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Benchmarking Engineering Curricula with the CDIO Syllabus*

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Four internationally-renowned universities—Chalmers University of Technology, Linköping University, Royal Institute of Technology (Sweden), and the Massachusetts Institute of Technology (USA)—developed a benchmark survey that may be used by any engineering school to benchmark curricula for teaching of personal, interpersonal and system building skills. These skills are enumerated in the CDIO Syllabus. Teaching activities were categorized as Introduce, Teach or Utilize, based on intent, time spent, and linkage to learning objectives, assignments and assessment criteria. Interviews were used to collect the data from instructors of the schools' engineering programs. The data was then reduced and analyzed to illuminate patterns of teaching. The results indicate that much effort is expended in covering these topics, but often in an inefficient, uncoordinated and unplanned manner. For example, there are often frequent repetitions of introducing a topic, without ever teaching it. In other instances, students are expected to utilize knowledge without having been taught it. The results of the benchmark survey indicate that a consistent and deliberately designed curriculum in this area could demand no additional resources, yet provide a much more effective education. The survey gives useful indications of how to begin such a curriculum redesign process.

INTRODUCTION

UNIVERSITY ENGINEERING programs must educate students in a technical discipline as well as in a broad set of personal, interpersonal and system building skills. The students must learn these areas of knowledge and skills comprehensively, and in the allotted time. During the 20th century the models of engineering education to accomplish these goals evolved. The century began with the hands-on practice-based model, taught largely by practicing engineers. The middle of the century brought the engineering science model. Taught primarily by engineering researchers, it laid a strong foundation of fundamentals, but de-emphasized actual engineering practice. Recently, this model has come under criticism as having become too abstracted from engineering practice. It perhaps failed to meet an underlying need—that the university must educate not only technically expert engineers, but also those who can build and operate new value-added engineering systems in a modern, team-based environment.

As an evolution of the engineering science model, a few universities adopted a problem-based learning model, in which projects became the organizing principle of the education. It is an excellent model for development of interpersonal and system-building skills, but makes projects, rather than disciplines, the organizing principle of the education [1–3].

In recent years, four leading engineering universities have partnered to create a new engineering education model, named CDIO [4]. Those schools are Chalmers University of Technology, Linköping University, and the Royal Institute of Technology, in Sweden, and the Massachusetts Institute of Technology in the USA. The CDIO Initiative, as the partnership is called, envisions an education that stresses the fundamentals, set in the context of the product-system lifecycle, which can be thought of as having four metaphases: Conceiving—Designing—Implementing—Operating, hence the program name. The design of a CDIO education reflects two goals: that university students must develop a *deeper working knowledge* of the technical fundamentals, while simultaneously developing the skills to lead in the *creation and operation of new products and systems*.

A CDIO-based curriculum is organized around

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the disciplines, but with CDIO activities interwoven. Disciplines are mutually supporting and interacting. The program is rich with student projects complemented by internships in industry, and features active, experiential, and group learning set in both the classroom and a modern learning workshop-laboratory [5, 6]. By participating in a set of authentic personal technical experiences centered around conceiving, designing, implementing and operating, students attain both of the desired objectives: they develop the skills needed to build systems, and they better master the sought-after deep working knowledge of the fundamentals.

As the first step in establishing the CDIO model, and as described in detail in previous papers and reports, we developed and codified a comprehensive understanding of abilities needed by the contemporary engineer [7]. This codification, the CDIO Syllabus, is described below.

The goal of this paper is to develop and demonstrate a benchmarking technique that assesses an existing curriculum in terms of how it satisfies the educational goals for personal, interpersonal and system building skills that are codified in the CDIO Syllabus. The specific objective of this paper is to document the location and degree to which various topics of the CDIO Syllabus are now taught in the four partner academic programs. This benchmarking documentation will serve as the basis for subsequent curriculum redesign activity.

The four programs involved span university, disciplinary and national boundaries. Three of the universities are in Sweden; the fourth is in the USA. They are the Mechanical Engineering Program at the Chalmers University of Technology, Göteborg; the Vehicle Engineering Program at the Royal Institute of Technology (KTH), Stockholm; the Applied Physics and Electrical Engineering Program at Linköping University (LiU), Linköping; and the Aeronautics and Astronautics program at the Massachusetts Institute of Technology, Cambridge.

This paper begins with a description of the CDIO Syllabus, and of the stakeholder survey that delineates the desirable level of resource commitment that should be devoted to each CDIO Syllabus topic. A survey process for benchmarking the CDIO content of our existing programs is then described. Having conducted the benchmark surveys, the data is analyzed in three ways: organizationally for internal structure and efficiency; comparatively among universities; and qualitatively against the desirable resource commitment. Observations about the amount, distribution and pattern of teaching are then made, which are the precursor to effective curriculum redesign.

THE CDIO SYLLABUS

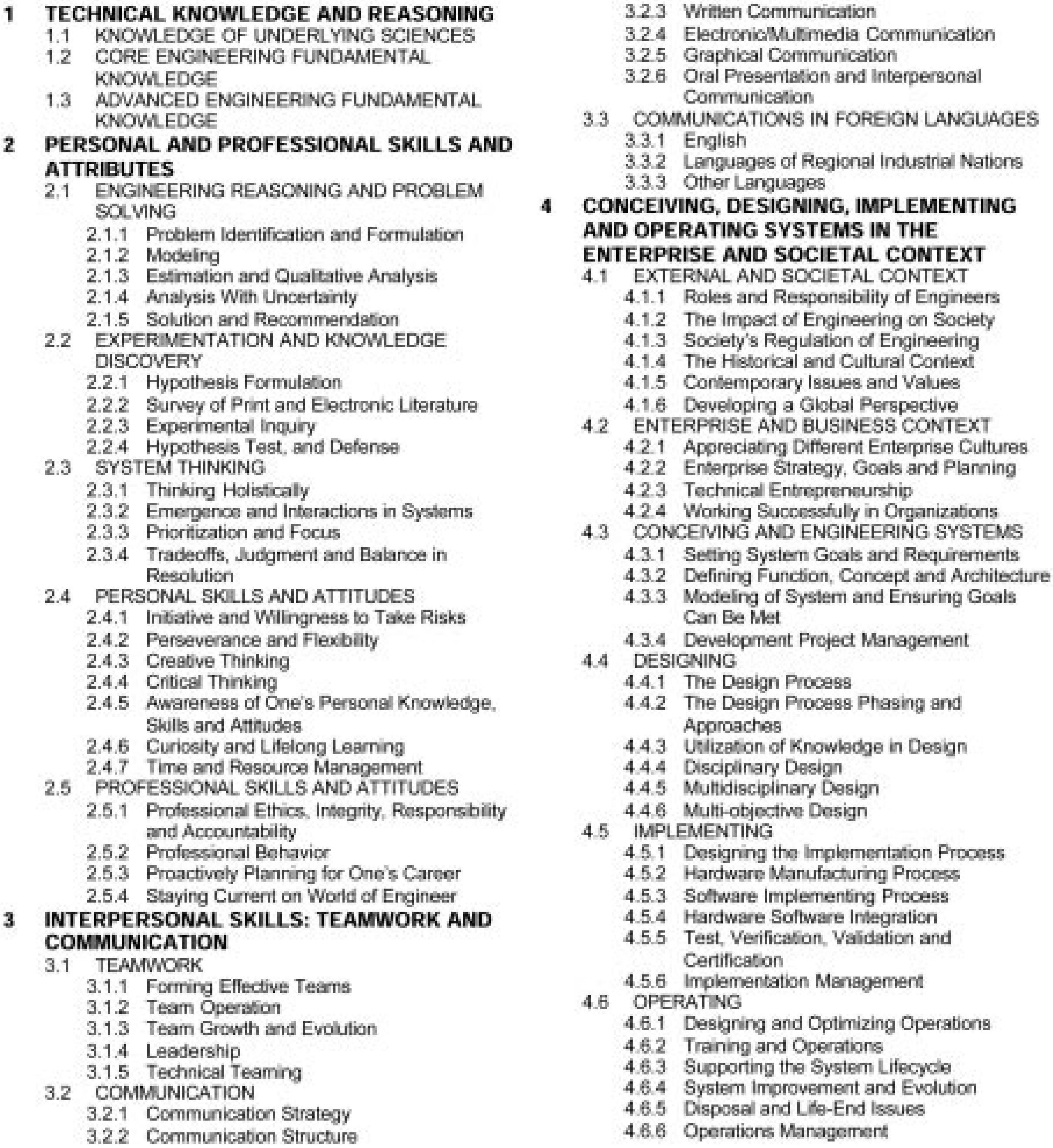
An initial product of the CDIO program was the CDIO Syllabus, a codification of the engineering knowledge, skills and attitudes needed by contemporary engineers [10–19]. The Syllabus essentially constitutes a requirements document for undergraduate engineering education. In assembling and organizing the Syllabus, our goal was to develop a clear, complete, and consistent set of detailed topics that facilitate implementation and assessment. The initial set of topics or requirements, were derived from an examination of resources from the last 50 years delineating desired skills and attributes for engineers [1019]. One important source was the ABET (Accreditation Board of Engineering and Technology) EC 2000 criteria for accrediting engineering programs. There is a strong correlation between the topics in the CDIO Syllabus with ABET's criteria 3a–k [9].

We began by reformulating the underlying need to be met by engineering education. We assert that graduating engineers should be able to *conceive—design-implement-operate—complex value-added engineering systems in a modern team-based environment.* Once this CDIO premise is accepted as the context of engineering education, more detailed goals can be derived.

The true departure point for the derivation of the CDIO Syllabus' content is the simple statement that *engineers engineer*; that is, they build systems and products for the betterment of humanity. Graduating engineers should appreciate engineering *process* (conceiving, designing, implementing and operating), be able to contribute to the development of engineering *products* (complex value-added engineering systems), and do so while working in engineering *organizations* (a modern team-based environment). Implicit is the additional expectation that engineers, as university graduates, should develop as *whole, mature, thoughtful individuals* [8].

These four high-level expectations map directly to the first level organization of the CDIO Syllabus. Examining the mapping of the items 1 through 4, the first levels of the Syllabus, to these four expectations, we can see that a mature, thoughtful individual interested in technical endeavors possesses a set of *personal and professional skills*, which are central to the practice. In order to develop complex value-added engineering systems, students must have mastered the fundamentals of the appropriate *technical knowledge and reasoning*. To work in a modern team-based environment, students must have developed the *interpersonal skills* of teamwork and communications. Finally, to create and operate products and systems, a student must understand something of *conceiving, designing, implementing, and operating systems in the enterprise and societal context*.

Figure 1 is the CDIO Syllabus, in condensed form, which shows the breakdown of these four goals into second and third levels. For example, the first goal, 1 Technical Knowledge and Reasoning, is broken down into three second level elements, the first of which is 1.1 Knowledge of



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 Tradeoffs, Judgment and Balance in Resolution
- 2.4 PERSONAL SKILLS AND ATTITUDES
  - 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 Engineer

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 COMMUNICATION
  - 3.2.1 Communication Strategy
  - 3.2.2 Communication Structure
  - 3.2.3 Written Communication
  - 3.2.4 Electronic/Multimedia Communication
  - 3.2.5 Graphical Communication
  - 3.2.6 Oral Presentation and Interpersonal Communication
- 3.3 COMMUNICATIONS IN FOREIGN LANGUAGES
  - 3.3.1 English
  - 3.3.2 Languages of Regional Industrial Nations
  - 3.3.3 Other 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 Ensuring 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
- 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

Fig. 1. The CDIO Syllabus (condensed).

Underlying Sciences. 1.1 is further broken down into four third-level elements, the first of which is 1.1.1 Mathematics. We refer to these levels generically as the 'X.X' level for the second level and the 'X.X.X' level for the third level. It is important to note that the full CDIO Syllabus exists at up to five levels of detail.

This breakdown is necessary to transition from the high level goals, to the level of teachable and assessable skills. The organization and content of the four main parts will now be discussed.

Part 1 of the Syllabus is Technical Knowledge and Reasoning. Modern engineering professions rely on a necessary core Knowledge of Underlying Sciences (1.1). A body of Core Engineering Fundamental Knowledge (1.2) builds on that science core, and a set of Advanced Engineering Fundamentals (1.3) moves students toward the skills necessary to begin a professional career. This is the curriculum that engineering school faculty usually debate and define. Therefore, the CDIO Syllabus merely leaves a placeholder here, since the Part 1 details will vary from field to field.

In the remainder of the Syllabus, we have included the knowledge, skills and attitudes that all engineering graduates are likely to require. Part 2 of the Syllabus is Personal and Professional Skills and Attributes. The three modes of thought most practiced professionally by engineers are Engineering Reasoning and Problem Solving (2.1), Experimentation and Knowledge Discovery (2.2) and System Thinking (2.3). Each starts with a subsection which is essentially 'formulating the issue,' moves through the particulars of that mode of thought, and ends with a section which is essentially 'resolving the issue.' Those personal skills and attributes, other than the three modes of thought, which are used primarily in a professional context, are called Professional Skills and Attitudes (2.5). The subset of personal skills that are not primarily used in a professional context, and are not interpersonal, are Personal Skills and Attitudes (2.4).

In Part 3, the Interpersonal Skills are outlined. The Interpersonal Skills are a distinct subset of the general class of personal skills, and divide into Teamwork (3.1), Communications (3.2) and Communications in Foreign Languages (3.3).

Part 4, Conceiving, Designing, Implementing and Operating Systems in the Enterprise and Societal Context, presents a view of how product or system development moves through four metaphases: Conceiving (4.3), Designing (4.4), Implementing (4.5) and Operating (4.6). The chosen terms are descriptive of the hardware, software, and process industries. Conceiving runs from market or opportunity identification through high level or conceptual design, and includes development project management. Designing includes aspects of the design process, as well as disciplinary, multidisciplinary, and multi-objective design. Implementing includes hardware and software processes, test and verification, as well as design and management of the implementation process. Operating covers a wide range of issues from designing and managing operations, through supporting product lifecycle and improvement, to end-of-life planning.

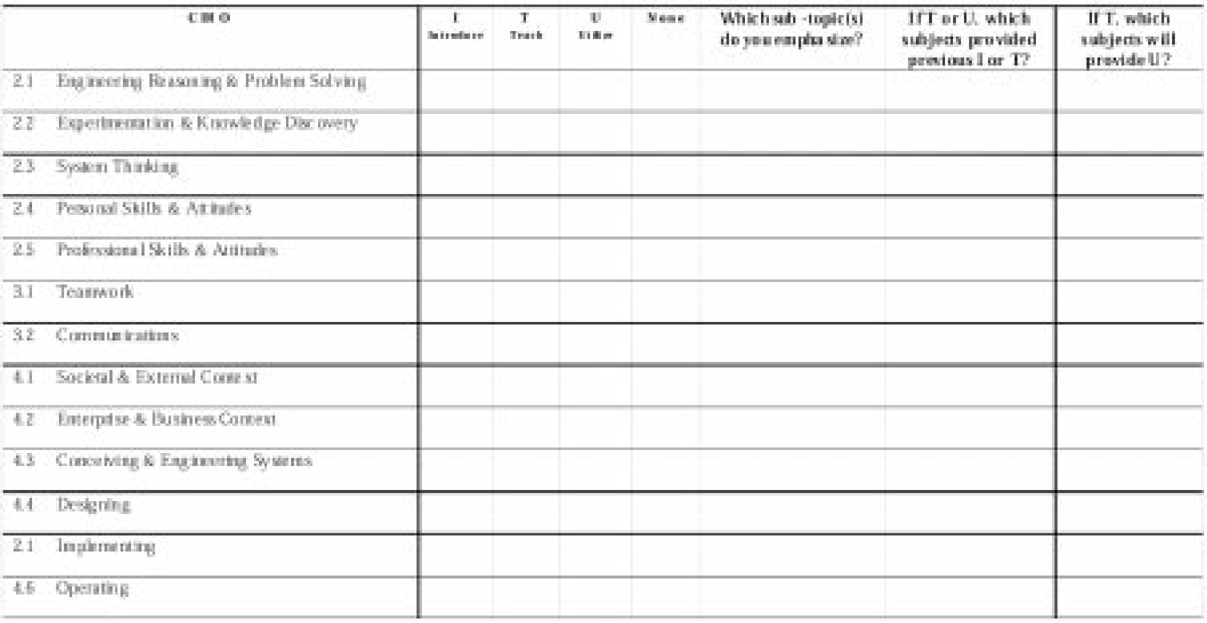
Products and systems are created and operated within an Enterprise and Business Context (4.2), and engineers work and enterprises exist within a larger Societal and External Context (4.1). An understanding of these frameworks is essential to the successful practice of the engineering profession.

Once we had determined our topics, we created a process to translate the list into substantive requirements. We began this process by conducting a stakeholder survey. The survey questionnaire asked two main questions for each second level (X.X) topic. The first question asked respondents' opinions of proficiency levels desired of graduating engineers. The second asked respondents to assign a resource level to each topic in such a way that the resources would total 100 points.

We surveyed students and four groups of professionals: faculty from within and outside our university; mid- to upper-level leaders of industry; our institutions' recent alumni (about five years following their graduation); and our institutions' older alumni (about 15 years following their graduation). The results were compiled for the programs at the four universities and are compared below to the benchmark results.

BENCHMARK SURVEY PROCESS

Before curriculum redesign could even begin, we needed to understand exactly how our existing curricula stood up to the expectations of the CDIO Syllabus. The four universities collaboratively composed a survey (Fig. 2) to probe the extent to which CDIO Syllabus topics were



CDIO	I Introduce	T Teach	U Utilize	None	Which sub-topic(s) do you emphasize?	If T or U, which subjects provided previous I or T?	If T, which subjects will provide U?
2.1 Engineering Reasoning & Problem Solving							
2.2 Experimentation & Knowledge Discovery							
2.3 System Thinking							
2.4 Personal Skills & Attitudes							
2.5 Professional Skills & Attitudes							
3.1 Teamwork							
3.2 Communications							
4.1 Societal & External Context							
4.2 Enterprise & Business Context							
4.3 Conceiving & Engineering Systems							
4.4 Designing							
2.1 Implementing							
4.6 Operating							

Fig. 2. The CDIO benchmarking survey form as used by MIT.

currently covered in their undergraduate engineering courses. For each of 14 CDIO topics at the second (X.X) level, faculty were asked if they currently Introduced, Taught, and/or Utilized the topic in their course.

After we observed that the word 'teach' was used to describe a great number of varying activities occurring within courses, we decided to make the distinction among Introduce, Teach, and Utilize (shortened to I, T and U). It was apparent that various levels of effort and depth were associated with different activities and the one-word label 'teach' was not adequate to describe these various levels. Thus, the definitions of Introduce, Teach and Utilize were composed. Each definition contains six elements: intent, relationship to learning objectives, time, relationship to assignments, relationship to assessment, and examples. The definitions of Introduce, Teach and Utilize, as the terms are used in the benchmarking study and this paper, are as follows:

Introduce

- Touch on, or briefly expose, the students to this topic.
- No specific learning objective of knowledge retention is linked to this topic.
- Typically, less than one hour of dedicated lecture/discussion/laboratory time is spent on this topic.
- No assignments/exercises/projects/homework are specifically linked to this topic.
- This topic would probably not be assessed on a test or other evaluation instrument.

Examples of *Introduce:*

1. At the beginning of class, an example is given of the operation of an engineering system (4.6) to motivate an aspect of the design. However, no explicit discussion of the design or analysis of operation is presented.
2. An ethical problem or dilemma (2.5) is presented to the students that sets the context of an example or lecture. However, no explicit treatment of ethics or its role in modern engineering practice is presented.

Teach

- Really try to get students to learn new material.
- The learning objective is to advance at least one cognitive level (e.g. no exposure to knowledge, knowledge to comprehension, comprehension to application).
- Typically, one or more hours of dedicated lecture/discussion/laboratory time are spent on this topic.
- Assignments/exercises/projects/homework are specifically linked to this topic.
- This topic would probably be assessed on a test or other evaluation instrument.

Examples of *Teach:*

1. The process and methodology of product design (4.4) are explicitly presented to students through lectures and presentations, and then practiced by the students in a graded project or assignment.
2. Several workshops are presented on working in teams and group dynamics (3.1), and a coach works with students on improving teamwork throughout the semester's team project. The students' teamwork skills are assessed along with their project results.

Utilize

- Assumes students already have some proficiency in this topic.
- No specific learning objective is linked to this topic, but the student will use knowledge of this topic to reach other learning objectives.
- No time explicitly allotted to teaching this topic.
- Assignments/exercises/projects/homework are not designed to explicitly teach this topic.
- Tests or other evaluation instruments are not designed to explicitly assess this topic.

Examples of *Utilize:*

1. When taking a course other than communications, students are expected to use their skills in preparing and giving oral presentations (3.2) that explain their work. However, no explicit instruction in oral presentation skills is given.
2. When working in a laboratory session, students are expected to use their experimentation skills (2.2) while carrying out assignments and research. However, no explicit instruction on techniques of experimentation is given.

BENCHMARK SURVEY PROTOCOL

Each of the four universities completed the CDIO Curriculum Benchmarking survey using its own CDIO project members, but using the same survey protocol. The survey was completed through a face-to-face meeting between the CDIO project member and the faculty member responsible for each course. At the three Swedish universities, the interview was conducted at the same time as a second survey on teaching methods. All interviews took place during the 2001–2002 academic year. There were 22 interviews conducted at Chalmers, 20 interviews at KTH, 28 at LiU and 16 at MIT. The Swedish schools conducted their interviews in Swedish; MIT conducted its interviews in English.

In all cases, the entire suite of the compulsory courses in a specific program was benchmarked. Representative courses in upper class years were also surveyed. Of course, in all academic programs, students choose some electives to complete their degree program, often from among tens or even hundreds of options. It would be impractical to survey all of these courses.

Interviews began with an explanation that the goal of the curriculum benchmark survey was to benchmark in which courses, and to what degree, CDIO topics were currently deployed, so an effective redesign of the curriculum could take place. The respondents were reminded of the background of the CDIO project, and then shown the condensed version of the CDIO Syllabus, the survey form, and the definitions of Introduce, Teach, and Utilize. The respondents were then asked, 'In relation to your course, do you I (Introduce), T (Teach) or U (Utilize) this topic (e.g. 2.1)?' and 'Which sub-area(s), if any, do you emphasize (e.g. 2.1.1, 2.1.2)?' Respondents could choose more than one response from among I, T and U, although they were reminded that by definition, teach automatically implied introduce.

The questions were repeated for 2.2 through 2.5, 3.1 through 3.3, and 4.1 through 4.6. Respondents were encouraged to discuss course activities with the CDIO project member if they were unsure which definition best fit, and the project member and respondent would then agree on the label. The written definitions of I, T and U were consulted often, and every effort was made to assure consistency of the responses to these definitions. Frequently, faculty respondents and interviewers needed to consult the expanded version of the CDIO Syllabus to determine the specific content of a topic. One of the most difficult questions for the respondents concerned 2.3 System Thinking. This difficulty was probably due to respondents' preconceived opinions of the definition of System Thinking.

The survey form was designed to collect data about the second (X.X) level of CDIO topics, for example 2.1 Engineering Reasoning and Problem Solving. The Syllabus subdivides 2.1 into third (X.X.X) level topics, for example 2.1.1 Problem Identification and Formulation, 2.1.2 Modeling. At times, a faculty respondent would state that within an X.X topic, one of the X.X.X topics could be rated as a Teach, but the rest were an Introduce, or None. In such cases, the second or X.X item was rated a Teach, and a note made. Two of the universities, Chalmers and LiU, collected complete sets of information on all of the topics at the third level of detail.

Additional questions were also asked: 'If your answer was T or U, which courses, if any, provide the previous I?'; 'If your answer was T, which courses, if any, will provide U?'; and 'Do you have any additional comments?'

Finally, additional respondent information was obtained, including the name of the instructor, the number of times the instructor had taught the course, and whether the instructor was familiar with the CDIO Syllabus. We also collected course information including course name and number; whether it was new, stable or undergoing significant reform; and whether it had an associated set of learning objectives.

The interviews often had several positive developmental aspects. Among those was that they caused instructors to reflect on their courses, and see the possibilities of including some of the skills in an explicit way. Another aspect was the positive and trustful contact the interviewer developed with the instructors, and yet another was that the interviews underlined the need for faculty members to obtain additional knowledge about curriculum design and the CDIO program.

There were inherent limitations in the survey process. The survey results captured a moment in time, and reflected the observations and opinions of the current instructor of the course. The survey protocol required the cooperation and attentiveness of the respondent for rather lengthy periods—30 to 90 minutes of questioning, the longer time being more typical if the detailed X.X.X level of information was obtained for every item. Generally, instructors responded positively to the interviews. In some cases, during the course of the interview, their stance became markedly brighter as they realized the significant and positive effects of their teaching. A very few faculty respondents appeared short of time and did not seem to thoughtfully respond; some became agitated if the interviewer pressed for more information.

Some instructors seemed concerned that not many CDIO skills appeared in their courses. It was therefore important to assure them that the purpose of the investigation was not to evaluate or rate their courses but only to identify the starting point of the CDIO endeavor. Even though the respondents were encouraged to accurately report on their courses, it may be the case that a few faculty respondents skewed their responses to appear as if they were already embracing the CDIO initiative. Additionally, small inconsistencies inadvertently introduced by the four interviewers and the two languages used cannot be discounted.

Within the limitations mentioned, we feel that the survey produced an acceptably accurate benchmarking of the existing curricula, and certainly provided far more insight than existed prior to this exercise.

RESULTS

The results of the curriculum benchmark survey were analyzed for internal consistency, comparatively and against the consensus resource allocation level.

The raw data at the second (X.X) level CDIO Syllabus topics is shown in Fig. 3 for the Applied Physics and Electrical Engineering Program at LiU, which will be used consistently as an example.

The figure shows the compulsory courses in the first six semesters, and then the courses taken in

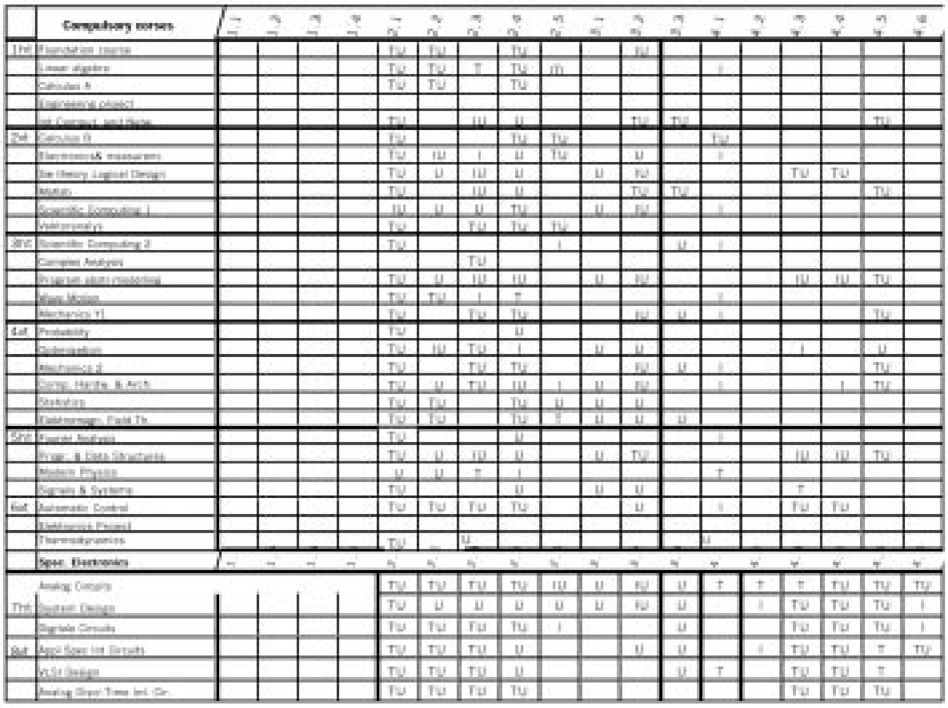


Fig. 3. June 2002 survey raw data for the second (X.X) level of the CDIO Syllabus topics in the eight semesters of LiU's Applied Physics and Electrical Engineering program. ITU = Introduce, Teach, Utilize. Slight differences between Figs 3 and 4 reflect program development over the 20012002 period.

the seventh and eighth semesters for one specialization, electronics. In the sixth, seventh and eighth semester, students take an additional four or five elective courses. In the ninth semester, a student is typically occupied with thesis work. Two project courses (in semesters 1 and 6) were under development at the time of the survey, and responses are not included in the figure. Individual entries in the matrix indicate if the instructor reported an I, T or U, or the allowable combinations, TU (Teach and then Utilize to promote learning of another topic) and IU (Introduce and Utilize to promote learning of another topic). Recall that neither IT nor ITU are allowable combinations, since Teach automatically implies Introduce.

Examining the pattern and occurrences of I, T and U in the raw data reveals interesting patterns. One is simply the large number of CDIO Syllabus topics covered by many courses. Faculty are aware that knowledge of CDIO topics is important. Therefore, they are eager to correlate elements of their courses with syllabus topics, which can explain faculty reporting the extensive number of topics covered. About 40% of all entries in the compulsory courses are combinations of I, T and U, which indicates wide engagement with CDIO Syllabus topics. However, the engagement is not uniformly distributed. About 65% of the course/topics entries in Syllabus Section 2 (Personal and Professional Knowledge and Skills) are occupied, while only about 40% of the Section 3 topics (Personal and Interpersonal) are filled, and a mere 20% of the Section 4 (Conceiving, Designing, Implementing and Operating) entries are filled.

Focusing on the entries for Teaching, the image changes a bit. Recall that Teaching is the activity specifically intended to change students' level of knowledge of a topic. While about 40% of the entries in Section 2 are marked Teaching, only 6% of the Section 3 entries and 8% or the Section 4 entries are so marked.

More insight is gained by examining Fig. 4, which indicates the frequency of occurrences of I, T and U for each of the second (X.X) level topics in the LiU program with a specialization in Electronics. There is strong teaching and utilization of topics 2.1 to 2.4, 4.1 and 4.3 to 4.5. In Section 3, Interpersonal Skills, we observe a pattern in which subjects are never taught, but are utilized for the learning of other topics. This is somewhat anomalous, as is the occurrence of an IU (Introduce and Utilize) in any given topic/course entry of Fig. 3.

Rather few courses touch on topics 2.6, 4.2 and 4.6. This pattern of utilizing without teaching is repeated in the data from the other three programs. Figure 5, which shows just the teaching activity, but for all four universities, indicates patterns similar to the more complete data set shown for LiU.

The data for all four universities reveal that there is a great deal of engagement with the CDIO Syllabus topics, but there is much repetition of I and T with little, if any, evidence of a coordinated design of this aspect of the curriculum. In fact, this presents an opportunity for redesign—it appears that the precious resource of time is already committed, but probably not used efficiently or consistently.

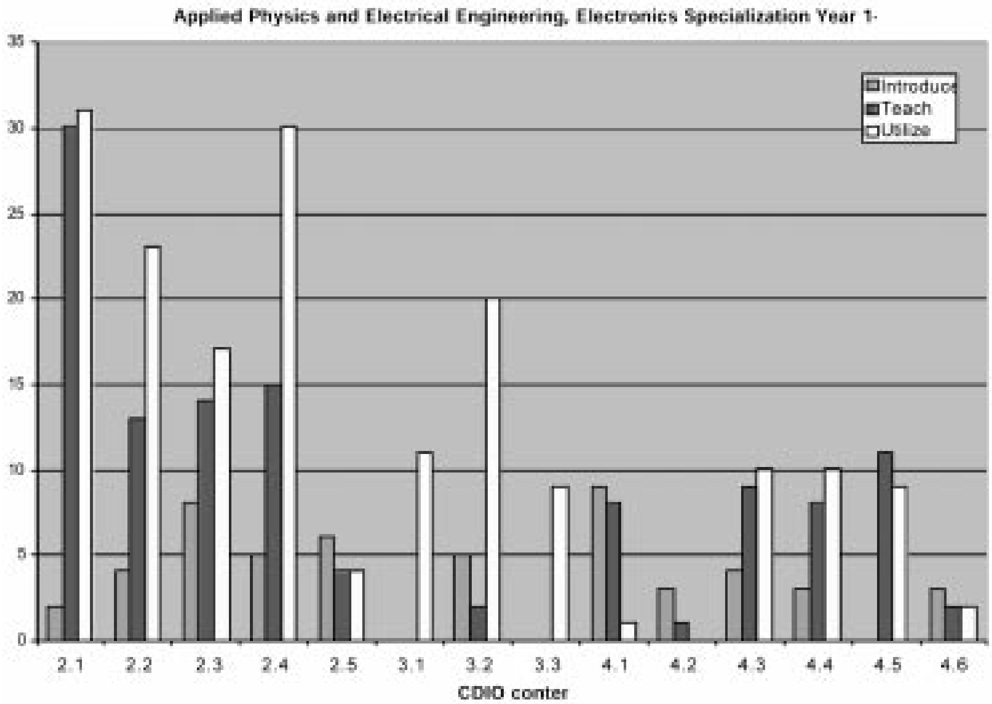


Fig. 4. Introduce, Teach and Utilize at the second (X.X) level in LiU's electronics specialization program as of June 2001.

Delving into the data at the third (X.X.X) level reveals additional information. Figure 6 shows the percentage of occurrences of I, T and U for 3.2 Communications subtopics in the LiU and Chalmers compulsory courses investigated. There is good teaching and strong utilization of communications at the two programs, but the details show that this activity is highly concentrated in 3.2.3 Written Communications. There is relatively little teaching of communications strategy and structure, or in the other communications media. Not unexpectedly, reporting I,T and U activity of the second level topic as the maximum of the activity of the third level can mask relatively lower levels of efforts on other subtopics. This is an inherent weakness in performing the survey only at the second level.

An analysis of the CDIO curriculum benchmarking data can be made by comparing the reported activity (for the compulsory courses) with the desired level of resource commitment indicated in the CDIO Syllabus stakeholder survey by the professional respondents, as discussed above. In order to make this comparison, a composite index was constructed, which we feel approximately represents the occurrences of *Introducing* a topic, *Teaching* it and *Utilizing* it, from an instructor's standpoint.

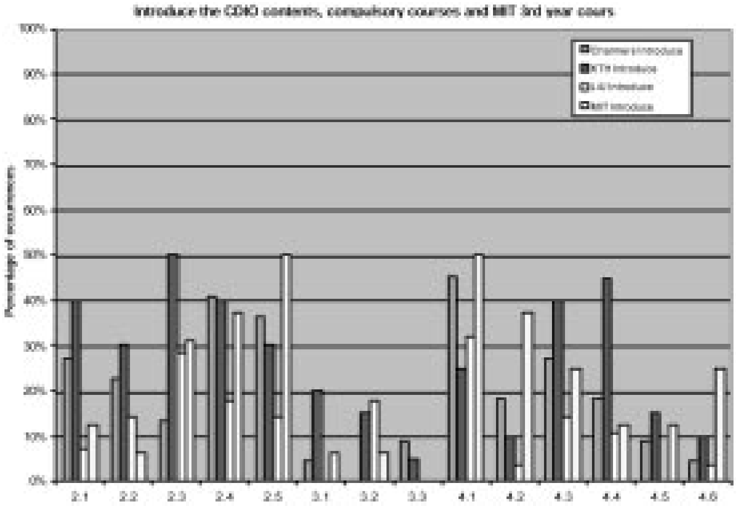


Fig. 5. Teaching activity for the four participating universities.

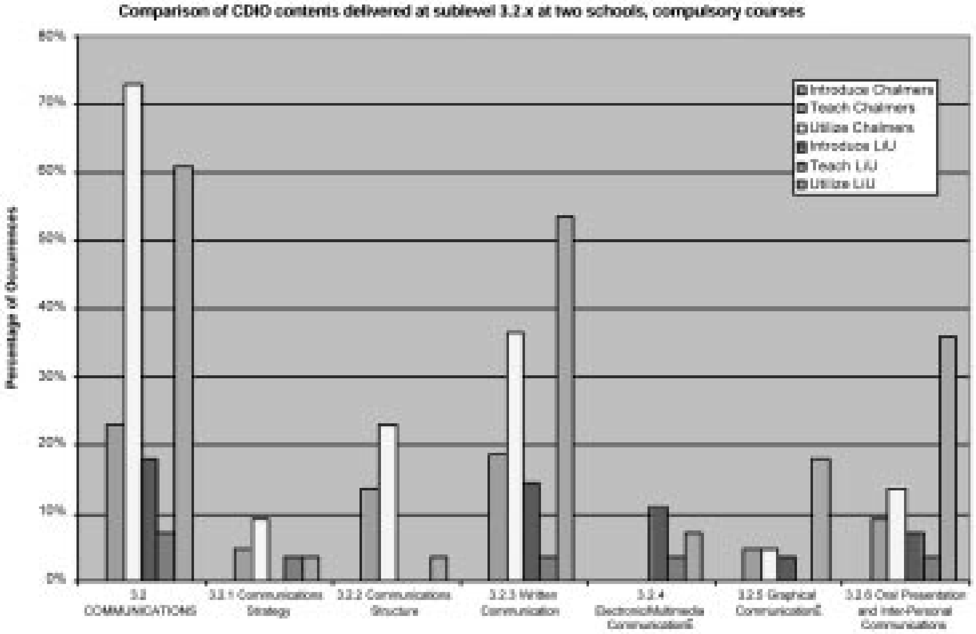


Fig. 6. Occurrences of Introduce, Teach and Utilize for 3.2 Communications subtopics in the LiU and Chalmers compulsory courses.

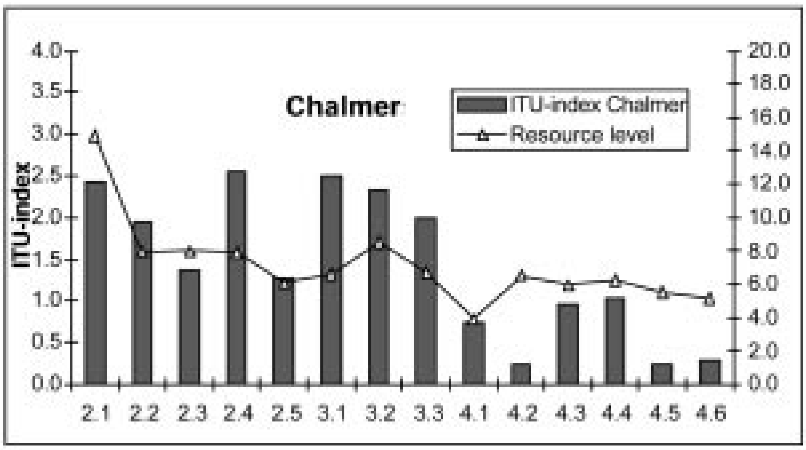


Fig. 7. Introduce, Teach and Utilize comparison for Chalmers.

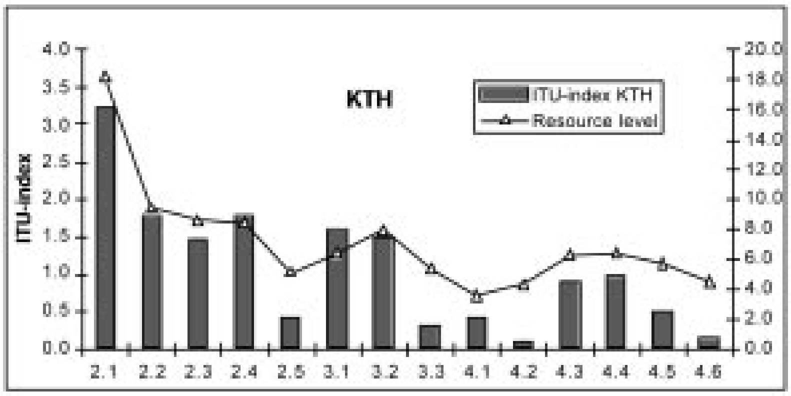


Fig. 8. Introduce, Teach and Utilize comparison for KTH.

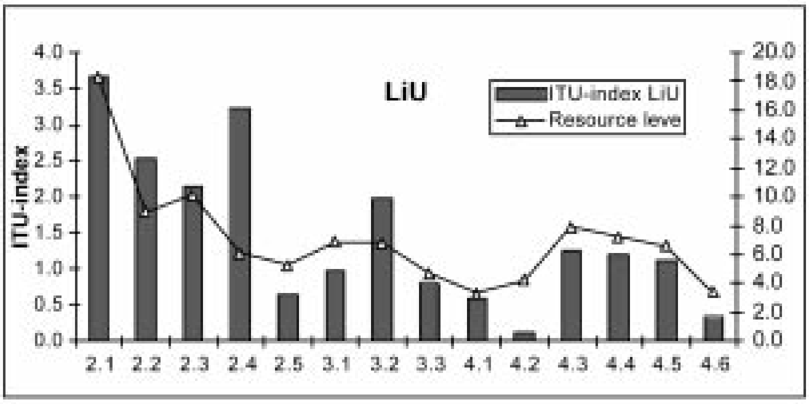


Fig. 9. Introduce, Teach and Utilize comparison for LiU.

The ITU index was defined as:

$$\text{ITU Index} = \frac{0.1\sum_{i=1}^{N} I + \sum_{i=1}^{N} T + 0.3\sum_{i=1}^{N} U}{(N/10)}$$

where N is the number of benchmarked courses. This obviously weights I at 10% and U at 30% relative to T.

Figures 7 through 10 show the comparison of the ITU index with the CDIO Syllabus survey resource commitment data for the four programs. Note that the index and the survey are plotted on different scales, and the similarity in their absolute magnitude is purely reflective of the choice of scales on the plots. The real information is contained in the relative levels of the ITU index and resource commitment data for each CDIO Syllabus topic. The results for each of the four programs are discussed below.

Chalmers results

Figure 7 shows the comparison for Chalmers. The comparison is reasonably good, with the actual ITU index being relatively low in Section 4, particularly in 4.2 The Enterprise Context, 4.5 Implementing, and 4.6 Operating. However, recall that this is a representation of the compulsory courses.

By design, most of this content is supposed to be covered by the elective courses in the last 1.5 years of the program. Topics 2.4 Professional Skills and all those in Section 3 Interpersonal Skills are relatively high compared to resource level. These two sections are supposed to be covered by the compulsory courses of the program. Improving instruction organization and efficiency will be considered in program revisions.

KTH Results

The general trends in the comparison between the current teaching activities (represented by the ITU index) and the average resource levels show reasonably good agreement (Fig. 8). It is particularly interesting to note that the major gaps were associated with the skills and knowledge having the lowest desired resource levels. A surprisingly good agreement was noticed in the Section 2 Personal and Professional Skills and Attitudes, 3.1 Teamwork and 3.2. Communications, which all are rated very high in desired average resource levels. However, it is believed that these teaching activities to some extent represent repetitive introduction and teaching; that is, presenting the same or similar content, at a relatively low cognitive level, in several courses. The largest gaps at KTH are observed for categories 2.5 Professional Skills and Attitudes, 3.3 Communications in Foreign Languages and the entire Section 4 Conceiving,

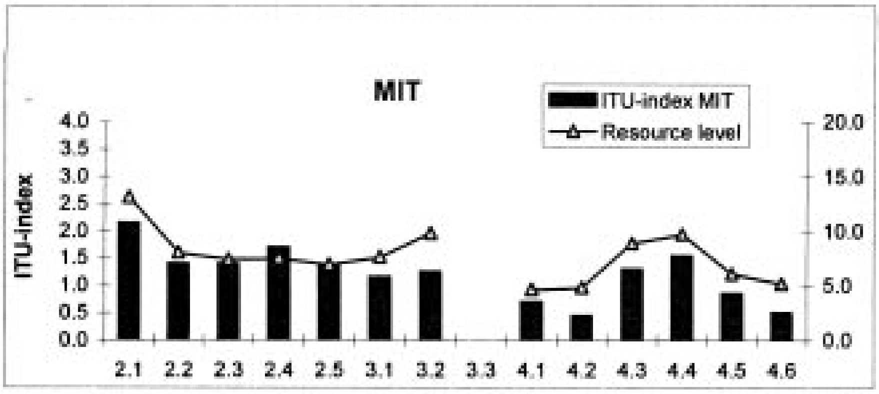


Fig. 10. Introduce, Teach and Utilize comparison for MIT.

Designing, Implementing and Operating Systems in the Enterprise and Societal Context. Although some of these gaps are covered to different degree in electives not included in the investigation, they represent clear drawbacks in traditional engineering education, and need to be considered in a redesign of the curriculum in order to meet the requirements for the expected proficiency of a graduating engineer.

LiU Results

At LiU the overall data for teaching activities (the ITU index) and the desired resource levels show a good overall agreement, considering the uncertainties in the data (figure 9). For 2.4 Personal Skills and Attributes, and 3.2 Communications the ITU index level is relatively higher than suggested by the resource data. In a way, these differences may be regarded as positive and need no change.

However, we must not rule out that over-interpretation of 'personal skills' might have occurred for 2.4. The higher level in 2.2 may be expected because of the nature of the program, which has a high experimental component. The situation is the opposite for 2.5 Professional Skills and Attributes, 3.1 Teamwork, 4.2 Enterprise and Business Context, and 4.6 Operating. The difference for 2.5 and 3.1 should be expected considering the present curriculum, but should be addressed in redesign. Items 4.2 and 4.6 are covered in elective courses.

MIT Results

MIT data suggest that there is a good match between level of desired resource level and amount of coverage a CDIO skill received (figure 10). Shortfalls are most pronounced in 3.2 Communications, 4.2 The Enterprise Context, and 4.6 Operating. The latter two were expected, but the under commitment of resources in 3.2 Communications was surprising in view of strong efforts in this area. This will be considered in redesign. Interestingly, at MIT it was observed that students were asked to Utilize the following skills before, or without ever being, taught the skills: 2.4 Personal Skills & Attitudes, 2.5 Professional Skills & Attitudes, 3.1 Teamwork, and 4.5 Implementing.

OBSERVATIONS

A process has been developed and demonstrated for benchmarking curricula against a set of outcome-based criteria, in this case the CDIO Syllabus. Observations and conclusions can be made with regard to the process and the results obtained.

The survey process gathered important data on the occurrences of instruction in personal, interpersonal, and system-building knowledge and skills throughout the curriculum. Data collected was reasonably complete, accurate and precise. The precision of the results is attributed to the carefully crafted definitions of Introduce, Teach and Utilize, and the extensive explanation of the topics contained in the CDIO Syllabus. The accuracy and completeness were significantly aided by the person-to-person interview format, conducted by an education professional.

Survey limitations included the fact that it captured a particular moment in time, and therefore reflected the observations of the individual who was teaching a given course in the designated academic year. In principle, the instructors for several years could be surveyed (if the teaching assignment rotated). This would significantly increase the survey effort. The survey accuracy depended on the willingness of faculty to participate, and the truthfulness of faculty responses.

The survey results are indicative of the experience of students in the programs examined, but because of specializations and electives, any given student will take more courses than those surveyed, which tended to be only the required courses.

Unexpectedly, the survey proved a good instrument of faculty education, engaging the faculty, educating them about the CDIO Syllabus, and exposing them to issues designing a curriculum to meet these objectives.

The benchmark survey definitely helped to identify the disconnect between the current curricula, and the desired inclusion of the CDIO Syllabus topics. Knowing the location of the gaps, overlaps and overabundance of teaching occurrences in the current curricula will provide invaluable information for redesign. The specific results of the survey are quite informative:

- There is clearly a significant fraction of the curriculum time currently devoted to teaching personal, interpersonal, and system building skills, but the occurrences are not evenly distributed, and are dominated by personal skill instruction.
- There is strong evidence of inefficiency, with topics including many repeated occurrences of Introduce and Teach. There was no evidence apparent in any of the programs of a consistent plan to teach these skills.
- There were a number of cases in which instructors would Utilize a topic that had been Introduced (sometimes many times) but never Taught.
- Despite the absence of deliberate design, there were significant similarities in the pattern of teaching of the skills among the four universities, and also reasonable agreement with the CDIO Syllabus survey results on the desired distribution of teaching resources.

As a whole, these results indicate that a consistent and deliberately designed CDIO-based engineering curriculum could be implemented with existing resources, yet provide a much more effective education for the students. The survey provides useful indications of how and where to begin this process in each program.

As a final note, it must be emphasized that the allocation of teaching resources, and the creation of curricular plans in no way ensures that the students will attain the desired level of competence in these topics. Rather, it is the combination of a well-designed curriculum, effective pedagogy, and student effort that will allow the attainment of this goal.

CONCLUSIONS

This paper focused on an important early step in the curricular change aspects of the CDIO Initiative. In order to reach our goal of educating engineering students in a technical discipline as well as in a broad set of personal, interpersonal and system building skills, improvements must be made to curricula. The challenge is to find innovative ways to make double duty of teaching time so that students develop a deeper working knowledge of the technical fundamentals while simultaneously learning CDIO skills. This requires changes in curricular structure, exploiting extracurricular and extra-campus learning opportunities, development of new teaching materials, and integration of new teaching techniques.

The CDIO Syllabus and the benchmarking results guided the transformation of existing programs in the four universities to CDIO-based programs. These became the basis for four enabling implementation activities: reform the *curriculum* structure and content; reform and improve *teaching and learning* strategies and approaches; develop and use the new *workshop-laboratory* learning environment; and employ an *assessment* process, which measures student and program progress towards consensus goals, with feedback for process improvement. Future papers will describe these implementation activities that build upon the benchmarking results.

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