INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
3 & 4 SEPTEMBER 2015, LOUGHBOROUGH UNIVERSITY, DESIGN SCHOOL, LOUGHBOROUGH, UK

EXPERIENCES OF EMBEDDING BLENDED PHYSICAL AND DIGITAL MAKING INTO DESIGN EDUCATION

Barney TOWNSEND and Andrew FORKES
Royal College of Art, London South Bank University

ABSTRACT
This paper considers modern concerns that a new generation of designers are rejecting traditional methods in favour of purely digital ways of designing. The study is contextualized in some of the relevant theory, and describes a selection of projects across academic levels from the design curriculum at the authors' institution that illustrate a blended approach to digital and physical design pedagogy. Results are presented from a survey of final year students who have experienced this approach, exploring the extent to which these methods are now embedded within their practice. The results suggest that although CAD use is prevalent in their natural practice, and some of the recognized problems associated with it are more evident than in professional CAD users, the students have adopted our approach of designing across digital and physical platforms.

Keywords: Digital, physical, designing, making, blended learning.

1 INTRODUCTION

The toolkit of methods by which ideas may be explored, represented and developed has never been more extensive for designers, supported particularly in recent years by seductive digital manufacturing techniques such as 3D printing. Whilst this technology has existed for almost as long as the CAD systems that drive it, it has gained significant cultural currency in recent years, since the expiry of certain patents engendered an explosion of affordable desktop machines, democratizing the technology to a level never before seen. In design education, both prior to and at University level, this trend, coupled with the prevalence of CAD and photorealistic screen-based visualizations has shifted the gamut of making skills to the digital arena. Jonathan Ive, in an interview at the Design Museum in 2014, highlighted this erosion of making and craft skills from design curricula as 'tragic' [1]; David Kelley of IDEO describes prototyping as "thinking with your hands" [2] – which carries an implicit sense of the physical and craft based techniques that are absent from purely digital design work. Richard Sennett describes how "CAD is often used to hide [problems]… it can be used to repress difficulty" [3]. Mindfulness of these concerns, supported by observation of student practice, has guided the design of teaching methods and coursework projects for undergraduate design and engineering design students at London South Bank University (LSBU). The objective of a new curriculum model, introduced in 2011, was to embed an integrated approach to design that embraces, wherever possible, the appropriate use of both digital and analogue modes of working, limiting effects of "circumscribed thinking and bounded ideation" [4] and reinforcing immediacy, reflection on process and 'fit' of the product outcome.

2 CAD AS A TOOL FOR CREATIVE DESIGN?

In order for a representation of a design concept to be given tangible form through digital manufacture, it must first be described explicitly in CAD; 3D printing provides a physical embodiment of the digital model, and thus the software packages become the gateways to the tools of digital making. The implications and limitations of the use of CAD in creative design have been the subject of extensive discourse for at least two decades, a full review of which is beyond the scope of this paper. It is well established that as a tool for engineering, and for detailed, precise development, visualisation and communication of mature design ideas, CAD augments human capabilities hugely. It seems though, that CAD has been incorporated into the practice of design as swiftly as the technology, the hardware, and the interfaces have been developed, with little pause for consideration of the impact on creativity and the traditional design process flow.

Computer systems inherently require precise and explicit input from the user. Modes of input and interaction in CAD have now evolved from what began as digital simulations of established ‘classical’ practice, the use of drawing boards for orthographic projection drawing. Some of the mechanisms by which CAD can limit creative design ideation were recently re-examined by Robertson and Radcliffe [4]. They describe ‘circumscribed thinking’ (the system constrains the thinking of the designer through limitations in representational capabilities or the skill level of the user), ‘bounded ideation’ (the adverse motivational effects on creativity that result from negative or frustrating experiences using the software), and ‘premature fixation’ (how the complexity of a CAD model as it evolves disincentivises the designer from making fundamental, topological changes to the design).

This is in stark contrast to the typical ways that designers work at the front end of a project, the ideation or creative stage. When sketching ideas with a pencil, designers embrace ambiguity, abstraction, and imprecision in order to facilitate an experimental creative flow of ideas. The specific, precise input required by computers – in particular, parametric modelling systems - is inherently contradictory to this creative flow by “distancing the designer from the cognitive thought of creation” [5]. Other authors such as Bermudez and King have shown that manual representations are more appropriate at the conceptual design phase [6]. They predicted, even at that relatively embryonic phase of digital adoption, “not the extinction of the analogue in the hands of the digital but rather a coordinated and collaborative coexistence of both representational systems”. Oxman considers whether “digital design is a unique phenomenon – a new form of design – rather than merely conventional design accomplished with new media”, and suggests that “digital design and it’s growing impact on design and production practices are suggesting a need for a re-examination of theories and methodologies in order to explain and guide future research and development” [7]. We accept, therefore, that these discussions are by no means novel, but in this paper, we reconsider them in the light of the modern ubiquity of digital content creation and manufacturing tools, and the question of whether an emergent class of ‘Digerati’, or ‘digital *literati*’ [7] are rejecting traditional, analogue making skills for models produced solely through digital means.

3 BLENDING PHYSICAL AND DIGITAL MAKING IN DESIGN EDUCATION

A module restructuring exercise offered the opportunity to revise the delivery of design courses at LSBU; the guiding objective was to embed blended approaches to digital and physical making through practice-based coursework projects. A structure was developed that placed Design Thinking and Practice as the central core module (50% of the available credits for each academic year), into which skills were fed through supporting modules. This teaching model aimed to foster an appropriate balance between digital and physical design methods; we believe that bringing the data set out of the computer and onto the workbench provokes ideation through the immediacy of manipulating physical materials, and the opportunity to react in real time and space; the likelihood of physical spatial inconsistencies brings serendipitous possibilities for novelty; and collaboration is fostered through the ability to interact over the tangible representation. The following sections will describe some of the projects from our curriculum that illustrate this approach.

4 LEVEL 4: AN INTRODUCTION TO THE ‘PHYSICAL/ DIGITAL’ BALANCE

At level 4, the core content is fundamental cognitive design skills involving creativity techniques, concept development, and user empathy. These are supported with a strong toolkit of practical skills that include design sketching, physical making, graphical (digital) communications, and CAD, alongside discipline (and course-) specific specialisms such as applied engineering maths and physics or social sciences such as ethnography.

The ‘Pen Project’ provides a vehicle for the introductory CAD course. Assuming no prior experience of digital design, students are taught the principles of solid modelling through bespoke video tutorials, inspired by the Khan Academy [8] model of teaching mathematics. Students must design a pen from a billet of aluminium tube, with separate components for an end cap and a nib detail, and housing an off-the-shelf refill cartridge. The accompanying lecture course covers the capabilities of manual lathes and milling machines, and then focuses on conventions of engineering drawing. Students submit a set of engineering component and assembly drawings, derived from a 3D solid assembly; the components must show evidence of both milled and turned features. The following semester, in another module, the students are taught how manufacture their pens in an engineering workshop, working from the previously submitted drawings. Content includes the practical and safety aspects of using the associated machinery, and empathy for the tools of production. The intention is that when students work from drawings they have produced themselves, missing dimensions, or overly complicated details require mental leaps and decisions to be made on the workshop floor – decisions which are only possible if the designer is also the maker. The drawings become vehicles for verified dimensions and occasionally drastic design changes, losing the veneer of permanence, as they become tools for iteration. The final work pieces are often the result of a combination of happy accidents, developments bought about by compromise or radical departures from the original intent following enlightenment through physical manipulation of machine, material and process. This workflow direction, from digital to analogue, was specifically chosen in order to highlight the problems that can arise from purely digital designs.

The 'Electric Vehicle Challenge' provides a second explicit example of blended physical and digital designing at level 4. Students are provided with a small electric motor and gearbox kit, including axles and laser cut wheels. They are required to assemble these, explore gear ratios, mount them to a chassis and design an external surface shell, initially by modelling in foam and subsequently vacuum formed in HIPS. The vehicles are raced head to head at the end of the semester down a 20 metre track; each must carry a 'passenger' in the form of a 30 gram (rubber) egg. The motors are exaggeratedly underpowered for the mass of the assembly; in order to be competitive against their peers, a high level of craftsmanship is required in the construction, assembly, and alignment of the components. Students are taught about gear ratios, basic electronics, principles of aerodynamics and styling, and the use of jigs and other devices for precision manufacture and assembly. Concurrently to the physical assembly process, in the CAD module students are tasked to reverse engineer all of the core vehicle components using parametric software to create a virtual assembly. They explore product architecture digitally by creating multiple configurations of the components to select an optimum design. The chassis design is derived from the configuration of components, and the profile is output for laser cutting. When complete, the solid assembly is imported into surface modelling software, where simple organic curves are drawn around it to derive the external shell surface – providing an introduction to the principles of surface modelling in CAD.

5 LEVEL 5: EXPERIMENTS ON MICE

'Experiments on Mice' is a coursework project at level 5 that builds on these skills, introducing more complex techniques in surface modelling, in detailed design development with solid modelling packages, and in output to digital prototyping and manufacturing systems including 3D printers and laser cutters. The students are tasked to design computer mice. The mouse was chosen for a number of reasons: it is an intrinsically ergonomic object that requires physical modelling to ensure a comfortable fit to the hand in use; it is of a size that allows cost effective 3d printing for a class of approximately 50 students; the core components can be bought cheaply for reverse engineering and assembly into the models (both physical and digital); and it requires at least two plastic components that fit closely together and are typically injection moulded, with all of the associated design detailing required. The project is initiated with approximately 8 hours spent in a prototyping workshop, during which the students use sketching, and physical model making in foam (subtractive) and plasticine (additive) to define a range of optimal forms, one of which is selected to begin digital modelling. From that point, models can be 3D scanned, importing the scanned mesh to surface modelling software. Those that 3D scan must use the mesh data as an underlay over which to build a native CAD surface model from original curves. The physical models are used to sketch control curves onto in order to plan the surface modelling strategy. Once the external surfaces are built, students are encouraged to produce physical 'reality check' models to confirm scale and ergonomics. In order to save the material costs of 3D printing at this stage, and to emphasize speed and efficiency in the use of model making, their models are produced using planar sections, laser cut in 5mm foam. This ability to quickly evaluate the low fidelity models in tangible form frequently results in further design iterations (through manual reshaping of the foam), again reinforcing to students the need to treat purely digital representations with caution. Once surfaces are finalised, they are imported to solid modelling software in order to split the components, and apply thin walls, ribs, bosses, draft angles, lips, and all of the other associated features of injection moulded components. This emphasizes 'good housekeeping' on the surface model – if surfaces are not properly stitched or accurately trimmed, it will not translate easily to a solid model. The completed parts are output to be 3D printed, which requires significant post-processing work from the students in sanding and assembling their designs, particularly in priming and spray painting the finish, and understanding the additional tolerances that the paint finish requires. As they complete the physical assembly of the models, they also produce high quality digital renderings, and animations to show exploded views and other features of the design. Thus the students gain experience of a multifaceted approach to digital design that is inherently grounded in the physical model.

6 LEVEL 6: DEVELOPING PERSONAL PRACTICE

At Level 6, students are expected to demonstrate their design skills by applying them at a higher cognitive level through self-directed 'major projects'. The teaching at this stage is predominantly through one-to-one tutorials. The students propose a design brief (through negotiation with tutors) and spend the year exploring, designing, and developing a range of speculative answers to the posed research question. There is a requirement for a highly resolved, functional prototype to be presented at the final submission, but also the expectation that this is the latest in a long string of experimental models throughout the year, using both physical and digital methods as appropriate to the project and the design stage. This is a well-established model in undergraduate design pedagogy; the relevance to this paper is in the observation of a tendency amongst students to procrastinate with physical model making, and a reluctance to move from either paper or screen-based representations into the physical realm. Speculated reasons for this included misplaced faith amongst students in the authority of CAD based representations, and the perception that greater marks might be awarded to explicit and precise digital models, regardless of the quality of the underlying concept, following Sennett [3]. In response to these concerns, a subcomponent assessment point was introduced to the project, with a submission in February of 'proof-of-principle' and 'sketch' models. This simple expedient of making explicit the requirement for early stage physical prototyping has paid dividends in pushing students to take the leap into making, producing a range of form exploration models in foam or similar, ergonomic rigs to explore human-scale interfaces, technology layout schematics evidencing potential product architectures, and prototype electronic circuits using open-source electronics prototyping platforms such as Arduino. This has provoked a renaissance in the art of multi-modal tinkering; both digital CAD and coding excursions and physical experimentation with components and form have become part of the same iterative design loop, using these experiments to feed their design development.

7 ASSESSING THE UPTAKE OF THIS APPROACH

In order to explore the effects of the pedagogical approach illustrated in the previous section, a survey was conducted of current Level 6 (final year) students from the cohort that will graduate in the summer of 2015. This was the first year group to have been subject to the new teaching model introduced in 2011. The questionnaire design was based loosely on that of Robertson and Radcliffe [4], but was adapted to fit the student cohort and their level of experience. 14 students responded, which is approximately 1/3 of the cohort. The first question simply asked how often students chose to use CAD as in their normal design practice. It was emphasized that this referred to CAD use by choice, as opposed to when required to as an explicit part of coursework marking criteria. None of the respondents replied that they "never" use CAD. 36% stated that they use CAD "occasionally", 36% "about half of the working time", 21% "most of the working time", and only 7% "constantly". Thus, 64% of the respondents indicated that they use CAD at least half of their working time. The next few questions explored the frequency of use of five different modes of working, using both analog and digital techniques, in four design situations, as described in Table 1.

Table 1. Modes of working and design situations explored in the study

Modes of working:	Design situations:
• Working directly with a CAD program • Using output from a CAD program such as printouts or 3D printed models • Using physical models produced by analog (manual) methods • Verbal discussions • Free hand sketching	• Communication of an immature design concept • Communication of a mature design concept • Visualisation of an immature design concept • Visualisation of a mature design concept

Students were requested to rank their use of each method of working, in each of the four situations, by frequency of 'very often', 'often', 'occasionally', 'rarely' or 'never'. For the purposes of a comparative analysis, responses of 'never' scored 0, 'rarely' scored 1, etc. up to 4 for 'very often'.

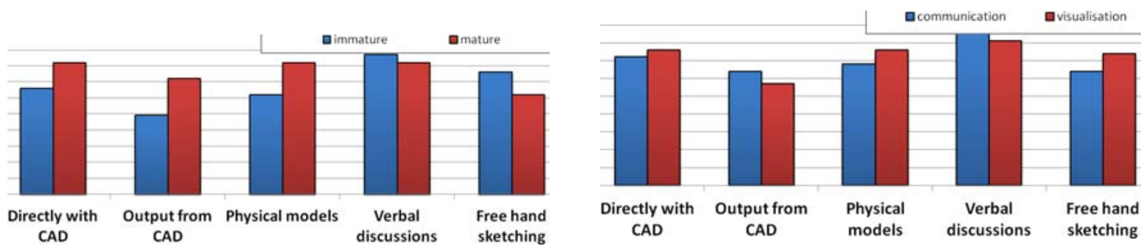

Figure 1. Comparison between preferred mode of work when designs are immature or mature, and comparative use of different modes of work

For the comparison between immature and mature design stages, the results for both communication and visualization modes were combined. At immature stages, students favoured the use of verbal discussions and freehand sketching over the use of CAD, but still used CAD more than physical modelling, either as digital output resulting from CAD use, or constructed by manual means. At mature design stages, free hand sketching was, predictably, the least prevalent. Physical models, verbal discussions, and working directly in CAD were used in equal amounts.

For comparison between communication and visualization scenarios, the results for both immature and mature designs were combined. For communication, again verbal discussions took precedence by some margin, followed by the use of CAD; there was close parity across the other modes of working. For visualization of design ideas, there was again relatively little between all categories, except for 'output from CAD' which was somewhat lower.

The following two questions examined the effects of 'bounded ideation' resulting from the motivational state of the students when using CAD, and 'circumscribed thinking' as a result of the limitations imposed by the software.

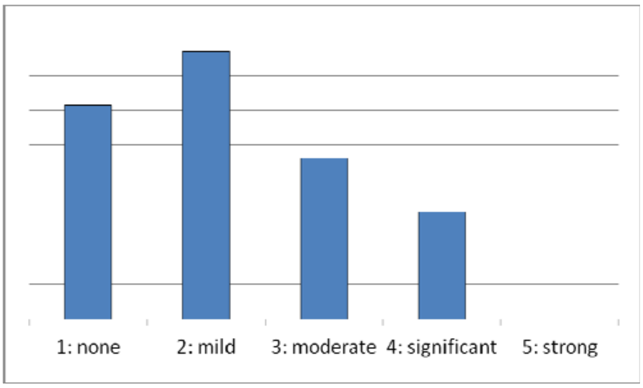

Figure 2. Extent of bounded ideation

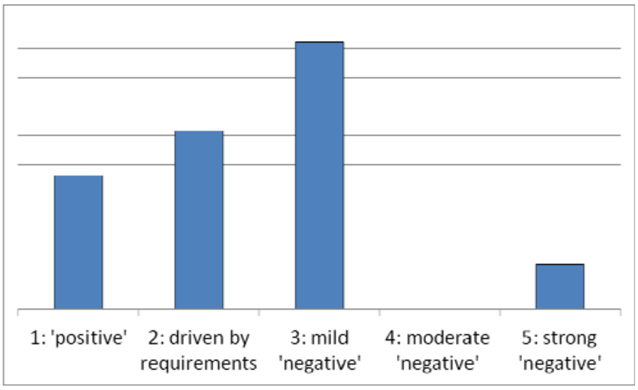

Figure 3. Extent of circumscribed thinking

The high frequency of responses 1 and 2 in Figure 2 suggest that bounded ideation is not significant issue for the majority (65%) of students. However, the remaining 35% of respondents (by comparison with 17% in the original study by Robertson and Radcliffe [4]) are still affected by moderate or worse motivational issues when using digital means of designing. This might be cause for concern in the context of CAD professionals, but on reflecting that respondents to this survey are at undergraduate level, it may be somewhat mitigated by the further training and experience students will undergo as their careers progress, or the option to choose career pathways within the industry that do not require high levels of CAD use.

With regards to circumscribed thinking, exactly half of the respondents felt that they their use of CAD was either driven solely by the requirements of the task, or that they were positively enabled by the digital tools to go above and beyond requirements. By contrast, Robertson and Radcliffe [4] found this figure to be 77% in CAD professionals. The remaining respondents in our study therefore all felt that to some degree their thinking was constrained either by the perceived limitations of the software or their own skills at using it.

8 CONCLUSIONS

This paper has described four examples of projects that illustrate our approach to blending physical and digital methods in design education. It should be emphasized that these are by no means comprehensive; brevity has dictated that much be left out. They are presented to provide some context to the educational experiences of the students who responded to the survey.

With only 14 respondents in total, the survey results should be treated with caution from a statistical point of view; this is a key limitation of this study. The results are presented to guide reflections on the pedagogical approach that may be of interest and value to other practitioners and educators in this field. Individual responses will, of course, have been influenced by the current educational stage of the students; despite being asked to reflect on their natural practice, irrespective of formal academic requirements, it is inevitable that their immediate context will have an effect.

Predictably, all of the students use CAD to some degree, but the fact that 64% of them use CAD more than half of their working time suggests that digital media are firmly established as a significant design tool of choice.

The comparison between modes of working at different design stages reveals some points of interest. Verbal discussions were overall the most prevalent. This might be a consequence of the style of teaching, which is to a great extent (and particularly at level 6) delivered through personal discursive tutorials; it also reinforces the social nature of professional design practice.

At immature design stages, students still prefer free hand sketching to the use of CAD, suggesting that they have not rejected traditional means of ideation, although CAD was slightly preferred to physical models. The parity between the use of physical models and CAD at mature design stages would support the assertion that students have engaged with the blended physical and digital pedagogical approach; this parity is also apparent in both communication and visualization of design concepts. Whether or not this is a causal relationship is less certain – it may simply be a reflection that our model is well aligned to current design practice and the natural inclinations of the upcoming generation of designers.

Physical models produced as an output from CAD scored generally lowest. This is possibly due to the nature of access to the technology: democratisation has not (yet) extended to the level that most students own 3D printers themselves, and thus their access to them is somewhat limited. As one respondent said in a comment “Digital ways of working [in CAD] can be done overnight, for free, in your bed room with a cup of tea. Model making requires access to a workshop and tools which costs”.

The higher incidences of bounded ideation and circumscribed thinking (relative to those from CAD professionals [4]) reinforces the need for a curriculum that blends the best of both physically and digitally driven ways of designing and making.

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