Investigating a totally digital approach to concept generation and design development during industrial design practice

Abstract: During the professional practice of industrial design, digital methods are used extensively to support the generation, development and specification of creative three dimensional (3D) form. Despite the increasing capabilities of digital methods, the nuances of practice continue to require non-digital methods. This paper reports on research that identified emerging and established digital design technologies to define an approach for total 'Digital Industrial Design' (DID) that employed only digital methods with no post-process finishing e.g. smoothing/painting of rapid prototype parts. This was evaluated using action research in which all phases of DID were used to design two stylistic variations of a consumer product. The paper concludes that DID has the greatest potential for change and benefit during Concept Generation and Design Development. To maximise impact, the case study was translated into in a web-based resource to facilitate understanding of the process and designed outcomes from DID.

Keywords: industrial design, product design, digital design, computer aided design, action research, sketching

1 Introduction

In the early 1960s, Ivan Sutherland, a PhD student at Massachusetts Institute of Technology (MIT), developed the first interactive Two Dimensional (2D) Computer Aided Design (CAD) system called "Sketchpad" (Sutherland, 1963). From these beginnings, CAD software started to move out of academic research and into commercial use, thereby allowing engineering designers and industrial designers to progress to digital methods. Incremental growth has now resulted in a wide variety of digital tools that have the capacity to impact on the activities associated with professional industrial and product design practice. Despite this capability and the ambitious claims of software and hardware developers, professional practice in industrial and product design continues to be undertaken using a hybrid approach that integrates both digital and non-digital techniques (Authors, 2011). One of the reasons for this is that the commercial constraints of professional practice necessitate the use of proven techniques when working with fee paying clients. This can results in resistance to change due to the risk posed to the client relationship if work fails to be delivered on time and to specification. In contrast, academic research that employs design activity is not constrained by a client/practitioner relationship and has the potential to make a significant contribution to issues relating to practice that cannot readily be explored in a commercial environment. The authors believe that a key contribution of academic research to design practice is in the impartial evaluation of new methods and approaches that have the potential to disrupt existing practice and identify opportunities for paradigm shift. The competitive and closed nature of professional practice also means that it has a natural tendency to evolve without open reflection and academic research can make a significant contribution to exploring change.

Whilst academic research has a history of reporting on the emergence of individual design technologies and their potential to impact on practice, there is value in the contextualisation of activities that must be undertaken before and after the proposed intervention to avoid the exposure of only a partial picture. To fully contextualise and build on the stand-alone studies that have explored the role and contribution of digital methods to professional practice, this paper reports on a research project to investigate the potential for a model of practice in which the core activities of industrial and product design are undertaken using only digital methods. It is acknowledged that this represents a somewhat provocative approach as opinion is divided on the capacity of digital methods to replace established non-digital techniques.

In developing the methodology for the study, the scope was restricted to addressing the following research questions:

1. What digital tools and methods are available to replicate those of non-digital industrial design practice?
2. How should digital tools and methods be employed to support an entirely digital approach to industrial design?
3. What are the key issues arising from the implementation of an entirely digital approach to industrial design?

The methodology to answer these questions employed a literature review for Questions 1 and 2 and action research for Question 3 which included design proposals for a consumer product. In addition to providing rich data on the issues relating to the implementation of Digital Industrial Design (DID), the design activity resulted in extensive material with which to illustrate the designed outcomes. This material was collated into a web-based case study to make the DID approach and outcomes accessible to academics, practitioners and students. The authors believe that this form of outcome is particularly important if research into design practice is to be accessible to the practitioner community.

2 Industrial Design and Product Design

Use of the term ‘product design’ can be problematic as it is used to refer to industrial design, engineering design, or combination of both (Unver, 2006). As a professional activity, industrial design is well defined, with prominent design historians identifying its origins during the industrial revolution when craft-based production changed to a process in which the creative form-giving became separated from the means of production i.e. designers did not make the items that they designed (Heskett, 1980).

In defining the profession of industrial design, Conway notes the distinct association with professional institutions and publications (Conway, 1987). The largest and oldest professional society for industrial design is the Industrial Designers Society of America who define industrial design as: “... the professional service of creating and developing concepts and specifications that optimize (sic) the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer” (IDSA, 2014). In contrast, the term product design is not represented by any dedicated professional. The United Kingdom Design Council (Design Council, 2014) acknowledges that product design “….can have a wide remit” and “….is an integral part of the wider process of developing new products….” thereby indicating that it can be used to describe industrial design, engineering design and activities that span between the two.

Where product design focuses on study or professional activity that involves the more technical roles involved in new product development (employing predominantly scientific methods), 'engineering design' appears to be a more appropriate descriptor. Engineering design has been described by Dumas as "The development of a product from its technical conception through detail design, and the design of the related manufacturing process and tooling" (Dumas, n.d., p.3). In the UK, the Institution of Engineering Designers actively supports the profession of engineering design, with members being eligible for the award of Chartered Engineer (Institution of Engineering Designers, n.d.).

This paper acknowledges that the terms industrial design and product design are in common use and can refer to identical or contrasting professional activities. In terms of use within this paper, industrial design will be used to refer to the distinctive profession that is responsible form-giving during product development.

3 Industrial Design Practice

There are numerous academic models for the phases of industrial design practice, such as 'Analysis, Synthesis and Evaluation' proposed by Jones (1963); Archer's 'Analytical Phase, Creative Phase, Executive Phase' (1965); Cooper and Press' model of 'Concept, Embodiment, Detail, Production' (1995); and the 'Investigation of Customer Needs, Conceptualization, Preliminary Refinement, Further Refinement and Concept Selection and Control Drawings, Coordination with Engineering/ Manufacturing/Vendors' of Ulrich and Eppinger (2003) Whilst it is acknowledged that industrial designers may undertake activities that are precursors to the visually creative form-giving, such as product analysis and the generation of cultural/user insights, the three stages employed in this study focus on the distinctive and core capabilities associated with defining product form. These stages acknowledge the models as previously identified and, in the context of this paper, are summarised by Pipes as concept generation, design development and specification (1990).

3.1 Concept Generation

Concept generation involves the tangible visualisation of the designer's first thoughts in response to the design brief. They will be, by necessity, spontaneous, lacking detail and numerous. The visual flair and ingenuity required for this phase is distinctive to the industrial design profession and requires the use of techniques that facilitate this rapid and reflective activity, with sketching being the preferred option (Prats et al., 2009).
Although a highly creative activity, the industrial designer must be aware of constraints that impact on concept designs, such as the size of circuit boards and other components. To provide additional feedback on emerging concepts, designers translate their two-dimensional (2D) sketches into three-dimensional (3D) sketch models (Ulrich and Eppinger, 2003) using materials that can be quickly worked by hand, such as card and closed cell foam.

3.2 Design Development

Following presentation to the client and/or key stakeholders, one or more concepts are selected as proposals that have the greatest potential to progress to production and be resolved in greater detail through design development. Attention to manufacturing detail is a particular focus of this phase (Baxter, 1995). During Design Development, the loose and sometimes vague sketches produced during concept generation are translated into 3D geometry using CAD. In addition to defining component details, suitably trained industrial designers may use CAD for the analysis of technical parameters such as mould flow and stress.

Design Development ends when the design has been evaluated and approved for manufacture which may require several levels of presentation to facilitate further decision-making. For example, once 3D CAD has been employed, highly detailed, photorealistic visualisations, called presentation drawings (Pipes, 2007) or presentation renderings (Authors, 2011, iD Cards 2011), are produced to give a clear indication of product appearance for approval prior to the production of a fabricated appearance model. Appearance models have the exact appearance of a proposed production item and allow full visual evaluation by clients and stakeholders (Kojima et al., 1990). Even when using additive manufacturing, appearance models still require a significant amount of hand finishing and skilled fabrication and, as such, remain relatively expensive (Authors, 2003).

3.3 Specification

Specification requires the parameters for each component to be defined in preparation for manufacture (Baxter, 1995). This is typically undertaken using 3D CAD and results in fully specified components that can also be used to generate the production tooling. Prior to commissioning tooling, the details of production components would be checked by producing tooling prototypes via additive manufacturing.

4 Digital Design Tools

Digital design tools have the capacity to enhance industrial design practice by efficiently modelling complex geometry (Sequin, 2005); digitising complex geometry from a physical object by 3D scanning (Willis et al., 2007); photorealistic rendering (Loosschilder, 1997); technical analysis (Unver, 2006); communication (Lau et al., 2003); reduction in the number of errors (Pipes, 2007); and facilitating collaboration (Author, 2009). Digital design tools have also been developed to support concept generation activities by using biomimetic software that proactively generates and evolves form, either spontaneously (Author, 2001) or based on initial design inputs from the user (Krish, 2011).

Despite the fact that digital tools appear to have the capacity to replicate some or all of the characteristics of non-digital methods, a hybrid approach that blends digital and non-digital techniques is still employed by students and practitioners (Author, 2011). Reasons for this appear to relate to the more iterative Concept Generation phase, as the methods associated with design development and specification employ a rigour that is appropriate to the use of 3D CAD.

Sketching is a key activity for concept generation and reasons cited by practitioners for retaining non-digital methods as opposed to using 3D CAD are its inherent spontaneity and convenience (Ronning, 2008). Techniques of digital sketching are now employed although this requires significant investment in hardware and software in contrast to the more modest pen/pencil and paper. This issue was summed-up by an experienced practitioner member of the Industrial Designers Society of America who, when asked to comment on the capabilities of digital sketching, stated that, “Digital sketching is not as flexible as paper-based sketching that offers ease of use, speed and freedom and it is cost effective” (Aldoy, 2011). In the context of using a relatively large table-top pen display, such as the Wacom Cintiq, this comment is understandable. However, the use of a compact and highly portable Tablet PC that allows the screen to be flipped over and used as a touch-sensitive drawing surface (see Figure 1) challenges the larger sketching tools and has received positive feedback during use by students (Aldoy, 2011).

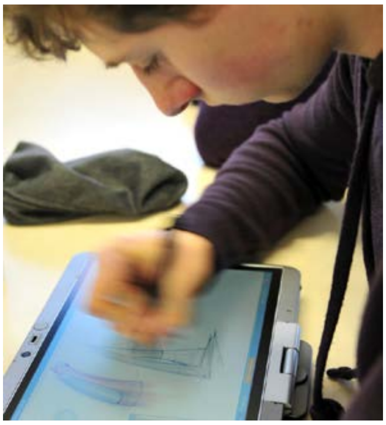

Figure 1. Designer undertaking sketching during concept generation using a Tablet PC

Academic research to explore the use of the pen display is limited and the significant studies have focused on their contribution to collaboration as opposed to the creative form-giving process. In using the digital tablet and paper-based techniques to investigate the interaction between junior and senior industrial designers, it was reported that the pen display facilitated greater control (Lee and Wei 2007) although Tang et al (2011) noted that “the design process of the digital and traditional environments were similar in terms of the speed of the design process”.

The production of a 3D physical sketch model that has the spontaneity of a 2D sketch using digital techniques is problematic due to the sophisticated level of tactile interaction that takes place with the modelling material. The alternative is to avoid the use of sketch models but the issue of a lack of physicality has been identified by McCullough (1998) who comments that, “What good are computers, except perhaps for mundane documentation, if you cannot even touch your work?”. The aim of the form-giving that takes place during the production of a sketch model is to translate 2D visualisations into a physical object through direct interaction with an emerging form. As a means of translating the activity that would typically take place in a workshop into a digital process, haptic feedback modelling has been developed to enable the designer to ‘feel’ a digital model that is displayed on a computer monitor via a pen-type stylus on a

moveable arm. Whilst this technology can reproduce some of the interactive form-giving associated with workshop activity, there are limitations in its suitability for use by industrial designers (Author 2005).
The advent of 3D Printers as an alternative to high definition/durable additive manufacturing systems has significantly reduced the cost of components, with manufacturers claiming to be up to a fifth of the cost lower and five to ten times faster (3D Systems, n.d.). These systems have the capacity, depending on the machine being used, to be produce parts in a monochrome material or, when identified in the digital part specification, can be multi-coloured and include graphics that would typically be produced as badges or transfers. Models produced using the multicolour 3D printing systems can, therefore, have the characteristics of a full colour and badged appearance model, albeit with a reduced level of surface finish.
When the full range of digital design methods that are available to industrial designers are transposed onto the three phases of practice (Concept Generation, Design Development and Specification), it is possible to identify the potential for a totally digital approach that removes all non-digital techniques. The key feature of this approach is that no paper-based or workshop-based activity takes place as all digital outputs are complete solutions and require no other finishing process such as the removal of stepping and paint finishing for components produced using additive manufacturing. The development and evaluation of this DID approach will now be discussed.

5 Digital Industrial Design (DID)

An overview of the digital methods employed by industrial designers has been given by Yan et al. (2006) who identify these as Reverse Engineering, Rapid Prototyping Engineering, Virtual Reality Technology, Tactile Design Technology, Products (sic) Styling and Digital Modelling Tool (sic). A model for the integration of digital methods is proposed by Yang but this represents more of a diagrammatic overview as opposed to a sequential approach that could be applied by industrial designers. As a result, the conclusions to the study can only speculate on the merits of the proposed ‘Digital Product Design System’.

The benefits of digital design methods have been widely reported and previously discussed in the section on Digital Design Tools. General approaches have been identified by Yan et al. (2006) and opinion sought from students, practitioners and academics on the potential for a total strategy for digital industrial design (Author 2011, Author 2011). However, no substantive case study has been undertaken in which a clearly defined theoretical approach to DID is integrated into practice and evaluated during product design activity. This research project has employed this methodological and the theoretical approach to DID will now be defined in the context of Concept Generation, Design Development and Detail Design and Specification.

5.1 Concept Generation (DID)

5.1.1 Phase 1: Capture of Engineering Hard-points (3D Scanning)

Concept generation for DID commences by digitising internal product components, such as circuit boards and motors (hard-points), that must be included in the design proposal. This generates 3D digital models for the hard-points that can then be used as a guide for Digital Concept Sketching and Digital Sketch Modelling. 3D scanning systems that are suitable for the capture of engineering hard-points include laser-based non-contact systems such as FARO Scan-arm or for greater accuracy, but reduced versatility and speed, more traditional co-ordinate measuring machines (CMM).

5.1.2 Phase 2A: Digital Concept Sketching (Interactive Tablet)

A pen tablet is employed to produce Digital Concept Sketches with the application of tone or colour to add 3D effects using techniques that are analogous to those of paper-based sketching with marker. Whilst it is acknowledged that 3D CAD may be used to generate concepts and there have been studies claiming that this supports creativity whilst designing (Musta'amal, et al. 2009), the rigour of the modelling process for 3D CAD makes it unsuitable for the rapid and spontaneous externalisation of ideas (Yang, 2003). The software used to support Digital Concept Sketching has a requirement to emulate the capabilities of paper-based tools where quality of line is particularly important to designers. Interactive tablets that are suitable for Digital Concept Sketching include the Wacom Cintiq and Hewlett Packard Elite Book Tablet PC. Software suitable for Digital Concept Generation includes Adobe Photoshop and Autodesk SketchBook Pro.

5.1.3 Phase 2B: Evolutionary Form Generation (CAD Add-in)

Software is now available to facilitate the generation and evolution of form-based geometry in support of the industrial design concept generation. When integrated with Digital Concept Sketching, this can foster the emergence of design ideas (Soufi and Edmonds, 1996). Software suitable for augmented form generation includes EvoShape (Evoshape, n.d.) and Morphogenesis (Morphogenesis, n.d.).

5.1.4 Phase 3: Digital Sketch Modelling (Haptic Feedback Device)

The transition from 2D sketches to 3D form marks a significant development in the form-giving process and is a key phase of industrial design practice. During DID this is facilitated through the use of a haptic feedback device that allows the designer to receive a degree of tactile feedback from a virtual material as this is actively sculpted. The scanned geometry for internal components can be imported into the digital modelling environment to ensure that these fit within the emerging forms. Haptic feedback devices suitable for Digital Concept Modelling include the SensAble Phantom/ FreeForm system (Author, 2005).

5.1.5 Phase 4: Tactile and Visual Evaluation of Sketch Models (Monochrome 3D Printing)

Digital Sketch Modelling allows the designer to receive a degree of tactile feedback from a digital material as the form emerges. If this geometry is then used to produce a 3D printed sketch model, the designer has access to something that has a resemblance to a sketch model that would have been produced by hand using closed cell foam in a workshop. Monochrome 3D printing systems that are suitable for Tactile and Visual Interaction with Sketch Models include the ZCorp ZPrinter and 150 the HP Designjet 3D.

5.1.6 Phase 5: Rendered Concept Sketches for Client Presentation (Interactive Tablet)

Having used 2D and 3D digital methods to originate and translate design concepts into proposals that have sufficient merit to warrant presentation to the client, these can be formalised through the preparation of concept sketches that have been produced with a degree accuracy but retain the appearance of being loosely defined. The ease with which tone and colour can be applied to these enables the effective production of Rendered Concept Sketches. These represent the key creative outcome from industrial design activity as they allow the client to see a large number of creative design options from which they can select one or more for further development. Hardware and software used for the production of rendered concept sketches is the same as that used during the Concept Generation Phase 2(a).

5.2 Design Development (DID)

5.2.1 Phase 6: Refinement of Form (3D CAD)

To facilitate Design Development, there is a need for the concepts selected at the end of Concept Generation in Phase 5 to be rigorously defined using 3D CAD. As the 2D Rendered Concept Sketches presented for approval in Phase 5 would be based on the Digital Sketch Models that were produced using a haptic feedback device in Phase 3, this geometry could be imported into a CAD system for use as the starting point for the full definition of geometry. The loosely defined nature of 2D Rendered Concept Sketches and 3D Sketch Models means that there is an inevitability that these will evolve when rigorously modelled in 3D CAD. 3D CAD systems that are suitable for refinement of form include Pro Engineer/Creo and SolidWorks.

5.2.2 Phase 7: Virtual Prototyping (3D CAD)

The capacity to use the 3D CAD geometry for Virtual Prototyping facilitates performance testing without the need for physical prototypes. The reduced time taken for the analysis of a virtual prototype when compared to a physical prototype means that more design iterations can be examined and better optimised designs can be achieved. The analysis undertaken can cover physical properties such as analysis of the strength of a component under load; interaction with airflow; and the build-up of heat in electrical products.

5.2.3 Phase 8: Photorealistic Visualisation for Client Presentation (3D CAD)

The most effective way to communicate the outcome of design development to a client is by rendering the 3D geometry that was used to refine the form and undertake virtual prototyping. The high degree of realism afforded by photorealistic CAD visualisation is sufficient to give the client and potential users a clear indication of what the production item would look like. Most rendering software allows the generation of animations of the component or product. This can enhance the level of feedback to the client as specific features of the design can be highlighted. Software that is suitable for photorealistic rendering includes KeyShot, Bunkspeed, Autodesk Showcase and 3ds Max.

5.2.4 *Phase 9: Low Fidelity Appearance Model for Client Presentation (Multi-Colour 3D printing)*

The production of physical models that have the exact appearance of a product is a time consuming and expensive activity as they are predominantly hand-made by experts using sophisticated workshop facilities. Whilst the use of additive manufacturing has made a significant reduction to timescales, components produced by this technology still require considerable hand finishing to create a surface finish that is suitable for an appearance model (Authors 2003). The scope of DID necessitates outputs to be entirely digital and the development of multi-coloured 3D printing has the capacity to directly deliver something that has a very close association with an appearance model. Multi-coloured 3D printing produces models with a relatively rough, powdery surface finish and all components must be fused together so part lines between individual components are problematic or not possible.

As these models deviate from an appearance model to some degree, a more suitable term might be 'low fidelity appearance model'. However, despite limitations, the process has the potential to produce full colour models that include all graphics and, as such, can have a high level of detail. Low fidelity appearance models have the potential to be used either with or after photorealistic visualisations to facilitate client approval.

5.3 Phase 10, 11, 12: Specification

As the industrial design solution progresses to the specification phase of DID, well established and proven techniques are employed. These are Phase 10, Detail Design (3D CAD); Phase 11, Pre-production Prototypes (Additive Manufacture); and Phase 12, Tooling Simulation (3D CAD). Whilst these phases must be acknowledged, the activities as part of the DID do not provide any new knowledge but their contribution to the entire DID must be acknowledged for completeness.

6. Methodology

The DID research employed an individual case study where the researcher (Author), who had undergraduate and masters degree qualifications in industrial design plus commercial experience, undertook the design of a consumer product using DID. This design activity was overseen by a researcher with more substantial experience as a practicing industrial designer (Author) who took on the role of design manager. Additional CAD/engineering expertise was provided by Author.

In focusing on a specific method that can be applied to collect data within the case study, action research is of particular relevance when exploring issues relating to professional practice (Moore 1983, Gomm and Hammersley 2000, Cohen and Manion 1980). Action research has been defined by Cohen and Manion (1980) as:

> ….. an on-the-spot procedure designed to deal with a concrete problem located in an immediate situation. This means that the step-by-step process is constantly monitored (ideally, that is) over varying periods of time and by a variety of mechanisms

> (questionnaires, diaries, interviews and case studies, for example) so that the ensuing feedback may be translated into modifications, adjustments, directional changes, redefinitions, as necessary, so as to bring about lasting benefit to the ongoing process itself.

The notion of an "action research cycle" is noted by Robson (2002) and involves "planning a change; acting and then observing what happens following the change; reflecting on these processes and consequences; and then planning further action and repeating the cycle". There are similarities between action research and reflective designing, in which the subject or researcher undertakes creative practice and articulates the process and outcomes. The process of reflective designing is described by Schon (1983) where:

> The designer's moves tend, happily or unhappily, to produce consequences other than those intended. When this happens, the designer may take account of the unintended changes he has made in the situation by forming new appreciations and understandings and by making new moves. He shapes the situation, in accordance with his initial appreciation of it, the situation 'talks back', and he responds to the situation's back-talk.

Observations by a researcher or a video camera cannot record what a designer is thinking and a method of data collection was required to obtain an account of the designer's reflection when employing DID. Techniques such as shadowing participants have the potential of being disruptive and having to recall an activity (such as through an interview) sometime after the event can result in details becoming inaccurate (Pedgley 1997). In light of this, the use of a retrospective diary, where writing takes place at some point after an activity was identified to be more effective. This approach has been shown to facilitate understanding of the designer's experiences with the capacity to identify inconsistencies (Pedgley 2007; Webster 2004) and that it is an established method of data collection in social sciences where records can be produed at the subject's own pace in a relatively unobtrusive fashion (Bartlett 2011).

In the DID case study, an electronic pro-forma diary sheet was generated and used to record both written and sketched reflection on the various design activities. The written reflection was categorised as "Key Activities and Output" and "Reflection", with annotated sketches recorded under "References" which were linked to the two written headings. An example of a diary entry can be seen in Figure 2.

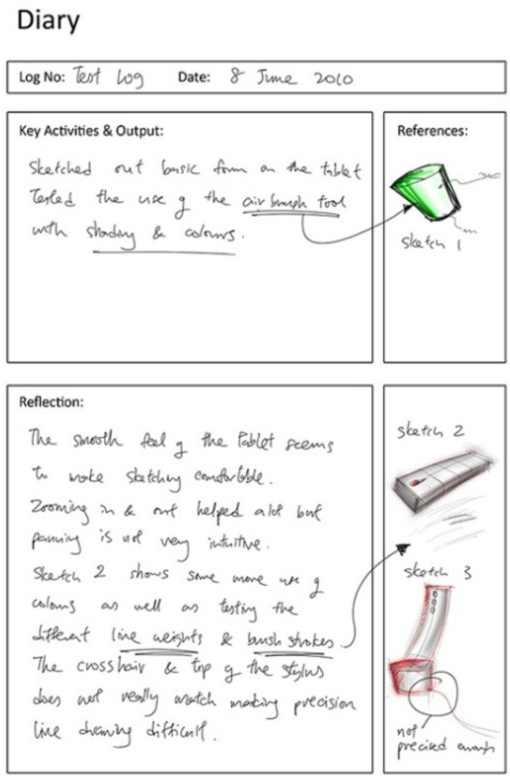

Figure 2. Example of a diary entry during Digital Concept Sketching

The diaries were analysed using coding and clustering (Miles and Huberman 1994) at the end of the case study and significant findings in relation to conventional practice identified.

When employing DID in the case study, it was necessary to prevent the stylistic direction adopted for the product from affecting the outcomes i.e. would a geometric design present fewer or more challenges for DID than a freeform design? This involved taking two stylistic directions for the industrial design of an Internet telephone handset; one using predominantly geometric elements based on planar surfaces and the other taking an organic, freeform strategy that had compound curvature. This represented a departure from professional practice but made a significant contribution to the research methodology and demonstrates ways in which academic research can be used to investigate issues relating to practice.

The key activities and findings from the DID case study will now be discussed and supported by using selected design outcomes plus findings from the use of the diary. Although some of the elements of DID resulted in no issues, all phases are discussed and images of outputs provided for completeness and contextualisation.

7 DID Case Study

7.1 Concept Design

7.1.1 DID Phase 1: Capture of Engineering Hard-points (3D Scanning)

In preparation for Digital Concept Generation, the electronic circuit board and components to be housed within the product were scanned using a FARO Scanarm V3 non-contact laser scanner and saved in .stl file format. A shaded view of the scanned component can be seen in Figure 2.

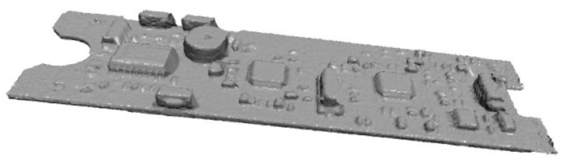

Figure 3. Shaded view of scanned electronics components

7.1.2 DID Phase 2(a): Digital Concept Sketching (Interactive Tablet)

Digital Concept Sketching is typically undertaken using a tower PC and desktop interactive tablet such as a Wacom Cintiq. This research employed a more self-contained and portable tool by using the interactive screen and stylus on a Hewlett Packard Elitebook 2730p Tablet PC with a 1.86GHz processor as seen in Figure 1. The use of the Tablet PC was selected as a portable design tool that was more closely linked to a designers sketch pad. To facilitate the use of the Tablet PC for Digital Concept Sketching, shaded elevational views of the scanned electronics were imported into Adobe Photoshop for use during Digital Concept Sketching. During this process, it was noted that the use of the interactive tablet did not offer instantaneous access to the sketching media (unlike pen paper) due to the boot-up time and it was considered as being relatively cumbersome due to its weight. There was also a need to calibrate the stylus to maintain accuracy and the viewing angle had to be adjusted to produce a comfortable orientation for sketching. An example of a concept sketch produced using the Tablet PC can be seen in Figure 4.

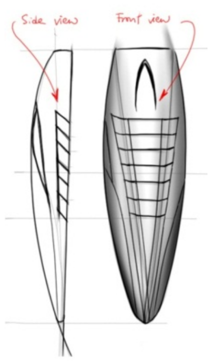

Figure 4. Digital concept sketch

7.2.3 DID Phase 2(b): Evolutionary Form Generation (CAD Add-in)

As a relatively recent development in tools to support industrial design, augmented form generation through generative or evolutionary software has the potential to foster innovation through the unexpected and unplanned generation and evolution of form. During the DID case study, this was undertaken through the use of the EvoShape CAD add-in which offered novel geometric forms and encouraged the emergence of new ideas. However, as prototype software at the time of the case study, the user-interface was slow and unintuitive leading the designer to feel that this factor was limiting the enhancement of the creative process.

Examples of EvoShape outputs for phone design inspiration that was generated using the software can be seen in Figure 5.

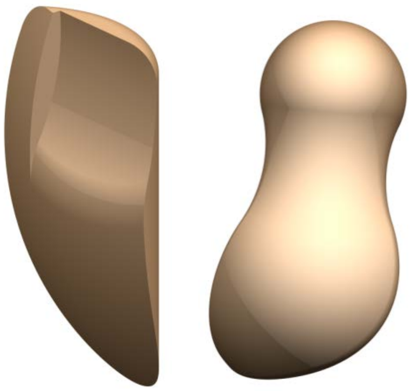

Figure 5. Shaded view of forms generated using Evoshape software

7.2.4 DID Phase 3: Digital Sketch Modelling (Haptic Feedback Device)

The translation of 2D Digital Concept Sketches into a 3D format followed the same principle of non-digital methods where closed cell foam would be shaped in a workshop. However, during DID, a SensAble Haptic feedback device along with Freeform software was used with the support of an expert user to maximise access to its full functionality. In use, the intuitive nature of the sculpting operation was found to be problematic unless the form was generated using CAD-type modelling methods. Records from the diary referred to the sculpting activity as being analogous to holding a piece of foam and sculpting with a knife/abrasive paper although it was difficult to get the required smoothness of finish. The diary also noted that the required effects could be achieved when the CAD-type functionality was employed which was similar to using pre-formed cutting tools in a workshop. Whilst successful outcomes were achieved (see Figure 6), they were through the CAD constrained approach that was not analogous to the more sculptural activity that would take place in a conventional workshop.

Figure 6. Shaded view of a Digital Sketch Model

7.2.5 DID Phase 4: Tactile and Visual Evaluation of Sketch Models (Monochrome 3D printing)

Tactile feedback from the haptic interface was limited and, to support the physicality that is central to industrial design practice, the models were downloaded to a monochrome 3D printing machine (Z Coporation Z310) for the production of physical models. These models had a close association with closed cell sketch models and provided extremely useful feedback for ergonomic and visual evaluation. The diary noted that these were significantly heavier that closed cell sketch models although an opportunity exists to develop software that can automatically shell-out the interior to reduce the amount of material used. One of the six 3D printed Sketch Models can be seen in Figure 7.

Figure 7. Physical sketch model produced using haptic feedback modelling followed by monochrome 3D printing

7.2.6 DID Phase 5: Rendered Concept Sketches for Client Presentation (Interactive Tablet)

Rendered concept sketches formalise early design proposals and provide a format suitable for evaluation by designers and other stakeholders. A key advantage noted in the diary that arose from the use of the Tablet PC was the portability and convenience for use when in transit (e.g. on trains and planes) as it removed the need for a sketch pad and associated media. An example of a

Rendered Concept Sketch for client presentation that was produced using the Tablet PC can be seen in Figure 8.

Figure 8. Rendered Concept Sketch Digital suitable for client presentation

7.3 Design Development

7.3.1 DID Phase 6: Refinement of Form (3D CAD)

The modelling of form using 3D CAD represents standard practice when a design has been selected for development. However, a key advantage of DID noted in the diary was that existing haptic feedback geometry was available as the starting point for this process and this was identified as a significant efficiency gain. The emerging 3D CAD model that exploited the geometry from the haptic feedback modelling can be seen in Figure 9.

Figure 9. Shaded rendering of emerging CAD model

7.3.2 DID Phase 7: Virtual Prototyping (3D CAD)

The use of virtual prototypes for simulation and testing of mechanical properties is standard commercial practice and no issues were identified from its integration into the DID approach. An example of virtual prototyping can be seen in Figure 10 which shows the results of stress analysis on the handset. The different colours indicate different levels of stress being predicted under a specified loading case.

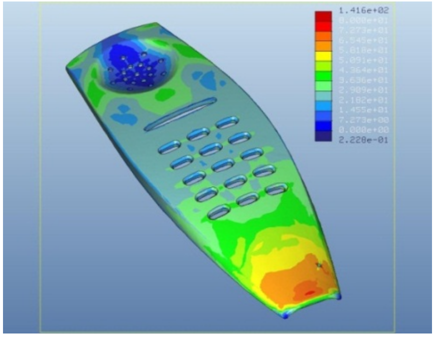

Figure 10. Simulated stress analysis during Virtual Prototyping

7.3.3 DID Phase 8: Photorealistic Visualisation for Client Presentation (3D CAD)

The use of Photorealistic Visualisation for client presentation is standard commercial practice and no issues were identified from its integration into DID. An example of the rendering for the organic design or Internet telephone handset can be seen in Figure 11.

Figure 11. Photorealistic Visualisation during Design Development

7.3.4 DID Phase 9: Low Fidelity Appearance Model for Client Presentation (Multi-Colour 3D printing)

Once detailed 3D CAD geometry has been generated, additive manufacturing is generally used to produce components for appearance models. However, components produced by additive manufacturing include stepped features from the build process. As these components do not have a smooth surface finish, they must be sanded and painted before assembly. These skilled craft activities must be undertaken by hand and this level of post-process finishing and fabrication was considered as being beyond the scope of a total DID approach. As an alternative approach, multi-colour 3D printing was employed in the DID to produce a Low Fidelity Appearance Model as an alternative to a more conventional appearance model that would look exactly like the proposed production item. To achieve this, it was necessary to define colours, logos and use the 3D CAD software to ensure that all individual components were attached. As the model used for the DID case study this model had been accurately modelled, no issues were identified found and all parts correctly mated together.

Whilst the two Low Fidelity Appearance models produced during the DID case study had a textured finish and some of the colours were not as intense as those achieved by painting, they required no post-process finishing whatsoever and all graphics were in place. It was accepted that the low fidelity appearance model did not have the precise representation of an appearance model but, having obtained a quotation from a professional model maker, an estimated 95% reduction in build time was identified. The diary noted an opportunity to integrate the Low Fidelity Appearance model with the Photorealistic Visualisation (see DID Phase 8) to ensure that the design proposal was fully and accurately communicated. An example of the Low Fidelity Sketch Model for the organic design can be seen in Figure 12.

Figure 12. Low fidelity sketch model for one of the 6 design proposals

7.4 Specification

As previously discussed under 5.3 Specification, for completeness Phase 10, 11 and 12 were undertaken as part of the case study and are included in the web-based dissemination resource but no new knowledge was anticipated or arose from this activity.

8 Dissemination

As a complete industrial design case study that explored the potential for an entirely digital approach, significant material arising from the DID case study became available for dissemination. The DID approach plus the designed outcomes were considered to be of value to students, teachers, practitioners and researchers which led to a web-based tool being developed to demonstrate the process and outcomes. This included the phases of DID in the context of Concept Generation, Design Development and Specification; thumbnail images of the designed outputs that could be enlarged for greater clarity; and a brief overview of the project. The web-based DID case study was launched in Devember 2013 at http://homepages.lboro.ac.uk/~cvijg/DID/. The three phases of DID plus thumbnail images as used on the web-based tool can be seen in Figure 16).

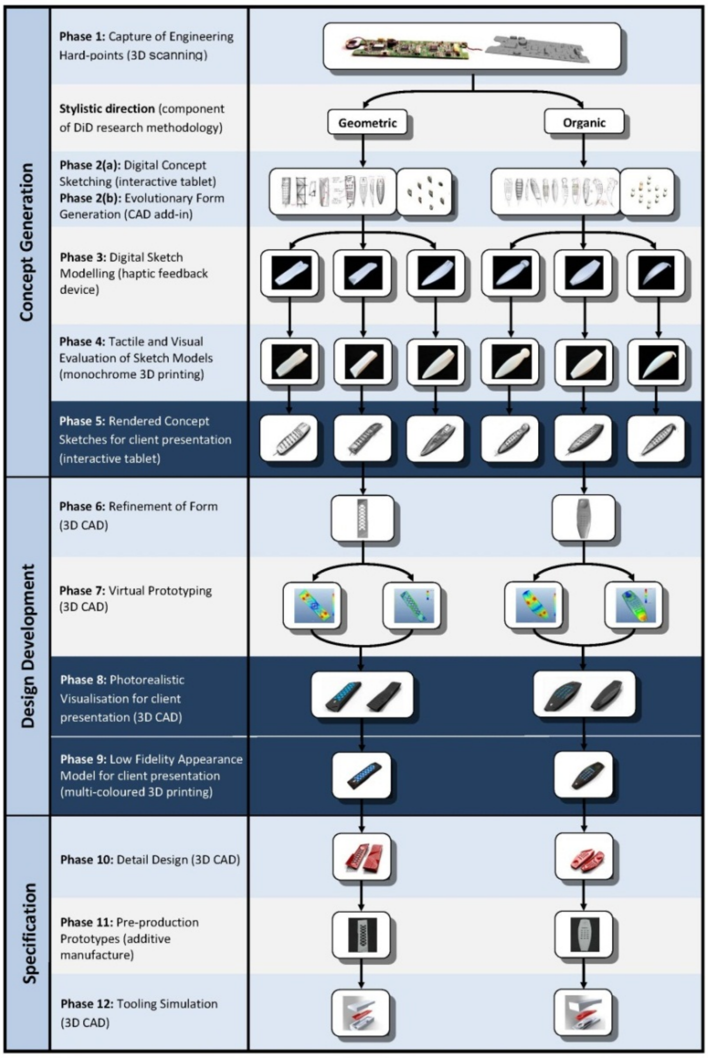

Figure 13. Interactive diagram used for DID web tool

9 Conclusions

The research has identified a range of digital tools that have the capacity to support industrial design practice (Research Question 1); proposed a new theoretical approach to the way that industrial designers work (Research Question 2); and identified key issues arising from the implementation of DID through action research (Research Question 3). The case study was used to generate research data through a process of reflection (using a diary) that was supported by the collation of outputs from the design activity (images and physical models). It must be acknowledged that the scope of the study was restricted to a hand-held consumer product with the only limitation to scale being the size of 3D printing machines.

The findings indicated that the greatest potential for the introduction of additional digital methods was during Concept Generation, where haptic feedback modelling and monochrome 3D printing has the capacity to replicate, at least in part, the tactile form-giving that is associated with workshop-based sketch modelling. Advantages of this approach are that it removes the need for workshops and their associated costs. It also facilitates efficiency gains by re-using the 3D geometry of the Digital Sketch Model when undertaking 3D CAD in Phase 6 (Refinement of Form) during Design Development. This would not be possible when using closed cell foam in a workshop but there were limitations in the capacity of haptic feedback modelling to replicate workshop activity.

The Low Fidelity Appearance Model captured the key features of the proposed product with a high degree of detail but at a fraction of the cost and time required for a more conventional appearance model produced by fabrication and/or additive manufacturing. Whilst the Low Fidelity Appearance Model did have limitations in terms of surface finish and durability, when combined with the Photorealistic Visualisations of Phase 8, a comprehensive insight into the total product was generated. The degree to which stakeholders in new product development would acceptance these media as part of the decision-making process is yet to be identified and has the potential for future research. Anything that deviates from an artefact that does not have an exact resemblance to a production item would be problematic but the author’s position is that efficiency gains may require a degree of compromise.

Beyond answering the research questions, the project demonstrated a methodology that integrates action research in the form of design practice. Whilst there is a need to carefully monitor the quality of design activity that takes place when such methods are employed, the added value in terms of designed outcomes can be significant. This is particularly relevant as universities and funding bodies seek to demonstrate impact of research beyond academia and the development of the DID web tool with content that is of relevance to practitioners can be seen as a strategy to support this. The methodology and its findings can therefore be seen as an approach that supports the translation of a theoretical knowledge framework into tangible examples of designed outcomes.

References

3D Systems (n.d.). Retrieved 24 January 2014 from http://www.zcorp.com/en/Products/3D-Printers/spage.aspx

Aldoy, N. (2011). *An Investigation into a Digital Strategy for Industrial Design Education*. Unpublished doctoral thesis. Loughborough University, Loughborough, UK, p.316 , pp. 169-176

Authors. (2011). A Review of Digital Industrial and Product Design Methods in UK Design Education. *Design Journal*, *14*(3). p. 358

Archer, L. B. (1965). Systematic Method For Designers. In Cross, N. (Ed.) *Developments in Design Methodology*. Chichester: Wiley, p.64

Bartlett, R. 2011. Using diaries in research with people with dementia. Realities toolkit #18: December 2011. Realities, Morgan Centre, University of Manchester. Retrieved 24 October 2012 from http://www.socialsciences.manchester.ac.uk/morgancentre/realities/toolkits/diary/18-toolkit-using-diaries.pdf , p. 6

Baxter, M. (1995). *Product Design: A Practical Guide to Systematic Methods of New Product Development*. London: Chapman & Hall, pp. 262 - 263

Cohen, L. and Manion, L. (1980). *Research Methods in Education*. London: Croom Helm, p. 178

Conway, H. (Ed.) (1987). *Design History*. London: Harper Collins , pp. 4-5

Cooper, R. & Press, M. (1995). *The Design Agenda: A Guide to Successful Design Management*. Chichester: Wiley, p.38

Design Council Accessed 21 January 2014 from http://www.designcouncil.org.uk/about-design/Types-of-design/Product-design/Introducing-product-design/

Dumas, A. (no date). Theory and Practice of Industrial Design. Retrieved 28 May 2012 from http://www.urenio.org/tools/en/Industrial_Design.pdf p. 3

Author (2005). An evaluation of haptic feedback modelling during industrial design practice. Design Studies 26 (5). pp.487 - 508)

Authors (2003). A Comparative Evaluation of Industrial Design Models Produced using Rapid Prototyping and Workshop-based Fabrication Techniques. *Rapid Prototyping Journal, 9*(5), pp. 344 – 351

Evoshape (n.d.). Retrieved 16 January 2014 from www.evoshape.co.uk

Gomm, R. and Hammersley, M. (2000). *Case Study Method*. London: Sage Publications.

Authors (2001) Genetic Algorithms in Computer-Aided Design. *Journal of Materials Processing Technology, 117*(1-2), p. 216

Heskett, J. (1980). *Industrial Design*. London: Thames & Hudson, p. 10

IDSA. Accessed 21 January 2014 from http://www.idsa.org/what-is-industrial-design

iD Cards. Retrieved 14 January 2014 from http://www.lboro.ac.uk/departments/lds/research/groups/design-practice/

Institution of Engineering Designers (no date). Accessed 21 January 2014 from http://www.ied.org.uk/about

Jones, J. C. (1963). A Method of Systematic Design. In Cross, N. (Ed.) *Developments in Design Methodology*. Chichester: Wiley, p.11

Krish, S. (2011). A Practical Generative Design Method. *Computer-Aided Design*. *43*(1) , pp.88-100

Kojima, T., Matsuda, S., Shimizu, Y. & Tano (1991). *Models and Prototypes*. Tokyo: Graphic-sha Publishing, p. 83

Lau, H. Y. K., Mak, K. L. and Lu, M. T. H. (2003). A Virtual Design Platform for Interactive Product Design and Visualization. *Journal of Materials Processing Technology*. *139*(1-3), p. 402

Lei, L-C and Wei, W-J (2007). Behaviour analysis between paper sketching and interactive pen display sketching in collaborative design. Proceeding of the 2007 11th International Conference on Computer Supported Cooperative Work in Design. Melbourne Australia, p307

Loosschilder, G. (1997). A Picture Tells a Thousand Words: Testing Product Design Concepts using Computer-Aided Design. *The Design Journal*. *0*(1), p. 45

McCullough, M. (1998). *Abstracting Craft - The Practiced Digital Hand*. Cambridge: MIT Press. p. 25

Miles, M. B. and Huberman, A. M. (1994). Qualitative Data Analysis. Thousand Oaks, California: Sage Publications Inc

Moore, N. (1983). *How to do Research*. London: Library Association Publishing.

Morphogenesis (n.d.). Retrieved 16 August 2012 from http://www.solidthinking.com/pdf/en-US/sTinspired85brochure_Letter.pdf

Musta'amal, A. H., Norman, E. and Hodgson, T. (2009). Gathering Empirical Evidence Concerning Links Between Computer Aided Design (CAD) and Creativity. *Design and Technology Education: An International Journal*. *14*(2), pp. 53 - 66

Pedgley, O. (1997). Towards a method for documenting industrial design activity from the designer's perspective. IDATER 1997 Conference, Loughborough University, p. 218

Pedgley, O. (2007). Capturing and analysing own design activity. 28 (5), p. 463

Authors (2011). A Taxonomic Classification of Visual Design Representations used by Industrial Designers and Engineering Designers. *The Design* Journal. *14*(1), p.75

Pipes, A. (1990). *Drawing for Three Dimensional Design*. New York: Thames & Hudson, p.58

Pipes, A. (2007). *Drawing for Designers*. London: Laurence King, pp.20 - 35

Prats, M., Lim, S., Jowers, I., Garner, S. W. and Chase, S. (2009) Transforming Shape in Design: Observations from Studies of Sketching. *Design Studies*. *30*(5), p.503

Robson, C. (2002). *Real World Research*. London: Blackwell, p. 217

Ronning, O. (2008). *Sketching Part 2: Paper in a Digital World*. Retrieved 18 January 2014 from www.artefactgroup.com/#/content/sketching-part-2-paper-in-a-digital-world

Schon, D. A. (1983). *The Reflective Practitioner*. London: Temple Smith, London, p.79

Sequin, C. H. (2005). CAD Tools for Aesthetic Engineering. *Computer-Aided Design*. *37*(7), p.736

Soufi, B. & Edmonds E. (1996). The cognitive basis of emergence: implications for design support. *Design Studies 17*(4), pp. 451 - 463

Sutherland, I. E. (1963). SketchPad: A Man-Machine Graphical Communication System. In *American Federation for Information Processing Societies Conference Proceedings Volume 23*, pp. 323-328

Tang, H. H., Lee, Y. Y. and Gero, J. S (2011) Comparing collaborative co-located and distributed design processes in digital and traditional sketching environments: A protocol study using the function-behaviour-structure coding scheme. Design Studies 32, p22

Ulrich, K. T. & Eppinger, S. D. (2003). *Product Design and Development*. Boston: McGraw-Hill, pp.198-200

Unver, E. (2006). Strategies for the Translation to CAD-based 3D Design Education. *Computer Aided Design & Applications*. *3*(1-4), p.323

Webster, H. (2004). The Design Diary: Promoting Reflective Practice in the Design Studio. In Transactions on Architectural Education, European Association for Architectural Education (EAAE) *Architectural Design: Monitoring architectural design. No. 24*, p. 11

Willis, A., Speicher, J. & Cooper, D. B. (2007). Rapid Prototyping Objects from Scanned Measurement Data. *Image and Vision Computing*, *25*(7), p.1174

Yan, Z., Hongke, T., Li, G., & Guangyu, Z. (2006). Digital Technology and Digital Product Design. In CAIDCD: *7th International Conference on Computer-aided Industrial Design and Conceptual Design*. Hangzhou: IEEE

Yang, M. C. (2003). Concept Generation and Sketching: Correlations with Design Outcome. In *Proceedings of the 15th International Conference on Design Theory and Methodology*. ASME Digital Library.