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EXPERIENCES FROM THE TRANSFORMATION OF AN ENGINEERING EDUCATION INTRODUCTORY PROJECT DESIGN COURSE INTO A PROJECT DESIGN-BUILD-TEST COURSE

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Abstract

This paper describes the changes made to an introductory course in Mechanical Engineering at Chalmers University of Technology to transform it from a project design course into a project design-build-test (DBT) course. The aim is to inspire engineering educators to introduce practical hands-on build (manufacture) elements in their curricula through an account of the positive experiences gained. The introduction of a build element already in the introductory course rather than towards the end of the curriculum is a novelty which seems, in their own opinion, to improve the students general understanding of the theory of product development and its tools and the necessity to plan ahead in the design process to consider factors related to the production and use of their designs. The opportunities to combine theoretical and practical work and to get to see the final result of a product development process have also generally been very appreciated by the students.

1 Introduction

Engineering education has experienced profound changes after the Second World War as a result of the rapid expansion of scientific and technical knowledge. While most pre-war engineering teachers were practicing engineers themselves, educators of later generations have in many cases been technical experts specialized in fairly narrow fields. In the teaching of engineering skills, this has led to a general tendency to devote relatively more time than before to well-defined scientific problems and less to open-ended engineering design problems, with all the complications associated with the latter. This shift from synthesis towards analysis in engineering education has produced graduating students that compared to earlier generations are probably better at analysis but not as good at synthesis, which is really what engineering is all about.

The above observations created reactions in the 1990's, from industry and related organizations as well as from academic faculty, that are touched upon in a paper by Rugarcia et al. [Rugarcia, Felder, Woods & Stice 00]. In Chalmers University of Technology this resulted in a redesign in 1995 of the 4,5 year Mechanical Engineering (ME) programme in an attempt to return to a more design and synthesis oriented curriculum. An element of this change was a new course – 'Introduction to Mechanical Engineering' – that was developed with an overall aim to give the first year students an introduction to ME and the mechanical design process as well as to motivate them for their further studies. A novelty in the course was a design project of the kind that Raucent has labelled pre-project [Raucent 04], and that the students carried out in teams of about four. The underlying idea for this has been discussed in papers by Mourtos & Furman [Mourtos & Furman 02] and Larochelle et al. [Larochelle, Engblom & Gutierrez 03]. Each team picked a problem from real life and designed a solution to it, which was presented orally as well as in a written report at the end of the course. The technical complexity of these problems was of course comparatively low, since fresh students are still at the high school level in terms of engineering and technical problem solving knowledge. The design project as well as the course as a whole was well received by the students. The course, which comprises four weeks of full time work for the students, has since then been given to the Chalmers ME newcomers during the first semester of each academic year.

In 2000 Chalmers entered into a joint project with the Royal Institute of Technology (KTH), Linköping University (LiU) and the Massachusetts Institute of Technology (MIT) to further reform its ME programme in response to the perceived deficiency in the teaching of engineering practice. This project, The CDIO Initiative [www.cdio.org], aims at developing students' Conceiving, Designing, Implementing and Operating (CDIO) skills. The CDIO Initiative has since its start expanded to incorporate more member institutions, and it is now into its fourth year. During the course of the CDIO development work, and as a consequence of it, it has become apparent at Chalmers that design-build-test (DBT) activities should be included in the engineering curriculum not only earlier but also to a greater extent than before. A DBT experience is a learning event where the learning takes place through the creation of a product or system. 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. It was therefore decided that a new workspace, The Prototype Lab, should be equipped with appropriate hand tools and machines and used in undergraduate mechanical engineering education to teach the students hands-on skills that would allow them to take the last step in the design process, which is to build and test what they have designed. It was also decided that the first DBT exercise in the ME programme should be carried out in the introductory course. The Prototype Lab was opened in May 2003 and was first used in the course 'Introduction to Mechanical Engineering' during the first semester of the academic year 2003-2004.

This paper presents how the 'Introduction to Mechanical Engineering' project design course that was originally introduced in 1995 was transformed into a project DBT course in 2003, and what the experiences are from the first run of it. Results of the change will be presented, as well as plans for the further development of the course that will take effect in the academic year 2004/2005. The focus will be on the build-test activities.

2 The project design course

The specific contents of the 'Introduction to Mechanical Engineering' project design course have gradually changed over the years from the first run in 1995. An early version of the course was presented in a paper by Malmqvist [Malmqvist 97]. Gustafsson and several co-authors have presented the 2001 version of the course in comparison with introductory courses at collaborating CDIO institutions [Gustafsson, Malmqvist, Newman, Stafström & Wallin 02] and [Gustafsson, Newman, Stafström & Wallin 02]. In the 2002 run of the course, it had evolved into the structure shown in Figure 1.

	First semester of academic year 2002/2003	
	1st study period	2nd study period
Lecture and exercise topics	Computer Literacy Information Search Study Techniques Human Factors in Engineering Communication Teamwork	Supporting subjects * Design Methodology Sketching
Teamwork activities	Essay Writing	Design Project

*) Engineering and The Environment, Gender and Engineering, Engineering and the Society, and Professional Engineering Experience.

Figure 1. 'Introduction to Mechanical Engineering' course structure in 2002.

Computer literacy included basic competence in the use of the computer system of the School of Mechanical Engineering at Chalmers, and software for word processing, spreadsheets, communication etc. The Information search covered techniques for searching electronic media, and the element Communication treated oral as well as written communication.

Supporting subjects are labelled as such because they were not of primary importance for the students to be able to complete the design project.

Since all the nominally 150 beginning ME students took the course 'Introduction to Mechanical Engineering', it was very teacher-intensive with more than twenty junior and senior teachers and instructors engaged. Ten of them supervised the teamwork activities.

There were typically three students working together in each technical essay writing team. The essays were written in Swedish and besides being checked by the respective supervisors they also had to be submitted to an expert on language and report writing who scrutinized them and suggested changes to them that had to be carried out before they were finally approved.

The design projects in the course were carried out in student teams of four. The teams were encouraged to come up with their own problems to work on, but they could also pick a problem from a given list of ideas or ask the supervisor to suggest a problem. All problems were technically comparatively simple, since the students competence in the engineering disciplines was still effectively at the high school level. Examples of problems were "Collapsible wheelbarrow", "Can opener for the handicapped" and "Brake system for prams". The students then listed customer requirements, brainstormed to produce possible solutions and used standard techniques taught in the Design Methodology lectures to select the best of their concepts. The design projects ended with a written report that included sketches and simple drawings of what had been designed. Each team had to make an oral presentation of the report to the other teams that shared the same supervisor. The reports were mainly checked and graded with respect to their technical contents by the respective team supervisors, since after having written the technical essay the students were considered sufficiently good at writing.

3 The project design-build-test (DBT) course

When it was decided that the design project in the course 'Introduction to Mechanical Engineering' should be extended to also include a build-test phase, it became obvious that it had to start already in the first study period to allow building and testing to take place in the second study period. The redesigned course took on the structure that is shown in Figure 2.

	First semester of academic year 2003/2004	
	1st study period	2nd study period
Lecture and exercise topics	Computer Literacy Information Search Human Factors in Engineering Written Communication Teamwork Design Methodology Sketching	Study Techniques Oral Communication Supporting subjects *
Teamwork activities	Design Project (theoretical design)	Design Project (build-test)

*) Engineering and The Environment, Gender and Engineering, Engineering and the Society, and Professional Engineering Experience.

Figure 2. 'Introduction to Mechanical Engineering' course structure in 2003.

Sketching was moved from the second to the first study period since this skill is primarily exercised in the conceptual design phase. This made it necessary to remove something else from the first study period. One or several course elements also had to be taken out of the course altogether if the workload for the students was to remain unchanged. Essay writing, the other teamwork activity in the course, was selected for cancellation because it would not be practical to run two project activities in parallel. However, since the Essay writing had in previous years proven to increase students' skills in report writing, it was decided that it would at least be partly compensated for by having the language expert scrutinize the design project reports instead. Finally, in order to get a more even work load distribution over the two study periods, Study techniques and the part of the Communication element that treated oral presentations were moved from the first to the second study period.

The introduction of DBT meant that the students would now do practical work with the use of potentially hazardous tools and machines. A safety information session of two hours with groups of eight students attending was therefore introduced prior to the building phase. After this session the students got permission to work in The Prototype Lab and use its' hand tools and simpler machines, which were considered to be sufficient for their purposes. In order to get access to use NC machines and other heavier and more complex machines the students had to pass a special test or ask a lab engineer to help them. The ten teachers who were going to supervise the students had to go through the same safety procedure as the students did.

Table 1. Condensed CDIO Syllabus, showing three levels of content detail [Crawley 01].

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

3.1 Course contents relative to the CDIO Syllabus

The CDIO Syllabus [Crawley 01], displayed in Table 1, is a formal summary of the different skills that a graduating student should possess according to the CDIO Initiative, based on opinions from faculty, academia and industry. Each of the skills should thus be taught in an undergraduate engineering education programme. Table 2 shows which syllabus items that are treated in the project DBT course 'Introduction to Mechanical Engineering', as well as to what depth, expressed by the levels Introduce, Teach and Utilize respectively. Syllabus items 2.2.3, 4.5.2 and 4.5.5 printed in bold type have been added to the table after the introduction in the course of the build-test element.

Table 2. CDIO Syllabus contents and levels of 'Introduction to Mechanical Enginering'.

CDIO SYLLABUS ITEM	INTRODUCE (I)/ TEACH (T)/ UTILIZE (U)	EMPHASIZED SUBTOPICS IN CDIO SYLLABUS
2.1 Engineering Reasoning & Problem Solving	T	2.1.1, 2.1.5
2.2 Experimentation & Knowledge Discovery	T, U	2.2.2, **2.2.3**
2.3 System Thinking	I	2.3.1, 2.3.4
2.4 Personal Skills & Attitudes	I	2.4.3-4, 2.4.6-7
3.1 Teamwork	T, U	3.1.2
3.2 Communications	T, U	3.2.3, 3.2.5-6
4.1 Societal & External Context	T	4.1.1-2, 4.1.4-6
4.3 Conceiving & Engineering Systems	T, U	4.3.1-2
4.4 Designing	T, U	4.4.1-2
4.5 Implementing	I	**4.5.2, 4.5.5**

Table 2 clearly shows that the aim of the course is not primarily to develop students' skills in technical knowledge and reasoning, but rather to train them in various other skills that an engineer must possess.

4 Experiences from the first run of the project design-build-test (DBT) course

The modified course was first run during the first semester of the academic year 2003/2004. During the design phase in the first study period it was noticeable among some of the students that they were aware of the fact that what they were now designing they would also (have to) build later on. A few of them did not look forward to this, while others could not wait to get started in The Prototype Lab. It was also obvious that some student teams took the building into account in their designs, a tendency which had been less apparent in earlier years when the design project ended with drawings and simple sketches of the designs.

When the student teams had completed their designs at the end of the first study period they were asked to specify what they would need to build their products so that The Prototype Lab could be stocked with sufficient types and quantities of materials. This was particularly important since the lab was brand new and had no previous supplies. There was no formal requirement on the teams to present bills of materials. However, teams with well defined designs could fairly accurately tell what they would need while other teams who had not given the same consideration to the building phase of their projects had more vague ideas about this and needed to consult the engineers who were to assist them in the lab. Most questions were solved in this way, and when the teams started to build, they all got off to a good start. In addition to standard materials and components (i.e., wood, Perspex, screws etc.), each team was also allowed to buy special components that they would need (i.e.

wheels, other machine elements etc.) for up to SEK 500 after consultations with and approval by their supervisor and the lab engineers.

There were about fourty project teams in the course, but only six of them were allowed to work in the lab at the same time. Each team was given access to the lab for three four-hour periods, which was what was estimated that they would need in order to be able to finish their products. This was also roughly the maximum time that could be allocated to building and testing within the total course time. If some teams had had problems to finish on time it would have been possible to allocate a few extra four-hour periods for building, but they all finished on time, a few even after only two of their three work shifts.

The building work went very well for most groups, and no accidents or even incidents occurred. All groups managed to present something functional, either a scale or full scale model of their product or a model that displayed some function of it.

At the outset of the course no standard test procedure for the finished models had been specified, since it was unclear how much time it would take to build them. The final testing was therefore not very rigorous, but in principle amounted to checking that the models fulfilled all the criteria set in the list of requirements that had been specified at the start of each project.

Photos of the built models are displayed at www.ptl.chalmers.se.

4.1 Results from questionnaires to students

At the end of the course the students were asked to answer two questionnaires. One of them contained questions about the course as a whole and was produced by the Student's Union. The other questionnaire was produced by the person responsible for the course (i.e., the author of this paper) and was devoted to questions about the build-test phase of the projects.

4.1.1 The questionnaire made by the Student's Union

This questionnaire comprised nine questions (in Swedish), of which two were concerned with the build-test phase of the projects. 124 students answered the questionnaire.

Question 9 was: "*How do you like doing practical work?*", which is here interpreted as referring to the build-test phase of the projects in The Prototype Lab. It could be answered on a scale of 1-5, where 1 was the most negative and 5 the most positive. The answers were

Grade	1	2	3	4	5
Number of answers	2	8	17	45	52

Median	4
Mean value	4,1
Standard deviation	1,0

Another question was: "*What do you think about the time allocated to work (in The Prototype Lab in this course)?*" The answers were

Too short	About right	Too long	No answer
3	98	13	10

4.1.2 The questionnaire made by the course responsible

126 students answered this questionnaire. It contained eight questions (in Swedish) of which five were of multiple-choice type and hade a scale of 1-5 with the meaning

Not at all	A little	To a certain degree	A lot	Very much
1	2	3	4	5

The questions and answers are summarized below.

Question 1: "*Do you think that the building work has contributed towards reaching the course goals?*"

Median	4
Mean value	3,7
Standard deviation	0,9

Question 2: "*Did you find it stimulating to design when you knew that you were later going to build a model of what you had designed?*"

Median	4
Mean value	3,8
Standard deviation	0,8

Question 3: "*Do you think that the building has made you learn more about the product development process than you would otherwise have done?*"

Median	3
Mean value	3,2
Standard deviation	1,0

Question 4: "*Do you think that there was a good connection in the course between the design and the build phases?*"

Median	4
Mean values	3,5
Standard deviation	0,9

Question 5: "*Do you think that your team received the help that you needed during the build-test phase, in terms of quantity as well as quality?*"

Median	4
Mean value	3,8
Standard deviation	0,9

The students could add comments of their own to some of these questions, and they were also asked what they would do differently if they were to do the same project again and what could be improved in the course regarding the building phase. For obvious reasons it is not possible here to present all comments and answers, but in general the students seemed to be very satisfied with the opportunity to combine theory and practice, and they felt that they had succeeded. Many of them also expressed that it had been great fun to build. During their projects they had also noticed that it is important to plan the work, that the design phase is important for the final product to become successful, that their designs should perhaps have been more developed before they started to build them, that they should have studied a larger number of alternative solutions to their problem and that it is difficult to change things after you have started to build your model. There were also students who felt that they had let manufacturing considerations take priority over the product functionality, in the sense that they ought to have been "braver" and aimed for a more qualified design.

Critical comments were mainly of two types. Some students complained that they had not had a lecture on materials, which made it difficult for them to know what to build from. Others thought that the selection of materials available in The Prototype Lab was too narrow. A few had wanted more advance information on what tools and machines that were available in the lab, so that they could have taken that into account in the design process. The other type of critique was related to the restrictive policy for the use of machines in The Prototype Lab, which was adhered to throughout the course in order to prioritize safety. Some students who considered themselves competent enough to use more complex machinery were of the opinion that they should have been allowed to use it, although none of them took or passed the test required to be allowed to do that.

5 Discussion and conclusions

The general feeling among the faculty and the staff that were involved in the building stage of the course was that it went very well; that it met with the learning expectations and that most students seemed to appreciate it. This also correlates with the students' answers to the questions in the questionnaires and has led to a demand for more DBT experiences. It is also in agreement with the opinion of a group of five students who took the course in 2002, before it was changed, and who were interviewed 1,5 years after their course ended and said that they believed that it would have been useful for them to have a DBT experience already in year one and that they wish that they would have had such an opportunity. The experience after the course is therefore that it confirms the findings from a survey among DBT courses in three Swedish and one American university, carried out as part of the CDIO Initiative, that DBT experiences seem to motivate students, integrate different engineering disciplines, train system development and nontechnical skills such as teamwork and communication, and that they therefore play a key part in engineering education [Malmqvist, Young, Hallström, Kuttenkeuler & Svensson 04].

Chalmers is now in a period of transition from the present educational structure to that known as the Bologna 3+2+3 model, which will take effect for all students who begin their studies at Chalmers in the autumn of 2004. Within the Bologna model Chalmers ME plans to offer DBT elements in courses in all of the first three years of the engineering curriculum, and possibly also in the master programmes that follow thereafter. We will thus device a structure that supports a gradual build-up of students' knowledge in engineering design as well as train their teamwork and presentation skills and motivate them for their further studies, of which the course presented in this paper is the first building block. This new structure will also cater to those students who at the end of the introductory course immediately asked which the next course was in which they would be allowed to design-build-test. Students who want to do extracurricular DBT work can also join the XP society at Chalmers, the members of which have access to The Prototype Lab during hours when no activities are scheduled there.

The estimated time needed for the project teams to be able to finish their models proved to be just right, judging from the fact that all teams finished on time and only a few ahead of time.

6 Future modifications of the course

In the next run of the course, during the first semester of the academic year 2004/2005 the elements Communication and Teamwork will expand in a planned effort to build on the knowledge gained in this course in later courses. CAD will also be introduced as a new subject, and the course volume in terms of workload for the students will increase by 25%.

A lecture on construction materials was requested by many students last year and will also be added in the next run to help them choose the proper materials and manufacturing methods for their models, and each project team will be required to present a bill of materials at the end of the first study period. This will stimulate them to finalize their designs and come even better prepared to the building phase, and it will also simplify the acquisition of materials for The Prototype Lab so that every team will have available what they need.

In order to make the product development sequence complete in the course it is necessary to introduce a formal procedure for testing of the resulting models to verify that they fulfil the requirements that were specified at the start of the projects.

Finally, the supervisors need to be better prepared for their tasks in order to be able to give maximum support to their teams in The Prototype Lab. The majority of the supervisors do not have any or limited knowledge of materials and production methods.

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