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Using Theory to Improve Design Instruction in a New Common First-Year Programme For Engineers

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Using Theory to Improve Design Instruction in a New Common First-year Programme for Engineers

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INTRODUCTION

We represent a group of lecturers teaching a design module in a new common first-year engineering programme, delivered for the first time in the 2014-5 academic year, which provides a single entry point for all honours Bachelor of Engineering majors at our institution. In this paper, we describe the rationale and format of the

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Design Projects module. We explain how we used theories by Crismond and Adams [1] in the module and what we observed in doing so.

The Design Projects module comprises three separate group-based design projects. It has four weekly contact hours over the entire academic year and accounts for ten ECTS credits (out of 60 earned in first year). Each student takes part in one semester of robot building, half a semester of bridge design and construction, and half a semester designing and constructing a model energy efficient building. A student completing the module should, inter alia, be able to: operate effectively within a design team; apply engineering concepts and design tools to solve engineering problems; and solve problems by following appropriate specifications and standards.

To enhance our team's efforts in explaining effective design process to students, a small group of lecturers volunteered to participate in a project proposed by a visiting Marie Curie Fellow. Individually, we read the article "The Informed Design Teaching and Learning Matrix" [1] and analysed its two-page matrix. We then met several times to discuss the matrix and its relevance to our module. Having found this very useful, our aim in writing this paper is to introduce the matrix to a wider audience and to make it more accessible for ourselves and for others to use.

1 MATRIX AND LITERATURE REVIEW

The Informed Design Teaching and Learning Matrix was developed by Crismond and Adams using Boyer's scholarship of integration as the underlying conceptual framework [1]. Their research process involved extensive literature review, akin to meta-analysis of publications on design process across various disciplines.

The Marie Curie Fellow on our team has followed the development of this rubric since 2008, when Crismond presented a draft copy at a National Conference on the Beginning Design Student that was held in Atlanta, Georgia [2]. The Fellow had been using it to teach architecture students and had published the draft rubric, with Crismond's permission, in prominent publications for university planners [3] and architecture educators [4]. She also integrated the rubric into a new tool that she presented at SEFI in 2012 [5]. Her blog about Crismond and Adams' revised matrix attracted the attention of another member of our team, who used it as the basis for a class discussion on design practice. These two were both involved in the Design Projects module, so they distributed Crismond and Adams' paper to all tutors on that module with an invitation to join a discussion about both the matrix and how to use it.

The current matrix compares how 'beginning' and 'informed' designers approach a number of design strategies, describing learning goals and useful teaching approaches to each strategy. For example, the first strategy listed is "Understanding the challenge". According to the matrix, beginning designers approach this from a problem-solving stance, treating design tasks as "well-defined, straightforward" problems and attempting to solve them prematurely [1, p. 748]. By contrast, informed designers attempt to frame the problem. Crismond and Adams propose learning goals that "Define criteria and constraints of challenge" and "Delay decisions until critical elements of the challenge are grasped". Finally, they recommend teaching strategies that prompt each student to: State criteria and constraints from the design brief in one's own words; Describe how the preferred design solution should function and behave; and reframe the problem based on investigative solutions.

In *Table 1*, we reinterpret one aspect of Crismond and Adams' matrix to provide a quick comparison of approaches related to each of its design strategies. We highly recommend that design educators reference Crismond and Adams' matrix in its entirety in their article in the Journal of Engineering Education [1].

In each of the following three sections, tutors from one specific project describe how they used the matrix in their teaching.

Table 1. Summary of contrasting behaviours of beginning and informed designers, distilled from Crismond and Adams' Informed Design Teaching and Learning Matrix.

Strategy	Beginner's Approach	Informed Approach
Understanding the challenge	Working to solve the problem	Working to frame the problem
Building knowledge	Skipping research	Conducting relevant research
Generating ideas	Treating ideas as scarce	Using ideas fluently
Representing ideas	Drawing & modelling at surface-level	Drawing & modelling at surface-level deeply
Weighing options & making decisions	Ignoring benefits & trade-offs	Balancing benefits & trade-offs
Conducting experiments	Confounded tests & experiments	Valid tests & experiments
Troubleshooting	Addressing glitches in an unfocused way	Addressing glitches in a diagnostic way
Revising / iterating	Using a haphazard or linear approach	Using a managed & iterative approach
Reflecting	Seldom reflecting on the process	Continually reflecting

2 ENERGY CUBE PROJECT

In this six-week project, teams design and construct a model of an energy efficient building using cardboard, clear plastic, and glue. The task combines elements of mechanical; manufacturing and design; and building services engineering. A fundamental learning outcome of the module is that students be familiar with design process and apply design tools to solve engineering problems. Our approach aligned each week's activity to the industry Stage-gate design process illustrated in *Fig. 1*.

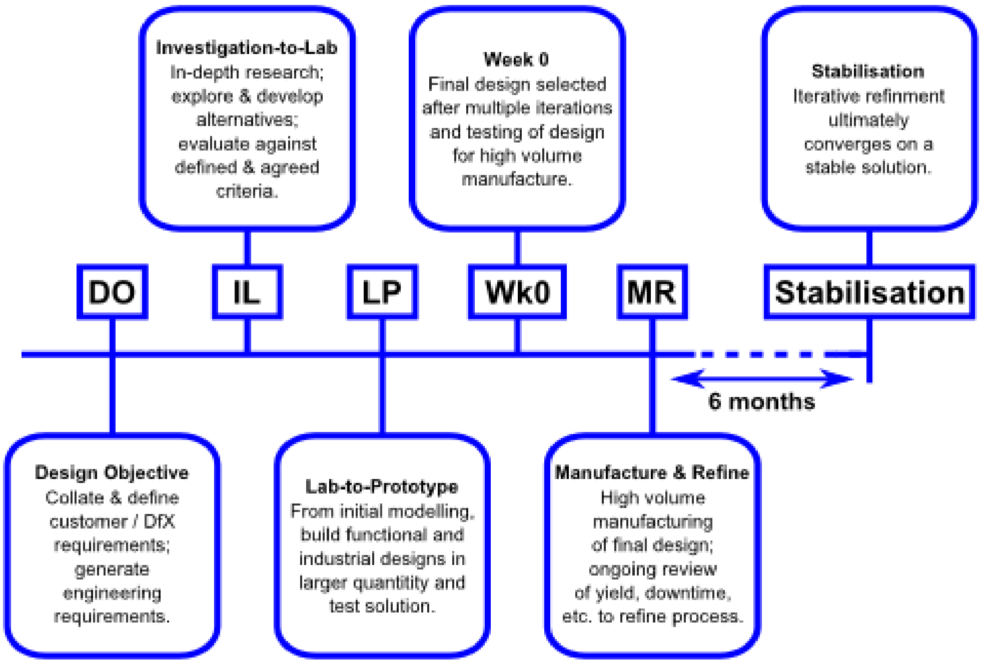

Fig. 1. High-level overview of an industry Stage-gate process.

In real-world design projects, many functional disciplines are involved in bringing a new product from concept to commercialisation, including marketing, supply chain, manufacturing and R&D, in a cycle that might last 24 months. This project focuses on the role of the R&D team and the outputs expected from them at each stage. Due to the project's time constraints, process stages from Week 0 onwards were omitted.

A review of academic material [6,7,8] and online resources [9,10] was undertaken to find out how design process is taught to second- and third-level students. This helped to simplify the design process so that our students could gain a basic understanding of it while completing rudimentary tasks that real-world designers undertake.

Two priorities were to emphasise an engineering design team's customer focus and to highlight the structured and iterative nature of the design process. Time constraints precluded process iterations, but it seemed attainable to introduce the early stages of the design process and specify clear deliverables for each phase. The customer focus was incorporated via a 'story-based' brief (which outlined requirements) and by tutors acting as customers, clarifying requirements and answering questions.

In week 1, the design process was outlined using the flow diagram shown in *Fig. 2*. This is a simplified version of the Stage-gate process used in industry, adapted from online teaching tools [9]. Each week, teams had a specific goal that aligned to a stage in the design process. The weekly goals were: 1) Generate design specification documents; 2) Create a concept evaluation matrix and select two preliminary designs; 3) Make detailed construction drawings; 4) Construct a final model; 5) Test the performance of the model and record results; and 6) Submit and present a report, including recommendations for improvement.

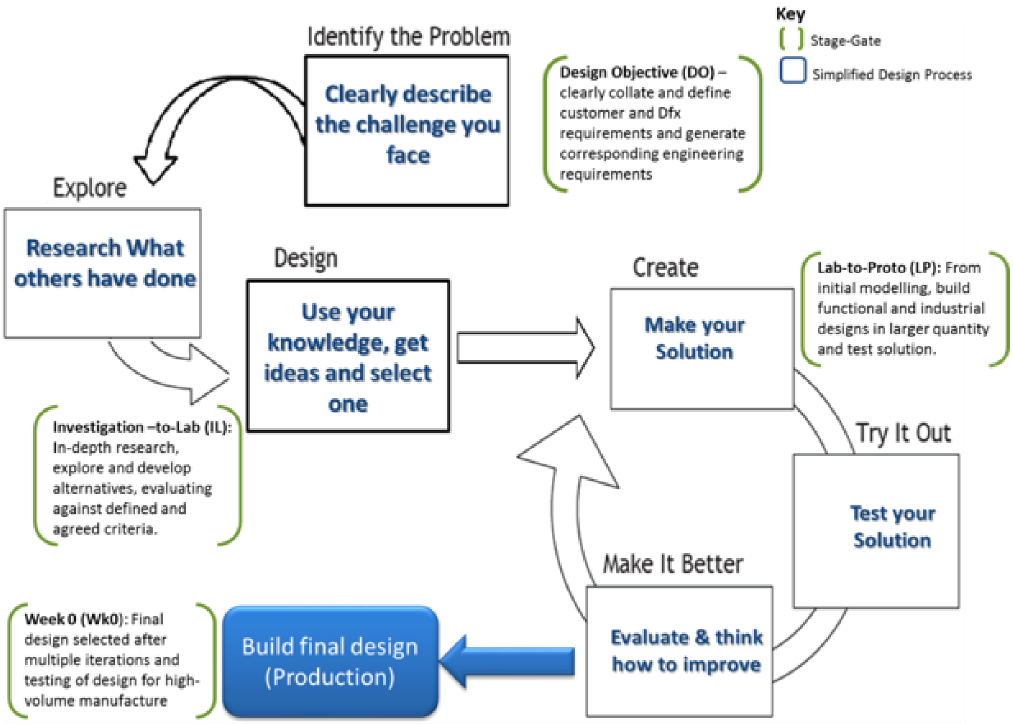

Fig. 2. The Engineering Design Process from [9] compared to an industry Stage-gate process.

After one project cycle using the process described above, a comparison was made with Crismond and Adams' matrix to see whether it could improve the learning experience. Students had struggled to relate the requested outputs (e.g. the design specification and evaluation matrix) with the overall project objectives. The timeframe provided limited scope for research and exploration and the value of these design tools and of the research stage did not seem to register with students.

The relevance of Crismond and Adams' matrix to this project was highlighted by the fact that each of the design strategies and corresponding teaching approaches in it aligned in some way with the prescribed activities and outputs of the project. However, it was the explanation of behaviour patterns based on levels of design experience that provided the most valuable guidance on teaching design to beginners. The fact that 'informed' designers delay design decisions and perform investigations and research to learn about a problem prior to brainstorming solutions is not obvious to beginning designers.

The focus on representing ideas was also useful, reinforcing the need for teams to create prototypes, sketches and 3D drawings to support analysis of concepts before choosing a design. The reference to being comfortable with ambiguity also resonated because this is a particularly challenging and misunderstood aspect of engineering design. Overall, the matrix proved invaluable in teaching design process. For educators, it provides specific guidance for each design phase as well as an insight into what students might be thinking or feeling. For beginning designers, it provides a clear framework and a defined goal to work towards.

3 ROBOSUMO PROJECT

In this 12-week project, students work in teams of (typically) three to build a small autonomous robot to compete in a sumo tournament. Each sumo bout consists of two robots trying to push each other out of a circular arena. The tournament rules impose various constraints on the design of the robots, including size and weight restrictions. In week 1, each team received a bag of components including a microcontroller, motor and breadboard. The kit contained enough parts to commence practical work, but was not sufficient to build a sumo robot. Teams needed to develop their own solution to the sumo problem and source the required materials, subject to a strict budget.

Each student's RoboSumo grade comprised four equal components: 25% for the team's competition ranking; 25% for his/her contribution to an effective group process; 25% for his/her contribution to the technical attainment of the team; and 25% for his/her individual blog. Each week's one-hour lecture supplemented a three-hour lab session.

An intermediate task – the *Race to the Wall* – took place in week 6. It was a simple time trial in which each robot drove across a table to touch a wall, then reversed and stopped on a black line. The primary aim of this task was to make teams face a deadline and potentially fail to get their robot working in time. The task itself was not summatively assessed, but to motivate engagement, performance in the *Race* was used to determine the seeding for the final tournament (and could therefore influence a student's grade). It was at this point in the module that students were introduced to Crismond and Adams' matrix during the weekly lecture and invited to reflect on whether it could shed light on any of the design errors they might have made in their preparations for the *Race to the Wall*. The matrix helped teams to recognise some of their own ineffective practices and identify more effective alternatives.

4 BRIDGE DESIGN PROJECT

This six-week project involves the design and construction of a footbridge. The concept stemmed from discussions with Prof Tom Cosgrove who is an advocate of Problem Based Learning (PBL) and carries out a similar project in University of Limerick. The project is aligned with a nationwide competition launched by Engineers without Borders Ireland in 2014 [11], which encourages students to design sustainable infrastructural projects for developing countries.

In line with a PBL approach, teams received minimal guidance and specifications. The problem description was '*Design a pedestrian bridge to span 6m across a river for use in emergency situations in Nairobi,*' with the requirement that the design and construction methods should be appropriate to the local conditions, materials and skilled labour available in Nairobi. Each session, students worked in teams of 4 or 5 during weeks 1-4 to research, design, analyse and present a solution. The tutors chose one winning team each cycle that built and tested a full-scale bridge over a campus pond (*Fig. 3*). Non-winning teams built balsawood models that were tested in the lab (*Fig. 4*). Construction took place in week 5 and testing took place in week 6.

Fig. 3. Testing of the full-scale bridge.

Fig. 4. Testing of balsawood models.

Table 2. Bridge Design project marking scheme.

Aspect	% Mark	Comments
Teamwork	40%	In week 1, students were required to produce a 'Team Charter', stating the team rules and penalties for lack of inputs, etc. Each team member's score was recorded weekly, yielding this teamwork mark.
Project folder	30%	Engineers in industry must keep records of research and preliminary design, minutes of meetings, design decisions, drawings, etc. This 30% weighting highlights the importance of keeping accurate records.
Quality of bridge	20%	Determined by the tutors based on quality of research and analysis.
Group presentation	5%	All teams presented to the class weekly on their progress. In week 4, teams gave their final 'Client Presentation'.
Individual reflection	5%	Students were asked to reflect on the experience one week after completion.

The weekly class was purposefully ill-defined. The only requirement was that teams start the session with a 'Design Team Meeting' (to mirror what happens in industry) and end the session by presenting their progress to the class. Tutors circulated, providing guidance and feedback. No formal teaching was done and teams were encouraged to try novel designs and construction techniques.

The tutor who designed the project had recently joined academia following 20 years in industry as a consulting structural engineer. Her pedagogical approach emphasised self-directed learning, record keeping and the importance of the design team, aiming to mirror the reality of a consulting engineer. When introduced to Crismond and Adams' matrix following the first project cycle, her initial concern was that the students had not explicitly been 'taught' anything about design process; they were simply launched into the project and learned by experience. However, it was concluded through discussion with the other tutors that it is desirable for students to encounter different perspectives on design process in different ways over the year.

In her observation of students working in teams and her analysis of their reflections, the tutor who designed this project identified instances of both beginning and informed designer's approaches. Some examples of each are presented in *Table 3*.

Table 3. Examples of beginning and informed designers' approaches in the bridge design project.

Strategy	Beginner's Approach / Informed Approach
Understanding the challenge	The problem was very simple so students began brainstorming bridge designs immediately. However, this generated a lot of questions on what materials were suitable etc. so there was also evidence of 'problem framing'.
Building knowledge	Teams spent week 1 researching. They understood that until they had a list of materials and looked at different bridge designs, they could not proceed further. In some ways, this worked in their favour.
Representing ideas	Initially, students were reluctant to put sketches and designs on paper or to suggest ideas. However, as the year progressed, students became more confident and increasingly relied on models and drawings to explain ideas.
Weighing options & making decisions	It was noted that some teams who had previously completed the Energy Cube successfully applied a decision-making matrix they had used in that project.
Revising / iterating	This was perhaps where students most lacked experience. In the final week of construction and testing, although the design and structural analysis were complete, teams haphazardly added parts to increase the bridge's capacity.

Her own reflection on the matrix highlighted a key point: Students *were* moving from beginner's approaches towards more informed approaches. In particular, the difference between the first and third project cycles was striking. There were evidenced increases in independent research, confidence in putting forward ideas, analysis of pros and cons of different designs and, most dramatically, representing ideas. For example, in the third cycle, several students created lollipop stick models to communicate their proposed design to their team.

The matrix provides a framework for acknowledging the expected outputs from our students and identifies the attributes that signal progress along the designer experience line. However, one aspect which the matrix does not explicitly deal with is the importance of being a good team player. Engineers need confidence in their own ideas, but must also listen to others and work as a team to deliver a product.

5 CONCLUSIONS

In our first year of the Design Projects module, Crismond and Adams' matrix played a dual role. Firstly, it enhanced student learning, both by providing teaching strategies and by *defining* what we wanted them to learn. Secondly, it provided an excellent focus for discussion among the diverse team tutoring the module's three projects. The matrix captures aspects of design practice that are central to all three projects and presents its contents in a concise form that even those colleagues who were too busy to read Crismond and Adams' full paper could connect with immediately.

This module, which is a defining element of our new first-year engineering programme, is delivered by a large team of tutors from various engineering disciplines, most of whom had not worked together previously. While students experience all three projects, each tutor only has direct experience of one project. Our discussions about the matrix helped to build trust and mutual awareness between those tutoring on different projects. The matrix maps the common ground shared between the three projects in a way that is accessible to teachers and students. When students review each project, the matrix nudges them towards reflecting *metacognitively*. In so doing, one might hope that they become better able to leverage insights gleaned from a past project in their work on future projects.

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