Enhancing the Manufacturing Knowledge of Undergraduate Engineering Students: A Case Study of a Design-Build-Test Challenge Involving Folding Bicycles

ENHANCING THE MANUFACTURING KNOWLEDGE OF UNDERGRADUATE ENGINEERING STUDENTS: A Case Study of a Design-Build-Test Challenge Involving Folding Bicycles

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ABSTRACT

Many engineers currently in professional practice will have gained a degree level qualification which involved studying a curriculum heavy with mathematics and engineering science. While this knowledge is vital to the engineering design process so also is manufacturing knowledge, if the resulting designs are to be both technically and commercially viable.

The methodology advanced by the CDIO Initiative aims to improve engineering education by teaching in the context of Conceiving, Designing, Implementing and Operating products, processes or systems. A key element of this approach is the use of Design-Built-Test (DBT) projects as the core of an integrated curriculum. This approach facilitates the development of professional skills as well as the application of technical knowledge and skills developed in other parts of the degree programme. This approach also changes the role of lecturer to that of facilitator / coach in an active learning environment in which students gain concrete experiences that support their development.

The case study herein describes Mechanical Engineering undergraduate student involvement in the manufacture and assembly of concept and functional prototypes of a folding bicycle.

KEYWORDS: Design-Build-Test, Group project, CDIO

1. INTRODUCTION

In 2005 the US National Academy of Engineering advocated in its report 'Educating the Engineer of 2020' [1] that the "the essence of engineering, the iterative process of designing, predicting performance, building and testing, should be taught from the earliest stages of the curriculum" if graduate engineers are to be adequately prepared to find solutions to the major problems that will face society in the future. Project Based Learning (PBL) advocates cite the development of a range of personal, interpersonal and professional skills in addition to the opportunity to apply disciplinary knowledge in an environment which mimics professional practice as being among the benefits of such an educational approach [2], [3] and thus graduates from PBL programmes are potentially better prepared to meet these grand challenges. PBL students have been shown to find such problem based experiences challenging, motivating and enjoyable [4]. Programmes featuring significant amounts of PBL also tend to benefit from higher retention rates [5]. The skillsets developed in a PBL based curriculum are highly prized by industry which also enhances students' employability prospects.

Effective implementation of PBL however is not a simple matter and not always executed well. The formation and management of project groups can be difficult and students in dysfunctional groups have found the experience painful [6]. Faculty members often do not have experience of managing similar projects in an industrial setting [3] and are also often unfamiliar and uncomfortable in the role of mentor or coach, which is considered preferable for PBL, compared to their normal role of lecturer [7],[8],[9]. There are also infrastructural issues such as access to appropriate workspaces for the construction of prototypes, as well as the associated costs of providing these workspaces and the costs of manufacturing high fidelity and functional prototypes. Indeed some meta-analyses of PBL have found significant variation among implementations, negative effects where PBL was implemented poorly by non-expert tutors [10] and less knowledge acquired by students on PBL programmes when tested by exams [11]; although significantly this knowledge was retained for longer when retested at a later date. Such variations in implementation and hence uncertainty of positive outcomes, along with the necessary paradigm shift required in teaching approach and associated resources could all be reasons inhibiting more widespread adoption of PBL.

The Engineering Council through its UK-SPEC document defines the graduate level Specific Learning Outcomes (SLOs) for engineering programmes in the UK. The Accrediting body for Mechanical (MEE) and Product Design (PDE) Engineering degrees in the School of Mechanical and Aerospace Engineering (SMAE) at Queen's University Belfast is the Institution of Mechanical Engineers (IMechE). For MEng graduates the IMechE specify an expectation that higher level learning outcomes such as imagination, creativity and innovation will be developed through open ended DBT exercises and design work including group projects. In response to this requirement the Stage 3 MEng group projects in MEE have adopted the group project model developed on the CDIO inspired PDE degree pathway established in 2004. Since 2012 both pathways have been enrolled on the same 15 ECTS Stage 3 module MEE3060 (Design Project 3M). The mode of delivery, the supervision, assessment methods and the project workspaces used have all been significantly influenced by CDIO and the work of others from around the world who have shared their expertise and experience through the CDIO community. The CDIO Initiative, an international collaboration of over 100 universities, aims to improve engineering education by teaching in the context of Conceiving, Designing, Implementing and Operating products, processes or systems.

Previous incarnations of the stage 3 design project had been paper and CAD based only and did not involve the manufacture of any prototypes. The current instance, however, extends the experience gained by the students so that they get the opportunity to evaluate the outcomes of their design decisions and also gain a practical understanding of issues related to various manufacturing processes through assembling and testing their own designed components. Note, the objective of the module is not to develop workshop practice to the level of a technician practitioner but rather to give the design engineers and engineering managers of the future a hands-on practical experience to enhance their understanding and learning of manufacturing issues.

2. CASE STUDY: Folding Bicycle Design Challenge

Several themes run concurrently under the same module code but the majority of the MEE students in 2014-15 (9 teams) and 2015-16 (11 teams) undertook the challenge of designing a folding bicycle for urban commuters. This theme was developed as a joint effort between collaborators of the CDIO UK & Ireland region and has run in parallel at a number of institutions over the last two years [12].

2.1 Module Organisation

The MEE3060 (Design Project 3M) module is a full year 15 ECTS advanced team project which combines the application of technical knowledge with personal and interpersonal skills. Each team starts with or defines a design brief for an innovative product, process or system. The team then specify objectives, conduct a comprehensive literature review and/or market research, produce a product design specification and a work plan for the project. Tasks include the detailed design of the product and the manufacture and testing of concept and functional prototypes. Design parameters are investigated with respect to product performance and where appropriate computer aided engineering (CAE) analysis tools are used to refine and optimise the design.

Table 1 – MEE3060 Module Learning Outcomes and Equivalent IMechE Specific Learning Outcome (SLO) Codes

Module Learning Outcomes	**SLO code**
Extract data pertinent to an unfamiliar problem, and apply its solution using computer based engineering tools when appropriate	E2m
Apply knowledge and comprehensive understanding of design processes and methodologies and adapt them in unfamiliar situations.	D1m
Generate an innovative design for products, systems, components or processes to fulfil new needs	D4m
Manage the design process and evaluate outcomes	D6
Demonstrate an awareness of the framework of relevant legal requirements governing engineering activities, including health, safety, and risk issues.	S4
Engineering workshop and laboratory skills	P2
Utilise extensive knowledge and understanding of a wide range of engineering materials and components	P2m
Make use of technical literature and other information sources	P4

The assessment consists of five group elements (50%) and two individual elements (50%) as outlined in Table 2 below.

Table 2 – MEE3060 Assessed Elements

Interim exhibition & concept prototype	Week 8	4x pairs of markers	10%
Interim group report	Week 10	2x supervisors	10%
General Arrangement & component drawings for engineering workshop	Week 12	Panel of experienced engineers	10%
Final group report	Week 20	2x markers	10%
Functional prototype & poster exhibition	Week 21	6x individual markers	10%
Supervisors' marks for individual performance during project	Week 21	2x supervisors	25%
Individual interview based on final group report & exhibition	Week 22	2x markers	25%

The final group reports are marked and the individual interviews are conducted by two assessors who have not been a supervisor of that project group, although they will have supervised another group and are therefore fully aware of the relevant design issues. The individual markers at the final exhibition are neither supervisors nor markers for the groups they assess. Overall the groups are assessed in some aspect of their project by almost all of the 20+ supervisors involved in these projects each year.

The panel of experienced engineers who assess the engineering drawings submitted to the Faculty workshop includes the workshop manager, the School's Production Manager and the module coordinator, who has 15+ years experience as a consultant design engineer.

Supervisors assign individual marks (weighted at 25% of the total for the project) for conduct and performance of each student in their group(s) during the entire project. This mark is based mainly on weekly observations during the required project review meetings, primarily in three main categories of Technical Contributions, Contribution to Deliverables & Collaboration. Supervisors may also consider other evidence of engagement and involvement in the project such as contributions to each group's SharePoint site.

Individual Interviews take place in the week after the functional prototype exhibition day. Each student is interviewed by the 2 markers of the group report. Each interview lasts 20 minutes and all students are asked up to 10 questions relating to any part of the group report, not just the sections they were responsible for. The markers meet in advance to agree a set of questions which cover and probe all aspects.

2.2 Facilities to Support DBT Projects

The cohort for MEE3060 alone is typically 75 students, working in groups of 5. In addition there are other modules with similar DBT requirements have been introduced on the Aerospace and Product Design Engineering pathways in the

School which doubles the numbers of students to be accommodated. This has required a considerable investment in workspaces over the past five years in order to enable the effective implementation of this type of DBT activity on an increased scale as the CDIO methodology is extended across more pathways and stages.

In 2014 the laboratory block was the third and last phase to be completed of the Ashby building complex refurbishment, originally built in 1965. The School's involvement in CDIO and the opportunity this afforded to learn from and evaluate the workspaces at other collaborating institutions had informed the refurbishment. Several laboratories, offices and storage spaces were repurposed to become group work and project rooms better suited to active and interactive teaching methods and DBT projects. The Student Design Centre (Figure 1) was previously an office for PhD researcher students but now houses a range of equipment to support concept prototyping including a large laser cutter, a CNC hot wire foam cutter and a flash cure photopolymer 3D printer. This Centre also includes meeting rooms and on a newly constructed mezzanine floor a suite of CAD workstations and open meeting spaces.

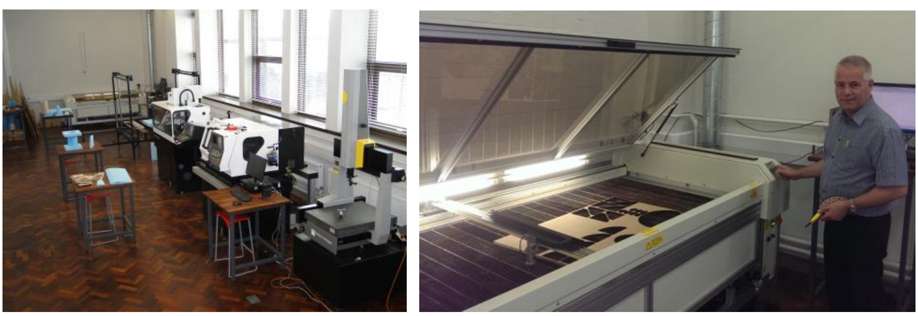

Figure 1 – Student Design Centre (SDC)

A pair of basement storage rooms full of old and unused test rigs and the detritus of decades of experiments have been transformed into two project rooms (Figure 2) equipped with lockers, workbenches, hand tools and a prototyping materials store.

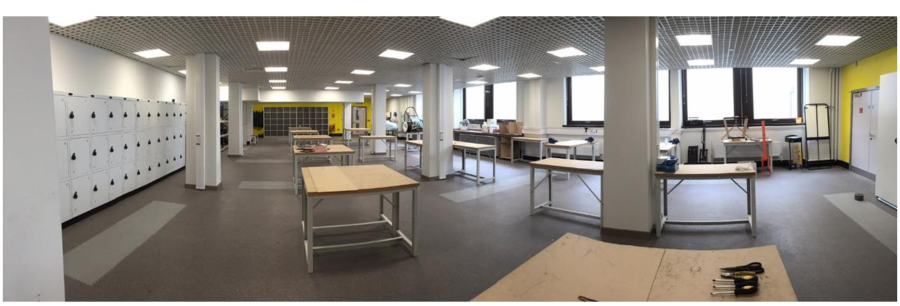

Figure 2 – Ashby Basement Student Project Room

Students are required to undergo induction training in the safe use of hand tools and general workshop health and safety before they are able to use these facilities. They pay a deposit for personal protection equipment and each team gets their own toolbox and locker.

2.2 Concept and Functional Prototypes

The students are instructed in a design process which encourages early “cheap and cheerful” prototyping of scaled concept models made from paper and card to evaluate different concepts ideas. They then quickly move on to full size concept models produced in the SDC. Figure 3 shows a folding bicycle frame concept model being assembled. The frame elements are waste water pipes which are glued together. The ‘bird mouth’ ends have been cut by the students using a template sheet generated from an unfolded tube model in the SolidWorks sheet metal environment. The rear forks are laser cut MDF sheets and the tyre is Styrofoam which has been cut on the CNC hot wire machine. The accuracy and fidelity of these concept models is such that the students are able to evaluate form and function, particularly of the folding aspect of their design, before committing to the time and expense of components in metal produced by the Faculty workshop. Gross errors are avoided because the concept models are good and the students understanding of the interrelation of components and the method of assembly is enhanced through the hands on processes.

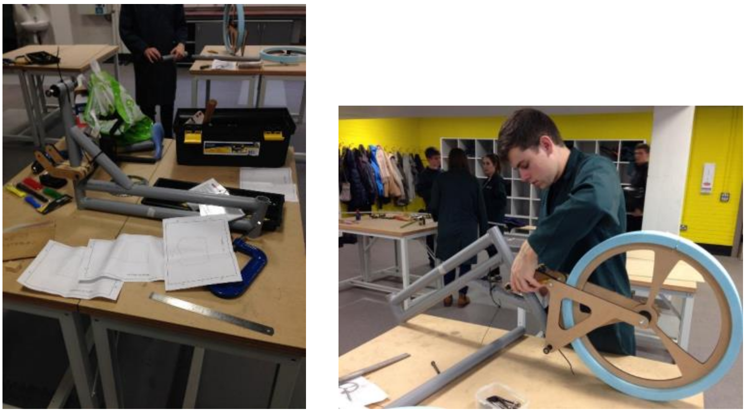

Figure 3 – Concept Prototype Construction

After the concept prototype exhibition in week 8 the students have 4 further weeks in which to refine their CAD models and produce engineering drawings for the functional prototypes. To assist them with their understanding of how these components will be manufactured they are first given a tour of the engineering workshop by the workshop manager and subsequently have tutorial / discussion sessions with the manager and technicians to further refine their designs with respect to ease of manufacture. No components get made in the workshop until they have been signed off by the School’s Production Manager and one of the supervisors; another filter to catch gross errors.

The fabrication of frames is scheduled to overlap with the January exam period and hence minimise the time when the students are waiting for parts to come out of the workshop. Welded steel and aluminium frames of varying diameters and gauge tend to have some inaccuracies and distortions. There is often the need for some minor rework so that bought in components integrate effectively. These issues reinforce the concepts of manufacturing tolerances and production quality through an authentic learning experience based on the students' own designs. Sometimes it is only at final assembly that a previously unknown (or unconsidered) issues arises; for example the lack of clearance between the pedals and the ground when turning a sharp corner, or how to assemble a toothed drive belt through a rear fork space frame.

Figure 4 – Functional Prototype Assembly

The final phase of the process is to test the functionality of the bicycles. This is where the students get direct and immediate feedback on the quality of their designs and the manufacturing implementation. The depth of understanding gained exceeds that gained from a paper or CAD design exercise .

There is also a competitive element to the design challenge in that the bicycles are compared to each other against a set of design criteria including mass, folded volume, acceleration from a standing start and maneouverability through a slalom course. The competition between teams working to a common brief has been seen to be an effective motivating factor. It is recognised that the common theme has also improved the quality of the assessment as the staff involved have a better understanding of what they are grading.

Figure 5 – Functional Testing

2.3 Costs

As stated in the Introduction there are significant additional costs associated with this type of DBT module when compared to a traditional lecture and examination style module. The infrastructure costs are the most significant of these but were largely met in this case by the refurbishment fund set aside by the university. The university refurbishes approximately 5% of its estate each year. As such each School should expect to be refurbished once every 20 years. When the School's turn came around we were ready to define what we wanted with respect to the CDIO style of teaching we were transitioning our programmes towards. Our experience of the facilities other CDIO collaborators already had in place provided case study exemplars on which to base our own plans. The Estates Department embraced our vision and worked with the School to transform our buildings. The cost of the phase 3 Ashby laboratory block refurbishment was approximately £6 million, but does include much more than the resources described in this paper.

The students are given a budget of £500 for materials and components for all phases of the project. On average each group spent £135 on materials and £170 on bought in components such as wheels rims, gears and brakes. The amount of workshop and laboratory technician time was logged against each group and averaged just under 60 hours per group.

3. DISCUSSION

Group composition was decided by the module coordinator so that, as far as possible, a number of parameters were balanced. Parameters considered included: whether or not a student had completed a year out sandwich placement, MEE Stage 3 subject theme selection and Grade Point Average at the end of Stage 2. It is perceived, although not currently supported by data, that the sandwich students (approximately 60% of the cohort) are better project students because of their industrial experience. The optional themes on the MEE pathway are considered so that each group has “experts” in CAE and materials science among their members.

The throughput capacity of the Faculty workshop can be an issue. With multiple groups working to the same schedule a bottleneck is almost inevitable. While the January exam period has in the past been used to minimise the delay there has also been a need to subcontract some of the work to outside parties in order that the frames and machined components are returned to the students in time to allow sufficient functional testing. It is prudent to set an aggressive schedule at the outset so that some adjustment can be made if manufacturing delays occur. The academic year is the one schedule that cannot change and it is not desirable that the students miss out on the deep learning of the final phase of the project because of manufacturing overruns.

Many lecturing staff, particularly at research intensive institutions, are not hired on the basis of their industrial project experience. Many will also not have experienced a CDIO / DBT / PBL based education in their own degrees and can feel out of their depth when asked to supervise this type of project. Since, as discussed in the introduction of this paper, the benefits of this type of teaching depends in large part on effective implementation it is therefore vital that adequate time and resources are set aside to develop staff teaching skills in this area. Indeed the CDIO Framework Standards 9 & 10 identify this need and focus on development of faculty CDIO skills and faculty teaching skills. Clear instructions and guidelines to supervisors are important and experienced supervisors should be partnered with newer members of staff to act as coaches in their development as mentors and facilitators of these project groups. Training sessions or seminars specifically in DBT supervision should also be considered as part of staff continual professional development.

Even with the supervisor and Production Manager filters to catch gross errors there will be components and assemblies manufactured which have design errors or oversights. This is not necessarily a problem as the students will likely learn more in these instances. In this respect the students should be encouraged to take some risks with their design and attempt to be creative and innovative in their design solutions. The students with a lightweight aluminium hinge which failed when going over a speed bump will be more inclined to reanalyse their design than the students with a steel hinge more appropriate to a bank vault.

The students tend to find this module challenging, as reported in their student evaluation questionnaires. When subsequently surveyed as graduates they additionally recognise the value of experiencing something close to an authentic experience of their actual roles in industry. The manufacturing knowledge and skills are only one aspect of the learning outcomes for this DBT project and the manner in which these are acquired is based on best practice pedagogy.

3.1 Concluding Remarks

The methodology described in this case study has proved effective but merely reflects a snapshot of current practice. The author’s intention is to further develop many aspects related to such DBT projects and welcomes collaborations from individuals and institutions with similar aspirations.

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