Evaluating the integration of digital design and prototyping tools in a problem-based learning tertiary level course

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ABSTRACT: This paper presents an example for tertiary level education institutions to establish and develop a digital design and prototyping course in a problem-based learning environment. The paper reports on a developed framework that was used as a basis for a computational design course involving a mixed cohort of architecture and industrial design students. Using a practical design brief, students went through a design process with an object (either physical or virtual) as an assessment submission, including providing an appropriate solution to an identified problem. This design scenario, involving the investigation of a range of possible outcomes, evaluates specific realisation tools that are currently bound in the academic domain and yet to be utilised effectively by industry. Outcomes of the course included a range of perception-challenging forms and a thorough evaluation of the course from the students’ experience of using both familiar and unfamiliar design tools. A quantitative analysis of the students’ self-reflection enabled the course leaders to refine the course structure, design brief, teaching methods, project context and outcomes that will improve the learning of successive years of students.

Keywords: Digital design, problem-based learning, student experiences, course design

INTRODUCTION

Technological developments in the systems, which support the design process, have provided the means to develop form-creating digital products which have the potential to establish standards of practice in a wide range of design disciplines. Digital form creation was enhanced with the development of CAD systems but the new systems far surpass the capabilities of the now common CAD systems currently in use.

The ability to enhance the design process comes at an expense, development costs etc see the adoption of these newer technologies are often priced out of the market the perception by practitioners is that the products need to provide outstanding value to the consumer to survive in the design domain. As identified above, CAD systems are an example of where high efficiency in producing reliable quality has resulted in the tool becoming an established part of the design process. Cheaper manufacturing methods resulting in lower product prices, coupled with an improved performance make innovations more viable and, in turn, a more valuable and desirable tool to industry professionals and familiar to the industry at large.

This paper evaluates the application of both familiar and unfamiliar tools, within a multi-disciplinary class of tertiary design students through and qualitative analysis of the students’ learning experiences. As well as being introduced to these technological innovations students engaged in the development of skills in the systems through the application of a problem-based learning (PBL) approach to student engagement with the content and the design processes through the application of the leading edge Technology.

Firstly, the paper introduces the course design and its use of a formal framework as a basis for students’ decision making and understanding of a digital design and prototyping process. It will detail the background of the students enrolled in the course and profile their abilities within a digital design and prototyping context. The paper then describes the course establishment process through its learning objectives, teaching methods and setup of the studio towards providing an engaging, interesting and sustainable experience. Examples of students work follow, with a brief insight into the projects from whence they were conceived, and the means in which they were formed. Their reflections on the course, and specifically their perceptions of digital design and rapid prototyping tools, were recorded in a survey with a quantitative analysis undertaken of the results. This survey, involved the development of a comprehensive questionnaire, was focused on 4 sets of questions: (1) Has the tool enabled them to develop a design more efficiently? (2) What device they found most/least useful towards their program of study? (3) What were their learning experiences during the course, and (4) How the course encouraged them in the exploration of digital
design? These questions will generate an understanding of how the students received the course, and specifically the tools and their reflection on using them in their prospective careers. Supported by the analysis of the survey result, the paper aims to provide an insight into the utilisation of a variety of digital design and prototyping techniques in realising a student form-generation project.

1. COURSE DESIGN

This computational design course created is an advanced digital design studio that is exploratory in nature and focuses on creativity in design form marking through the introduction and application of contemporary digital design and rapid prototyping tools and techniques. The course student population is drawn Industrial design and architecture disciplines. These design programmes are regarded as the nexus of art and science as they both adopt and develop technology. From a functional perspective, industrial designers and architects produce useful artefacts such as buildings and products as the end results of their design activities, which involve them in reflective practice on the potential of their designs to serve society. From a creative perspective, these systems also create aesthetic forms reflecting critical design philosophies, for example, those as realised in the Australian architectural landmark - the Sydney Opera House by Jorn Utzon, and the sleek product designs developed by Marc Newson. Nowadays, with the use of leading-edge digital design and rapid prototyping technologies, designers have more creative triggers and flexibility in producing complex forms that were not previously possible through the use of tradition design and crafting techniques, thus challenging our common perceptions about design and form marking.

The course was designed to provide students with exposure to the new leading edge technologies of design but these technologies were introduced utilising a student centred problem based learning approach with engaged the students in not only learning the systems but applying them to a self directed learning situation.

1.1. The course development and introduction

The aim of the course was to introduce the students, as future designers, to the creative and exploratory practice of digital design and rapid prototyping, and to equip them with state-of-the-art design knowledge and technical skills that reflect contemporary design culture. Specific learning objectives were:

- Understanding major bodies of digital design theories.
- Critically reflecting on contemporary design theories.
- Understanding a range of state-of-the-art digital design and rapid prototyping tools and techniques.
- Applying suitable digital design and rapid prototyping tools and techniques for exploring creativity in design form making.

The course was structured on the principal of a design project that enabled students to explore creativity in form utilising the introduced tools and techniques, as exercised throughout the semester. The design brief changes each year but always retains the open-ended type of problem structure to accommodate the different student backgrounds of industrial design and architecture. The open-ended structure encourages students to apply a more creative design process and facilitates engagement with the technologies. For example, the 2010 project required students to capture a particular aspect of the Newcastle City and to abstract and represent it through digital design and rapid prototyping processes. The design process involved the students in reflecting on the main digital design theories introduced in the course and through the application of the leading-edge tools and techniques, each student designed and produced a prototype with a form that is representative of a creative interpretation, abstraction and representation of the selected City aspect.

The course was delivered through weekly lectures and studios, which involved three contact hours per week over a 13 week semester. Students were expected to spend an additional seven hours outside of class time to research on digital design theories, conceptualise designs and explore the digital tools to which they would be introduced through the semester. The course schedule was developed using a progressive learning process by linking content from week-to-week to enable continuity in understanding, and for the students to gain a holistic knowledge of digital design with critical awareness of the advantages and disadvantages of specific technologies and processes in order to make critical informed decisions about your own design development. Teaching methods were enriched with a mixed media approach to communicating information through video, imagery, demonstrations, field trips, group work, hands-on workshop activities and one-on-one studio sessions. Besides the main project assessment item, student learning was assessed and monitored through 3 presentations divided over the length of the semester to assess their progress and provide direction through feedback comments.

The design project was exhibited at the end of the semester to an audience of fellow students and academic members at the School of Architecture & Built Environment at The University of Newcastle, and aimed to create discussions about the impact of digital design and rapid prototyping technologies on contemporary design culture, among different design disciplines.

1.2. Alignment with Problem-based learning principles

Design education takes many and varied forms across the range of design disciplines, for present purposes we use the term design education to mean development of ability to design, through processes of structured formal learning
and, through processes of formal assessment, verification of ability to design at graduation across the whole range from very pragmatic to very aesthetic design types. When considering design, for educational purposes, it is possible to regard it as having three different levels. Basic design, moderately complex design and highly complex design. Our task as educators is to move students across these levels of design the implementation of assessment tasks that challenge the students to move from basic to higher levels of abstraction. What is important for academics is to provide students with a diversity of design experiences that allow them to develop experience and skills across a range of design contexts (Cowdroy & Williams 2005).

Design education has always been associated with Problem Based or Project Centred Learning (PBL). PBL has been described as both an instructional strategy and a curriculum design. The majority of literature in PBL relates to the use of PBL as an instructional strategy (Maitland & Cowdroy 2001). It therefore lends itself to be applied to an elective subject that is a part of a Programme of study that applies multiple teaching approaches.

As an ongoing process, PBL can be employed as a design teaching approach that includes the facilitation of the emerging information and communication technologies. PBL characterizes how individuals construct their own understanding and knowledge of the world, through experiencing things and reflecting on those experiences (Mahoney 2004, Huitt 2003). According to this view, the learning process involves the followings:

- knowledge is obtained and understanding is expanded through active (re)constructions of mental frameworks (Abbott & Ryan 1999; Bransford, Brown & Cocking 2000)
- learning is an active process involving deliberate progressive construction and deepening of meaning (Spady 2001).

This distinction between facilitative thinking and thinking as behaviour is of fundamental importance to design education (Eraut 2000). For instance, the essential ability of a designer is not measured in terms of what is built, or in drawings depicting what is to be built, but in terms of the complex rationale that constitutes the design (of which the drawings and artefact are manifestations). Similarly, the essential ability of a design practitioner is measured in terms of design brief developed with a complex rationale, informed decision making and anticipating particular outcomes, which coalesce into a tangible design outcome. In the sciences, the essential ability is not the experiment (even in the most exotic research environment) but the complex rationale that prognosticates outcomes (‘the hypothesis’ and ‘framing of the research question’) from which that experiment follows.

The focus on thinking here does not deny the importance of the associated physical actions that characterise what a designer currently does in practice; but rather what our students will do as design practitioners. To this end as design educators we must expose our students to confronting what is now the future but what will be their future practice.

PBL has long been acknowledged as a teaching methodology that provides an integrative learning experience, so the opportunity to introduce futuristic application into a PBL structured learning experience is most appropriate. PBL provides a framework for considering the assessment of students engaged in applying future technologies to their Learning Experience.

Table 1 demonstrates how the course aligns with the principles of the implementation of PBL to provide an effective leaning environment.

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<thead>
<tr>
<th>PBL Implementation Principles</th>
<th>Student Outcomes</th>
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<tbody>
<tr>
<td>Development of high professional competencies</td>
<td>Students will learn the effectiveness of cutting-edge design tools and techniques to produce quality work</td>
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<tr>
<td>Reasoning which supports critical thinking and creativity</td>
<td>Students will learn appropriate use of tools relative to specific task within a design process</td>
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<tr>
<td>Provides an environment which encourages reasoned decisions in unfamiliar situations</td>
<td>Students will be introduced to the benefits of a variety of tools and to select ones that are appropriate to specific design tasks</td>
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<tr>
<td>Adaptability to participate in change</td>
<td>Students will evaluate their decision-making and their impacts</td>
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<tr>
<td>Appreciation of others point of view</td>
<td>Students will learn to react and produce design development from a Design Review</td>
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<tr>
<td>Encourages self evaluation</td>
<td>Students will learn how to reflect on their decision-making through a formal report</td>
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<tr>
<td>Work productively and effectively as a team member</td>
<td>Students will learn engage in a group project</td>
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1.3. The course roadmap

It has been recognised in the field that the use of leading-edge digital design and rapid prototyping tools has presented opportunities for supporting creative processes across the whole design life cycle (Sass and Oxman 2005; Kolarevic 2003). As witnessed in the latest development, they have also significantly impacted on design and design education. However as pointed out by Oxman (2007), most educational cases of such, for example, Stavric et al. (2007) were inspiring, yet they were often motivated and influenced by "individuals", without adequate considerations for a theoretical and pedagogical basis. The development of our course is based on a formal framework for utilising different digital design and rapid prototyping tools in design education.

The roadmap utilises three main categories of tools involved in a typical digital design and rapid prototyping project life cycle. The roadmap also provides a base for students to identify the suitable tools and techniques to form their own "path" for project development, according to their needs. The roadmap as illustrated in Fig. 1 comprises of three main components: Input Tools - tools that support the development and digitization of design representations; Design Interaction Tools - tools that support digital design interactions for conceptual and detailed design; and Output Tools - tools that support rapid prototyping design representations. Depending on the complexity and the timeframe of the project, the roadmap is recursive enabling further design development, evaluation and refinement.

Common physical Input Tools such as sketching devices and clay models were mirrored with virtual options by utilising digitising devices such as 3D scanners and haptic pen devices to generate the creative forms students desire, without being compromised by their (lack of) abilities in applying particular digital tools. The acquisition of the scanner and haptic pen provides the students with alternative means of generating their digital representations, with an emphasis to support their freeform designs. Sculpted physical models from clay or foam can be scanned into a 3D virtual model. The similar practice can also be conducted solely in the virtual domain by using a haptic pen device that offers clay-like form creation through a digital tactile interaction. 3D freeform design representations generated with conventional CAD software can be challenging and time-consuming in comparison to more geometrically based models, often resulting in restricted creativity and unfulfilled representations of the designers' intentions. The integration of the scanner and the haptic pen device would, in theory, increase creativity and realisation of intent. However studies into the application of haptic devices in design and design education are particularly limited. The outcomes of the course and students' perceptions on the issues will provide valuable insight.

Output Tools such as rapid prototyping (RP) devices have long been used in industrial design and are growing to be a major force within the architecture. Prototyping processes such as Computer Numeric Controlled (CNC) machinery and Stereolithographic techniques are enabling designers to accurately realise their concepts developed during their Design Interactions. Successful RP outcomes require suitable CAD strategies as a pre-requisite, which suggests that within the roadmap a process skill graduation must occur for the next design phase to begin.

![Figure 1. The digital design and rapid prototyping project roadmap.](image)

The roadmap is inclusive, which enables students to explore and alternate between the physical and the virtual domains, following the suitable path and finding the appropriate tools for their design needs. It is essential to balance and blend the tools from the both domains to ensure that the design process was to operate efficiently but not biased
to any particular elements or pathways. This supports the objective of design exploration and creation using varying realities, whereas the roadmap can serve as a structured framework for creating proven pathways that support such practices. Through tutorials, students are guided to master the tools. Through design exploration, they further understand the advantages and limitations of the tools, gradually refine the design concepts, and make informed decisions about their own individualised path on the project roadmap.

1.4. Facilitation of student learning

The schedule for the course was developed into stages of concept ideation, skill development and self-direction with weekly classes of a 1-hour lecture and 2 hours of tutorials. Lectures would be based on providing formal information to the cohort on topics such as creative form making, design theories and the Input & Output tools with tutorials engaging the students with practical tasks and demonstrations linked with the weekly topic. Basic, yet, thoroughly creative card and caly-based form making inspired the students to realise shape and

For skill development in the use of the Input Tools it was imperative to the success of the course that the students were able to access the equipment easily and exclusively. A digital design studio was established for this course, only to enable the students to self-direct their learning outside of class times. The studio housed a Haptic Pen, a 3D Scanner and a Design Tablet (sometimes known as an Interactive Display), each of which were attached to a dedicated Windows-based. It was essential to maximise the use of the devices by ensuring the computers performed well in graphics and memory, and had relevant software such as the Adobe Creative Suite, ArchiCAD and SolidWorks installed.

The nature of tutorials were to demonstrate techniques with students encouraged to enter the studio outside of class times to develop their skills in using these new and unfamiliar tools. The 2-hour tutorials were based on a learning by watching principle, mainly due to capacity issues, and also that it was vital for students to self-direct and reflect on their learning and use of the these tools.

2. COURSE OUTCOMES: SELECTED STUDENT DESIGN

The 29 designs emerged from the studio of the past two years have been very exciting, ranging from forms translated from sound waves, to forms influenced by 4D space, to forms that transforms traditional or nature patterns. The stimulus of the new theories and technologies and the opportunities of the project exhibition were also effective. Students’ “usual” ways of conceptual development and project implementation were challenged. Although further studies are required in order to understand the impact of the roadmap on students’ creative development, nevertheless, they were able to create new forms that challenged our common perceptions as required by the brief. The selected projects below showcases some of the works developed in the studio by adopting different paths on the project roadmap. Students were able to explore the opportunities presented in different approaches and alternated between the physical and the virtual according to their design needs.

The first example produced in 2009 presents a form for a bowl design that transformed from sound waves of a music piece. The student’s conceptual development started with the reflection on cultural significance through music. He highlighted the standout frequencies in a visual sense, namely their individual waveforms, and blended them in a 3D space for form creation. The three main stages identified are audio sampling to create sound waves (Fig. 2 left); algorithmic interpretation to create the desired 3D form (Fig. 2 middle); and the final rapid prototyping to develop the output (Fig. 2 right). The creative process is largely supported in the digital transformation process, from the sound waves to the functional 3D form. The student explored different theories and applications in order to develop a set of constraints for controlling the form transformation.

Figure 2. The transformation of audio waveforms by Michael Thorogood.
Students’ creative process can also be supported between physical and digital interactions. In the second example from the 2009 studio, the student selected a physical Buddha sculpture as a base for form creation, and aimed to design a decorative item with a reflection on deconstructivism. Firstly, she digitised a physical sculpture to develop a digital model (Fig. 3 left). The student then explored various techniques in order to deconstruct the digital model. The slicing technique (Fig. 3 middle) was selected as the mean to deconstruct the model into horizontal and vertical profiles. The developed profiles were then rapid prototyped in the laser cutter to develop the final outcome (Fig. 3 right). The creative process was hence supported between physical and digital interactions, through the digital profiling and the physical assembling.

Students responded very positively towards the digital design theories introduced in the course and they played an important role in inspiring and guiding students’ creative development, for example, generative design was one of the most popular and influential theories adopted by students in the 2010 studio. Figure 4 illustrates two different designs developed under such influence. Although each adopted a different path on the roadmap, both of the outcomes nicely captured the essence of generative design. The first design (Fig. 4 left) by Edin Merdjanic is a visual representation of the aboriginal identity in the Newcastle City. The aboriginal name of the main Newcastle area is “Muloobiba” meaning the “place of sea fern”. The design of the panels for the sea fern were generated algorithmically using the first census data gathered on the local indigenous population in 1829. The design was generated using a mainstream parametric design software by specifying rules to control the design process, and the prototyping was completed using FDM in order to suit the organic nature of the form. The second design (Figure 4 right) by Gemma Savio is a generative pattern transformation of two symbolic patterns captured from architectural elements in a popular urban street in the Newcastle City. The design aims to explore “ornamental identity” of the streetscape in the City. Different from the first design, the student adopted a “slow computing” approach here and manually developed the rules for governing the generative process. A standard modelling software was used to assist the visualisation and selection process. The elements of the prototype were then laser cut and assembled by the student.

3. COURSE EVALUATION: STUDENT PERCEPTIONS

A questionnaire was distributed to the students at the course conclusion to gain an understanding of the students learning experience of the course and the tools used in their creation process. The results were grouped to discover the student’s reflections on using the Input & Output Tools, their general course experiences, suggestions for course development and their intentions for further use of the tools introduced.
3.1 Student's perceptions of the input tools
From the input tools listed in Figure 1, students had opted to use more than one type of tool in their design process. The selected tools were evenly distributed among Physical 3D, Physical 2D, Virtual 3D – Direct, Virtual 3D – Free Form Modelling and Virtual 2D – Direct, with Virtual 2D – Free Form Design seemingly not as popular. The reasons behind their selection process was that, in 31% of cases, that students needed a device to support complex or unique form making and also that 24% were aiming to complete the project more efficiently. 20% felt that learning about new technologies was a factor in their decision making, with small numbers choosing supporting the conceptual development of the project (16%) and the fact they had used the technology or similar technologies before (8%). It was encouraging to see that students were ambitious and intrigued in their nature to try new tools and not to remain content with more commonly found methods.

The use of 3D CAD, as a means of form creation, was favoured by the majority (38%) of students, who stated it as being a very effective tool to use for realising their ideas. 28% were enticed by the lure of a new and unfamiliar device in the Haptic Pen but had mixed experiences, with the majority stating it did help them to develop design in a different way and explore different design options, but some believed it was ineffective. This was largely due to learning not only new device hardware, but also the software, and allowing time to learn both aspects outside of class time.

3.2 Student’s perceptions of the output tools
The decision to choose subtractive or additive means of rapid prototyping was almost equal with 56% opting for the Fused Deposition Modeller and 44% preferring to use a Laser Cutter or CNC machine. The rationale behind these decisions was based on being able to produce the project more efficiently (39%) and to support complex or unique form making (31%). These results demonstrated that the majority of students were being economic with choosing appropriate tools for their purpose rather than being lured into selecting new tools for no reason.

From every response returned, the uses of all three main output tools were very effective in producing their design. Comments regarding time and precision are inherent of these digital manufacturing processes where their success is based on being able to produce forms directly from the CAD files with no active human involvement or error.

3.3 Student’s perceptions of the most useful tools
When asked about what device the students valued as being most useful, 21% of responses indentified the Haptic Pen and the same number listed 2D/3D CAD Systems. 18% of students preferred the 3D Scanner and also the FDM machine. These results suggest that digital design interaction and digital production tools are favoured over more traditional and analogue means of realising intent. Students reflected similar reasons to the choice of Output Tools in that being effective with time in producing complex forms was of paramount importance.

3.4 Student’s perceptions of the course
The students were asked for their opinions of the course to aid the future development of this relatively new and diverse course. Criticisms, both positive and negative, were invited as a means of determining success and assessing performance. Students believed that communication of information as being key to their learning with them appreciating feedback from teachers, environments to talk and information that was easy to understand. They identified that more time in tutorials was required for learning new technologies although they were very complimentary of being able to use cutting edge technologies. With many of this cohort soon to graduate, they believed in learning contemporary tools to be necessary to their offering of skills to industry. Hands-on and practical learning of the tools reinforced their need to learn in a project context and their reflections of their use for their future careers.

3.5 Student’s perceptions of further use of tools
With the students being able to assess the effectiveness of the tools through practice, it was encouraging to see that they would consider using them in the future. Comments that the some tools were not as daunting they appear and that it allowed them to be more creative showed that they now had an increased interest in their application. Some students had researched the cost of some tools, with one stating that they were not aware that 3D scanning was financially viable.

4. CONCLUSION
The overall responses suggested that students had learnt from information presented in lectures on the appropriate uses of the Input & Output Tools, and had applied the knowledge to their individual projects. Each student had submitted quality within the time constraints, which further reinforced their understanding of the course content and the occasions to use the tools within the design process.

Overall the introduction of both the teaching strategy and the technologically advanced design systems has been a success. Students readily acknowledge the effectiveness of these in confronting them with a significant and valuable learning experience that they will apply in their other courses. The students valued most notably the approach, the problem analysis and the aligning of the most effective design approach with the technology that will provide the best outcomes. But, as with most courses, there is room for enhancing the course and making it more relevant to students. Considerations in developing the next presentation of the course would include:
• Developing clearer assessment rubrics
• Enhancing the reflective aspect of the design process
• To consider Generative Design tutorials to partner the formal lectures
• Looking to develop further synergies with the contexts of the problem

What did become apparent in the delivery of the course is that the students’ initial tentativeness disappeared as they engaged with the newer technologies and applied them to a self developed and directed design scenario.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution and active participation of all enrolled students in the course.

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