AN INTEGRATED APPROACH TO DESIGN TEACHING IN A GENERAL ENGINEERING DEPARTMENT

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ABSTRACT

Design teaching is widely recognised as the core activity in engineering education, which integrates the subject specific technical contents with the social and technical needs. Design is the creation and development of products or systems to meet the needs and it involves significant technical and intellectual challenges. Integration of all engineering understanding, knowledge and skills are needed to solve the real problems. This paper describes an integrated approach to design teaching in a General Engineering department. The integrated approach emphasizes the need for systems and product design approach, and aligns the CDIO approach in the design teaching, involving: (1) the generation of general product concepts, (2) the selection of concepts between competing design solutions, (3) the application of engineering principal for detailed mechanical, electrical and software specifications and (4) the integration of the product designs. The exercise provides students with a platform to think across discipline-specific engineering fundamentals and to integrate technologies in product and system design. It also provides an opportunity to integrate technical fundamentals with personal and interpersonal skills for developing professional and leadership skills.

KEYWORDS

Design teaching, CDIO, Integrated approach, Design-implement experience

INTRODUCTION

There is a general recognition that design should be at the heart of the engineering curriculum, based largely on the observation that design is one of the core activities that professional engineers undertake [1]. Design is the creation and development of an economically viable product, process or system to meet a defined need. It involves significant technical and intellectual challenges and can be used to integrate engineering understanding, knowledge, know-how and skills to the solution of real problems. The requirement for design at the core of the education of professional engineers was enshrined in the UK-SPEC of Engineering Council's Standards [2], which stated, "the course must be taught in the context of design, which provides an integrating theme".

Design has become the central or core activity in our teaching and acts as a bond between various subject specific contents in our teaching. The Department of Engineering at Leicester is a Department with a general engineering philosophy; it offers a wide range of accredited undergraduate engineering courses, including aerospace engineering, communications and electronic engineering, electrical and electronic engineering, software and electronic engineering, general engineering and mechanical engineering. The broad base of our degrees aims to provide students with the skills to meet the technical challenges, enabling students to adapt to the changes in advanced technology and giving students a wider range of career options. Research and development in our design teaching follow our aim that our engineering programmes should graduate students who can design effective solutions to meet the current social and customer's needs.

The traditional model of engineering education is discipline specific, with a strong emphasis on the engineering science of that discipline. It was previously expected that graduates would work within their specialism. The reality of today's workplace is that employers (particularly the larger ones) expect graduates to join multi-functional teams engaged in the development of complex system projects. Even amongst smaller companies, there is still a need for graduates who can work across disciplines and who can integrate technologies allied to different disciplines. A unique feature of the design teaching at Leicester is the way in which 2nd and 4th year students interact in the solution of a multidisciplinary design problem. Our design teaching started from the so-called "partial design" approach [3] for a mechanical component, such as water bucket transporter, in 1990s, and then changed to a "total design" approach [3] for an integrated system, such as a robot, in early 2000s in which different disciplinary technologies were integrated into a system or product. Recently, we incorporated CDIO [4] concepts in our design teaching through (1) introducing active learning in design and (2) integrating technological and non-technological training in the design including communication, team work, and the awareness of social and society needs.

In this paper, we will explain the integration of design throughout our undergraduate curriculum, then introduce our project based 2nd year design learning using CDIO concepts, and finally we will address some ways of strengthening the active learning and the integration of technical and integrate technical fundamentals with personal and interpersonal skills in our design learning.

INTEGRATION OF DESIGN THROUGHOUT THE UNDERGRADUATE CURRICULUM

In the traditional curriculum, knowledge of each discipline is taught via a series of courses, and students become proficient at solving well-defined problems by the end of these. However, in reality, most of engineering problems are complex, open-ended problems that require synthesis of the knowledge gained in inter-disciplinary courses. For economic considerations, the best overall solution is not necessarily the best solution for each individual component of the problem. A good paradigm for design education is the integration of design throughout the undergraduate curriculum. Design is one of the five specific learning outcomes that graduates from accredited engineering programmes must achieve (see table 1). The five learning outcomes in the table were defined by broad areas of learning. Design has become the core of the 5 specified learning outcomes since design involves significant technical and intellectual challenges, is the creation and development of an economically viable product to meet custom's needs and can be used to integrate all engineering understanding, knowledge and skills to the solution of real problems.

Table 1 Specific learning outcome in Engineering Degrees [2]

1	Underpinning science and mathematics, and associated engineering disciplines, as defined by the relevant engineering institution
2	Engineering Analysis
3	Design
4	Economic, social, and environmental contexts
5	Engineering Practice

To fulfil the requirement for Professional Accreditation and to fulfil customers' needs, design education forms the spine of our curriculum and runs across the whole duration of undergraduate training, as illustrated in Table 2.

Table 2 Design teaching at the Engineering Department at Leicester

Year 1	First year design	10 credits
Year 2	Second year design	10 credits
Year 3	Third year research project on design	20 credits
Year 4	Fourth year project on design	20 credits
Year 4	Design management study	15 credits

In the first year of our course, the design module has 7 lectures, 40 hours practical drawing classes and 27 hours private study. Students are continuously assessed throughout the semester. During this period, design courses emerge as a means for students to be exposed to some flavour of what engineers actually do while enjoying an experience where they could learn the basic elements of the design process by doing case studies. At the end of first year training, students are able to demonstrate competence in the use of drawing conventions and standards, computer aided design and design methodology, and are able to convey basic information about engineering components and circuits. Through a few open-ended case studies near the end of the semester, students learn to break down a task into sections which can be analysed numerically, allowing a complete working system to be designed to meet a performance requirement.

In the second year of our course, the design module contains 6 lectures and 28 hours design classes and 45 hours private study and group work. This year, students will be grouped into design teams and all the teams will be assigned a design task. Students will design, manufacture the product or systems and compete with other design teams at the end of semester. Second year students will meet and report to their customers. They will be organised by a line manager, a role taken by a 4th year student, and apply their course work knowledge to make design decisions. Communication skills within a group environment are experienced together with the pressures of producing results and tasks on time, to budget and to specification. At the end of this module, students will have experienced a real-life scenario, which a design team might experience in industry. The format of second year design teaching follows the “Total Design” approach initially, but now incorporates “CDIO” concepts. The second year design teaching and the application of CDIO initiative will be presented in more detail in the next section.

In the third year, a design project can be chosen as a student’s project. This will be an individual project, which will occupy approximately one quarter of the student’s time. The project may be initiated by the student or selected from a list of topics offered by staff members. The design projects usually consist of the development of either a piece of equipment or a system. The third year design project covers application of the content of all courses taken. Oral presentation and written report are required. In a typical 3rd year design project, students shall be able to analyse existing designs such as troubleshooting and debottlenecking and more importantly to apply the knowledge of their discipline to the design of new processes or products.

In the fourth year, MEng students will have training in design management in the first semester and act as a line manager for the second year design teams in the second semester. In the 4th year design management study, students will experience the full design cycle, starting from market/social needs and technical drive for a new product, then market survey and profit margin for the new product, developing product specifications and selecting of design concept, and risk and fault tree analysis of the product. By the end of the 4th year, students will have a good appreciation of the skills required in managing the design of product or process from marketing to product release together with the skills and techniques required to manage and lead a design team.

In conclusion, we have integrated design teaching throughout our undergraduate curriculum to ensure that our undergraduate will be well prepared for an industrial career, without compromising the intellectual rigour of a single discipline course. Through the design training, we expect our graduates to have an understanding of the importance of systems thinking and a whole product holistic appreciation to meet the society and customer's needs. In the next section, we will introduce our implementation of the integrated approach design teaching as an example.

IMPLEMENTING PROJECT BASED LEARNING USING CDIO CONCEPTS

Evolution of Project Based Learning in Leicester

We have implemented project based learning in design since early 1990. In the second year of our course, students will be grouped into design teams and will be assigned an open-ended design task. Design teams will perform design, manufacture the product or systems and compete for the performance of the product with other design teams. As listed in Table 3, our project based design teaching started from so-called "partial design" approach [3] for a mechanical component in 1990s, and then changed to "total design" approach [3] for an integrated system in early 2000s through integrating different disciplinary technologies into a system or product. Recently, we incorporated CDIO concepts in design teaching through (1) introducing active learning in design and integrating technological and non-technological training including communication, team work, and the awareness of social and society needs.

Table 3 Design tasks in the Engineering Department at The University of Leicester since 1995

Year	Design task
1995	Container transporter
1996	Water bucket transporter
1997	A wheel-less locomotive device (plc based straight track)
1998	A wheel-less locomotive device (plc based wall obstacle on track)
1999	A moving autonomous transporter - rice collector with 2 walls)
2000	A moving autonomous transporter - block collecting from 3 locations
2001	Robot tug-of-war
2002	CD jukebox
2003	Ball bearing size sorter & distributor
2004	"Mars" rock sample collection system
2005	Autonomous Sled Transporter Vehicle
2006	Path Following Robot
2007	Wind Turbine
2008	Solar Panel
2009	Water turbine

Composition of Design Teams

The composition of the design team is shown in Table 4. The role of the MEng students is to manage the design project. As project managers they shall not be involved in executing the design, sourcing, building or testing the design. Rather, (s)he is responsible for: meetings, planning, progress monitoring, budget, technical guidance, presentations, audit and internal assessment. By doing these, the design module provides the 4th year MEng students with a real life experience for applying management principles.

Our department currently has 4 Visiting Professors in Principles of Engineering Design. The initiative of the Visiting Design Professor was supported by the UK Royal Academy of

Engineering. It enables distinguished, senior engineers in business to work with their academic colleagues to provide a bridge for undergraduates from education to industry. Their role is to demonstrate and transmit to students and staff that design is the integrating theme in all the engineering disciplines within the university. In our design teaching, Visiting Design Professors act as customers of the design by interviewing students and assessing their design at various design stages and give design lectures from an industrial point of view.

Table 4 Composition of design team at Engineering Department at Leicester

Team Managers (1-2)	4^{th} year MEng students
Customer (1)	Visiting Design Professor
Team Supervisor (1)	Staff member
Technical support (2)	Mechanical technician
	Electrical and software technician
Team Members (6-10)	Mechanical sub-team
	Electrical sub-team
	Communication and software sub-team

The team supervisor is a staff member of the Department who provides technical advice to the team and oversees the design activities in the team.

Team members are 2^{nd} year students who carry out the design. Typically the team consists of 2-3 mechanical students, 2-3 electrical and 1-2 software or communication students. They work together as a team while each member has his/her unique contribution.

Key Activities in Our Second Year Design

Our design teaching followed the “Total Design” concepts initially [total design] and we adapted CDIO concepts in our design teaching recently. Total Design is the systematic application, from the identification of the market/user need, to the selling of the successful product to satisfy the need. We used the product component of total design to achieve the integration of technical subject material in our design. Total design may be constructed as having central core activities – the design core, consisting of market (user need), product design specification, conceptual design, detail design, manufacture and sale. Though the adoption of CDIO concepts in our design we enhanced active learning in design and integrated technological and non-technological subject material in the 2^{nd} year design including communication, team work, and the awareness of social and society need. The active learning and the integration of technological and non-technological will be discussed in details in next section. In this section, we will present key stages/steps in our 2^{nd} year design.

Figure 1 illustrates the key stages in our design. Design starts, or should start, with a need that will fit into an existing market or create a market of its own. In the first semester of the second year, a staff member will meet with visiting design professor to plan/select a design task. Then the selected task will be passed to 4^{th} year MEng students for them formulate a Product Design Specification (PDS) – the specification of the product to be design. At this stage, the 4^{th} year student will assess the market/society needs, and ensure the PDS will meet the market/society needs. The PDS is usually finalised before Christmas, so the 2^{nd} year students will be informed about the PDS before the design semester starts. The PDS acts as the mantle for the total design activity because it places the boundaries on the subsequent stages of design.

Conceptual design is carried out in the first two weeks of the design semester after Christmas. The conceptual stage of the design is primarily concerned with the generation of solutions to meet the PDS. At this stage, each group member is expected to develop a minimum of one design concept for a system or a part of the system. After two weeks, students will be interviewed by a Visiting Design Professor (VDP); each member will have 5 minutes to present his/her selected concept and receive feedbacks from the VDP. After the interview, members of design team will work together to write a concept selection report. The report will contain:

- a morphological diagram or mind-map showing the range of solutions or devices considered for concepts,
- a sketch of concept that was presented to VDP during the interview,
- the criteria derived from the PDS for the design to meet the system requirements and the rules,
- a requirement tree showing expanded criteria and their weightings as decided upon by the team,
- a completed synthesis chart showing: specifications considered, weightings for each criterion and marks for each design concept and the totals, and
- a summary stating the outcome of the selection process and giving outline details of the final design with the division of task to subgroups.

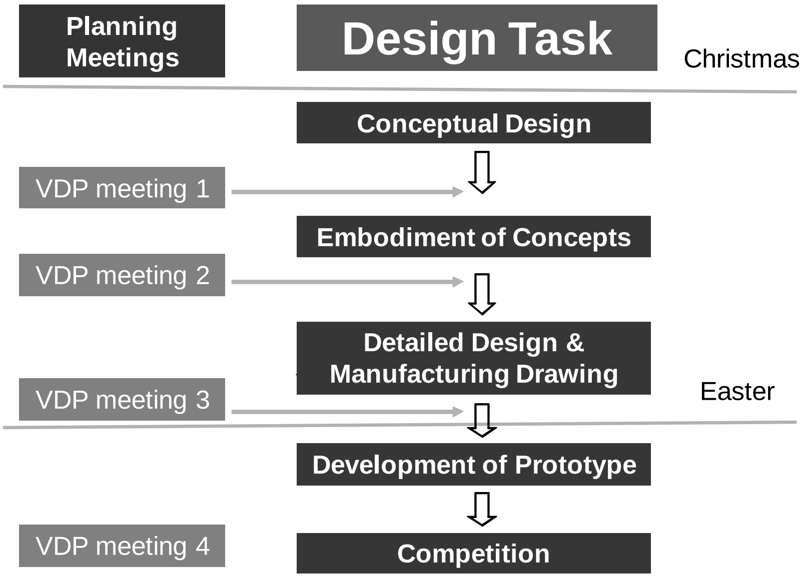

Figure 1. Flow chart illustrating the key steps in 2nd year design teaching at Leicester

In the **embodiment stage of the design**, students will have to expand concepts into more details in order to (1) better understand the concepts, (2) sort out the differences in technological approach, (3) define the component part of the whole system and (4) interface each component with those adjacent to it and its effect on the whole to ensure engineering compatibility. Students need to apply specific discipline-dependent techniques and technological knowledge such as stress analysis, thermodynamic analysis, properties of materials, electrical and electronic circuits, software, communication. After this design stage, students need to prepare a technical design report. A single design report is required from a team. The personnel authoring a section in the report must be named and a general section covering any predicted problem areas should be included. Only named contributors will be allocated report marks for their sections.The report shall contain:

- the details of the concept chosen with details of changes made as a result of *embodiment,*
- an assembly layout drawing, with items indexed, of the complete design,
- the selection of mechanical and electrical components,

- details of the sensing systems, etc.,
- the layout of circuit diagrams for printed circuit boards (PCBs) or/and a software flow chart for data-log and control,
- a list of problem areas that the group foresee in the production of a successful system using fault tree analysis of the system with ideas for overcoming critical faults

Design teams will be interviewed by a Visiting Design Professor (VDP) and the design will be modified according to the comments from VDP. When the design is approved by the staff member of the team, the design will progress to the **detailed design/manufacturing drawing stage**. In this stage, the technical support team work closely with the students to provide technical guidelines on component availability, local constraints in surrounding environment and interfacing components, testing, maintains and manufacturing facility, standards. Students will meet VDPs near the end of this stage to outline the current state of the prototype system, identify the problems experienced and discuss the feasibility of changes. Manufacturing drawings will be produced at the end of this stage and contain:

- an assembly sketch, with items indexed, of the complete design,
- detailed mechanical components and parts drawings using CAD printed full size,
- detailed circuit diagrams for PCBs,
- a detailed wiring layout for sensors, motors and actuators,
- a statement of departmental technical labour required by the various subgroups in parts manufacture and circuits together with the labour costs,
- a detailed parts list and sourcing, from internal stock or external companies to enable parts to be ordered together with the total estimated cost of the system including the labour.

The components will be either manufactured within the department or purchased from external resources. Each team has a budget of £200 to buy components from external sources and £400 for renting components and the cost for technician time in the Department. After Easter, the designed system/product will be assembled and demonstrated before the final competition. The demonstration will be the last chance to identify problems and consider the feasibility of modifications. A **Performance Competition** will be held in the last week of the summer term. This will be the final presentation of the system to the customers represented by all the VDP's who will be allotting a final mark, as a panel of judges, given in the light of all the required customer specifications and the appearance of the system.

The stages as depicted appear to have been gone through sequentially, but it must be emphasized that the design activities shall be operated **iteratively** at all stages**.** So the main design flow can and does reverse at any point in the design activity and some iteration is inevitable, but operating within the design rigorously and systematically will minimize unnecessary iteration.

Promoting Active Learning

Education is not just about the acquisition of knowledge, but the ability to apply that knowledge in a work force and ideally throughout all aspects of life. As engineering academics, we strive to impact real-world situations into our teaching and learning. Briggs (1999) [5] described four levels of thinking about learning and teaching as follows:

- Level 1: Learning is up to the students. A teacher's responsibility is to know the content well and to expound it clearly. When the students do not learn well, then it is due to something the students are lacking.

- Level 2: Teaching is treated as a performance. The teacher obtains an armoury of teaching skills. However, the teaching is focused on the skill itself, but the effectiveness of learning is dependent on the student learning

- Level 3: Teaching is seen as supporting learning. It recognises that learning can only be effective if it is engaged in an activity by the learner. The teacher's responsibility is to set up an environment of learning activities and assessments from which it is very difficult for the student to escape from without learning.

- Level 4: The level is the ultimate aim of higher education. Students take control. The focus is on how the student can manage what they do, initially within framework created by the teacher, but ultimately creating their own framework. There is no shortcut from level 1 or 2 straight to 4, a student cannot operate effectively at level 4 without having experienced level 3 teaching.

Levels 1 & 2 are usually termed as teacher-centred (transmissive) learning, while the levels 3 & 4 are termed as active (student-centred) learning. Active learning is a key element of CDIO concepts and it increases students' motivation, commitment, and retention [6]. Teaching in the Engineering Department at Leicester aims at levels 3 and 4, i.e. towards active learning. As described above, in our engineering design module, 2nd and 4th year students interact for a solution of a multidisciplinary open-ended design problem. Students make their own decisions on how to achieve the performance and to design their own product. This provides a unique opportunity for students at Leicester to reveal their changed conceptual understanding of the subjects and encourage students to restructure their existing knowledge in terms of the new way of thinking about the subject that they have learnt. This development was embodied by a statement from a 4th-year student who recently stated to one of us, "Were we really that bad when we were 2nd-years?"

Different students have different learning styles. To enable students to learn effectively we have tried to adopt approaches to teaching by designing our teaching with different learning opportunities to ensure that the learning is accessible to the largest number of students. In 1992-1994, a study was carried out at Leicester using the Approaches to Study Inventory [7] to measure Leicester students' learning styles, and the results are surmised as follows:

- Medical students most likely to take a deep approach to learning
- Law students differ in their reasons for study – largely external to subject matter
- Science (including Engineering) students are more likely to be surface learners

Comparing with students studying medicine and law, most engineering students are visual and sensing learners. Engineering students like to learn from the concrete experience, such as experiments, being the basis for observations and reflections, which allow them develop a 'theory'. This cycle is similar to so-called "Kolb's experiential learning cycle" [8]. As shown in figure 2, the cycle is a continuous process with the current "concrete experience" being the basis for observations and reflections, which allow the development of a "theory." The "theory" is then tested in new situations to lead to a more concrete experience. To enhance the learning effectiveness, Visiting Design Professors and invited practising designers will give a series of design lectures on presentation skills, design theory and practice using real design examples. Staff members of the design team have also tried to **link the design teaching with other disciplinary-relevant subjects**, such as solid mechanics, thermodynamics, programming and so on. In this way, students can reflect on their conceptual understanding of the subjects and restructure their existing knowledge in terms of the new way of thinking about the subjects that they have been taught.

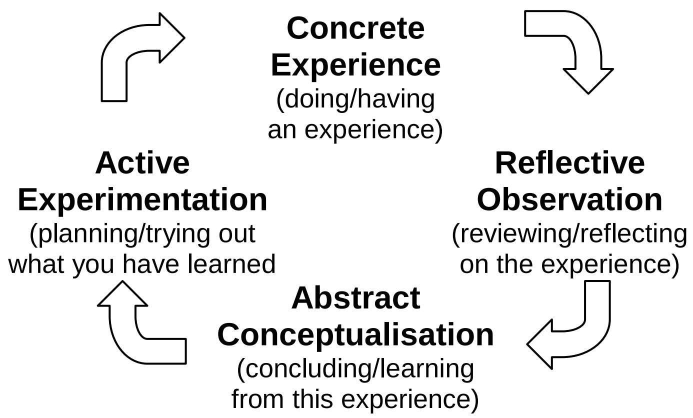

Figure 2. The Kolb learning cycle [8]

Integrating Technical and Professional Skill Training

Professional skill development is not a new concept, but it is becoming increasingly important. The engineering industry has been evolving rapidly, with the result that engineers are expected to have a wider range of skills [2]. Nowadays, engineers increasingly work in teams on projects and much of what we do is virtual rather than tangible. As one project ends, another begins, and so we move from project to project, from team to team, and from one workplace to another. As a result, engineering graduates need to have a solid grasp of disciplinary-relevant technologies, but they are also expected to have a good training in interpersonal skills such as communication, teamwork, and leadership. Indeed, it may be better to consider these “interpersonal skills” as necessary “professional competencies.”

Due to the multi-disciplinary nature of our Department, we integrated disciplinary-relevant technologies into our design teaching through the “Total Design” approach. Recently, some of the training in professional skills was integrated into our design teaching though the adaption of CDIO concepts through integrating technological and non-technological training in the design including communication, team work, and the awareness of social and society needs. In our design teaching process, communication skills within a group environment are experienced together with the pressures of producing results and tasks on time, to budget and to specification. Two lectures on presentation skills are given at the start of the design semester. Students will be interviewed by Visiting Design Professors 3 times during the design. Various presentation skills are required, such as formal presentation and around-the-table discussion with and without visual aids to describe, negotiate and defend the design.

A unique feature of our design teaching is the way in which 2nd and 4th year students interact in the solution of a design problem. The design team consists of mechanical, electrical, software and communication students and the design task contains mechanical, electrical, software and communication component. The overall design is a result of team work effort with clear individual contributions. The collaboration and team spirit is a key issue for the success for their design. MEng students act as line managers of the design team. They are responsible for the overall technical and people management together with budget control. At the end of design learning, students will have experienced a real-life scenario, similar to that which a design team might experience in industry.

For design teams, it is critical for members to hold frequent discussions to build consciousness among all members of the teams and styles of each person. These discussions are the foundation for **leadership development** for students during their university years. We encourage 4th year MEng to explore the importance of leadership and focus on ways that they can develop skills related to this vision, so that they can be of service to others in the design.

CONCLUDING REMARKS

An integrated approach to design teaching has been implemented in a General Engineering department. The integrated approach emphasizes the need for systems and product design approach, and adopts the CDIO concepts in the design teaching. The exercise of our design teaching provides students with a platform to think across discipline-specific engineering fundamentals and the adoption of CDIO concepts. It also provides students with an opportunity to integrate technical fundamentals with personal and interpersonal skills for developing professional and leadership skills.

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