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The value of indeterminate design tasks in teaching undergraduate engineers

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ABSTRACT: Early educational experiences (at school and university) do not serve students particularly well when it comes to design tasks. By the second year of an engineering degree, students know that there is a correct answer, pre-prepared by their teachers, to every problem they are asked to solve. This is very different from the world view of practicing engineers – especially in the area of mechanical engineering design where many solutions are novel and unique. A new philosophy is proposed and implemented that aims to develop students' confidence in tackling open-ended design tasks. In the course of two semesters, projects are set that get progressively more *indeterminate*, starting with a heavily analytical and determinate machine assembly design, through to a very indeterminate systems design project. On the way, the entire design cycle is introduced, but not followed, from start (user requirements) to finish (prototype manufacture and testing) in any one project. Instead, each project concentrates on developing an understanding of select sub-sets of knowledge and skills that, when *bolted together*, yield an understanding of the whole picture.

INTRODUCTION

The authors present here the results of a redevelopment of the second year design modules in the School of Mechanical, Materials and Manufacturing Engineering (M3) at the University of Nottingham in Nottingham, England, UK. Broadly speaking, the structure of the Engineering courses in M3 aims to put in place engineering sciences in the first two years of study. The third and fourth years of study develop professional practice and independent thinking through project-based work and introduce advanced level subjects. Design plays a central, integrative role within the curriculum and is common to all courses in both first and second year; in each of these years 30 credit points are allocated to design (from a maximum of 120 credit points per year). In their 3rd year, students carry out a group design project and an individual project (which can take a design focus) and, in 4th year, a group development project. It is important that design modules in the first two years of study put in place the skills necessary for students to tackle later-year design projects.

Design Teaching Background

Previous to the new initiatives, the School of M3 already placed a great emphasis on the central role of design within its engineering programmes, and had maintained a design and build project, has a visiting professor on the Royal Academy of Engineering scheme, and has an industry advisory board. All of these provided a good departure point for the development of the design curriculum and all have been incorporated into the new syllabuses. Design assignments conducted in a design office environment were the centrepiece and students would undertake four such assignments in their second year. In the previous year, these projects included the following:

- Indeterminate design: students develop a small air compressor (mass produced) to inflate car tyres;
- Design and build: students were asked to redesign the air compressor for prototype manufacture, then build and test;
- Detail design/machine design: students designed a centrifugal clutch for a weed trimmer (line cutter);
- Detail design/machine design: students were asked to design a gearbox for an agricultural tilling machine.

In reviewing the design syllabus for the second year, it was felt that the learning outcomes were not sufficiently and explicitly stated or relayed to students, and, on closer examination, many of the original exercises had learning outcomes that were indistinguishable from those of other exercises – even though the contents were quite different. The challenge posed was to maintain students' abilities in drawing and detailed design while improving their overall appreciation of the design cycle and confidence in undertaking more open-ended design work.

OVERALL PHILOSOPHY

The new syllabuses for 2nd year design were developed using the established good practices within the School as a basis, while maintaining the requirements of UK-SPEC and taking guidance from the *Conceive – Design – Implement – Operate* (CDIO) Syllabus and principles [1-3]. The overall educational aim was to improve students' understanding of the indeterminate nature of many design tasks and their confidence to tackle such tasks.

A new philosophy was developed that can be written as follows: to develop students' understanding of the roles and responsibilities of the engineering designer through familiarity with the design cycle and the management of design, and to develop competence in practical design by moving students' understanding from a deterministic approach through to a holistic approach.

At the same time as this philosophy was implemented, a general updating of the syllabuses was carried out to include:

sustainability in design, inclusive design, product design and design management.

Design Cycle

Central to a more holistic approach is an understanding of the design cycle and how design is managed and controlled. The Waterfall Model was adopted to emphasise this (see Figure 1). The Waterfall Model is a common tool within the medical device industry for describing the phases of design control [4]. However, it has been surrounded by controversy since its introduction because it can be seen as limiting the ability to iterate within the design process [5].

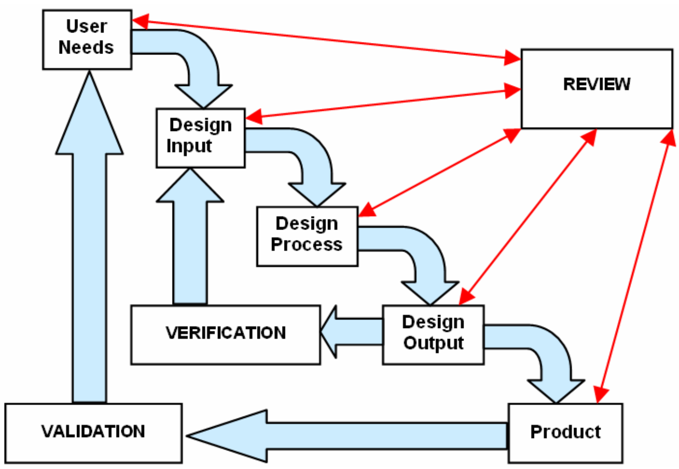

Figure 1: The Waterfall Model of the design cycle.

The Waterfall Model represents both breadth and depth of activity to the designer, as follows:

- The breadth of the activities prescribed by this model represents designers' responsibilities from the onset of the project in developing user needs statements through to supporting the product in use and to withdrawal from the market;
- The depth of activities prescribed by the model is tied up in each of the design stages (user needs through to product).

Underlying these is the iterative nature of design in the requirements for verification, validation and review, each of which can require the design process to loop back to an earlier stage (or stages) to ensure earlier requirements are met or modified.

Determinate to Indeterminate Design

Determinate design is a vital element in any engineering design education and brings a multitude of benefits, as follows:

- Limitation of the scope of a design assignment, thereby making it easier for students to understand the task set;
- A need/expectation on the part of students to incorporate analytical design;
- An opportunity to develop a design to the detailed level; this gives students experience in producing engineering drawings, and to specify components and assemblies;
- Group support – if all students (as individuals or groups) are set the same determinate problem, then all are able to *bounce ideas off each other* and generally support each other, and are thus better able to compare others' outcomes with their own;
- Simplicity in setting and marking the design assignments. If all students work on the same detailed design, then academics can compare submissions against prepared answers at a high level of detail.

But in itself, determinate design assignments only allow students to explore a part of the design cycle, namely detailed and embodiment design (both are part of the *Design Process* stage in the Waterfall Model) and parts of *Design Output*. Determinate design allows only limited scope for conceptualisation and choosing between concepts (both of which are also part of the *Design Process*), and no role in the specification of user needs or design input. Typically, within an undergraduate engineering programme, validation is not possible (it is outside the scope of most programmes), and verification is only possible where a design and build project is incorporated into the module.

To fully explore the role of the designer in all aspects of the design cycle, it becomes necessary to set indeterminate design assignments. Ideally, such assignments would follow the design cycle from user needs specification through to the validation of a finished product within a single design exercise. However, very few undergraduate engineering programmes would have the time and resources available for such a large undertaking.

A NEW APPROACH

The new approach allows students to become familiar with the design cycle from start to finish but, because of time and resource restrictions, not all in one project. It also leads them from determinate projects through to indeterminate.

The *zeroth* project involved the following: before the first design project commenced, an ice breaker assignment was conducted which explored what makes a design successful or fail. The stated learning objectives included: understanding of the breadth and depth of engineering design; literature searching skills; individual learning; critical thinking (analysing the information found and devising a set of criteria against which to judge designs); and presentation skills (arguing a case and answering others' questions in a tutorial group).

The first design project students undertake is determinate – a familiar approach for students. A typical example might be the design of a clutch mechanism and would include calculations, material selection and assembly drawings. Because this project is not design and build, only the embodiment and detail design processes are followed and no artefact may be tested. Learning objectives include design analysis (material selection, machine element design, and design for manufacture and assembly); individual design work and communications (solid modelling and drawing).

The second project is a reasonably determinate design and build project in which students must design and manufacture a simple machine. Each student spends around 2½ days in the machine shop in manufacturing activities. This project explores embodiment and detail design along with project management, design output, review and verification (testing). Learning objectives include hands-on skills in the manufacture of components and assembly of the machine, the integration of other course content (thermodynamics, statics and dynamics are needed to complete the design), the design of a prototype (this is very different from design for manufacture in that highvolume processes), teamworking (the team is required to adopt and manage a structure and tasks including Gantt charting, etc), CAD/drawing and other communication skills (task boundaries defined, detail drawings and an assembly drawing made), design analysis and component selection.

The third project is an indeterminate design (typically of a product) and focuses heavily on establishing who the users are and what their needs are. A small amount of detail design is required along with embodiment design, review and design control. Design output is in the form of sketches and rough models, and verification is, therefore, very limited. Learning objectives include group work (project management and intra-group communication skills), the design of a consumer product (this influences the choice of materials, tolerances manufacturing methods, form and function), indeterminate design (the design brief given is quite loose and it is for the design team to work out what the market wants, develop concepts, choose the best of the concepts, and complete the embodiment and some detailed design), user needs and inclusive design, CAD/drawing and other communication skills (with particular emphasis on hand sketching of concepts and simple model making).

The fourth assignment is a systems design project that focuses less on the design of technology and more on the influences of technology on society or environment. This sort of project does not map well onto the Waterfall Model, which might indicate a project of little scope, whereas in fact the scope is quite extensive, but where the later design steps are not followed. This year, the systems design project looked at aspects of providing heat and power to one of the campuses of the University of Nottingham. The remit emphasised sustainability through the triple bottom line, whereby social, environmental and financial attributes are balanced. Learning objectives included project definition (this is an indeterminate design project and students are responsible, in some part, for specifying the problem as well as providing a solution), the designer's role in projects and society, communication (students will prepare a poster and must efficiently communicate their objectives and design solutions and outcomes), systems thinking (interactions between their designed system and environmental, social and economical systems), as well as research (the use of information resources in preparing a design solution).

With each successive assignment, the projects become more open-ended. Figure 2 shows how the Waterfall Model (with its underlying design cycle) is explored in each of the projects.

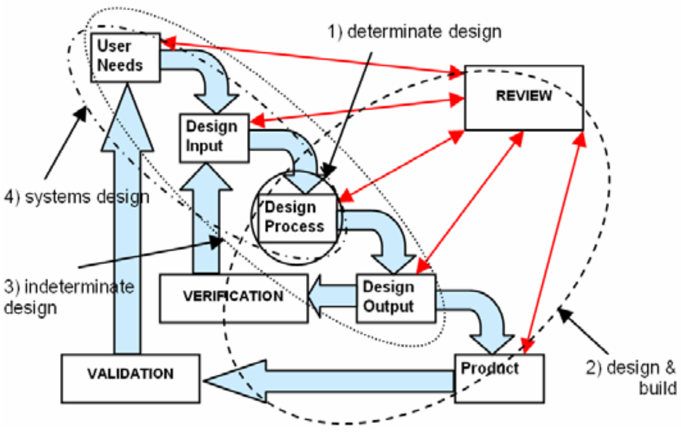

Figure 2: How projects map onto the Waterfall Model.

IMPLEMENTATION

Delivery

Design assignments are carried out in the *Design Office* sessions. These are two hours in duration each week throughout the two semesters. Students are separated into groups of four or five and are assigned a tutor for each project. About half of the projects are set as individual assignments and the other as group assignments. In group assignments, the group must divide the tasks among the individuals, produce timelines and manage their project as if in a commercial setting – role-play is an important aspect of group work and aids communication. The role of each tutor is to act as *Chief Designer* for their group.

Given the large number of students (around 180), a reasonably traditional lecture structure has been maintained and students attend two 1-hour lectures per week for the 13 weeks of each semester. The lectures were scheduled so as to precede assignments that drew upon them and comprise five major topics, as follows:

1. *Machine Element Design*: tribology, bearings, brakes, clutches, seals, joints, shafts, fatigue;
2. *Design Cycle*: design management, design control, design input, design output, user needs, validation and verification;
3. *Products*: product design, design successes and failures, inclusive design;
4. *Concepts*: creativity, choosing between concepts, concept evaluation;
5. *Design Topics*: design for manufacture, embodiment design, reliability, risk, sustainable design, systems design.

Each student will have undertaken basic machine-tool training in their first year, and will have completed a first-year design and build project using the workshop facilities. This practical nature is furthered in second year with students attending at least 2½ days of workshop practice to enable them to fabricate their design and build project. Students also attend four 2-hour CAE sessions throughout the year covering advanced modelling, mechanisms and FEA. It is felt that the use of an integrated CAE suite (*Pro/ENGINEER*) aids students' familiarity and allows practical skills to be fostered that students will be able to use in later year design projects.

Assessment

Assessment is weighted at 50% to formal end-of-semester examinations and 50% to coursework, including 10% for build and test, 4% for CAE work, and the remainder for project work. A range of assessment methods was used for project work, including engineering reports, design history file (which pulled together management, design input, output and review), poster presentation, as well as verbal reporting as a group. In the indeterminate design exercise, students role-played designers from a start-up company and made a *pitch* to a tutor role-playing a business development manager from an investment house. This reporting method was the most popular with both staff and students, as it gave time for instant and good quality feedback to students, captured imaginations and helped staff quickly get a feel for the quality of work and effort applied by each student in the team. Where appropriate, an element of competition is added to projects to encourage participation.

Encouraging participation by incrementally awarding marks for setting and meeting task goals ensured that work progressed relatively orderly and was not left to the final week. It also gave students the chance to apply their design management skills in a very hands-on manner. Experience showed that only 10% of the project mark is needed for this to be effective.

OUTCOMES

CDIO Objectives

The new syllabus takes the School of M3 further down the path prescribed by the CDIO Syllabus through the following:

- Standard 1: Allowing greater scope for conceiving (design, implement and operate were already established);
- Standard 2: Better focusing the learning outcomes and making these clearer to students;
- Standard 3: Design teaching at the University of Nottingham is seen as the glue that aids curriculum integration. This new approach helps to bind in some of the management and professional studies material, as well as the more analytical subject material (mathematics, thermodynamics, etc);
- Standard 5: Maintaining two design and build projects in core curriculum – other design and build opportunities are available to students in later projects, but not all projects contain a build element – some, for example, are purely computational;
- Standard 6: The refit and introduction of a new workshop, design studio and project space for students' project work, along with a new 24-hour access computer/CAE suite is a move towards meeting the workspaces requirement.

Other standards are met to varying degrees and will be addressed in time as the design curriculum is revised in the coming years across all levels.

Approach

The taught content was scheduled so that it preceded the project work that drew upon it. This has proven to be slightly problematic with topics being interrupted so as to squeeze in taught content just in time for a project and with topics needing to be rearranged each year so as to accommodate projects with different content. Students have complained that they perceive a lack of structure in the lecture sequence for these reasons. This is compounded to an extent because the modules are team-taught and the programme must be arranged to suit lecturer availability.

Student and Tutor Feedback

The University of Nottingham runs student evaluations of modules (SEM) and teaching (SET) every other year, but the University has chosen to run these each year for both design modules in the second year to gain a quicker indication of how effective the new approach is and how well received it is by students. Student evaluations of module provide both a qualitative (open-ended question) section and a quantitative measure (in the form of multiple questions, which students should score 1 (excellent) through 3 (neutral) to 5 (very poor)) of how well the modules were received. Quantitative measures from the SEM indicate better reception in both modules with scores improving by 0.2 points in each semester.

Qualitative comments indicated the following:

- Students enjoyed the practical nature of the design modules;
- Students liked the breadth of the design topics and variety brought by team teaching;
- It was felt that excessive marks were allocated to the examination and the amount of work in the assignments was not fairly reflected;
- Students enjoyed the integrated approach to CAE and the individual CAE exercises;
- *Studying mathematics is justified* by such practical use of mathematics in design classes;
- There is a preference for the two 2nd year design modules to be joined into one year-long module.

Responses from experienced tutors have been extremely positive. Prof. Kirk, the University's esteemed Royal Academy of Engineering visiting professor, endorsed this syllabus and has been involved actively in its implementation. Prof. Dominy, Managing Director of a local SME, has commented that the indeterminate and system design projects are what engineers (let alone designers) really carry out in order to define a product specification.

CONCLUSIONS

Design is a complex subject that must be experienced in order for it to be understood. Determinate design projects play an important role in the learning process in that they allow students to distil their knowledge from theoretical sciences into practical design solutions. However, meaningful solutions to the problems that will be faced by future generations will only be addressed through systems design, which, in itself, is entirely indeterminate in nature.

The teaching process to foster systems thinking from a closed form and determinate mindset is addressed within this article. The outcomes have been encouraging from the points of view of both engagement by tutors and student learning. Certainly, students have an improved level of confidence to tackle more indeterminate design tasks and a better set of skills available to do so. Future work will focus on enhancing teaching methods to improve knowledge uptake. Following on, the design curriculum over the full three to four-year course will be addressed to ensure continuity, while also meeting the UK specification through a greater level of adherence to CDIO principles.

REFERENCES

1. Engineering Council UK, UK Standard for Professional Engineering Competence. London: Engineering Council UK (2004).
2. Crawley, E.F., The CDIO Syllabus: a Statement of Goals for Undergraduate Engineering Education. Technical Report, MIT CDIO Report #1, Cambridge: MIT (2001).
3. CDIO, CDIO Principles (2006), http://www.cdio.org/tools/cdio_standards.html
4. Food and Drugs Administration, Design Control Guidance for Medical Device Manufacturers. Rockville: Food and Drugs Administration, 3 (1997).
5. Royce, W.W., Managing the development of large software systems: concepts and techniques. *WESCON Technical Papers*, 14, A/1-1-A/1-9 (1970).