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Fionnuala Farrell

Technological University Dublin, fionnuala.farrell@dit.ie

Shannon Chance

Dublin Institute of Technology, shannon.chance@dit.ie

Micheal O'Flaherty

Dublin Institute of Technology, micheal.oflaherty@dit.ie

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AN ENERGY CUBE PROJECT FOR TEACHING ENGINEERING DESIGN PROCESS

C. Fionnuala FARRELL¹, Shannon M. CHANCE² and Micheál O'FLAHERTY¹

¹School of Mechanical and Design Engineering, College of Engineering and Built Environment, Dublin Institute of Technology, Dublin, Ireland

²Marie Curie Research Fellow, College of Engineering and Built Environment, Dublin Institute of Technology, Dublin, Ireland

ABSTRACT

This year, the College of Engineering and the Built Environment at our institute inaugurated a new Common First Year design project module that helps inform students in the selection of a specific engineering discipline. Each student, prior to selecting their bachelor's specialism, completes three group-based design projects: a bridge design project (to familiarise students with civil and structural engineering), a RoboSumo project (involving robotics, programming, electrical and electronics engineering), and an Energy Cube project (introducing fundamentals of mechanical, manufacturing and design, and building services engineering). This paper focuses on how the engineering design process was taught via the Energy Cube. It is geared toward third-level engineering educators who want to introduce a structured approach to design (that makes explicit the critical stages and activities of design). The paper explains how "The Informed Design Teaching and Learning Matrix" [1] was incorporated into the Energy Cube project and shows how the Matrix can serve as a valuable tool for design educators. Finally, it presents key observations made by tutors over four separate occasions running the project and the modifications made to improve the students' experience based on the analysis of class discussions, student performance evaluations, and more than 130 student surveys.

Keywords: design process, problem-based learning, first-year engineering education

1 INTRODUCTION

A newly implemented Engineering Design Projects module provides students with practical experience of the engineering disciplines that are available for focused study at our institute. It prepares students for the type of learning they will encounter in subsequent study and practice. Tutors on each of the three design projects took the initiative to meet throughout the year to discuss methods for teaching 'design'. They explored ways to both diversify and align the teaching methods they used. In one of the three projects, entitled "The Energy Cube", students were introduced to design process theory via a short lecture that outlined key design stages, based on a typical stage-gate process used in industry. Students encountered a simple example to illustrate the process and completed an exercise to practice the initial stages of design. The teachers encouraged teams to adopt a similar approach in designing and building their Energy Cubes. Weekly activities and submittals were aligned to correspond with key stages of a design process so students could intrinsically experience it. In-class discussions were held around problematic areas, such as drafting a design specification document.

In this paper, Section 2 provides context and explains how the initial approach to teaching the design process was developed. Section 3 introduces the Energy Cube project and presents a week-by-week description of the module's content, with corresponding learning outcomes indicated. Section 4 describes student behavior. Section 5 notes how various recommendations from the design matrix [1] were integrated and explains how staff modified their approach to teaching design over time. Responses from a student survey highlighted the effect of these modifications (section 6). Concluding comments on the overall experience of teaching and learning a design process for entry-level engineering students are provided in section 7.

2 INCORPORATING DESIGN PROCESS THEORY

One fundamental learning outcome of the three-project module is that students become familiar with the process of design. In it, they apply design tools to solve engineering problems. To provide basic structure for the design process, the lecturing team aligned the project's weekly activities to a typical stage-gate product design process (as outlined in Table 1), which the lead author had used in industry.

2.1 Providing a real-world experience—a typical design process in industry

A typical stage-gate design process, used in industry to spur innovative product design, consists of several fundamental stages. The first stage establishes the design objective (DO). It identifies clearly the customers' need and determines whether it is viable for the company to meet that need. Customer requirements are translated into engineering requirements, with specific targets/thresholds set and agreed within a multi-functional design team. If the project successfully passes through this decision 'gate' the 'Investigation-to-Lab' (IL) stage follows calling for more in-depth research and exploration to develop alternatives. On approval, with some concepts proving feasible, the Lab-to-Proto (LP) phase is then conducted to develop concepts further. In this phase, stringent testing is conducted on proto-typed functional products and their integrating parts.

The next stages are primarily troubleshooting and optimising the design to meet all targets and ensure readiness for high-volume manufacturing (called 'Week0'). On meeting this, subsequently the product is released to manufacturing (MR). A stabilisation phase starts when the product reaches the end-user and initial customer feedback is received regarding product performance. This process can be streamlined and adapted as necessary depending on project risk and complexity [4]. There are defined activities to be completed at each stage by each functional area, such as marketing, supply chain, manufacturing, and R&D. In the case of the Energy Cube project, attention was focused on R&D with identified outputs and activities expected during each 'stage' from this perspective. The latter part of a stage-gate design process (from 'Week0' onwards) was omitted due to the short time allotted for the project. The project was not focused on tailoring the design for high-volume manufacturing and release, instead it focused on creating a one-off energy efficient building design and model.

<i>Week</i>	<i>Weekly Output</i>	<i>Design Process 'Stage'</i>	<i>Design Module Targeted Learning Outcome</i>
1	Generate design specification documents	Design Objective - identify the problem clearly.	[b] Apply engineering concepts & design tools to solve engineering problems. [e] Recognise engineers' social roles, and relationships between technology and society.
2	Create a concept evaluation matrix, brainstorm ideas and select two preliminary concepts	'Investigation-to-Lab' - Research & explore to generate ideas	[c] Solve problems by following appropriate specifications and standards, as well as [b].
3	Make detailed construction drawings, submit thermal predictions and step-by-step construction plan	'Investigation-to-Lab' - Evaluate Concept(s)	[a] Operate effectively within design teams [f] Produce solutions to basic engineering problems using graphical methods, as well as [c].
4	Construct final model using the allocated materials	'Lab-to-Proto' - Build Prototype	This week re-emphasises [a] and [c] as described above.
5	Test performance of models and record results,	'Lab-to-Proto' - Test Solution	[d] Communicate results, verbally as well as graphically, in addition to [b] and [c].
6	Submit and present (as a team) a final report that includes recommendations for improvement and reflection on experience.	'Lab-to-Proto' - Reflect & Analyse, troubleshoot & improve (iteration)	[g] Distinguish the roles various fields of engineering play in the overall profession of engineering, as well as [a] and [d].

Table 1. Correlation of Energy Cube Weekly goals and Design Project module Learning Outcomes

2.2 Simplifying the Design Process

An environmental scan of academic material [5, 6] and online resources [7, 8] was undertaken to see how the design process could be taught to third-level or even second-level (final-grade) students. This helped in tailoring the industry stage-gate process (outlined in Section 2.1) to this project. It simplified the model so students could achieve basic understanding and complete rudimentary design tasks. It was important not to overcomplicate the process given the broad spectrum of learning objectives and also to try to encourage students to enjoy the process and express creative flair without feeling constrained by stringent steps. It still aimed to expose students to tools real-world designers utilise.

2.3 Emphasising Important Aspects of the Design Process

It was verbally emphasised that an effective design process is both structured and iterative. Despite this, time was too constrained for iterative cycles. Students were asked to complete the vast majority of their work within six four-hour blocks. To echo the process driven nature of design, clear stages of the design process along with specified deliverables for each phase were introduced. Each team submitted and presented a final report that identified recommendations for future development and/or modification of their design. Although they did not conduct the actual refinement, the activity allowed them to troubleshoot and plan for future (hypothetical) iterations.

The role of the customer within an engineering design team was also emphasised. Customer-Centric Design, Human-Centered Design, and Quality-Function Deployment are all well established processes of ensuring design teams put the customer at the core of their design efforts. In this project, the client was incorporated via a ‘story-based’ brief, which described customer requirements. The percentage of marks allocated to various attributes reflected requirement prioritisation. Teaching staff positioned themselves as ‘the customer’—clarifying requirements and answering questions.

2.4 Teaching the Design Process

As mentioned above, students were introduced to design process theory via a simplified stage-gate model. They practiced this theory by completing a design exercise and were encouraged to adopt a similar approach in designing their Energy Cubes. Short tutorials were provided to help students develop specific skills, such as drafting a design specification document and creating a weighted evaluation matrix. Specific weekly goals (depicted in Table 1) were provided, based on practical outputs that R&D teams deliver in real-world design projects. The weekly outputs helped the lecturing team implicitly emphasise a structured approach to design. A recap of design process was given in the fifth session when discussing the requirements for the final presentation and report. An information pack was distributed to help students prepare ‘customer’ presentations, re-enforcing the process.

3 ENERGY CUBE ASSIGNMENT

The original Energy Cube project was developed by a team of lecturers within building services engineering to help students learn about various aspects of heat loss in a building envelope. The project was revised by a multidisciplinary team of engineering lecturers—including one of the original developers—to emphasise additional learning requirements such as design process, design tools such as CAD, and effective communication and teamwork skills. The project was taught in four separate blocks of six weeks over two semesters. In all, about 160 students were asked to design and construct (using a limited amount of corrugated cardboard, clear plastic, and glue) a model of a building at a scale of 1:100. The building models were to admit as much daylight as possible while being energy efficient and aesthetically pleasing. The designs had to meet specific customer requirements such as a minimum volume and glazing area. Cost was factored into the project via a deduction of points in cases where additional material was used during construction.

3.1 Project Weekly Goals and Module Learning Outcomes

Student teams completed most of their work in six four hourly class-sessions. In each session, students are presented with theories on structured ‘design process’ as well as being given specific goals aligned with the module’s learning outcomes. Table 1 indicates the relationship between the weekly outputs and each required learning outcome [a-g] alongside the relevant design process stage. Many broad outcomes must be achieved in a short time-period, and students have minimal prior-experience working in groups and with unfamiliar people. They must grasp core concepts quickly and develop basic design competencies. An over-riding expectation of the module is that students enjoy their initial taste of each discipline and are given the opportunity for exploration of many facets of the engineering world. In ‘Energy Cube’, grades/marks are allocated for each of the goals achieved by the teams. Self and peer assessment techniques are incorporated to enable individual marking of work conducted in groups. This is to facilitate reflection [2] and promote student engagement and performance [3].

4 OBSERVATIONS OF STUDENT BEHAVIOURS

To encourage students to develop their own ways to interpret the design process—and to enable them to explore and develop understanding of the design challenge—no additional information or templates were provided initially. Students were free to submit design specifications and evaluation tools

formatted according to their own understanding of the project information. This prompted them to consider the value and content of these design tools and adapt them for their own design purposes. It became evident very quickly (through a class discussion and in sharing the submitted design tools) that students did not understand the value of ‘identifying and defining the problem’. They understood neither how to concisely extract the most important information from the design brief that informed the direction of their design, nor how to determine the quality of various schematic proposals in order to select the most appropriate direction. The first cohort of students jumped directly into generating ideas and selecting one, without fully understanding their design objectives and without creating criteria to support their selection process. Because of limited time, the first cohort on this project proceeded without completing this stage. On the presentation day, in discussing options generated, few teams mentioned using an evaluation matrix or tool to help in the down-selection process. However, the teams that did mention defining quality standards provided memorable graphics to describe their work, driving the point home to other teams. Notwithstanding this, student teams had regularly questioned lecturing staff in their efforts to comprehend customer requirements during design development (thereby reflecting customer focus). They also provided recommendations for improvement at the end (expressly stating their intentions for design iteration).

5 USING THE INFORMED DESIGN MATRIX TO ASSESS BEHAVIOURS

To enhance our lecturing team’s efforts in (a) explaining effective design process to students and (b) modelling this type of behaviour for them, five of the 11 staff involved with the overall module volunteered to read and discuss the article titled “The Informed Design Teaching and Learning Matrix” [1]. The article’s two-page matrix was analysed and our project assignments mapped to it. The group met several times exploring ways to embed activities with effective practices and explain design practices effectively. Figure 2 provides an overview of the matrix (where it compares a beginner’s approach to an informed designers approach for various design strategies used in a design process) and it captures how applicable the Matrix is to this Energy Cube project.

Strategy	Beginner's Approach	Informed Approach	Energy Cube Applicability
Understanding the Challenge	Working to solve the problem	Working to frame the problem	Design Brief (9 pages) translated into concise design specification (1 page)
Building Knowledge	Skipping Research	Conducting Relevant Research	Research encouraged and facilitated
Generating Ideas	Treating ideas as scarce	Using ideas fluently	Idea from each group member encouraged
Representing Ideas	Drawing & modelling at surface-level	Drawing & modelling at surface-level deeply	Hand-sketches required as well as orthographic and surface development views
Weighing options & making decisions	Ignoring benefits & trade-offs	Balancing benefits & trade-offs	Evaluation matrix required prior to idea generation & populated matrix presented during customer presentation
Conducting Experiments	Vague tests & experiments	Valid tests & experiments	Dedicated tests discussed and performed to measure ability to meet design requirements
Trouble-shooting	Addressing glitches in an unfocused way	Addressing glitches in a diagnostic way	Results recorded and analysed, findings presented during presentation week and in report
Revising & Iterating	Using a haphazard or linear approach	Using a managed & iterative approach	Improvements required to be captured in presentation & report
Reflecting	Seldom reflecting on process	Continually reflecting	Reflection on project captured in report, presentation and student survey.

Table 2: Summary of contrasting behaviours of beginning and informed designers distilled from [1] with applicability to Energy Cube project

5.1 The Matrix influencing modifications to Energy Cube project

With regards to the Energy Cube, lecturers found it reassuring that the Matrix correlated well with prior industry experience—in sync with stage-gate product design methods. It mirrored the structure already created for the Energy Cube project (Figure 1). Interestingly, each of the matrix’s design and corresponding teaching strategies aligned somewhat with required Energy Cube outputs (Figure 2). This made clear the relevance of this Matrix to the Energy Cube project. In response to these findings, simple templates for the design specification and evaluation matrix were created so that students could populate them with relevant information rather than creating them from scratch. The templates helped reiterate and reinforce effective design practices. Marking was re-allocated to reward teams that developed, for instance, an evaluation matrix to support their selection process. These tools were

discussed briefly and provided in soft and hard copy, minimising formal lecturing time (aligning with student recommendations in end-of-project surveys). In keeping with the Informed Design Matrix, our emphasis on representing ideas in multiple ways helped re-enforce the need for the design teams to create scaled prototypes, detailed hand sketches, and 3D drawings of their ideas—encouraging teams to analyse their concepts before determining which proposals to build.

5.2 Using the Matrix to Guide Design Process

Overall, the Matrix’s identification of specific patterns of behaviour (and descriptions of how behaviours differ between novice and informed designers) provided excellent guidance on teaching design to beginners and in trying to understand the observations outlined in Section 4. It’s easy to forget, after years of professional practice, the tendency of novice designers to act prematurely when facing a new challenge. The practice of conducting investigations and research to learn about the problem (prior to brainstorming for solutions) is not necessarily an obvious step for individuals with minimum exposure to design. As a result, the staff facilitated team-based discussions acknowledging this tendency and helping students address their discomfort in having to define a specific problem from a multitude of information.

The Matrix proposed a range of teaching strategies enhancing our teaching team’s ability to explain ‘design strategy’ in different ways, thereby helping students understand ‘design’ more clearly. For example, students were encouraged to broaden their perspectives through: brainstorming to look at process of divergent thinking; reverse engineering; writing a product history; and reading case studies. The need to achieve a level of comfort with ambiguity—as described in the Matrix—resonated. It is recognised as one of the most challenging aspects of engineering design acknowledging that engineering does not lie in well-structured problems with clear definitions. Creativity and innovation can sometimes be stilted as a consequence of rushing to solutions immediately. Again this was acknowledged by staff through discussions. Students were reassured that uncertainty is natural and to be embraced at this stage in a design process, encouraging unconstrained creativity.

6 FEEDBACK FROM THE STUDENTS

On the last day of each six-week session, students were surveyed about the level of value and enjoyment they obtained in each session of the project (team-building, design process, designing the cube, the physical build, testing, and presenting their final designs). In total, 133 students responded to the survey with an overall response rate of 80%. Although just 10% of respondents listed the *design process* tutorial session as the most valuable, a full 20% indicated that *designing* the Energy Cube was the most valuable activity they encountered. When compared to the other sessions, the design process session was indicated as the least enjoyable session by 15% of respondents. To us, this suggests that while students may not necessarily appreciate—or enjoy—having to learn about design in *theory*, they appreciate being able *apply* these methods in practice. Their ratings may also indicate they do not yet see the role of theory in practice. After modifications were made to how the design process was taught, the percentage of students selecting design process as ‘most valuable session’ increased from 9% to 12%—yet the percentage of students voting it ‘least valuable session’ also increased from 13% to 24%. Happily, the percentage of students listing the design session as their *favourite* increased to 3% and as least *favourite* decreased from 21% to 13%.

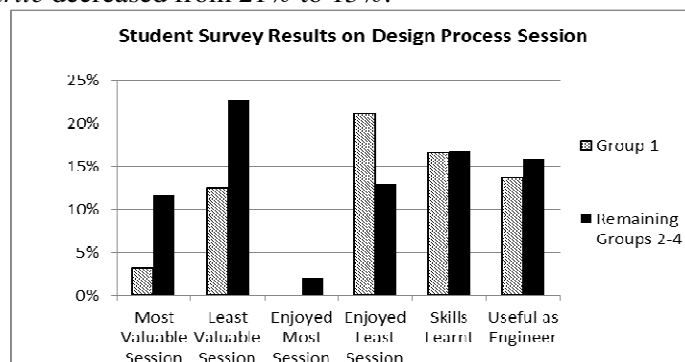


Figure 1: A comparison of Students’ response of the value and enjoyment they obtained during the design process session before (Group 1) and after (Groups 2-4) teaching modifications

17% percent of students felt they learnt the skill of designing via a structured process with 15% feeling it was the most useful skill to have as an engineer. This makes sense considering the complexity of learning to design. We also note that the other skills learnt—problem solving, the ability to draw and to participate effectively on a team—may be required in more engineering settings than design and may have been considered in the 15% rating students allocated to ‘design skill’. This low level of capacity students specified could possibly indicate that they did not see the connection between the structured design approach we provided and the process they followed. They may not correlate theory with the process they had just completed and learnt. There were improvements in the perception of the design process session among the students between the first cohort (weeks 1-6) and the remaining groups, as illustrated in Figure 3. After we modified the way we described ‘design process’, the remaining student cohorts ranked it as more valuable and marginally more enjoyable. They also indicated a slight increase in its usefulness as a skill for an engineer. Notwithstanding this, students still seem to struggle to see the value of the theory session even with the modifications made. On-going tutor-led discussions regarding how the design tools and design process theory fit into the project reflected some positive change over time, however.

7 CONCLUSION

Overall, the Informed Design Matrix [1] was found to be an invaluable tool in teaching design process. It helped lecturing staff understand what students might be thinking or feeling during each stage of the design project. It provided specific advice to teachers at each design phase. We believe it provides a solid framework and a clearly defined ‘end goal’ for new designers to work towards.

With regard to the Energy Cube, the very limited time allotted curtails the level of questioning, exploration, research, and depth each team could afford. Our lecturing team found a roundabout way to encourage reflection, troubleshooting, and iteration by using the students’ final report as a time for them to identify areas for improvement and reflect on design process. At this phase, we asked students to comment on the results they had found in testing their models. We asked them to recommend ways their designs could improve—these are aspects of iteration in design. Although there were mixed reviews regarding perceived value of the design session in the overall design project, and more work needs to be done to help students understand the value and enjoyment of design. In addition lecturers delivering the original building services energy cube module remarked on the much greater variation in designs among this group compared to their groups which tended to be, literally, cubes.

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