Supporting creative learning for rapid prototyping and additive manufacturing through lessons from creative learning for CNC routering and laser cutting technologies

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ABSTRACT

   This paper draws parallels between the introduction of rapid prototyping and additive manufacturing into the product design academic curriculum and the development of creative learning using CNC routering and laser cutting technologies. It contrasts 'top down' learning and 'bottom up' learning strategies in designing for CNC routering and laser cutting technologies, gives examples of staged learning and linked learning for theory and practice at different design education levels and reviews related industry / education initiatives.

   Specific examples of design students' project work using CNC routering and laser cutting technologies are discussed and inform recommendations to support the development of creative learning opportunities for higher education that respond to the academic imperative whilst providing a spectrum of design thinking approaches for the future innovative use of rapid prototyping and additive manufacturing. Challenges for design education in the development of this curriculum are identified and reviewed.

   In addition to direct student learning strategies, strategies for supporting professional development for product design academics to facilitate the innovative use of rapid prototyping and additive manufacturing technologies in creative academic programs are discussed to improve the potential of future product design professionals to be equally innovative in the use of these technologies in their careers.

INTRODUCTION

   The knowledge base of technologies for the industrial design discipline has constantly changed because of competitive research driven by commercial necessity to develop innovative processes, practices and materials to stay ahead. However, the introduction of additive manufacturing techniques into mainstream production requires arguably more of a change in thinking from industrial design practitioners than the evolution of manufacturing technology has previously necessitated. Not only do designers have to understand the constraints and opportunities in practical design terms but adjust to the impact on their role. Developments in rapid prototyping and additive manufacturing redirect the market towards mass customisation and the democratising of the production process, changing distribution practices worldwide. There is a rapidly growing need for new design thinking and skills to work in this global online studio environment. 3D Designers will increasingly work online with international clients and in the new area of online co-design and also with developing and digitally modelling 3D products for web sale and distance additive manufacturing. The skills and understandings needed will be different to those currently taught on Product and Industrial Design courses.

   How future designers learn about any manufacturing technology in higher education will affect how effectively they use – or don't use it – in the future. The ideal is to create designers who are imaginative enough to draw advances in the development directions of new technologies, rather than adapting their own practice to fit what is initially offered, based on retrospective requirements for design production, rather than innovation. This will challenge and feed the research and development activities of industrial practices and in turn open new pathways for innovation that can feed back into higher education and academic research.

   As rapid prototyping and additive manufacturing is introduced into the curriculum, lessons from the study and explorative practices of using CNC routering and laser cutting technologies in higher education can inform strategies to support innovation and imaginative application of those technologies new to the higher education design curriculum.

I. TEACHING DESIGN IN HIGHER EDUCATION

   To keep a degree level industrial design program current requires that the teaching responds to developments in industrial practice. More than that, it requires that the teaching promotes innovative, informed practice in the application of new technology. As design theorists advocate the development of T-shaped profile designers (Gerson, Ramond, 2009) who have a specialist area of understanding and a broad overview of design, the question arises of what is discipline specific knowledge? The content will inevitably change through time in response to changes in production practice and distribution or factors such as the impact of design on the environment and societies and it may be that traditional disciplines will gradually be replaced by areas of specialism, such as manufacturing, or design for education or health. However, working from the stand point of this time and therefore based on our knowledge and understandings now (and drawing on the historical origins of the discipline (Raizman 2010)), Industrial Design differs from other 3D design disciplines because of its focus on the ability to plan for an outcome to be consistently re-produced. In other respects, such as designing to respond to a situational brief (Loy: 2009), and designing to consider sustainable design practice strategies, such as replacing products designed for

lifecycle with product service systems designed for a closed loop approach (Loy: 2008), the discipline body of research knowledge is not significantly different to that of other 3D design disciplines, such as Architecture and Interior design where situational, problem solving projects are also undertaken.

Creative practice, so much the focus of publications about product and industrial design courses, is a necessary tool for industrial designers to possess, design thinking – the ability to redefine a problem based on initial research and plan strategies for addressing the issues identified is far more vital. The main focus of industrial design professional practice work is not creativity, but an iterative, cumulative process-led development practice based on thorough research and testing at each stage. In publications, this is a characteristic more commonly discussed as an engineering approach:

'Engineering design is a systematic, intelligent process in which designers generate, evaluate and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.' (Journal of Engineering Education 2005: 105)

Driving the effective production of practical designs within challenging and changing manufacturing environments is the reality of the work. Trying to keep the students up to date with the latest technology and manufacturing processes and the latest developments in materials in order to work in a range of manufacturing environments is a constant challenge. In fact, trying as an academic to keep up with the latest developments is a challenge. Even if it was then theoretically possible to teach students enough knowledge and understanding of current processes and materials the reality is that the body of knowledge would change very quickly once they graduated. Therefore it is important to teach students the ability to find out about new technologies and materials and keep themselves up to date throughout their career. Teaching students to become life long learners and proactive learners is fundamental. 'It is now increasingly accepted that the most important outcomes of education and training are about developing people, and not just what people know or understand'. (Race 2007: 126)

That said, an in-depth understanding of current technologies and materials is essential for credibility as a graduate – discipline specific knowledge should not be sacrificed for developing transferable skills, such as the ability to learn, but work in conjunction with it. This involves providing the students with and the opportunities to experience and understand the implications of design decisions.

These are the challenges facing the course planner and lecturer. How to keep the learning current and related to real world context, how to make sure the students have an effective, working knowledge of current practices and new developments, how to help the students to understand the implications of a new technology for their role and finally how to ensure that students have the confidence and ability to keep learning about new processes and materials after graduation. These points form the basis of the design of the learning experience for the student.

II. DESIGNING LEARNING: DESIGNING FOR DIGITAL PRODUCTION

The introduction of computer numerically controlled routering to the higher education curriculum (articles appeared in research journals in the nineties) focussed on digital modelling. This has provided a skills base that the introduction of additive manufacturing has built on. Since the mid-nineties, Product Design digital modelling has gained in importance in the curriculum, with projects drawing on digital modelling earlier in the design process. In order that the designer stays in control of the technology, rather than being driven by it, teaching practices have to be planned that support a proactive learning approach rather than reliant on didactic methods.

In his collaborative 2007 book, 'Making Teaching Work', One of the most high profile researchers in effective teaching strategies, Race, advocates five factors needed by students for successful learning – wanting to learn, taking ownership of the need to learn and accepting and setting targets, learning by doing, learning through feedback and making sense of what is being learned through reflection (2007:9).

A series of learning experiences on design for digital cutting technologies (CNC routering and laser cutting) were developed to explore different approaches to addressing the needs outlined in the introduction. These were tested and evaluated to illustrate the benefits and drawbacks of each practice and their outcomes. Suggestions for strategies for supporting good practice are discussed in the conclusion.

III. DIDACTIC LEARNING

A. Example of bottom up learning strategy

Just as in building a manufacturing model in a software program, such as Solidworks, in teaching and learning current practices 'bottom up' and 'top down' learning require different thinking and result in different outcomes – both in terms of the finished product, but also in terms of the understanding of the learner. In 'bottom up' learning, the student follows a series of set tasks that cumulatively provide knowledge about the process to be learnt. The tasks are traditionally introduced by an initial lecture explaining the structured process and the intended outcomes for the course. The initial lecture also traditionally includes a broad introduction to the practice, including complex examples. The sessions are taught didactically by demonstration and repetition. Only after this task work has been completed are design students given a design task with a base in the use of the particular technology.

In this first example, first year students are introduced to CNC routering using Vectorworks through 'bottom up' learning. There is an initial lecture with examples of how the technology has been used by designers not only in product design, but in architecture. The course then consists of twelve hours of contact time, divided into four sessions. Each session is run step by step, with the facilitator demonstrating an individual step with the students copying. The first sessions focuses on Vectorworks tools with the students copying a set of working drawings. In the second session the students are given a 3D model and asked to draw the working drawings for it, following the paced steps

suggested by the facilitator. In the third session the students have a demonstration of the CNC router in operation and are shown cut sheets. They are then asked to draw set pieces and have them cut. In the final session they design a model to be cut on the CNC router and create the cutting sheet for it. Their experiences and understanding, including of the original lecture, were discussed in informal student forums.

Fig. 1.   Examples of the models produced in the fourth session.

The items produced demonstrated an ability to create 3D models using 2D CNC routering. The benefits of this method included confidence expressed by the students in the facilitator and the validity of the course, a clear understanding of the required outcomes, and a 100% success rate with all 96 students creating a 3D model. The drawbacks were the lack of connection the students were able to make between their work and the work shown in the lecture, the lack of innovation and ambition in the projects and the lack of confidence in their own ability to create models again but without the facilitator and the lack of complex or creative thinking shown in the models themselves. Students learning through this method typically had to be taken through the steps again, particularly if there was a break before they used digital manufacturing again.

A. Criticism of didactic teaching and facilitator-led demonstration as a basis for learning.

Didactic learning functions only if the information is broken down into discrete elements for the student to memorise. However, when students concentrate on memorizing facts and instructions, they are not engaging with the content at a level that will support deep learning, rather than surface learning. Ramsdon notes that 'learning should be seen as a qualitative change in a person's way of seeing, experiencing, understanding, conceptualising something in the real world – rather than as a quantitative change in the amount of knowledge someone possesses.' (Ramsden cited in Biggs and Tang: 104). Lecturers need to understand how to support this change for digital technologies so that it creates positive outcomes for the student, particularly in terms of confidence and design thinking.

'The technology (*CNC routering*) has embedded in its own design structure a kind of knowledge that can impose itself on the user and supersede or make irrelevant the knowledge of the user.' (Furniture Society 2005: 14)

In order to effect qualitative change, Biggs and Tang emphasise the importance of relational learning, rather than the idea of having points and actions 'described'. They suggest a change in focus from what the teacher does to what the student should be doing and criticise an approach where the lecture is the assumed starting point for any learning experience.

'As teachers, we need to stop thinking about the next lecture that we have to give….this will probably mean not giving lectures.' (Biggs and Tang:105)

IV. STUDENT CENTERED LEARNING

A. Student engagement

To create a learning experience for designing using a digital production cutting technology that would effect a qualitative change as suggested by Ramsdon, the instructional practice would need to change. Weiner states that for deep learning, where a qualitative change of perception occurs, the experience needs to be learner-centered. The main challenge to didactic learning that Weiner identifies as fundamental for student-centered learning is a shift in the balance of power in the learning experience from the lecturer to the student.

'Students' motivation, confidence and enthusiasm for learning are all adversely affected when teachers control the processes through and by which they learn…..teacher authority is so taken for granted that most of us are no longer aware of the extent to which we direct student learning' (Weiner 2002: 23).

In order to change the drivers for learning on a course, the student role needs to be established as investigative, rather than as the recipient of knowledge.

'Courses *(in student centered learning)* are assignment centered rather than text and lecture centered. Goals, methods and evaluation emphasis using content rather than simply acquiring it.' (O'Brien, Millis and Cohen 2008: 19).

The starting points for the course in this context will therefore move from providing an introductory lecture on leading practice in the use of digital production technology, followed by set tasks guided by step by step instruction, to the use of problem based learning as the point of entry. According to O'Brien, Millis and Cohen, this will provide the students with a stronger sense of motivation for 'sustained inquiry'. What is important – and is on occasion missed by lecturers who use problem based learning, is the provision of appropriate, cumulative activities throughout the course that provide structure and research tools to the learning without undermining the student's role in driving the project.

'Successful courses balance the challenges to think critically with support tailored to students' developmental needs,' (O'Brien, Millis and Cohen 2008: 19).

A. Leads to top-down learning

'Top down' learning is design project driven. With the project set first the student focuses on the design aspect of the project. From this initial design work, the student will develop explorative research tasks with regards the use of the technology that may be inappropriate. The facilitators role will be to help them to explore their intention as purely as possible and not to try to shift their thinking into more tradition applications of the technology. Only after the students have tried out their own experiments are they introduced to contemporary understanding of the use of the technology.

In this example the students are given a design task that has as one of its drivers to demonstrate the difference between the possibilities of the laser cutter and CNC routering. In a top down learning exercise the students are given a brief, in this case to respond to the 2010 Powerhouse Museum Contemporary Lace competition which asks for design where the 'spaces are more important than the left material' and asked to create a demonstration piece for a commercial

interior setting. This course was not introduced by a lecture on current practice in the use of laser cutters but a series of activities on research and creative thinking. The emphasis in the first three sessions was on initial research and design ideas relating to 'contemporary lace'. The students were then asked to create experimental pieces based on that research and through those explore the differences between CNC routering and CNC laser cutting. The students were encouraged to use fabrics with the laser at this stage as they had little previous experience of using textiles and as a material that could be viewed as more temporary, it was hoped that students would feel more comfortable experimenting. The leading design consultancy, IDEO, highlights 'embracing experimentation' as one of the traits for a successful company explaining that 'if experimenting is part of your culture, you can respond.' An IDEO axiom is 'Fail often, to succeed sooner (Kelley, Littman 2008: 52)
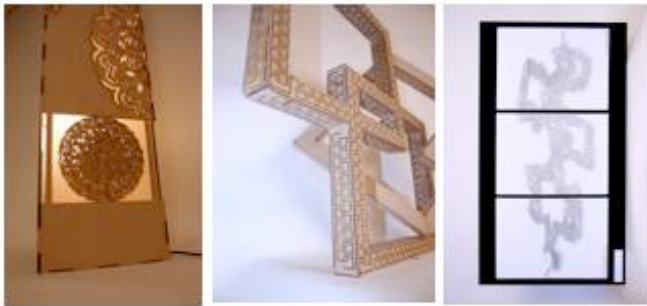

Fig. 2. Examples of laser-cut work produced in student led, problem based learning.

The students start with wide-ranging initial research into the idea of contemporary lace. The project proposals were diverse and included using materials that had not been explored on the university laser cutter before. Supporting activities therefore included an introduction to alternative material characteristics. The manifestations of the cuts were driven by the design requirements. On completion of the projects there was a final lecture showing contemporary innovations in the use of laser cutting.

The practical outcomes from this project were very interesting. The work was diverse and more ambitious than would have been set in directed tasks. On the positive side of the experience, the main difference was in student motivation and sense of ownership. The understanding they expressed through the questions they asked during the final lecture was significantly more informed than at the end of the didactic learning experience. Their confidence in their own ability for the future use of the technology was far higher and the relationship with the facilitators on the course was notably altered, with the students driving the inquiry and therefore the information they wanted to know to make their experiments and outcomes happen. On the negative side, planning for the use of equipment and planning for supplementary activities to inform the students in response to the directions they drove the project, was challenging. Also, some of the experimentation, by its nature, did not produce an outcome that was sufficient to inform design development and a small minority of students did not manage to complete a final outcome. The students themselves responded differently to the project. The majority enjoyed it far more than a traditionally taught manufacturing learning experience. A small minority expressed frustration that they were not provided with clear direction for the course overall and at each step.

V. SIGNIFICANT LEARNING

Current theory on learning and teaching builds on the student centered approach previously illustrated when learning about designing for laser cutting to designing courses and learning activities, to create what are termed 'significant learning experiences'.

'The central idea of this phrase is that teaching should result in something others can look at and say 'that learning experience resulted in something that is truly significant in terms of the student's lives'. In a powerful learning experience, students will be engaged in their own learning, there will be a high energy level associated with it, and the whole process will have important outcomes or results…they will clearly have changed in some important way.' (Dee Fink 2003: 6)

Raising the bar again, how does this translate into practical planning for learning in relation to manufacturing techniques? What can be done to ensure that learning for rapid prototyping and additive manufacturing is embedded in significant learning experiences? What can industry do to support the creation of those learning experiences?

VI. LINKED LEARNING

'Linked learning' has similarities to the approach of 'top down' learning, in that the drivers are design focussed rather than process focussed. However, a major difference is that the learning is linked to a larger project, where suitable with an external client, where the students can see the significance of what they are doing beyond the boundaries of the project, either for themselves or for the client. In this example first year students were given the opportunity to use CNC routering to create elements for structures they were building in the studio as Study Hubs. Uninhibited by a thorough, knowledge based understanding of the traditional applications and limitations of the use of CNC routering the students willingly set themselves more challenging tasks than a traditional, demonstration led project would include.

This project provided the students with a very real challenge that related directly to their own ideas and self expression and was going to be physically tested, at full size, in operation. The excitement of this project was intense. Students worked long hours and constantly demanded access to instruction on specific tools and technologies and information on materials and construction techniques. The whole process was project driven and required two full time lecturers, two tutors and an experienced technician for each session – and often outside normal contact hours. It was run over six sessions and started with scale modelling, testing and then full sized construction and testing. The use of the CNC router and additional support in designing for its use was offered and the students that chose to use it had very clear design intents in mind, although the development of the outcomes responding to those intentions altered in response to the technology and materials.

Evaluating the learning in relation to the use of CNC routering through this project showed that this experience

was quite different to the previous examples. In this case, the students' approach corresponded more to professional practice learning in that the students were strongly motivated to understand the technology and related materials within the context of a larger project and drove the CNC router specific learning by their own set of needs and design intent. Their relationship to the facilitator changed creating a far more co-learning situation as the facilitator worked with the student to meet those needs and intent. It was a very positive working environment for all concerned, with the only negative being the concern over managing the projects safely and within the timetable. On the negative side, although all students developed their transferable skills in relation to life long learning, the specific understanding of particular processes and materials was driven by their designs – for example one group focussed on design for, and application of, finishes, whilst others were involved in complex structural developments.

Fig. 3&4. Example above of student initiated and led design and build element as part of the construction of the 'study hubs' shown below (all photographs are from courses run with UTAS students).
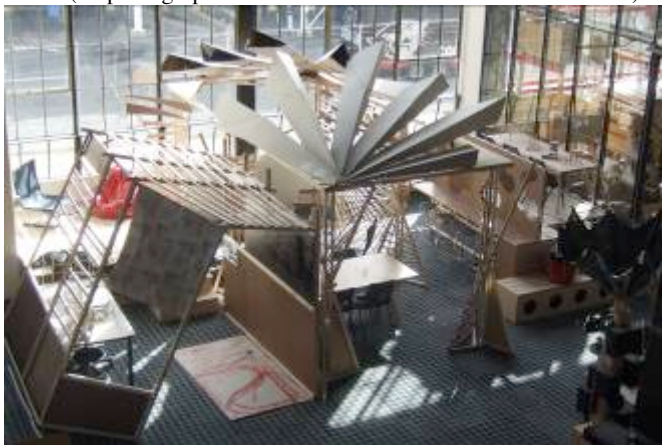
VII. LESSONS FOR THE DEVELOPEMNT OF LEARNING IN RAPID PROTOTYPING AND ADDITIVE MANUFACTURING

'We also know that students need to be challenged to think critically, and we know what kind of assignments will lead to critical thinking in our respective disciplines.' (Stevens, Levi 2005: 21)

As the examples illustrate, the most significant difference in the student learning experience is the different levels of autonomy resulting in behavioural differences by the students, particularly with regards their interaction with facilitators.

Creating designers who are pro-active, life long learners who can identify their own learning needs and direct their own learning is a positive outcome for the profession. Helping lecturers to create and manage significant learning experiences in relation to the changing professional practice and attitudes that digital prototyping and additive manufacturing create is the current challenge for the industry. Design education researchers recognise the different skills and outlook needed by product and industrial design graduate that will need to be reflected in the development of the curriculum. In response, there has been a development of global educational design studios that operate across countries and are becoming more prevalent (Bohemia: 2008) and more sophisticated.

Currently Selective Laser Sintering, Fused Deposition Modelling and Stereolithography (SLA) are gradually being introduced into higher education workshops. In addition, certain companies offer up to 50% educational discount to encourage a relationship between the graduate and the particular supplier. Finally, competitive on-line rapid prototyping services are emerging, such as Shapeways in the Netherlands and Sculpteo in France, where students can access prototyping at a cost level that makes experimental modelling possible. Now is the time where student centered learning that creates pro-active, confident learners with a deep level of understanding of the potential and opportunities created by the emerging technology needs to be introduced and supported by the industry. Learning from the experiences of working with CNC routering and laser cutting technology, creative, confident learners in control of the technology, in a position to lead developments rather than follow established practices, are more likely to be created by early introduction of significant learning experiences. The difficulty for academics is access to real world clients – local, national and where possible international - and projects that will not place undue pressure in terms of deadlines, yet provide genuine problem-based learning that engages and motivates the student.

VIII. STAGED INITIATIVES AND SUPPORT

'Staged learning' refers to the introduction of cumulative learning over time. If 'staged learning' was effective then students in primary schools would be introduced to ideas and processes and approaches that would be built on through secondary school and higher education. One of the challenges to 'staged learning' is the lack of communication between sectors and also targeted initiatives that are not linked to 'staged learning'. It is also hampered by the inconsistencies of access to technology in different schools and higher education institutions. Re-engineering Australia has introduced a series of learning activities that are for primary, secondary and higher education. Although these initiatives are a positive step, they are restrictively structured and are not cumulative in that the primary education initiative involves rapid prototyping, the secondary school initiative involves creating models with CNC routering and the higher education initiative is design development and construction based. For effective 'staged' learning, the initiatives would need to be cumulative. However, Re-Engineering Australia

has provided small format CNC routers to technology centre schools which has been very valuable in introducing these technologies to the education environment for both students and academics. Another initiative that has had an impact on schools and higher education has been the SLS RepRap, which is provided copyright free. Although this is now available pre-built, through companies such as Botmill and MakerBot, it is currently structurally strong enough to operate in a project work environment. Manufacturers, such as Roland, provide small format CNC routers, laser cutters, 3D scanners and rapid prototyping machinery but generally university departments have to apply for match funding grants to provide their students with large format digital cutting machinery.

CONCLUSION

The challenges for higher education with the introduction of rapid prototyping and additive manufacturing into the curriculum are two-fold. The first is the knowledge base within the department that will have to be expanded to include the new processes, materials, design constraints and opportunities. The second is more far reaching. The redirection of the market towards mass customisation and the democratising of the production process, changing distribution practices and co-design opportunities by these manufacturing developments mean that the skills and understandings currently taught on Product and Industrial Design courses will have to change. This has a far greater impact on pedagogy than previous developments. In a practical sense, marketing, business practice, international language skills and an understanding of the effects of cultural norms on professional practices throughout the world will need to become embedded into the curriculum. But in terms of a qualitative change of perspective for future designers to operate confidently in this arena, the lessons drawn from the examples of teaching and learning practice given suggest that learning experiences that are significant – both to the student and in relation to the industry – need to be developed and supported. This can only be done effectively through early collaboration between academics and industry.

A. Recommendations:

- Staged, linked planning for learning developed collaboratively in workshops with academics and industry representatives.
- Professional development workshops for full time academics to gain a deep learning understanding of the technology and its implications and facilitate innovative use.
- Where possible, offer opportunities for significant learning projects to academics that go beyond competitions and are linked to real world problems and issues.
- Offer prototyping and access to large format machines for higher education at discount rates.
- Rather than providing highly structured, restricted projects, invest in working with higher education to offer technical support for students in relation to student centered learning and significant learning.

- Provide material samples, information on material characteristics.
- Work with specialist educational developers to provide information for learners about processes designed to support a full range of learning styles, such as visual learners, social learners, context learners etc.
- Provide regular opportunities for students to disseminate the experimental knowledge they have gained during their learning experiences to industry partners to ensure a two-way understanding and to feed innovative practice back into industry.

Perhaps the most immediate of these, for the development of graduates with a meaningful understanding of the application of rapid prototyping and additive manufacturing, is the provision of industry support for academics to stay current, by creating sufficient opportunities (ideally significant learning experiences, but at a minimum practical workshops) to understand developments in technology and professional practice to help them to create learning experiences and materials informed by the experts in production practice, marketing and business practice.

Academics need to be confident enough of the subject matter to be able to work as co-learners on specific projects, ensuring the balance of power favours the student during their learning experiences for the engaging world of rapid prototyping and additive manufacturing.

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