



The Centre for
Engineering and Design Education

Approaches to the teaching of design

a guide by **Andrew McLaren**

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Approaches to the teaching of design

Overview

Design is an extremely wide subject, covering the whole range of disciplines within engineering. It is at the heart of what engineers do, and draws together all the skills and knowledge that we seek to foster in our students into an activity that has perhaps the greatest effect on society.

There are many approaches to the teaching of design, and each of them has a place in engineering education. These approaches range from the traditional to the truly innovative, encompassing tasks based on individual study and scholarship, to those that require all the skills of group work, management, logistics and communication.

This booklet seeks to provide a resource for all those with an interest in design, and the education and training of engineering students to carry out the design process. A brief description of the internal and external requirements for design in the engineering curriculum is followed by a review of different approaches to design teaching currently employed in engineering schools and universities worldwide. Suggestions for further reading about each approach and a reference section are also provided.

The requirement for teaching of design

There is a general recognition that design should be at the heart of the engineering curriculum, based largely on the recognition that design is one of the core activities that professional engineers undertake. The requirement for design at the core of the education of professional engineers was enshrined in the Engineering Council's Standards and Routes to Registration (Engineering Council, 1997), which stated *“The course must be taught in the context of design, which provides an integrating theme.”*

The most recently revised UK-SPEC standards (Engineering Council 2014), maintain design as a major theme in the competencies required of professional engineers. The word “design” is mentioned on numerous occasions in the UK-SPEC competence statements, most notably under the following general theme:

B: Apply appropriate theoretical and practical methods to the analysis and solution of engineering problems.

These general requirements, when translated into specific learning outcomes by individual professional bodies, retain and expand on the importance of design. For instance, the specific UK-SPEC learning outcomes published by the Institution of Mechanical Engineers (IMechE, 2013) are as follows (Table 1):

Table 1. Specific learning outcomes from UK-SPEC, as published by the Institution of Mechanical Engineers, with particular reference to design

D1	Investigate and define a problem and identify constraints including environmental and sustainability limitations, health and safety and risk assessment issues
D1m	Wide knowledge and comprehensive understanding of design processes and methodologies and the ability to apply and adapt them in unfamiliar situations.
D2	Understand customer and user needs and the importance of considerations such as aesthetics
D3	Identify and manage cost drivers
D4	Use creativity to establish innovative solutions
D4m	Ability to generate an innovative design for products, systems, components or processes to fulfil new needs.
D5	Ensure fitness for purpose for all aspects of the problem including production, operation, maintenance and disposal
D6	Manage the design process and evaluate outcomes

The QAA Benchmark statements for Engineering (2010) include reference to design activities, stating that *“Project work within an MEng programme would usually include both an individual research/design project and a more wide-ranging group project with strong industrial involvement.”* and *“within MEng programmes case studies, design work and projects are typically utilised more extensively, especially during the final year when they build upon the learning of the previous years.”*

The Royal Academy of Engineering has published two booklets on the importance of design. Their booklet *Design principles: the engineer’s contribution to society* (Royal Academy of Engineering, 2002), provides these guiding principles:

- Need** All design begins with a clearly defined need
- Vision** All designs arise from a creative response to a need
- Delivery** All designs result in a system, product or project that meets the need.

A series of four case studies is presented as examples of these principles in action.

The second booklet, *Educating Engineers in Design: Lessons Learnt from the Visiting Professors Scheme* (Royal Academy of Engineering, 2002), is prefaced by the following remarks:

■ *And what do we need to teach? We don't. We need to give the opportunity to gain experience and awareness in multi-disciplined team environments and let the confidence of youth loose on a prepared world. What can we give students in a university department? Experience of working in multidisciplinary teams working on realistic projects. The Visiting Professor's role in this is to develop appreciation of the power of ideas and the value that transferring knowledge can have.* ■

Professor Chris Pearce FEng,
Visiting Professors 2002 Workshop.

The Royal Academy of Engineering commissioned a report entitled *Educating Engineers for the 21st Century* (2006a). This in-depth study, carried out by Henley Management College, involved interviews with experienced industrial practitioners, and a large-scale survey of engineering companies. The report predicted a worsening shortage of high calibre UK engineering graduates over the next 10 years.

One of the working party's recommendations is of particular relevance to the place of design in engineering education (2006b):

■ *Engineering courses must become better aligned with the changing needs of business and industry. In particular, more and better quality project work is needed, based around real-life problems, ideally delivered in collaboration with industry. Work is needed to improve the approach to teaching to ensure students remain motivated and engaged, and graduate keen to pursue engineering careers. There are already important developments in this area, such as the pedagogic approach taken in CDIO, and team-based hands-on engineering. Developments of this sort will not only improve graduate performance in companies, but can also improve recruitment into engineering courses and student motivation.* ■

Characterisation of design teaching activities

Sheri Sheppard (Stanford University) and R. Jenison (1997a and 1997b) conducted an extensive review of first year (Freshman) design education in US engineering schools. While the study concentrated on first year modules, the general characterisation is valid for modules delivered at any level.

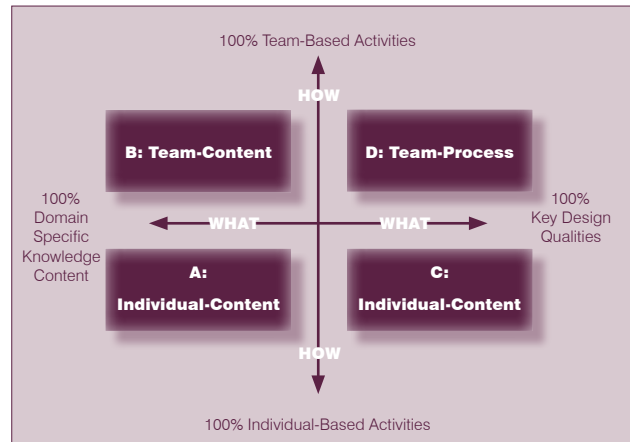


Figure 1. Schematic characterisation of design modules according to the method described by Sheppard and Jenison (1997a)

The authors characterised design activities according to a two dimensional matrix, reproduced in Figure 1. The horizontal dimension refers to **WHAT** is taught, with pure knowledge at the left hand end, and pure design at the right. The vertical dimension refers to the pedagogical approach, i.e. **HOW** the what is taught, with individual-based activities at the bottom, and team-based activities at the top.

They propose that design activities can be characterised according to which quadrant of the diagram they lie in, as follows:

- A. Individual-content centric** (e.g. most traditional lecture-based courses fall in this category);
- B. Team-content centric** (e.g. mainly traditional lab-based courses);

- C. Individual-process centric** (few undergraduate engineering courses fall here, but many studio art courses are here);
- D. Team-process centric** (e.g. most senior-level capstone design courses).

The authors address each of the quadrants in turn. For quadrant A, they review various innovative approaches that have been used to shift the position of traditional courses towards a more central position. Calculus, statics, strength of materials, graphics and CAD have all been addressed, usually by bringing elements of teamwork and problem solving into the class.

For quadrant B, they review courses that have well-defined, domain-specific objectives, but that use team and group work the majority of the time. This type of class is commonly termed inquiry-based learning.

Quadrant C is diametrically opposite quadrant B, and emphasises individual learning which utilises a process centric approach. This type of course is rare, the main example cited being a “Visual Thinking” course at Stanford, addressing core problem solving strategies.

Quadrant D emphasised team based activities focused on process. This type of course is relatively common, and tends to fall into two main groups. The first is where students study the artefacts and designs of others. This may be broadly labelled as “case-based learning”, and several examples are reviewed, including a class utilising mechanical dissection. A more detailed description of a class utilising this approach is described below. The second type of quadrant D class engages groups of students in designing, making and testing objects of their own creation. Many examples of

this type of class are given, full details of which can be found in the papers.

Innovation in the teaching of design

Traditional approaches

Within engineering courses, traditional approaches to design teaching have centred on discipline-specific modules. For instance, in Mechanical Engineering, the subject of machine design is often taught using textbooks that seek to treat the process in a comprehensive manner. Examples of such texts are Shigley and Norton:

- Shigley, Joseph (2014) *Mechanical Engineering Design* 10th edition. McGraw-Hill Higher Education. ISBN-13: 978-0073398204
- Norton, Robert L. (2014) *Machine Design: An Integrated Approach* 5th edition. Pearson Education. ISBN-13: 978-0273793267.

This approach emphasises the need for detailed specification of machine components within the design process, and the books reflect this by including detailed methodologies for sizing of components.

A more product design approach, involving the generation of a general product concept, and the steps that are involved in producing and choosing between competing design solutions is typified by the approach of Stuart Pugh:

- Pugh, Stuart (1990) *Total Design: Integrated Methods for Successful Product Engineering* Prentice Hall ISBN-13: 9780201416398.

This approach strongly addresses the learning outcomes described under D1, D1m and D2 of UK-SPEC (see Table 1.), i.e. identifying the problem and understanding the customer and user needs and the importance of considerations such as aesthetics.

There is a general consensus that while detailed design considerations are vital in engineering practice, students need concrete experience in which to root these concepts.

Design as the core of engineering programmes

Design is widely recognised as the core activity in engineering education, which integrates the subject specific technical content with the needs of customers and business. As mentioned above, this concept was a strong theme in the SARTOR curriculum requirements for Engineering Council accreditation. Many approaches to design teaching recognise this.

Most prominent among curriculum models that follow this pattern is the CDIO initiative.

The CDIO Initiative

The CDIO website introduces the initiative as follows:



■ The CDIO Initiative is an innovative educational framework for producing the next generation of engineers. It provides students with an education stressing engineering fundamentals set in the context of **C**onceiving — **D**esigning — **I**mplementing — **O**perating real-world systems and products.

The CDIO™ Initiative was developed with input from academics, industry, engineers and students. It is universally adaptable for all engineering schools. **CDIO™ Initiative** collaborators throughout the world have adopted CDIO™ as the framework of their curricular planning and outcome-based assessment.

www.cdio.org

The initiative grew out of collaboration between MIT and three engineering departments in Sweden, and has now expanded to a network of now over 120 CDIO partners worldwide.

The approach emphasises the need to teach engineering fundamentals (which will be discipline-specific) integrated with:

Personal and professional skills

- Engineering Reasoning and Problem Solving
- Experimenting and Knowledge Discovery
- System Thinking
- Personal Skills and Attributes
- Professional Skills and Attitudes

Interpersonal skills

- Teamwork and Leadership
- Communications

Product and system building

- External and Societal Context
- Enterprise and Business Context
- Conceiving
- Designing

- Implementing
- Operating

The CDIO Initiative (CDIO, 2004) has a set of 12 standards, described below:

The CDIO standards describe CDIO programs and enable schools to certify themselves if they are meeting the CDIO goals. These principles, or rules, distinguish the specific qualities of CDIO programs and their graduates. As a result, the CDIO Standards define the distinguishing features of a CDIO program, serve as guidelines for educational program reform, create benchmarks and goals that can be applied worldwide, provide a framework for continuous improvement, form the basis of a program's self-certification, and provide academics and employers with attributes that distinguish graduates of CDIO programs.

While it is recognised that these standards represent an ideal program, schools and departments are encouraged to adopt the standards in a progressive manner, and in this way the CDIO initiative is less prescriptive than might appear at first sight.

Some approaches to the teaching of design

Mechanical dissection

Stanford

Probably the best known example of the mechanical dissection approach to teaching design is the course ME99 at Stanford. *ME99 Mechanical Dissection: Course Outline*, Stanford University. Available online at: www-adl.stanford.edu/images/me99syllb.pdf

Students participate in four “dissections” of different artefacts: usually an HP printer, a fishing reel, a bicycle and one other artefact of the student’s own choosing. Students prepare individual presentations concerning the function of their artefact and how it works. They learn the “vocabulary of mechanical systems” through the study of their dissected artefacts and mini lectures on topics such as gears, fasteners, bearings and other mechanisms.

The class fosters an awareness of the design process, stimulates the students to communicate clearly and concisely, and develops their resourcefulness and problem solving skills. In addition, certain aspects of the engineering curriculum are reinforced through application to a concrete object. Topics addressed include free body diagrams, dynamics and strength of materials (Sheppard, 1992).

Strathclyde

The Department of Mechanical and Aerospace Engineering at the University of Strathclyde utilises mechanical dissection to teach design in the first year. In this case, a scrap motor car is dissected by groups of four students. (For much of the first year, students work in the same groups of four, in lab-based activities, problem-based and active learning classes.)

Each group selects a component and removes it from the car. (These are components that fulfil a mechanical function e.g. camshaft, valves, piston and connecting rod, clutch, gearbox, alternator, cooling system etc.). Once the component has been removed, disassembled and cleaned, each group spends approximately one hour in discussion with a member of staff. At this time, the function, physics (forces, stresses, torques,

temperatures) materials and manufacturing methods are discussed. Parts are selected for metallographic examination with a member of staff the following week.

The students are set the task of producing a technical poster covering the function, physics, materials and manufacturing of their component. They base this on the discussions with staff, but must do further research, carry out calculations and analysis themselves.

The poster is reviewed by two members of staff to correct mistakes and give formative feedback. The students then prepare short presentations that describe what they have learned to the rest of the class.

Further information on this class is contained in an evaluation case study for the Engineering Subject Centre Teaching Awards 2005 (Barker and McLaren, 2005).

Design-Build experiences

Many design modules require students to design and build some sort of engineering artefact, often in teams. This is a key element of the CDIO initiative, described above. Of particular interest in this context is CDIO Standard 5 (CDIO, 2004), namely:

Standard 5 — Design-Build experiences:

A curriculum that includes two or more design-build experiences, including one at a basic level and one at an advanced level.

Description: The term design-build experience denotes a range of engineering activities central to the process of developing new products and systems. Included are all of the activities described in Standard One at the

Design and Implement stages, plus appropriate aspects of conceptual design from the Conceive stage. Students develop product and system building skills, as well as the ability to apply engineering science, in design-build experiences integrated into the curriculum. Design-build experiences are considered basic or advanced in terms of their scope, complexity, and sequence in the program. For example, simpler products and systems are included earlier in the program, while more complex design-build experiences appear in later courses designed to help students integrate knowledge and skills acquired in preceding courses and learning activities. Opportunities to conceive, design, implement, and operate products and systems may also be included in required co-curricular activities, for example, undergraduate research projects and internships.

Rationale: Design-build experiences are structured and sequenced to promote early success in engineering practice. Iteration of design-build experiences and increasing levels of design complexity reinforce students' understanding of the product and system development process. Design-build experiences also provide a solid foundation upon which to build deeper conceptual understanding of disciplinary skills. The emphasis on building products and implementing processes in real-world contexts gives students opportunities to make connections between the technical content they are learning and their professional and career interests.

Evidence: Two or more required design-build experiences in the curriculum (for example, as part of an introductory course and an advanced course) - required co-curricular opportunities for design-build experiences (such as, research labs or internships) - concrete

learning experiences that provide the foundation for subsequent learning of disciplinary skills.

The early stage design-build experiences are often in the form of a set kit, with limited parts and options, from which the students have to construct a machine or object that meets certain design objectives. Within the CDIO scheme, this tends to address the **Implement-Operate** aspects, and the **Conceive-Design** parts are pre-defined within the module.

Senior design-build experiences, occurring later in the course, tend to address at least the **Design-Implement-Operate** aspects, and possibly also the **Conceive** part. There are a wide variety of outcomes from this type of module.

A recent review by Johan Malmqvist from Chalmers University of Technology (Malmqvist et al., 2004) details various design-build-test courses, and the lessons learned from their implementation.

Design competitions

Competition modules

Many design courses and initiatives have adopted the form of student competitions. Perhaps the most highly developed example of this approach is the course 2.007 Design and Manufacturing I at Massachusetts Institute of Technology (MIT). The course website describes it as follows:

The 2.007 course @MIT began in the 1960's and has been taught by Robert Mann, Woodie Flowers, Harry West and now Alexander Slocum. During the course of 2.007 you will learn design theory and methodologies and then demonstrate them in the construction of your robot. Good luck, but of course a good engineer never relies upon luck.

2.007 Design and Manufacturing 1, MIT.

Available online at:

http://pergatory.mit.edu/2.007/2.007_index.html

The competition generally takes the form of some sort of obstacle course, which robots have to negotiate and perform tasks which interact with the structure of the race course. However, this description in no way does justice to the competition, and the reader is strongly urged to view the videos on the MIT website for a true appreciation of what the students achieve.

A further example of this type of competition, also at MIT, is the Autonomous Robot Design Competition. This utilises a kit approach where student teams build Lego robots to complete a task. 6.270 Autonomous Robot Design Competition, MIT. Available online at: web.mit.edu/6.270/www/

Pre-University competitions

Design competitions are a popular activity for engaging school students with engineering. These usually take the form of a collaboration between schools and university engineering departments. There are a large number of these programs and a comprehensive review of schemes run in the USA is available at the website of the Engineering Education Service Centre, based in Springfield, OR, USA. Pre-Engineering Competitions. Engineering Education Service Centre. Available

online at: <http://www.engineeringedu.com> and visit the competitions tab on the home page.

Closing remarks

It is hoped that this booklet will provide a useful resource for teachers of engineering design, and stimulate further reading and research into different teaching methods and approaches. Design classes are very effective vehicles for integrating the different parts of the curriculum and providing real life experiences for engineering students. They can be challenging to teach, exposing staff to a whole variety of questions outside their own research experience, but can be extremely rewarding in the quality of interaction with students.

In the past the Engineering Subject Centre ran a number of events supporting design teaching and group working. The following list is not exhaustive:

Design Teaching in Engineering: Exploring Differing Approaches

Engineering Subject Centre Workshop
23rd March 2007, University of Strathclyde
<http://84.22.166.132/events/design-teaching-in-engineering-exploring-differing-approaches.html>

Teaching Sustainable Design

Engineering Subject Centre Workshop -
26th January 2005, Loughborough University
<http://84.22.166.132/events/teaching-sustainable-design.html>

Project and Group Work in Engineering

3rd – 4th September 2003, Loughborough University
<http://84.22.166.132/events/project-and-group-work-in-engineering.html>

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The Centre for Engineering and Design Education's team of specialists work closely with the engineering and design schools at Loughborough University to encourage effective and efficient practice and innovation in teaching.

The Centre builds on the achievements of the engCETL and the HEA Engineering Subject Centre, to further enhance Loughborough's reputation for excellence in engineering education.

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