

An Integrated Approach to the Teaching of Engineering Design

Rainer SEIDEL

Department of Mechanical Engineering The University of Auckland, Private Bag 92019, Auckland, New Zealand, Phone: +64-9-3737 599 Ext. 87578, Fax: +64-9-3737 479, E-Mail: rha.seidel@auckland.ac.nz, <http://www.engineers.auckland.ac.nz/~rsei001/>

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ABSTRACT: *Engineering design lies at the core of modern engineering education. Therefore the Department of Mechanical Engineering at The University of Auckland puts a strong emphasis on engineering design education in its undergraduate programme. In this paper the philosophy and practice of design teaching at the Department, the strategic development of design courses based on modern educational theory, and a number of common issues regarding engineering design education are discussed.*

Currently there is a design class in each semester of the Department's four-year BE programme. An outline of each year's design course is provided. The issues that are specifically discussed in the paper include the consistency between design courses and the role of computer-aided design in the engineering design curriculum. Other aspects covered are industry/university collaboration in design projects, staff workload and resource implications and the tension between creativity and structured design approach. Issues of team work in design projects, in particular the creation of realistic, but manageable design scenarios, project management, cheating, and fairness and assessment are discussed in detail. The paper concludes with an assessment of current design teaching practice and with recommendations for the future.

1 INTRODUCTION

Our current world is characterised by rapid and ongoing developments in every field of science and technology. These developments have led to an ever-increasing proliferation of factual knowledge, tools and techniques in all areas of professional engineering. In the past few years many of the traditional tasks and skill requirements of professional engineers have been replaced and/or changed by the introduction of computer and information technology-based methods such as Computer Aided Design and Manufacturing (CAD/CAM) and Finite Element Analysis (FEA). While a solid foundation of engineering science knowledge, a good understanding of physical and mathematical principles and practice in the application of a range of fundamental algorithms, procedures and equations to solve common problems in particular engineering disciplines are still basic prerequisites of professional engineering work in practice, there is more and more emphasis today on interdisciplinary collaboration, use of external knowledge sources and skills in open-ended complex problem solving.

These changes have influenced the demands made of engineering graduates by businesses that employ professional engineers as well as by professional organisations like the Accreditation Board for Engineering and Technology (ABET), the Institution of Engineers, Australia (IEAust) and the Institution of Professional Engineers, New Zealand (IPENZ). Whilst a good grasp of engineering science principles is still a fundamental expectation of modern graduate engineers, some of the most important requirements now are the ability to communicate effectively, the ability to work independently as well as in a team, and the ability to think both critically and creatively [Deans].

Many tertiary institutions have reacted on these changes and have adjusted their engineering curricula accordingly. In this process it has become increasingly clear that the teaching of engineering design plays a key role in the development of the attributes mentioned above. For example, the ABET Criteria for Accrediting Engineering Programs have recognised this by requiring that engineering students be prepared for professional practice by including a major design experience in their curriculum. This must be based on the knowledge and skills acquired in their coursework, and should incorporate engineering standards and realistic constraints such as manufacturability, sustainability, and environmental, economic,

political, social and ethical issues [ABET]. As a consequence design has gradually developed to become a focal point of the engineering curriculum in many educational institutions in the United States and elsewhere [Sheppard], including the Department of Mechanical Engineering at The University of Auckland.

Giving design such a prominent part in engineering education requires the consideration of a number of key issues which are discussed in this paper. They include the necessity of providing consistency between design courses in the different stages of the curriculum in order to present students a coherent and complete framework of professional design activities. Other important aspects are the challenge of project based learning and running team based design projects, in particular the creation of realistic but manageable design scenarios, collaboration with industry, and issues around project assessment.

2 THE ROLE OF DESIGN IN THE ENGINEERING CURRICULUM

Most subjects in the Bachelor of Engineering curriculum such as thermodynamics, mechanics, and dynamics and control are science or technology based with a relatively clear focus on a specific area of technological knowledge. Engineering design encompasses a much broader range of topics than most other subjects covered in the engineering curriculum. The major elements of a typical modern design syllabus are:

- design theory,
- design process,
- design tools, techniques, methodologies,
- design communication,
 - drawing, sketching,
 - drawing interpretation,
 - report writing,
 - oral presentation,
- CAD modelling and applications,
- design projects,
- design teamwork and project management.

The nature of the first four elements of this syllabus, i.e. design theory, process, tools, techniques and methodologies, and design communication is similar to that of other engineering subjects. This material is generally introduced at the start of the design syllabus and can be covered in a traditional lecture/assignment approach. It includes basic drawing and other communication skills that are necessary for students to present their ideas in a format that has become one of the 'trademarks' of the engineering profession. Other elements are other fundamental tools for idea development such as creative methods, techniques for decision making, etc., and an appreciation of the engineering design process and the various tasks that are required to develop a design brief into the model for a finished product. The objective is to equip students with the fundamental theoretical knowledge and skills to understand the nature of design and to start performing basic design tasks. Of course, it will be necessary to review some of these elements, and also cover more complex material as the needs arise at a later stage.

The role that CAD can, or should, play in the modern mechanical engineering design curriculum requires careful consideration [Seidel]. Many students in the first year of an engineering degree have little experience of engineering graphics and need to be made aware of the importance of clear, accurate and speedy technical and design communication within an engineering organisation. This means that they must be able to modify or redesign existing products, and for new projects draw 'what is in their mind' quickly and accurately. To achieve this students must be able to utilise the full range of industrial techniques – from sketching and drawing orthographic views using conventional manual drawing techniques through to using CAD software for design and analysis.

It is important to ensure that students do not treat a CAD system as the 'be all and end all' of the design course. CAD must be introduced as a tool to achieve design goals and not as an end in itself. Students must be asked to consider their current and future use of CAD tools in the broader context of product design, modification, analysis and production. To achieve this they need to be advised to consider CAD as being able to assist them in the following functions:

- A supporting role – CAD used to replace manual draughting techniques, and in particular to rapidly amend CAD-generated orthographic drawings.
- An enhancing role – CAD used to produce 3D models for visualisation and analysis and to enable designers to investigate quickly more design alternatives than is generally possible with manual graphical, technical and/or solid (clay, card, etc.) models [Dvorak].
- An enabling role – CAD also plays an enabling role in design processes by having become the front end for sophisticated Computer Aided Engineering (CAE) tools such as FEA and computational fluid dynamics. It also serves as input for other downstream computer-aided applications such as Computer Aided Process Planning (CAPP), Computer Aided Manufacturing (CAM) and Computer Aided Inspection.

Design projects play a vital role in providing students with a crucial attribute desired by industry for a newly graduated engineer: the ability to identify and define a problem, develop and evaluate alternative solutions, and effect one or more designs to solve the problem [Nicolai]. It is generally agreed that this attribute can only be developed by exposing students to the experience of open-ended problem solving which includes linking engineering science knowledge to complex, real-life design problems. Apart from the ‘hard’ engineering and technical issues, these problem solving activities should include a range of extra-disciplinary and ‘soft’ factors, such as economic, environmental, sustainability, manufacturability ethical, health and safety, social and political considerations [ABET].

3 CONSISTENCY OF DESIGN COURSES

It is obvious that this type of problem based learning can only be achieved by using quite complex project scenarios, and therefore requires careful planning and integration into the rest of the curriculum in order to prevent students from being seriously overburdened and confused. As in other complex and challenging subject areas it is important to structure the contents of the design curriculum carefully and introduce new topics and aspects in a logical and consistent way. Due to the large amount and variety of material and considerations which need to be covered, design project work should ideally span over the whole curriculum. They should lead towards and culminate in a capstone experience that is as realistic as possible, includes a broad range of the considerations mentioned above, and is typical of the problems faced by professional engineers in their particular area of discipline.

An important aspect that needs to be considered is the relationship between design work and the material presented in the various engineering science courses. Projects in the design courses in different years should be offered by different individuals who are from the main specialist teaching groups in the institution in order to create realistic scenarios and provide competent support for the students during their project work. However, this arrangement presents a challenge in maintaining an important common thread in the design courses. Failing to recognise and address this issue can result in a disjointed and sometimes even confusing design curriculum, where certain topic areas may be unnecessarily repeated or unknowingly omitted. Students may also fail to appreciate the progressive nature of knowledge accumulation in design during their curriculum, or be overburdened by design tasks that are too complex for their current level of understanding. It is therefore important to have a consistent design framework for the whole undergraduate degree course.

The framework should include all topic areas and aspects of design that need to be covered in the curriculum. Guidelines should be provided for the introduction, application and review of the different concepts. These guidelines then provide help for course organisers when a design course or project is planned. Likewise, the design guidelines serve as a focal point for the students who are able to see the design course in its entirety as well as a collection of discrete subjects and projects offered in different years. To achieve these objectives the Department of Mechanical Engineering has recently endorsed a set of design guidelines for its undergraduate degree programme [Anon. 2001]. They are structured into the two main areas of ‘Fundamentals of Engineering Design’, covering the topics of design processes, communication in design and basics of CAD, and ‘Engineering Design Applications’, with the topics design of machine elements, integrated design and design of mechanical systems. The different elements and concepts in each topic area are allocated to the various design courses within the Department’s four-year curriculum, providing a good overview at which level of the programme each of the concepts and topics is introduced, and reviewed and/or extended.

For the design guidelines to be effective a regular dialogue needs to take place among the design course and project organisers to inform each other about their course contents. The lecturer in a particular design project needs to be mindful of what has already been covered in earlier design courses so that due reference can be made to previously covered teaching material. Students also benefit from the lecturers being able to advise them about what is forthcoming in the design courses in future years.

4 DESIGN PROJECTS: ENHANCING CREATIVITY WITH A STRUCTURED APPROACH

For many people design epitomises the essence of professional engineering work. It combines the principles of engineering science with creative aspects, thus 'bridging the gap between function and structure of an artefact' [Galle]. However, to many engineers creativity is a nebulous concept that rests uneasily in the precise quantitative engineering world. Whereas a traditional engineering science-based course is often not perceived to be creative, design courses with large projects have the potential to develop the creative talents of students greatly, but they also have the potential to inhibit creativity greatly. The outcome depends upon the academic leadership and their understanding of the creative problem-solving process [Thompson].

Stimulating students' creative talents through design work is challenging: Engineering students often prefer the exactness and predictable nature of science-based problem solving. This trend is reinforced through common teaching and examination practices in the majority of courses in the undergraduate curriculum: for example it is relatively straightforward to prepare for an examination on the basis of problem sheets containing standard textbook questions. Open-ended, creativity-based problem solving as required in design projects is sometimes perceived as uncomfortable, 'airy-fairy' and as a major threat to the well-planned swotting schedule for achieving a specific examination result.

Brainstorming is by far the most commonly used creative technique in design teaching [Pahl]. In Auckland it is introduced in a project in the first semester of Year 1, and applied extensively in conceptual design projects throughout the curriculum. Other techniques that combine creative idea development with systematic approaches, for example function analysis, objective trees, and morphological analysis, are introduced in 'service lectures' for the various conceptual design projects throughout the curriculum.

Design teachers must be aware that students often try to shortcut the creative process by coming up with one 'great idea' for the solution of a given design problem, and *a posteriori* attempting to craft an artificial process around it in order to justify their approach and satisfy the project requirements. To avoid this students at Auckland are required to use and submit a formal design workbook that documents the evolutionary nature of their design work. Over the years the design workbook has become a consistently applied tool in the majority of design project work, and often accounts for a substantial part of the assessment, in particular in team project where students have to submit a team report.

The Department also emphasises the idea of design as a series of interrelated tasks within a systematic design process (see e.g. [Pahl]). This makes it easier for students to appreciate the relevance of creativity in the process, in particular when additional, more structured techniques such as function analysis and morphological analysis [Dominick, Dym] are also introduced. These tools also help students to organise and structure their work in open-ended design projects.

5 TEAMWORK ISSUES

The ability to work in a team has been identified as one of the most important attributes that students are expected to develop during their undergraduate engineering degree course [ABET]. At Auckland, teamwork is emphasised and practised in most of the Department's design courses, starting in the first year of the degree programme, although a significant proportion of design work still has to be performed on an individual basis. Specific teamwork arrangements should be based on the nature of a particular project, the level of students' experience and the particular examination requirements set by the project organiser. Some of the main benefits of team projects include the honing of good interpersonal communication skills, experience in dealing with conflicting views and dissent, practice in the division of work tasks and labour, and enhancement of the creative potential of team members [Denton].

On the downside, some students attempt to take advantage of teamwork arrangements in order to get a 'free ride', or to avoid certain types of tasks, such as CAD modelling, structural analysis, or report

writing. The Department has developed a range of tools such as confidential peer assessment, oral interviews and specific work and submission instructions for students in some projects to eliminate these problems as much as possible. Assessment procedures vary depending on the specific requirements of each project, taking the above factors into account and attempting to achieve an objective and balanced account of each student's abilities at the end of each design course. An important element of this is the careful grouping of students into a new and fair mix of teams for each project in order to avoid 'ghettoisation' of low performing and international students with English as a second language, who in Auckland comprise about 1/3 of the design classes. In particular for these overseas students team work in design is a prime opportunity for mixing with their colleagues from different cultural backgrounds.

6 DESIGN COURSE STRUCTURE

At the Department of Mechanical Engineering at the University of Auckland design has always played an important role in its four-year undergraduate curriculum, and a project based learning approach has been adopted in its design courses since the early 1990s [Anon. 1993]. Over the years, virtually all academic staff members of the Department have participated in various design projects, and there have been several occasions when the strategy of design teaching has been discussed in special meetings, and subsequently formulated as departmental policy [Anon. 1993, 1994, 2001].

In 1995 the University of Auckland changed its three-term academic year into a consistent two-semester system. The Department of Mechanical Engineering took this opportunity to re-evaluate its undergraduate teaching and implemented a new curriculum that reflects the requirements of mechanical engineering graduates in the New Zealand industrial and business environment [Deans]. Engineering design now accounts for about 15% of the overall teaching content, and there is a design class in every semester of the undergraduate degree course, the vast majority of them organised as project based learning experiences.

In the following a brief overview of the design courses in the Department of Mechanical Engineering is presented. As mentioned above, the Department's design activities are aligned through the application of a coherent framework, and are based on a common design philosophy which is communicated to students in their course handouts:

- Providing an evolutionary, coherent course structure from Year 1 to Graduation:
 - From easy to complex;
 - from straightforward to sometimes vague and confusing;
 - from the fundamental principles and basic techniques to their practical applications.
- Covering all major aspects of mechanical engineering design; -Exposing students to all aspects of design work;
- Educating them to become Professional Engineers rather than drafts(wo)men.

Year 1 design

In the first year of their engineering studies students are introduced to engineering drawing, graphics and written design communication. The Engineering Faculty uses a 3D CAD package (the conceptual design system Pro/DESKTOP[®]) in both first year design courses. This is seen as a major component of the first year engineering design curriculum, emphasising state of the art, high-quality graphic communication, and supporting the Department's conceptual design and three-dimensional solid modelling activities.

Year 1 students still have very limited knowledge of engineering science principles. Apart from the above communication issues the emphasis of design at this level is therefore mainly on generic, open-ended problem solving. Additional elements of the design course objectives as stated in the course outline are:

- To provide students with a comprehensive, generic and discipline-independent design framework based on best-practice design methodology, a scientific and systematic approach, and the principles of modern design theory;
- to provide students with a solid foundation of common design concepts, methods and tools that will support all their future design activities at the School and in professional practice;

- to help students learn a structured methodology for approaching and solving new and unfamiliar problems;
- to give students experience in applying those methodologies to real design problems;
- to allow students to experience the joys of a successful design process with a positive outcome; and
- to give students the confidence to be able to solve new problems in other (work) situations.

The design course in Semester 1 concentrates mainly on the development and practice of visual communication skills, like drawing and sketching, which culminates in the introduction of CAD for the creation of a solid model of a given technical object. Team project work is introduced in a 'fun' project at the end of the course. In this project students have to design and build a truss bridge from a given number of hot dog sticks and specified glue and fasteners. They have to apply their engineering mechanics knowledge from the Mechanics course run in parallel during the semester to create a structure with the highest possible load bearing capacity over a given span. At the end of the course designs built by the student teams in the School's laboratories are tested to determine yield and failure mode.

The first project in the Semester 2 class is considered the cornerstone project of Year 1 design. It is based on a relatively vaguely defined client statement of an engineering design problem, which students first have to process systematically through the needs assessment phase into a formal product design specification. In the next project phase students have to apply a systematic approach, and a number of creative techniques and decision making tools, to create a range of concept ideas, to select one of these alternatives, and then to develop this into a comprehensive conceptual design proposal. The underlying theory as well as recommendations for teamwork and project management are provided in form of service lectures and comprehensive course handouts. Students are allocated into groups of four to benefit from teamwork during their project work. However, students must present their work in form of individually written design reports and workbooks in order to practice written communication skills. A confidential peer assessment process is used to ensure fairness and efficiency of the design process in each team.

The second project reinforces the use of the CAD tool to embody design intent. Students have to model a portal frame in such a way that later design modifications can be performed as efficiently as possible, and present a design report, reflecting on their modelling process. The final project in Year 1 is performed as a design competition, where students have to design and build a device for the transport of a delicate object. All projects create a large amount of enthusiasm and excitement amongst the students, in particular as a number of business organisations sponsor prizes for the best results in the competition.

Year 2 design

Whereas the first year design classes are common to students of all engineering disciplines at the University of Auckland (around 540 students in total in 2004), Year 2 is the first year of specific engineering design classes for mechanical engineering and mechatronics students (around 110 students). The main aim is to help students establish a firm foundation for all future mechanical engineering design activities, as well as engage themselves with design projects that require them to use the knowledge gained in courses such as engineering mechanics, thermodynamics and mechanics of materials.

In the first semester, the basics of engineering drawing, including fits and tolerances, are reinforced before the students get introduced to a professional CAD tool, i.e. Pro/ENGINEER[®]. This is also the recommended tool for the design courses in subsequent years when CAD is required. The second semester design course is structured as a mixture of design projects and lectures on specific design topics. The Warman Design and Build Competition project, open to 2nd year mechanical engineering students in Australia and New Zealand, is the first one in the project series. The Department has been very successful in the finals of this competition, which is an indication for the effectiveness of the design teaching in the Department. The Warman project is followed by two other projects that require students to carry out basic structural analysis and engineering mechanics calculations. The lectures in the design course cover topics such as design processes and design of machine elements, and the use of catalogues for the selection of standard and off-the-shelf components for the design tasks is introduced.

Year 3 design

In Year 3 students have reached a level of competence in a range of engineering science topics upon which more demanding design projects can be built. Design work in both semesters is completely

project-based, with teaching limited to the introductory lectures of the course and each project, and to occasional service lectures to address specific issues raised in particular projects. The learning objectives are based on the knowledge and experiences gained in the two previous years of design study, and emphasise the development and reinforcement of good design and work practices and the ability to present designs in a clear and precise manner.

Students have to perform two projects per semester. Each project provides a different emphasis regarding project topic, range of design tasks and techniques to be applied, group work, and submission requirements. For example, the first project in 2004 covers the conceptual design of a utility vehicle loading attachment, is performed in teams of four with individual design reports to be submitted, and an additional oral interview. Emphasis is placed on the creation of an as realistic as possible professional scenario. The design task is introduced as a letter from a fictitious company asking for the submission of a conceptual design proposal by each of the 'design consultancies' consisting of the student teams. Another important aspect that comes into play at this level is the more 'business-oriented' style of presentation of their proposal. This requires them to consider the 'selling power' of their oral and written presentation, the clear explanation of their design approach and their decision-making processes to their client, and the consideration of more 'fuzzy' factors such as manufacturability, cost, customer-oriented value and aesthetic appeal of their design.

The next project requires the design of the mechanism for an electric toothbrush using Pro/MECHANISM[®] by pairs of students, who have to submit individual reports and also have to present their dynamic design models to their tutors on a CAD workstation. The other projects concentrate on design tasks in the area of thermodynamics, strength of materials and dynamics and control. One of them covers the complete design process from initial concept to working drawings, whereas the last one is another design and build project.

Year 4 design

The design classes in the final year of the mechanical engineering degree course are again project based, with students required to perform four major design projects during the year (in parallel to their two-semester final year project, which often also includes major design aspects, and thus could be considered the capstone project of the undergraduate degree course). The learning objectives of the design course are:

- To apply principles studied in Years 2, 3 and 4 in a professional way , using a wide range of advanced engineering methods;
- to develop some understanding of 'Design for X' concepts (assembly, manufacture, fatigue and fracture, quality, etc.);
- to gain an appreciation of issues relevant to design in a wider context, e.g. all product life cycles from idea generation (including market analysis) through to disposal of the product;
- to show competence in the synthesis and detailed design of a major product; and
- to further practise teamwork

Projects are organised by the Department's main teaching groups who ensure that their respective project task is of high professional standard and relevant to their particular discipline. For example, the project organised in 2004 by the Manufacturing Systems Group covers the concept of 'Design for Competitive Advantage'. It is organised in conjunction with a local industrial company which has asked the class to develop design concepts in order to rejuvenate its well established range of consumer products in the Australasian marketplace. Student teams apply methods such as value engineering, morphological analysis and multi-attribute decision-making to identify the scope for improvement in the existing product range, select a particular area for improvement and come up with conceptual solutions and innovations that satisfy the technical and commercial requirements of the industrial client. In recognition of the commercial value of the work and to create maximum amount of enthusiasm amongst the students, the company has sponsored major prizes for the most valuable concepts developed.

7 CONCLUSIONS

The strong emphasis on design teaching and the consideration of the requirements of modern professional engineering practice in the Department of Mechanical Engineering has resulted in a cohesive

and effective four-year design course structure. Design thus has become the focal point of the undergraduate degree programme and a common avenue for the application of concepts covered in various engineering science courses. Covered by a framework of consistent guidelines, the design courses feature a combination of theoretical and practical aspects of design and maintain a sensible balance between factual, science-based material and open-ended, creative elements. The role of CAD has been carefully considered, and the importance of teamwork and collaborative design has been duly recognised in the programme. In spite of occasional minor problems such as cases of student cheating, excessive workload and ambiguously defined project specifications the design programme has been a great success, and many students consider it as the highlight of their curriculum.

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