculum, each institution is also focusing on its introductory courses. These initial experiences are designed to motivate students to study engineering, to provide personal experiences that foster a deeper understanding of fundamentals and to provide early exposure to system building. Chalmers has revised its Introduction to Mechanical Engineering, KTH its Perspectives on Vehicle Engineering, and MIT its Introduction to Aerospace and Design. LiU has developed a new introductory course, Engineering Projects-Y, for its programme in electronics and applied physics.

At the same time, each partner is working on one or more projects that enhance disciplinary linkages, including a machine elements design and manufacture project and a mechatronics course at Chalmers, a solar-powered aircraft at KTH, an electronics course at LiU, and an electric aircraft in a Unified Engineering course at MIT.

The Curriculum theme is taking the lead in the design and development of Instructor Resource Modules (IRMs) to provide faculty with teaching and learning resources for integrating CDIO skills education into the curriculum. Four prototype guides are under development: oral and written communication, communication in foreign languages, teamwork and professional ethics. Additional guides will be developed in subsequent years of the collaboration. The IRMs will also be freely available on the Web.

Table 1: Intended CDIO outcomes.

	Curriculum	Teaching and Learning	Laboratories and Workshops	Assessment
Programme	Models for curriculum structure and design	Understanding and addressing barriers to student learning	Models for the design and use of laboratories/workshops	Tools and processes for programme evaluation
Student Experience	Curricular materials for CDIO education	Active and experiential learning with enhanced feedback	Workshop-based educational experiences	Tools and processes for assessing student achievement

Other recent Curriculum theme activities include:

- Major redesigns of each participating school's curricula to integrate the CDIO model. For example, KTH introduced four new/revised programmes for 2003.
- A revised Web-based Syllabus survey has been designed.
- LiU has developed and implemented the Lightweight Interactive Project Management model in CDIO project-based courses for student years 1, 3 and 4.

TEACHING AND LEARNING

The main goal of the Teaching and Learning theme is to increase student's learning through:

- Problem formulation;
- Increased active learning experiences;
- Immediate feedback;
- Improved instructor skills.

In the first year, each institution conducted interviews and surveys of its respective instructional staff to determine what teaching methods were in use. In addition to more traditional methods of lecture, recitation and problem sets, instructors promote learning through student presentations, teamwork, laboratory exercises, hands-on projects and design-build experiences.

As a result of the CDIO Initiative, instructors have engaged in joint projects to improve teaching and learning. For example, instructors at all four institutions introduced *muddiest-part-of-the-lecture* cards to encourage interaction in lecture-based classes and improve immediate feedback of students' conceptual understanding [4]. LiU and MIT are working with personal response systems and other new technologies, both for independent study and class interaction [5].

Examples of progress by the Teaching and Learning theme include:

- A new Problem-Based Learning (PBL) course at Chalmers, Environmentally Adapted Product Development and Manufacturing, has been developed, carried out, evaluated and reported.
- A new method for increasing student conceptual understanding in the Signals and Systems course at MIT has been developed and a preliminary report presented.
- The Report, *Assessing & Enhancing Conceptual Understanding*, has been presented.
- Workshops on both student and teacher education have been presented.

As the Initiative continues, the Teaching and Learning theme includes the following:

- Organising additional faculty and student workshops.
- Publishing technical briefs on innovative teaching methods.
- Expanding the use of electronic response systems.
- Continuing to develop problem formulation and case study approaches.
- Investigating and testing new instructional technologies.

WORKSHOPS AND LABORATORIES

The main objectives of the Workshops and Laboratories theme are to:

- Develop the infrastructure and facilities to support educational initiatives;
- Introduce design-build experiences within existing courses;
- Promote active, team-based, hands-on project work.

First-year projects were largely devoted to single-institution endeavours. For example, Chalmers has designed a new prototyping workshop and virtual design studio, KTH has introduced a new creativity lab-workshop in its redesigned aeronautics and lightweight structures courses, LiU has introduced labs and workshops in its electronics and computer technology courses, and MIT has built its Learning Laboratory for Complex Systems.

The Workshops and Laboratories theme identified 12 modes of instruction for effective use of laboratories in engineering education. These varied uses help to determine the requirements of laboratory spaces. They are:

- Class Lab Mode: occasional use, short duration, storable.
- Large Systems Mode: yearlong project, design intensive, dedicated space, product thrust, close connectivity to the outside.
- Design Product Mode: large-scale project, term length, virtual design, dedicated space, breakout-report spaces.
- Tinkering Mode: occasional, temporary workspace.
- Experiment Mode: desktop project, one to two terms, student developed.
- Research Design Support Mode: in-and-out capacity, temporary team design space, weeks to months in duration
- Graduate Thesis Mode: one or more years, equipment needs, dedicated space, in-and-out capacity.
- Large Student-Project Mode: large-scale project, dedicated space, large physical components, after hours.
- Linked Projects Mode: multidisciplinary, one term or less, multi-use lab experiments, joint labs and designs.
- Teaching in Labs Mode: occasional, presentation area, demonstrations.
- Income-Generating External Mode: ongoing, in-and-out testing, days or weeks duration, dedicated space.
- Outreach Mode: weekly, accommodate visits, lectures, presentations.

Most recently in the Workshops and Laboratory theme, MIT has refined its Learning Laboratory, new labs have opened at Linköping, while the prototyping lab has been reconstructed at KTH and Chalmers.

New design-build-test experiences have been implemented at the Swedish institutions. Examples of products that have been developed in these courses are a solar-powered aircraft at KTH, and a racecar at Chalmers. In coming years, the Laboratory and Workshops theme will outfit and operate the labs designed in the first year, create new courses with design-build opportunities, expand the current laboratories and workshops, coordinate with other educational projects and development efforts, as well as support capstone design experiences.

ASSESSMENT

In the first year, the Assessment theme engaged in activities in four main areas: creating learning objectives, assessing CDIO skills, course evaluation, and programme evaluation. Chalmers, KTH, and LiU held faculty workshops on writing and classifying learning objectives. The team focused on communication skills, creative and affective skills, as well as alternative assessments in mathematics. All four institutions examined and described their procedures for end-of-course evaluations by students, and LiU and MIT initiated Web-based course evaluations. In the area of programme evaluation, LiU implemented an approach called the Balanced Scorecard [6]. Furthermore, MIT evaluated its programme using the Accreditation Board for Engineering and Technology's (ABET) EC 2000 [7].

The theme developed new tools for assessing technical courses and for assessing design-build-test experiences. The former address the proper formulation of learning objectives, utilise oral examinations and concept questions to assess deep understanding and develop concept maps of student learning. The latter include adapted scoring guides, the use of oral presentations and techniques for peer- and self-assessment.

New methods for evaluating educational programmes were developed including the use of baseline interviews, longitudinal studies and portfolios for assessing student learning during the whole programme, the use of Balanced Scorecards to display programme status and a range of techniques for course evaluations, such as Web-based course evaluation questionnaires, course panels and instructor reflective memos.

CDIO EXPANSION

By the Initiative's second year, with CDIO development and application well underway, the original partners began an outreach effort in order to encourage CDIO adoption by a select number of additional schools [8]. These early potential adopters were approached based on their commitment to apply the CDIO concept, the diversity of their programmes, their potential for contributing new ideas to the benefit of all Initiative members, their enthusiasm for joining the collaboration and their willingness to secure resources to support their participation.

The first school to join the original partners was the Technical University of Denmark (DTU), Copenhagen, Denmark. Other institutions laying the groundwork for joining are located in Canada, Finland, Ireland and the USA. In addition, the South African Ministry of Education has a high-ranking representative closely involved with the CDIO Initiative to explore the introduction of CDIO in that country. This diverse and growing collaboration will ensure the continued evolution and improvement of this project.

SUMMARY

The international collaboration of the CDIO Initiative has resulted in an exemplary partnership of professionals committed to the reform of engineering education. It is

fostering the learning and sharing of ideas, projects, and materials bridging programmes, institutions, languages and national boundaries.

CDIO is an open architecture endeavour. It is specifically designed for, and offered to, all university engineering programmes to adapt to their specific needs. It is an ongoing developmental effort. Participating universities will develop materials and approaches to share with others. Many already have unique capabilities that could enrich other programmes. Therefore, we are developing an open, accessible architecture for the programme materials for the dissemination and exchange of resources.

In designing and administrating CDIO, its creators reached beyond the traditional walls of engineering institutions to assemble a unique development team of professionals involved in key areas like curriculum, teaching and learning, assessment, design and build, as well as communication. These professionals are available to provide information and assist others who want to explore adopting CDIO in their institutions. There is a wealth of development material available, ranging from model surveys to assessment tools and reports from institutions that have implemented the CDIO Initiative.

Contacting the CDIO team can be done via e-mail on info@cdio.org. More information on the CDIO Initiative can be found by visiting www.cdio.org.

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