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THE INTEGRATION OF RAPID PROTOTYPING WITHIN INDUSTRIAL DESIGN PRACTICE

BY

MARK ANDREW EVANS

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

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Addendum

Institutional Repository Copy: Formatting

The original thesis was produced using Word for Macintosh and, prior to publication on the Loughborough University Institutional Repository, was archived using Word for Windows. Conversion of the archive copy to pdf has resulted in changes to the original formatting that has resulted in issues such as distortion to tables and text for figures appearing on the following page.

External Examiners for the PhD were Professor David Durling and Professor Martin Wooley.

Dr Mark Evans
August 2009
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To evaluate the methodological approach through its application during the industrial design of a new product.

To compare and contrast models produced using rapid prototyping.
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Three-dimensional appearance models represent an essential outcome of industrial design practice, facilitating the origination, evaluation and specification of exterior form. As manufacturers face increasing pressure to reduce time scales for new product development, the production of such models using conventional fabrication techniques must be appraised. As a means of economically translating digital geometry into one-off components, rapid prototyping has the potential to contribute towards a reduction in lead times for the production of appearance models. The objective of this research is to propose a methodological approach for the effective integration of rapid prototyping within industrial design practice.

The field and practice of industrial design is defined, the technology of rapid prototyping discussed, and their integration proposed through a draft computer-aided industrial design/rapid prototyping (CAID/RP) methodological approach. This is exposed to practitioner feedback, modified, and employed as a revised CAID/RP methodological approach during the industrial design of a nylon line trimmer. The product outcome is used to compare and contrast the production of an appearance model via rapid prototyping, an appearance prototype via rapid prototyping, and an appearance model via conventional fabrication techniques.

Two issues arise from the use of the revised CAID/RP methodological approach: the production of stl files and the lack of physical interaction with product form. In addition, the emergence of rapid prototype sketch modelling systems following the line trimmer case study provides an opportunity for further enhancement. A strategy for the resolution of these issues is proposed, and their effectiveness evaluated through additional case studies. The resulting CAID/RP methodological approach is subject to validation through practitioner interviews and a normalised rating/weighting method. The positive feedback acknowledges the significance of the CAID/RP methodological approach through a reduction in product development lead times and enhancement of professional practice. The project makes a contribution to new knowledge and understanding in the area of professional practice through the definition and validation of operational paradigmatic change.

**Keywords**
Design; industrial; product; rapid; prototyping; models; professional; practice.
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Les Pickstock for making many of the models required for this project.

The industrial designers who contributed valuable feedback during the course of this project.
Abbreviations

2D – Two dimensional
3D – Three dimensional
CAD – Computer aided design
CAID – Computer aided industrial design
CNC – Computer numeric control
DFM – Design for manufacture
DTI – Department of Trade and Industry
FDM – Fused deposition modelling
GA – General arrangement
IDSA – Industrial designers society of America
IGES – International graphics exchange system
LOM – Laminated object manufacture
MIT – Massachusetts Institute of Technology
NPD – New product development
RP – Rapid prototyping
SGC – Solid ground curing
SLA – Stereolithography
SLS – Selective laser sintering
SME – Small to medium sized enterprise
stl – Stereolithography data exchange format
Introduction

Lead times and product development
A requirement to reduce New Product Development (NPD) lead times has become a focus of management effort throughout manufacturing industry. (Erhorn and Stark 1994 p27, Rosenthal 1992 p68, Cooper 1993 p90) The rationale for this has been summed up by Matti Otala, the Director of Research and Development for the German Telecommunications company Telenorma: “As a result of increasing international competition, product lifecycles have been shortening in almost all product categories. This has resulted in a demand for faster product development processes in order to keep up with the competition”. (Product Development and Design Practice 1991 p11)

Erhorn and Stark note that towards the end of the twentieth century, the competitive factors involved in manufacturing industry changed, moving from cost, quality and innovation, to flexibility and reduction in time to market. (1994 p27) In an environment of increasing competition, they see opportunities for commercial success occupying smaller and smaller timeframes: “if you are months late to market, your product may never be profitable”. (ibid p28)

The ability to launch a product either ahead of the competition or shortly after is not the only reason for reducing NPD time-scales. Rosenthal states that shorter development cycles enable a company to wait longer before starting a
project, thereby facilitating the use of the most recent technological advances or consumer data. (1992 p68)

The need to reduce time scales can also be at odds with a requirement to cut down the failure rate by “doing it right”. (Cooper 1993 p98) Cooper offers five strategies to assist in achieving a reduction in NPD time scales, but only one of these has direct relevance to industrial design: parallel processing. Undertaking NPD activities concurrently (parallel processing) enables activities to be carried out simultaneously, thereby enabling more activities to be undertaken in a given time frame. (ibid) In terms of industrial design, the aim would be for a methodological approach that would enable parallel processing with others involved in product development.

Despite an acknowledgement of the benefits of reducing NPD time scales, Cooper comments that, unless managed carefully, such attempts can result in costly errors due to omission and oversight. (ibid p92) The net result of poorly executed attempts to reduce NPD lead times “not only add delays to the project, but often lead to higher incurred costs and even product failure”. (ibid) As a means of overcoming or reducing such problems, professions involved in the design of buildings, artefacts and systems have adopted, or are exploring, a variety of modelling strategies, including virtual reality, virtual prototyping, virtual manufacturing and virtual assembly.

Virtual reality is defined as “a computer generated world involving one or more human senses and generated in real time by the participants actions”. (Bertol 1997 p67) Bertol goes on to add the significance of the immersion of the user within the virtual environment: “Virtual reality visual representations are provided by stereoscopic perspective views. The introduction of depth simulation, obtained by stereoscopic viewing which reproduces the process of binocular vision, is an essential factor in virtual reality environments.” (ibid)

The ability to interact with a realistic rendered environment has proved to be an effective means of visualisation in architecture, where it is not viable to produce full-size models of buildings prior to construction. NBBJ, the fifth
largest architectural firm in the world, make extensive use of virtual reality in their Sports and Entertainment Division. (Von Woodtke 2000 p108) Applications include its use during the design review process, marketing, and the promoting of facilities. (ibid) As sports stadia make up a significant proportion of NBBJ’s portfolio, the use of virtual reality has proved to be particularly effective tool in the positioning of seating in locations where the view may be obscured by the building structure. (ibid)

Despite the use of virtual reality as a design and evaluation tool in architecture, the requirement for physical models remains as they “help visualize how the pieces go together and are a useful display for clients and their constituency”. (ibid) It is significant to note that the digital geometry used in the modelling of the virtual reality environment can be utilised in the production of the physical model by generating the tool path for computer numeric control (CNC) machining. (ibid)

Virtual prototyping is distinct from virtual reality in that it does not necessarily involve the use of immersive stereoscopic viewing techniques. It is virtual in the sense that it is a digital representation of an engineering solution, “and with such a prototype, engineers can dramatically increase the number of iterations in the design, and at the same time reduce prototyping and testing costs.” (Harrison 1998 p25) As a predominantly engineering-based application, the Boeing Company have employed virtual prototyping to reduce time to market during the development of aerospace components. Despite Boeing’s access to state of the art technologies, “the reality is that no single tool, or family of tools from a single software vendor, allows the engineer to easily create a complete virtual prototype of an entire system.” (ibid) In an attempt to resolve the limitations of virtual prototyping within the automotive industry, Faithful et al (2001 pp231 - 243) propose the use of a hybrid system that integrates virtual prototyping with the production of a scaled physical prototype, and Huizinga et al suggest a similar strategy but with the use of full-size prototyped components. (2002 pp33 – 47) The continuing requirement by engineers for physical prototyping during this process is stressed by Huizinga et al when they state that “underpinning the process
purely with computer aided engineering predictions, without performing any physical tests, can result in an unpredictable shortcoming in the design that may not be discovered until very late in the development process”. (ibid)

Within the automotive industry, full size physical appearance models continue to be produced as part of the decision making process for the verification of form. As the only way to confidently make such decisions is with full-size life-like representations of vehicles, the use of clay models produced by highly skilled sculptors remains within this industry. (Car Styling March 2002 p28) These techniques were essential in the production of full-size representations of the Chrysler Crossfire sports car for the 2001 Tokyo Motor Show (ibid) and final design iteration of the 2001 BMW 7 Series saloon. (Car Styling January 2002 p18 - 19)

Virtual manufacturing can be employed when prototype testing (either virtual, physical or both) has confirmed the performance characteristics of the design. It “lets production engineers create life-like, full-action mock-ups of automated production systems on a computer workstation, then analyse and debug them before investing in capital equipment”. (Yaman 2001 p400) For processes such as injection moulding, this enables cycle time to be modelled and the effects of changes in temperature and cooling time to be evaluated.

Having identified the materials and processes from which the products will be made, virtual assembly can simulate how the individual components will be put together. The benefits can be significant due to the large number of permutations of assembly that result in an identical product. Virtual assembly enables these permutations to be evaluated as “each sequence implies a different degree of difficulty for the various assembly operations, resulting from the different mechanical constraints imposed by the different sequence of operations. Selection of a good sequence of assembly operation is a crucial factor in maximising the production profitability and has great impact on the assembly line balancing, machine utilization and feasibility of subassembly operations.” (Choi and Guda 2000 p283)
Virtual reality, virtual prototyping, virtual manufacturing and virtual assembly require a design proposal on which to base the modelling operations. However, developments in computer programming are now contributing to reductions in NPD time scales through the automation of elements of design activity. In engineering design, design automation has been employed through the use of genetic algorithms in the specification of engineering detail. Genetic algorithms operate by “emulating an evolutionary process where the solutions become more appropriate the longer the software is allowed to run”. (Barker 1998 p203) Toropov and Mahfouz have used genetic algorithms to generate the specification of beams required for steel frame building structures through the integration of design rules (British Standards) and finite element modelling. (2001 pp 437 – 460)

Design automation is not restricted to engineering design applications. Hsiao and Huang have employed neural networks in the development of a method of design automation that facilitates the generation of product form “by providing basic design elements and shape generation rules”. (2002 pp 67 – 84) Neural networks manage computer data in a way that more closely simulates the parallel processing operations of the brain than conventional step by step serial processing. (Barker op cit) By processing data in this way the computer can “deal with fuzzy and complex issues that cannot be handled by serial methods.” (ibid)

The strategy developed by Hsiao and Huang was applied during the design of an office chair and involved the following phases: survey of existing products and identification of key product elements (armrest, back, seat, back support, supporting base); selection of image words to assist with evaluation (e.g. practical, elegant, steady); the representation of each product as 3D computer models; the programming of shape generation rules for permissible deformity; the identification of characteristics (as words) for the new design and manipulation of form by the neural network programme to produce a product proposal. (op cit pp 70 – 71) The relatively crude product outcome from this study indicated that that this technology has some way to go before design
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automation will be in a position to make a contribution or challenge to professional industrial design practice.

The use of appearance models during industrial design practice: an opportunity for time compression?

As a profession involved in the design of manufactured products, industrial designers make extensive use of three-dimensional (3D) physical models, employing these during the generation, development and specification of proposals. At the specification stage in particular, a 3D appearance model becomes an essential instrument in the client’s decision-making process as it enables form to be more accurately evaluated prior to an investment in the tooling for manufacture.

The production of appearance models has evolved from methods closely related to pattern making, whereby solid materials are formed using predominantly craft-based techniques to produce moulds for metal casting. An appearance model is a representation of an artefact that would ultimately be manufactured using mechanised production processes such as injection moulding, die-casting, and pressing. The production of appearance models involves the translation of design intent into a 3D physical form and, as a labour intensive process, the lead times and costs involved in their production are dependent on complexity and resources available.

To put the time-scales required for the production of appearance models into context, the relatively simple tyre inflater, seen in Figure 1, was produced in a professional model making workshop over a five-day period with 28 hours attributed to the shaping of material by hand and machine (the additional time being required for adhesive and paint drying).
The more complicated digital camera, seen in Figure 2, was produced using identical resources over an eight day period and required 46 hours of model making time.
Time-scales of several weeks can be required for the production of appearance models for larger products, such as lawnmowers and vacuum cleaners. With such lengthy lead times, any opportunity for time compression must be considered as this would bring forward the industrial design decision making process and contribute to a reduction in NPD lead times.

Rapid prototyping is capable of producing complex 3D physical objects by hardening, cutting or fusing material as layers in condensed time scales. It involves the remote production of components from 3D computer geometry, and, as such, it is volume, not complexity, that contributes to component cost. In contrast, when employing workshop based fabrication techniques complexity is a key issue, with more complex forms being more expensive as
they take longer to produce. Rapid prototyping, as its name suggests, has the capability to produce components faster, as the build is an automated process.

As yet, no methodological approach has been devised to facilitate the use of rapid prototyping during industrial design practice, although extensive material on the nature of the profession and rapid prototyping is available. This study has been initiated to fulfil the need for considered and documented research into a methodological approach for the effective integration of rapid prototyping within industrial design practice, with the aim of reducing lead times for the production of appearance models and enhancing output. It makes a contribution to new knowledge and understanding in the area of professional practice through the definition and validation of operational paradigmatic change.

**Research methodology**

The focus of this study is in the field of professional practice, with an objective to facilitate the integration of a specific technology (rapid prototyping). As such, the use of case study methods was considered a relevant and reliable research tool. Case studies have been described as an approach to research as opposed to a research method (Moore 1983 p44), with a capability, “to describe and understand the phenomenon ‘in depth’ and ‘in the round’ (completeness). In this role, case studies serve a useful purpose, since many important issues can be overlooked in a more superficial survey.” (Birley 1998 p36) In addition, the way in which data are collected and analysed “implies the collection of unstructured data, and qualitative analysis of those data.” (Gomm 2000 p3) The principle of an in depth investigation into the integration of rapid prototyping within industrial design practice through the use of cases study methods forms the core of this study.
In focusing on specific methods applied as part of case study research, Moore (*op cit* p44), Gomm (*op cit* p3) and Cohen and Manion (1980 p178) identify action research. Action research has been defined 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.

(Cohen and Manion 1980 p178)

The cyclical nature of action research has been identified by Birley, who sees it as being conducted by a professional into their own activity, the aim of which is to bring about an improvement in practice. (Birley 1998 p34) Action research was therefore considered particularly appropriate in meeting the objectives of the project, as it represented a recognised research approach for the facilitation of improvements in the execution and understanding of practice. (Garner 1999 p69)

In employing action research through a series of case studies, a strategy of reflective designing will be adopted, whereby the author undertakes the role of the industrial designer and articulates the process and outcome. The activity of reflective designing is described by Schon when he states that:

> 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.
(1983 p79)

The use of action research through a series of case studies forms a primary research element for this project, and whilst these result in design outcomes, the focus will be on the process and not the specific product outcome. This contrasts with Scrivener’s definition for technology research projects which he sees as being distinct from science or humanities research but sharing a number of common features. (www.herts.ac.uk/artdes/simsim_conexre2pract/10 February 2001) Technology research projects focus on the production of a new artefact that is a useful demonstration of a solution to a known problem, but knowledge reified in the artefact can be described, is widely applicable and transferable, and is more important than the artefact itself. As an example of a technology research project, Scrivener discusses the design of a robot arm. (ibid) Technology research projects have the following attributes:

1. Artefact is produced.

2. Artefact is new or improved.

3. Artefact is the solution to a known problem.

4. Artefact demonstrates a solution to a problem.

5. The problem is recognised as such by others.

6. Artefact (solution) is useful.

7. Knowledge reified in artefact can be described.

8. This knowledge is widely applicable and widely transferable.

9. Knowledge reified in the artefact is more important than the artefact.
Whilst there was some potential to integrate the structure of Scrivener's technological research projects into this study, the weighting of the artefact (attributes 1, 2, 3, 4 and 6) was inappropriate for an investigation into process.

The principal research methods used for this study are literature review, case studies and action research. Survey methods are also employed to support the major case study, and a weighting/rating method used to appraise the methodological approach. These methods have been integrated into a five phase research strategy, involving: literature review; definition and application of the draft CAID/RP methodological approach; comparative evaluation of physical models; resolution of modelling issues; appraisal framework.

The literature review of Phase 1 explores the nature of industrial design and capabilities of rapid prototyping. This provides the parameters for the study by giving a working definition of industrial design, identifying the activities involved in professional practice, and contributing an overview of rapid prototyping.

Phase 2 defines a ‘draft CAID/RP methodological approach’ that integrates computer aided industrial design techniques with those of rapid prototyping. As a precursor to a major case study, the draft CAID/RP methodological approach is exposed to practitioner feedback, and information sought on the extent to which industrial designers employ rapid prototyping. Survey methods are an accepted form of data collection, being employed through a postal questionnaire sent to every industrial design consultancy in the UK that was a member of the Chartered Society of Designers. (Birley and Moreland 1998 p31, Moore 1983 p10) Having analysed the results of the survey, any relevant findings will be integrated into a ‘revised CAID/RP methodological approach’ as the outcome of Phase 2.

Phase 3 evaluates the revised CAID/RP methodological approach via a major case study. This phase generates an innovative product proposal, applies the
modelling methods of the CAID/RP methodological approach, and concludes with an appearance model and appearance prototype produced using rapid prototyping, and an appearance model produced using conventional workshop techniques. The two appearance models and appearance prototype enable a comparative analysis to be made between the outcomes from rapid prototyping and conventional workshop-based fabrication techniques.

Phase 4 provides an opportunity to reflect on, and modify, the revised CAID/RP methodological approach through an additional case study by employing the cyclical nature of action research as identified by Cohen and Manion (1980 p178) and Birley. (1998 p34) This Phase will enable any issues identified in Phase 3 to be resolved before validating the CAID/RP methodological approach using an appraisal framework in Phase 5. The appraisal framework will employ interviews with practitioners and the application of a normalised weighting/rating method. (Pugh 1991 pp92 – 99) The outcomes from the appraisal framework will give a percentage score for the success (or otherwise) of the CAID/RP methodological approach.

The five phase research methodology is illustrated in Figure 3.
Figure 3: Five phase research methodology
Research objectives

The principal objective of this research is:

- To propose a methodological approach for the effective integration of rapid prototyping within industrial design practice.

Additional objectives are:

- To undertake a literature review with respect to the nature of industrial design and rapid prototyping so as to illuminate the research field and determine parameters for the methodological approach.

- To evaluate the methodological approach through its application during the industrial design of a new product.

- To compare and contrast models produced using rapid prototyping with those of workshop-based fabrication techniques.

- To identify any issues with the methodological approach and devise a strategy for their resolution.

- To validate the methodological approach through the use of an appraisal framework.
Designing

Designing encompasses “some of the highest cognitive abilities of human beings, including creativity, synthesis and problem solving”. (Cross et al 1996)

In attempting to classify design activity, Jones argues that designing is neither art, science or mathematics, but a hybrid activity with elements of all three. (Jones 1992 p10) He suggests that whilst artists and scientists interact with the physical world in its current state, and mathematicians utilise abstract relationships that are independent of historical time, designers “treat as real that which exists only in an imagined future and have to specify ways in which the foreseen things can be made to exist” (ibid pp10-11)

In the opening chapter of his text on design methods, Jones cites a total of eleven definitions of ‘designing’, some of which differ considerably. (1992 pp 3-4) In identifying the key attributes, Jones believes that it is necessary to focus on the core effect of the change in situation brought about by a new design, and as such sees the effect of designing as “to initiate change in man-made things”, thereby predicting a future state that will only be implemented if the predictions are correct. (ibid pp 4-9) This notion of designing as constructing and predicting a future state was identified by Archer in the mid-1960’s when he commented that “a key element in the act of designing is the formulation of
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a prescription or model for a finished work in advance of its embodiment”. (Cross 1984 p58)

Acknowledging that designing involves the prediction of a future state, Archer believes that it is only possible to consider a sculptor as engaging in designing providing they produce a drawing of their intended outcome. (ibid p58) If sketching is not undertaken in the formulation of the outcome, Archer considers it more appropriate to describe the activity as ‘creating’, not designing. (ibid) Archer summarises his definition of designing when he states that it involves “not only a prescription or model, but also the embodiment of the design as an artefact”. (ibid) He goes on to acknowledge that a degree of originality is also required.

Definition of industrial design

Many professional groups can be involved in ‘designing’, and Archer acknowledges that his definition includes the following activities: “architecture, most forms of engineering (including some systems engineering), certain sciences, all industrial design, and most applied art and craft”. (Archer in Cross 1984 p59) As the focus of this study is within the field of industrial design, it is necessary to establish a working definition for the activities of this profession.

With the advent of the industrial revolution in the eighteenth century England, the means of producing objects started to change from a craft tradition to one of machine based manufacture. Heskett sees this move from craft to mechanical production as the beginnings of the industrial design profession. (1980 p10)

The term industrial design implies design for industry, and it is acknowledged as involving the manufacture of artefacts by mechanical production processes. (Heskett 1980 p10, Lucie-Smith 1983 p7, Pulos 1986 p3, Van Doren 1954 p3) A literal interpretation of this could lead to the assumption that all design for industry is a form of industrial design, although Walker notes that for many
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scholars, all designing that involves a distinct attention to appearance is in fact industrial design. (1989 p27)

Conway is more specific when she identifies industrial design as a distinct design activity, and makes a useful classification of the design professions when she identifies the key specialist activities as dress (or fashion) and textiles, ceramics, furniture, interior design, industrial design, graphics, and environmental (including town planning). Conway has arrived at these classifications through the identification of their respective professional institutions, publications, and areas of design specialisation. (ibid pp4-5)

Having distinguished industrial design by its use of mechanised production techniques and professional affiliations, the definition can be extended to involve:

a process of creation, invention and definition separated from the means of production, involving an eventual synthesis of contributory and often conflicting factors into a concept of a three-dimensional form, and its material reality, capable of multiple reproduction by mechanical means.

(Hesketh 1980 p10)

The separation referred to by Heskett is significant in this context as it contrasts the designer craftsperson who physically produces the artefact, with the industrial designer who delegates mass manufacture to a production line. Archer cites a distinction with pottery and jewellery that is made by the hand of the designer, which he feels belongs within the sub-class of craft rather than into the general field of industrial design. (op cit p59)

Industrial design can therefore be considered as being distinct from the other design disciplines in that its practitioners define the appearance of 3D products intended for mass production. (Heskett 1980 p10, Lucie-Smith 1983 p7, Pulos 1986 p3, Van Doren 1954 p3) Caplan’s definition therefore appears relatively succinct when he states that “industrial design determines the form of objects
that are to be mass-produced by machines, rather than crafted by hand”. (1969 p1)

In defining product form, an industrial designer makes judgements about appearance. Black sees this as being the key role of the industrial designer when he states that “the speciality of the industrial designer is aesthetics: his technical training and experience are the essential armature for giving form to the utilitarian and symbolic need of mankind”. (1983 p214)

Whilst industrial designers must possess some knowledge of engineering and production methods to meet manufacturing parameters, Pipes sees the general pattern of professional practice as being “responsible for the styling, and then, handing over the design at the general arrangement stage.” (1990 p15) David Sharbaugh, President of the US consultancy Point to Point, regards the role of the industrial designer as being to produce product proposals that are “aesthetically pleasing, contemporary and sellable to consumers in today’s market”. (C3 March 1999, p23) The creative contribution made by his company is supported by the engineering staff of the client organisation, working together to ensure that the industrial design proposals are viable as commercial products. Whilst some industrial design consultants may not wish to be referred to as stylists, the definition of product form appears to be the most distinctive role within their professional remit.

References to industrial design involving the mechanical production of three-dimensional objects could also be applied to engineering design, but the role of providing aesthetic judgement sets the two professions apart. Indeed many manufactured products require no consideration towards their appearance, for example engineering components. Pugh clarifies this in his definition of industrial design when he states that “form, shape, colour, and aesthetics fit into the arts socket, and thus the whole can only logically be explained as (industrial) design - not engineering design”. (1996 p93) Rosenthal adds to this distinction by noting that “while the many technical specialists involved in product design and development consider one or more particular aspects of the product, the industrial designer is trained to focus on the product as a whole”. (1992 p98)
Whilst industrial designers may become involved with the engineering details of their designs to varying degrees, the acknowledged focus of professional activity is in terms of appearance and functionality. This was effectively illustrated in the 2000 Channel 4 television series “Designs on your ……….. “ in which the London based consultancy Seymour Powell undertook a range of industrial design commissions for UK manufacturers. During the design of a bra that included a polymer support structure, Seymour Powell originated and developed the design proposal, but the detailed engineering design was contracted to a third party, Pankhurst Design and Developments. (Design Week 27 October 2000 p5)

The definition of form is rarely the only activity to be undertaken by the industrial designer. Caplan acknowledges this when he states that:

Appearance might be subordinate to any or all of a number of other design factors: safety, convenience, production costs, ease of manufacture, wise choice of materials. Appearance might lead a customer to buy, but it could not in itself lead to a satisfied customer. A successful design had to integrate performance with appearance, while appealing to the consumer and making a profit for the manufacturer. (op cit p3)

This is reiterated by Loewy when he states that form must be integrated with the product requirements of “function, ease of operation, maintenance, cost of upkeep, storage, cost of manufacturing, packaging, shipping, display, safety, fail-safe operations, and clear, simple, operational instruction leaflets”. (1980 p18) Whilst ‘functionalist’ design in its literal sense refers to the fact that “use should determine the form of an object, and that if an object is made to function well, it will by definition be beautiful”, in popular usage, form and function (or functionality) have become separated. (Marcus 1995 p12) Hence Powell states that “industrial designers are concerned not only with the appearance of the product, but also with its function. They may work on the product at any level, from a quick re-styling of an existing item to a complete design from scratch,
but they will always be thinking of it as a functional object that is going to be used”. (1990 p14) Esslinger, founder of Frog Design, adds to this distinction when he comments that “no matter how elegant and functional a design, it will not win a place in our lives unless it can appeal at a deeper level, to our emotions” (Sweet 1999 p 9)

The definition for the activity of industrial design within this thesis is based around a responsibility to define product form and ensure effective use, with an awareness of the manufacturing processes that will be employed in its production. This is clearly articulated in the definition from the Industrial Designers Society of America (IDSA), who state that “industrial design is the profession that determines the form of a manufactured product, shaping it to fit the people who use it and the industrial processes that produce it.” (http://www.idsa.org/glance f.htm 12 May 2000)

**Industrial design practice**

With the distinct remit of defining product appearance and functionality within a commercial manufacturing environment, industrial designers are required to communicate their proposals effectively and economically. As much of their work focuses on the emotional issue of appearance, the communication of such qualities can be more difficult than those of engineering detail. Cunningham and Hughes of Black and Decker have identified three key challenges faced by industrial designers. (Co Design 07.08.09 1996 p86). These are defined as:

- Selling concept proposals to the organisation
- Ensuring that ideas will work when they appear “in the flesh”
- Communicating the proposed geometry to the design engineer
  
  *(ibid p86)*

The challenge of “selling the concept proposals” is seen as arising from the non-design background of the business managers within an organisation who
“may be unable to visualise new concepts from verbal or written statements about product characteristics” (ibid p86) Case study feedback from a product design commission involving the author, and managed by Mike Veveris (a lecturer in product design at the University of Derby), indicated that the “selling of concept proposals” requires a relatively high degree of realism if they are to be correctly interpreted by non-designers. During a consultancy exercise for a major high street retailer, problems arose when the client asked to see sketch work in advance of the formal concept presentation. Whilst this interim presentation had not been specified in the contract, in order to maintain a good working relationship with the client, the design team agreed to the request.

The commission involved the design of a visual theme that could be extended to a range of products, and the unscheduled presentation was made using the design work undertaken using simple sketches. Unfortunately, the client did not like the idea presented. Faced with a need to progress the project, the industrial designer worked over the weekend to produce two additional concepts and illustrated all three as marker renderings. On seeing these, the client decided that they did in fact like the design that was previously presented in a sketch format. The design had not changed, but the realism with which it was presented had, thereby enabling the client to comprehend the nature of the proposal. Whilst anecdotal, this incident proved to be an effective illustration of the need to select carefully the most appropriate media and techniques when “selling the concept proposals” as identified by Cunningham and Hughes (Co Design 07.08.09 1996 p86)

Archer has identified five key phases of activity that can be applied to all designing (and industrial design). These consist of: getting the brief (sometimes with designer input), examining the evidence (gathering/evaluating information and prioritising sub-problems), the creative leap (conceiving the basic idea or solution to a problem), the donkey work (the embodiment of the solution), the final steps (manufacture). (1963 pp7-14) Monohan and Powell’s notion of professional practice is similar to that of Archer, with the essential phases being the briefing, research, idea generation, development and presentation via
drawings, and detailing of the design in preparation for manufacture. (1987 p102)

The Department of Trade and Industry (DTI) in the United Kingdom has also defined the typical stages of an industrial design practice, embodying the key elements as cited by Monohan and Powell. (Managing Product Design 1992 pp3-8). The three distinct phases identified are: “getting to concepts”, “design development” and “implementation”.

‘Getting to concepts’ includes the process whereby the client produces and evolves a definitive design brief. Once the brief has been prepared, the industrial designer can commence the design work, starting with “concept design” which involves the translation of ideas into visual representations. (ibid p5) The presentation of the proposals to the client as renderings is called “first concepts”. (ibid p6)

Having had at least one concept approved by the client, design development can progress and “final concept(s)” produced, these being presented as renderings or foam models. In specifying the design solution, “layout drawings” are used to define the form, and a “diagramatic model” (in foam) may be used to assist with this. On the presentation of a foam diagrammatic model, design iteration may still be required, so “design refinement” may be undertaken. Design refinement includes modifications “that could significantly cut costs and will add to the product’s usability and desirability.” (ibid p6) “Model-making drawings” or general arrangement (GA) drawings embody the refined design “but omit most internal detail”. (ibid p7) “They would include draw angles, mould breaks, and assembly details. They would not include tolerances and other engineering details and cannot be used directly by a toolmaker” (ibid) Model-making drawings are necessary for the production of a “final appearance model” which “resembles the intended appearance of the product as closely as possible”, although the DTI stress that this is not a working prototype. (ibid) The design development phase concludes with a “design freeze”, after which any alterations to the product become impracticable.
The final phase of “implementation” is the point where the manufacturer takes over from the industrial designer as production and marketing of the product commences. It is “the point of hand-over from the design consultants to the in-house team”, although the industrial designer may be retained to maintain the integrity of their design intent. *(ibid p7)* However, it must be acknowledged that those industrial design consultancies with expertise in engineering design may undertake this phase on behalf of the client. Activities performed by engineering designers will include the preparation of “engineering drawings”, followed by “prototyping”, “testing”, “tooling”, a “pre-production run”, and finally “production”. *(ibid p7)*

In a survey of international industrial design consultancies, Pipes has identified three generic activities undertaken during professional practice. *(op cit p58)* These do not include the information gathering activities as identified by Powell *(op cit)*, Monahan et al *(op cit)*, and Archer *(op cit)*, but focus specifically on the production of design ideas. The phases identified by Pipes are concept generation, design development, and specification. *(op cit p58)* These phases are also specified by the IDSA who define the key professional activities as “creating and developing concepts and specifications”. *(Rowe 1997 pp1 – 12)*

Figure 4 illustrates the generic elements of industrial design practice based on the definitions of the IDSA *(ibid)*, Archer *(op cit p6)*, Monahan *(op cit p102)*, Pipes *(op cit p58)*, Powell *(op cit p11)* and the DTI *(op cit pp3 – 8).*

![Figure 4: Generic activities of industrial design practice](image-url)

Whilst it must be acknowledged that no two industrial design commissions are identical, when undertaking concept generation, design development and specification, the following outputs are generally required: visualisations (ranging from pen and pencil to realistic rendering); appearance models, and
the communication of design detail in preparation for manufacture (via GA drawings and an appearance model).

The cost and functionality of computer hardware and software that is capable of making a useful contribution to industrial design practice has evolved over the last two decades, and its use within professional practice may be on various levels. Gus Desbarats, the Managing Director of Alloy Product Design, does not believe that digital design techniques should simply mimic conventional manual techniques, eg pen and marker. (C3, March 1999 p26) For maximum financial and professional return he feels that new working practices must follow. He believes that:

> if designers simply buy computers to automate old processes they will end up losing money - they just become new artists with very expensive magic markers. To make any real progress new tools usually require new processes to realise their true potential, and therefore a new way of thinking and a new way of working have to be embraced. (ibid p26)

Desbarats has identified three distinct groups that he believes have emerged as a result of the introduction of digital design techniques. The first group are the “Lovable Luddites”, which he sees as “the old guard wedded to the romance of the old techniques”. (ibid p26) The second group are “New Artists” who are “designers for whom the replacement of the magic markers by a mouse has enabled them to create faster, more realistic visuals”. The final, and most significant group for Desbarats, are the “New Professionals” who “embrace the control, efficiency and responsibility of the master (CAD) model paradigm and hugely benefit themselves and their clients as a result”. (ibid p26)

Not surprisingly, Desbarats’ preference and philosophy for his own practice is based around the strategy of the New Professional, who integrates the capabilities of digital design techniques with new working practices that include the ability to share model data. He refers to this as the “Master Model
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Paradigm” whereby those involved in product development share and interact with digital product geometry that is centrally maintained (ibid p28). Such a strategy employs advanced computer modelling applications and high levels of concurrency to reduce product development time-scales and provides a key business advantage for a manufacturer.

As discussed in the introduction to this study, the reduction of product development lead times is now a common goal for manufacturing organisations, and strategies such as those espoused by Desbarats may contribute to this. Reducing NPD time scales and launching a product on the market ahead of a competitor gives an organisation the opportunity to achieve an earlier return on investment. A significant benefit from this is the fact that the financial return can be increased over the whole product life: “by being first to launch a new product, manufacturers usually manage to achieve a larger market share, not only in the first few months but often throughout production”. (Cooper, 1995 p213).

The principal objective of this thesis is to propose a methodological approach for the effective integration of rapid prototyping within industrial design practice. To identify when and how rapid prototyping might be employed it is necessary to identify the range of techniques employed throughout industrial design practice. These will be divided into “conventional” (non-digital) and digital industrial design techniques. The term “conventional” will be used to identify the industrial design methods and techniques used prior to the advent of computers, being defined as “following accepted custom”. (Collins Concise English Dictionary 1987 p244) For example, the use of manual techniques of design representation such as marker rendering and pencil/pen sketching, will be referred to as conventional techniques. Those employing computers will be referred to as “digital”.

The nature of conventional and digital industrial design techniques will now be discussed in the context of the three phases of concept generation, design development, and specification as defined by the IDSA (Rowe op cit pp1 – 12), Archer (op cit p6), Monahan (op cit p102), Pipes (op cit p58), Powell (op cit
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p11) and the DTI (*op cit* pp3 – 8). As physical models can be produced during all three phases, these will be discussed under the separate heading of physical models and prototypes to avoid repetition.

**Conventional techniques**

Drawing is a mode by which form can be generated, manipulated and presented using a two dimensional (2D) media. Its significance as an essential skill for the industrial designer is rarely understated: “a designer who cannot draw well is at a severe disadvantage” (Pipes 1990 p8). Powell reinforces this when he states that “an industrial designer who cannot draw is certainly less efficient and always less creative than one who can”, (1990 p6) and Jones regards drawing as “the one common action of designers of all kinds”. (1992 p4)

The key activities of the industrial designer are to originate and develop product concepts and present these with clarity and economy. Pipes succinctly sums up this remit when he identifies its three main functions for an industrial designer:

> It is a means of externalizing thoughts and sorting out multifaceted problems; it is a medium of persuasion that sells the idea to the clients and reassures them that their brief is being satisfied; it is a method for communicating complete and unambiguous information to those responsible for the product’s manufacture, assembly and marketing.

(*op cit* p6)

Having acknowledged the significance of drawing, the various levels of application will now be identified during the three phases of concept generation, design development, and specification.
“During the concept phase, many potential product ideas are collected and, through a screening process, those ideas most likely to yield products which will significantly contribute to the company’s goals and objectives are selected for more detailed consideration”. (Floyd et al p18) In producing these product ideas, the industrial designer must be capable of capturing and manipulating complex 3D form as efficiently as possible. (ibid) To this end, drawing represents a key skill for the industrial designer, being essential for the effective communication, interpretation, and facilitation of design ideas. (Garner 1999 p24).

When the design of a product commences, sketching is relatively spontaneous with limited detail. Pipes refers to this activity as “concept sketching”, and sees it as analogous to the designer “thinking aloud with a pencil” (op cit p80). He goes on to point out that often these somewhat ambiguous marks on the page can lead to further design ideas. (op cit p80) This evolution of the design via concept generation has been explored by Edmonds and Soufi who defined elements of this activity as “emergence”. (Design Studies 1996 Volume 17 Number 4 pp451 – 463) They found that the uncertainty and ambiguity that are characteristics of the sketch work undertaken during concept generation performs a key role in the production of further ideas. (ibid p451) The significance of this is summed up by Garner who states that:

The very lack of clarity inherent in freehand drawing may be an important catalyst in creative transformation of information. If designing – and particularly conceptual designing – is a process of problem formulation, conjecture, evaluation and improvement, then designers require a modelling tool which has the speed and flexibility to support this.


Media employed by the industrial designer vary according to personal preference, but Powell has identified pencils and fine-line pens as being the most flexible and durable media for concept generation. (op cit p13)
To ensure that concept generation takes account of the specific engineering details that must be integrated within the product, orthographic views of components may be used. This may involve an “underlay” technique in which translucent paper is placed over component drawings and used as a guide. Whilst undertaking the industrial design of a voice synthesiser, Rodd Industrial Design adopted such a strategy. They used 2D orthographic views of the electronic components as underlays onto which forms were sketched during concept generation. (C3 January 2000 p17) Despite the fact that Rodd Industrial Design employed an extensive range of digital design techniques, the significance of pens and paper was acknowledged: “there is still no better way to progress on a product than with face to face discussion over a piece of paper and coffee.” (ibid p17)

Kojima et al refer to the technique used for concept generation as thumbnail sketching. (1991 p7) Whilst essentially identical to Pipes’ notion of concept sketching, Kojima et al make the significant point (in terms of audience and drawing quality) that “it is not necessary for a third party to ever view them” (ibid p7). This does not imply that it is acceptable for the sketches to be intelligible to anyone other than the designer, as when working in teams it is essential that the sketches can be interpreted by a third party. The significance of this legibility is summed up by Powell when he states that “if you can communicate your idea well to others, then you are also better equipped to communicate them to yourself. “(op cit p6) An example of sketching undertaken by the author during concept generation for a lawnmower can be seen in Figure 5.
Powell goes on to identify a more sophisticated form of sketching called sketch rendering. *(op cit p70)* Rendering involves the application of colour, tone and detail to add realism, and the key to effective sketch rendering is the use of this technique with speed and spontaneity to create impressions of form without excessive detail. An example of sketch renderings produced by the author during the industrial design of a lawnmower can be seen in Figure 6.
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Figure 6: Sketch rendering undertaken during the industrial design of a lawnmower

As a relatively high degree of realism is required to enable a client to interpret a design proposal, a more controlled form of rendering is generally used for formal presentations as the client needs to understand the key features of the proposal. To this end, Pipes believes that these renderings should be “as realistic-looking as possible” (op cit p8), and Powell states that to avoid ambiguity the designer should “be striving for as photographic a likeness as can be achieved”. (op cit p73)

Media used in rendering have included a variety of colour media such as watercolour, drawing inks, gouache, acrylics, oil paint, pastel, pencil crayon and airbrush, but the marker pen has evolved as the preferred option. Reasons for its popularity are identified by Martin when he states that:

the single medium combines attributes of both drawing and painting media, since the marker tip can be use to produce fine lines or broad areas of colour; and the technique is rapid and encourages a bold approach which gives a powerful impression of
three-dimensional form. The technique is economical and the effect of a confidently drawn marker rendering is undeniably impressive.

(1989 p110)

An example of an elevational rendering of a lawnmower produced by the author using ink, marker and crayon can be seen in Figure 7.

![Lawnmower rendering](image)

**Figure 7: Mixed media rendering produced during the industrial design of a lawnmower**

To give an impression of 3D form and an accurate visualisation of the product, conventional renderings may be produced in perspective. Perspective recreates the effect in which objects further away from the eye appear smaller. Hence, for a product with a series of buttons along a surface, those closest to the viewer would appear larger than those further away. Martin refers to this as convergence, and comments that:

This is the basic principle of perspective which states that parallel lines receding from the viewer appear to converge. Objects positioned along these lines diminish in size with their distance
from the viewer. Perspective drawing involves plotting the degrees of convergence and diminishment in relation to the viewer’s location, the positioning of objects viewed, and the farthest point of sight, the point of convergence. *(ibid p57)*

Perspective effects can be mathematically modelled, and various systems have been devised to assist the designer in achieving this, although it is ultimately the designer’s responsibility to ensure that the perspective effect aids the communication of the product proposal. With this in mind, Martin acknowledges the need for interpretation when he states that “no system should be allowed to overrule the artist’s own sense of the visual correctness of a representation”. *(ibid p57)*

Less frequently used are the 3D effects of isometric and axonometric. With isometric, receding lines are all projected at 30 degrees from the horizontal, and all ellipses are 35 degrees. For axonometric projection an orthographic plan view is projected parallel to the picture. As the viewer is accustomed to seeing the world in perspective (which is absent from both isometric and axonometric projections), images produced using these techniques appear distorted. Martin notes that “this form of representation appears incorrect three-dimensionally - any horizontal plane appears to rise - because there is no allowance for the principle of convergence as used in perspective systems”. *(ibid p64)* They may however be useful in the illustration technical information.

**Design development**

Having presented the client with design proposals at the conclusion of concept generation, “after further analysis, one or more products that are consistent with the company’s available resources will be selected for development”. *(Floyd et al p19)*. Design development involves the assimilation of client feedback and the resolution of product details, particularly in terms of design for manufacture.

The resolution of product detail during design development involves the use of media and techniques identical to those of concept generation, albeit with
greater control e.g. elevational views. Basic engineering drawings may also start to be employed.

At the conclusion of design development it is necessary for the client to approve the proposal. The most effective means of achieving this is through the production of renderings. Having presented these proposal renderings, should further modifications be required, additional design development can be undertaken until the client finally approves the proposal.

**Specification**

The media employed in the specification of product form using conventional techniques are the general arrangement (GA) drawing and appearance model. Pipes defines the role of the GA as to:

> communicate a designer’s concepts to those responsible for manufacturing the components of the product and assembling them with pre-sourced proprietary items to create the finished object. As such the drawings must be complete and unambiguous.
> *(op cit p124)*

The most common construction method for a GA is orthographic projection which:

> describes three-dimensional form by a series of diagrammatic views in which the form is ‘flattened out’. The essential elements are plan view, front elevation, and end elevation. This is the minimum needed to explain the overall structure and volume unambiguously.
> *(Martin 1989 p63)*

In preparing a GA, Powell notes the essential requirements of fixing dimensions, resolving ergonomic issues and finalising production methods:
this is the real meat of the design process where the designer juggles with all the conflicting factors to perfect the final solution. The decisions made during this phase need to be discussed with the client before a finished model can be commissioned. (op cit p145)

Powell makes extensive use of relatively simple GA drawings during concept generation and design development by converting them into renderings. (op cit p145) This can be used to enhance realism and is particularly useful when communicating design details to personnel who are not so familiar with conventional line drawn GAs.

An example of a GA produced by the author during the industrial design of a lawnmower can be seen in Figure 8.

![Figure 8: GA produced during the industrial design of a lawnmower](image)

Considerable detail can be present on a GA, but this can be greatly reduced if the drawing is supported by the production of an appearance model. The appearance model then takes over in the specification of product form.
Provided there are no design changes, the GA drawings used to produce the appearance model may be used by engineering designers to prepare the fully specified engineering drawing required for production tooling. In some cases this may be undertaken by the industrial designer, although the engineering ability and effort required may be considerable. The level of detail required is identified by Pipes:

The GA gives the overall disposition of the product, the arrangement of its component parts and the way they are to be put together. It gives the overall dimensions and usually includes a parts list that refers the reader to the whole hierarchy of the more detailed drawings: sub-assembly and discrete assemblies, and the individual detail and sub-detail drawings. These show more manageable sections of the product, with every essential dimension and allowable tolerance documented. These drawings also include information detailing the material the part is to be made from, its surface finish and treatment (ground, anodized, painted, and so on). The tolerance and finish of a part have a significant effect on the type and precision of tools that can be used and hence the cost of manufacture, so they must be chosen and documented with great care.

(op cit p124)

Whilst there will of course be exceptions, for those industrial design consultancies without the necessary engineering design expertise, the process of “implementation” is undertaken by the manufacturer. (Managing Product Design Projects 1992 p7)

Physical models and prototypes
The translation of a design proposal from 2D to 3D is regarded by Lucci et al as being a critical phase during industrial design activity as “the construction of three dimensional models widens the range of design control and presents...
itself as a rich design tool”. (op cit pvii) As such the role of a physical model may be two-fold: to assist in the development and specification of form.

Whilst a variety of media and techniques can assist in the 2D representation of product proposals, it is only when the designer moves from 2D to 3D that the form can be fully evaluated. Powell emphasises the importance of the 3D model when he states that:

> it is through the model, of course, that an idea reaches three dimension for the first time, and both designer and client can truly assess the design. A rendering can never be a substitute for a model and it is a fool who goes straight into tooling without investing in a model (many have done it and learnt the hard way!). (op cit p11)

At its most fundamental, a model has been defined as "a way of making a trial that minimises the penalties for error". (Judson 1980 p112) For a product that may require significant capital investment, design and production errors must be corrected at the earliest possible opportunity. The consequence of a flawed design can be a product recall, or at its most extreme the injury or even death of a user. Given that a manufacturer wishes to generate profit, a model therefore has a fundamental economic function in ensuring that whatever is manufactured will not result in a financial loss.

During the early stages of NPD it can be beneficial to translate ideas into a 3D form. Under such circumstances it is not viable to model all aspects of a product, but ensure that it "contains only those elements of reality that are needed to solve the problem". (Judson 1990 p112) This notion of the model as a focused simplification of a system is reiterated by Brown when he states that, "no model is ever a perfect representation of the real thing. If it were it would be a replica" (1983 p64).

Lucci et al make extensive use of 3D physical model techniques during professional practice. (1989 pp38 – 45) In contrast to the views of Pipes (op cit)
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and Powell (op cit), they have found their techniques to make a more significant contribution than drawing:

We believe that the model is a medium for the designer, not the goal. The energy required for building models should, therefore, be minimal in order to encourage the use of this powerful agent in the design process. We teach this with a minimum of equipment, a minimum of material, and a minimum of time. The model becomes then a real tool that can be used, altered, and ultimately discarded without concern for the time and energy spent in its construction. Nonetheless, the results can be so good that often it is suitable as a presentation model. (ibid p45)

Few publications make reference to the models produced by industrial designers, but Emori has identified the 'qualitative model' that has the external appearance of a product but “lacks proper functioning”. (ibid pp3 - 5) Qualitative models may be referred to by industrial designers as ‘block models as they have historically been produced from solid materials as internal components were not required. Jellutong is a popular hardwood for use in the production of block models because of its ease of working and ability to achieve a relatively high level of surface definition. A more descriptive phrase used by the DTI (1992 p7) and Baxter (1992 p287) is “appearance model”, as this indicates a focus on the embodiment of appearance but not function. The term appearance model will be used to identify the non-working physical representations of industrial design proposals that fully define exterior form and finish.

As the term 'model' may be used to represent many forms of 3D artefact, it may be not be considered necessary to distinguish this from the notion of a 'prototype'. From the definitions of models already identified by Brown (op cit p64), Emori (op cit pp4 – 5), David et al (op cit p1), it can be assumed that a prototype is in fact a form of model. However, when discussing professional industrial design practice, it is helpful if a distinction is made between appearance models and prototypes. This is recognised by Luzadder who
Industrial design defines a prototype as “a full-size working model of a physical system” (1975 p29) and Mayall notes that “it is a wise designer who tries to get his prototype version as close to the production model as possible.” (1997 p117) Baxter acknowledges the “problems with words” when identifying a distinction between models and prototypes, but goes on to state the need for a distinction within professional practice. (op cit p286)

The term prototype will therefore be used to identify a full-size, working representation of a design proposal. In addition, to distinguish between the prototype that embodies functionality only from one that includes both functionality and appearance, the term “appearance prototype” will also be used. Appearance prototype will define the physical representation of a design proposal that integrates functionality (i.e. it works) with the form of the production item (as with an appearance model). A prototype will embody functionality only.

To further illustrate the distinctions between these three forms of physical representation and place them in the context of professional practice, they will be illustrated via case study material. In addition, a fourth 3D representation, the “sketch model”, will be introduced to complete the definitions for the key physical outcomes from industrial design practice.

3D sketch models are produced during the concept generation and design development phase of the design process, their function being to assist with the designer’s decision making, not necessarily the client’s. Lucci et al see sketch models as performing a similar modelling role to 2D sketching, hence their name. (R Lucci et al1998 pix)

Sketch models can be produced from the most basic of 2D information, and sometimes none at all. A consequence of the speed with which it is possible to manipulate the media is that the definition of form may take place by actually working the media. A wide range of materials can be used, but card and Styrofoam continue to be popular as they can be worked relatively quickly whilst achieving a satisfactory level of surface definition. An example of a
Dyson, the UK vacuum cleaner manufacturer, continues to make extensive use of sketch models using cardboard and foam “during the very early stages of the product design process” (Mills C3 February 2000 p14), and Rodd Industrial Design use foam in the assessment of form and ergonomics. (C3 January 2000 p17) Whilst the designers at Rodd Industrial Design may have access to the 3D computer geometry of a component, it is still considered essential “to have a real 3D model as early as possible”. (ibid p17) They see a potential pitfall in using 3D CAD too early as this can encourage a premature focus on design detail instead of the total concept.

Despite the extensive use of digital design techniques, industrial designers continue to maintain their enthusiasm for sketch models. Bill Evans, president of San Francisco industrial design consultancy Bridge Design, states that:
it is worth remembering that while it is easy to be romanced by all of this computer-aided design and virtual prototyping, the tried and tested foam model, generated in an afternoon from simple 2D drawings, will often beat out its hi-tech sister in both schedule and cost.

(ID Magazine September/October1997 p85)

Prototypes are seen by Kojima et al as having an experimental function which may focus on performance with the exclusion of appearance. (op cit p38) This is reiterated by Knoblaugh who refers to prototypes as always being full-size, but bearing little resemblance to the finished product. (op cit p15) An example of the prototype drive system for a lawnmower produced by the author can be seen in Figure 10.

Figure 10: Prototype drive system produced during the industrial design of a lawnmower

Appearance models enable senior management to approve a proposal prior to production. In slightly broken English, Kojima et al state that the appearance model “should provide the exact image of the object in order to achieve its necessary consensus”. (op cit p83) Whilst appearance models are undoubtedly powerful tools for the communication of design intent, Powell makes reference to the fact that that they are expensive (being hand-made) and can take considerable time to produce. (op cit p11) Despite this, whilst referring to industrial design, Kochan stresses that for design approval, “aesthetic design requires a physical object in every case”. (1993 p22)
Pipes regards the production of appearance models as being part of the specification phase of industrial design activity. (op cit p58) It is the activity whereby the form and details defined by the industrial designer can be unambiguously communicated to a third party. An example of an appearance model used to define the exterior form of a lawnmower can be seen in Figure 11.

Despite Pipes’ reference to the role of appearance models during the specification phase of industrial design practice, they can also play a role in the generation of product form as discussed by Lucci et al. (op cit pvii) This can occur when producing appearance models of complex forms that have only been loosely defined via proposal renderings and GAs. In such cases, the industrial designer defines elements of the form by actually manipulating the model-making material, and when satisfied with the outcome the surface is painted to form part of the specification for the product. Owen believes that this manipulation of form through direct manual interaction is invaluable when
working with complex surfaces. (Law 2001 p24) Contrasting the use of clay with 3D CAD and CAID software, Owen comments that “nothing can replace the learning experience of getting to grips with the real thing”. (ibid)

This mode of working was employed by the author during the industrial design of a chain hoist for a major UK manufacturer. The project involved the complete redesign of an existing product, combining a revised engineering solution with more efficient and durable production processes for the exterior mouldings. Having had the basic layout of the product approved by the client at the conclusion of design development (via renderings), the production of an appearance model was authorised. During production of the curved chain box, the sweep of the arcs were considered excessive, and the form was amended using techniques more closely associated with sculpture than model making.

The form was defined through the direct interaction with material. The outcome was paint finished and presented to the client, and on its approval became the revised specification for this component. An appearance model of the chain hoist can be seen in Figure 12, with the chain box identified within the white circle.
In contrast with appearance models that communicate form only, appearance prototypes embody both form and functionality. (Knoblaugh 1958 p15, Kojima et al. 1991 p38) Knoblaugh believes that appearance prototypes should be exact copies of the production item as “it is the product, made by hand, and is the final check before tooling is begun”. (op cit p15) If an appearance prototype does not have an exact resemblance with the production item, it can more accurately described as a prototype as identified by Knoblaugh. (op cit p5)

Kochan notes that appearance prototypes constructed using conventional workshop techniques can take considerable time and effort to produce due to the complexity of fabricating high definition exterior surfaces with internal cavities. (op cit p22) An example of such cavities on the underside of an appearance prototype produced for a lawnmower design lawnmower can be seen in Figure 13.
The requirement to make the appearance prototype an exact visual representation of the production item can cause problems as the bonding of material rarely has the strength of production processes such as injection moulding. It can therefore be necessary to supplement adhesives with mechanical joints that must be disguised e.g. by countersinking and then filling screw heads. In the fabrication of the appearance prototype for the lawnmower illustrated in Figure 13, adhesives were supplemented by mechanical fixings. Whilst labour intensive, these methods can prove extremely effective in maintaining structural integrity. The appearance prototype lawnmower can be seen undergoing performance testing in Figure 14.

Figure 14: Appearance prototype used for performance testing
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Conventional industrial design methodological approach

Having identified the conventional media and techniques employed during concept generation, design development, and specification, it is apparent that there may be overlap between modelling media and phases e.g. 2D sketching may be used during concept generation and design development. By integrating the three generic elements of industrial design practice as defined by the IDSA (Rowe 1997 pp1 – 12), Archer (op cit p6), Monahan (op cit p102), Pipes (op cit p58), Powell (op cit p11) and the DTI (op cit pp3 – 8) with the conventional industrial design techniques employed a conventional industrial design methodological approach can be defined. This involves the integration of modelling media and technique with design activity (see figure 15).

![Figure 15: Conventional industrial design methodological approach](image)

This methodological approach commences with the concept generation phase, involving the production of design ideas in pen, pencil, marker, and other mixed media. Following the selection of one or more concepts, mixed media are used to produce proposal renderings that enable the design to be evaluated by the client. On the selection of one or more concepts, design development facilitates the addition of further detail and/or modifications to the concepts required by the client. On completion of design development, the modified design can be presented as proposal renderings, usually with greater definition than those produced during concept generation. A feedback loop is included in the design development phase as it is possible that this activity may be undertaken more than once.
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On approval of the design proposal produced during design development, the specification of the exterior form must be undertaken. Whilst this may be achieved using GA drawings, it is not uncommon for highly complex forms to be specified via an appearance model. In practice, it tends to be a combination of both, using GA drawings to specify the general form before moving into model making. Areas of complex curvature that would be difficult or time consuming to define through drawings could then be specified via the appearance model. As a non-working physical representation of the product, the appearance model must be approved by senior management prior to the investment in production tooling or progression to a more expensive appearance prototype.

The engineering expertise required to produce an appearance prototype may be outside the professional remit and capabilities of the industrial designer, although their production for relatively simple products such as the children’s cutlery described in Chapter 6 may be viable. Whilst appearance models are acknowledged as being a distinctive output from industrial design practice, the production of appearance prototypes is less well defined, but the potential makes it necessary to include them in the conventional industrial design methodological approach.

**Digital techniques**

The commercial use of Computer Aided Design (CAD) emerged in the early 1980s, proving to be faster and more efficient than traditional paper-based methods of engineering drawing. (Dean in Engineering Designer, March 1999 p3) 2D CAD remains a powerful design tool, but Dean sees its inability to clearly “see” what is being designed as a fundamental limitation. (ibid p3) He states that “where 2D CAD offers a series of snapshots of a part made of lines, circles and arcs, a 3D model represents the whole part in a singular form, removing any ambiguities”. (ibid)
Dyson, moved from 2D to 3D CAD in 1996 for two reasons. Firstly, 3D CAD was seen as a more effective means of representing highly complex component geometry when compared with 2D techniques: “it could take anything up to three drawing sheets in order to establish what the curve was supposed to be on a single part”. (C3 February 2000 p14) Secondly, it enabled Dyson to adopt a master model approach to product design, whereby “downstream applications and processes, such as documentation production, rapid prototyping and manufacturing etc. are driven from the 3D master product model held in the CAD/CAM system database.” (Mills in C3 February 2000 p14)

The first 3D CAD applications were wire-frame modellers, defining models by generating boundaries of edges and vertices. They did not show surfaces and were therefore limited in terms of realism. This was resolved when advances in hardware and software led to the advent of surface and solid modelling packages.

Surface modellers were developed to define the complex freeform shapes required in the aerospace and automotive industries. They produce surfaces of zero thickness, differing from solid modellers in that they have no topological data connecting the surfaces. Care must therefore be taken when using 3D surface geometry for rapid prototyping as unclosed surfaces (e.g. Mobius strips) render the model impossible to build without corrective operations.

Surface modellers are particularly suited to the definition of complex compound curves, making them ideal for use when producing “aesthetic shapes”. (Jacobs 1993 p78). In a research paper exploring the transfer of CAD data for rapid prototyping, Jamieson identifies the difficulties experienced in generating the required form when he comments that “many solid modellers do not offer the flexibility of surface modellers.” (in Dickens 1994) As such, surface modellers have been specifically developed for industrial design applications, and when integrated with powerful rendering capabilities, are referred to as computer aided industrial design (CAID) as opposed to CAD.
Whilst CAD could be considered a generic term to embody all digital modelling systems, CAID is now a recognised term to describe dedicated industrial design software that can effectively generate complex organic forms and render these with a high degree of realism (e.g. Alias Studio). Potter succinctly sums up the key differences between systems when she states that “CAID is a tool for creative people who need freedom to experiment with shape and form”, whilst CAD “implements the rigor and discipline of engineering”. (Potter 2000 pp21 – 28) This definition is expanded by Potter when she comments that CAID is:

> designed to facilitate the creative process by letting users push and pull shapes and immediately visualize the effect. Engineers don’t push or pull their CAD models. They position geometry precisely, often specifying exactly where something should go by typing in a number. In fact the underlying philosophy of CAD is precise and numeric, involving variables such as clearances, tolerances, wall thicknesses, draft angles – about as far as you can get from ‘free form’. (ibid)

Compatibility of CAD and CAID remains an important feature for the effective collaboration between industrial designer and design engineer. Potter maintains that this collaboration is essential as “it allows the industrial designer’s vision to continue through to product engineering and manufacturing, ensuring that what the designer intends can be built”. (ibid) She does however point out that the sharing of CAD and CAID files between systems is notoriously difficult. (ibid)

At present, Alias Studio is recognised as the highest level of CAID software, with other well established packages including Pro-Designer, Rhino, ICEM Surf, Imageware and DeskArtes. Prior to the advent of the Windows NT Workstation, all high-level CAID software required a UNIX operating system, but there is now a move by the leading CAID software houses to move to the lower cost platforms. (Pasternack 1999 pp34 – 36)
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Accepting the limitations and advantages of solid modelling and surface modelling, the integration of both systems may be required during product development. Bob Buxton, of industrial design consultancy Buxton Wall McPeak, acknowledges this when he comments that “such (solid modelling) packages are fine for designing square boxes with radiused corners, but to achieve anything more subtle, it is necessary to seamlessly integrate surface modelling with solid modelling.” Rapid News Volume 4 Number 3 p34) By integrating a surface (Alias Wavefront Design Studio) and solid modeller (SDRC I-DEAS) the Manchester-based industrial design consultancy Geo were able to “harness the best qualities from both sets of software - Design Studio works well for concept modelling, whilst I-DEAS is excellent for more detailed modelling.” (MCAD April 2000 p19)

Optima Wheels, the US manufacturer of alloy wheels, integrated both surface and solid modellers during NPD using SurfaceWorks and SolidWorks respectively. Whilst SolidWorks was used to fully specify the components for production, as a solid modelling package it was not ideally suited to the generation of the complex forms required by the industrial designer. As both packages were compatible, it was possible to import the surfaces into the solid modeller for translation. “SurfaceWorks allows us to do freeform design, which is very important for wheel designs. Most of the shapes can eventually be modelled in SolidWorks; however, we cannot obtain the complex surfaces that are required.” (C3 March 1999, p28)

One of the leading centres of industrial design is Philips Design Studio. Employing 400 designers in 25 studios around the world, Philips Design Studio produce industrial design solutions for the Philips Electronics Group based in the Netherlands. The main digital design tool employed is Alias Studio software. Its uptake by Philips was a major endorsement of the surface modelling software, and is described as “the conceptualization tool of choice across all the Philips Design offices”. (C3 January 2000 p20) Whilst the industrial designers at Philips use Alias, engineering designers employ Pro Engineer for technical development, with each professional group retaining
CAD vendors appear to be acknowledging the limitations of solid modellers and not attempting to compete directly with CAID systems. Rowell cites a product manager for the Unigraphics CAD system who indicated that the company would be providing some enhanced design functionality but not attempting to go “head to head” (with CAID). (Rowell 1997 p1) However, Paternack describes an attempt to gain market share from the CAID software suppliers when he states that “CAD vendors have added styling capabilities to their packages, making the use of these tools a serious option for consumer product designers” (Pasternack 1999 pp34 – 36)

**Concept generation**

Spontaneity and speed have been identified as key requirements when undertaking concept generation (Pipes 1990 p80). Conventional sketching facilitates this, and whilst it is possible to emulate such techniques using 2D digital drawing and image manipulation software such as Illustrator and Photoshop, they still require drawing ability. However, the use of such software does enable unwanted marks to be completely erased (by editing), and the image to be immediately converted to a digital format such as JPEG. Commenting on such techniques, consultancy director Paul Pankhurst points out that “like most other designers, the concept usually starts with a series of sketches and the usual design intent capture tools are Corel Draw or Adobe Illustrator. These will then be imported into Adobe Photoshop in order to create photo-realistic images of the concept that the client can examine. Once the client gives approval, the real 3D work can begin in earnest.” (C3 November 1998, p28)

A similar strategy is employed by Rodd Industrial Design who undertake initial concept generation using pens and paper, before moving into digital media such as Adobe Illustrator and Photoshop (C3 January 2000 p17). This approach involves the scanning of the pen line-work and its import into a suitable drawing or image manipulation package.
This use of 2D digital drawing is no different to mixed media technique as geometry is not defined and the basic hand-eye co-ordination skills are virtually identical. It therefore appears that whilst concept generation can be undertaken with 2D digital drawing techniques, their uptake remains a matter of preference. This is summed up by Warburton who concluded that during concept generation “no reasons appear to be evident to support the use of digital technologies for its own sake”. (Co Design, 04.05.06 1996 p22)

By its very nature, concept generation requires minimal effort to give an impression of 3D design intent. This is noted by Pipes when he states that “conventional CAD at an early stage can stifle creativity by its insistence that the designer provides the system with exact dimensional and geometric information right from the start”. (op cit p88) A hybrid research-based product that crosses the boundaries between sketching and 3D CAD modelling was developed by Tovey. (Design Journal 1999 Volume 2 Issue 2 pp34 - 41) The system was intended for automotive stylists and used techniques defined by the author as “sketch mapping”, where the speed and spontaneity of sketching was integrated with 3D CAD. The process involved the texture mapping of the designer’s orthographic sketch information onto a wire-frame CAD 3D surface model. There was then the possibility to rotate the sketch-mapped image in real-time. The CAD model could be refined by printing out a perspective view and using this as an underlay to refine the sketch detail and finally texture map the sketch back onto the CAD model. The refined sketch was then used to further manipulate the CAD surfaces to achieve a closer resemblance of the design intent.

Whilst Tovey’s research represents a strategy for the progression from sketch to virtual 3D model, it appears relatively crude, lacking the spontaneity and control needed when defining sculptural forms. A more viable strategy was presented by Alias at the Solid Modelling Conference in Birmingham on 8 March 2000. The demonstration showed how the Alias software could be used to produce a loose conceptual product idea through 2D digital sketching, followed by the digital tracing of the form using the more controlled CAID
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functionality as elevational information followed by its conversion into a 3D surface model. In many respects the Alias software was performing similar operations to that of the application developed by Tovey but in a more intuitive and seamless package.

Sketching, whether based on conventional or digital techniques, remains an essential part of the initial stages of concept generation. However, having established design direction, the opportunity exists to begin to employ 3D computer modelling via CAID. For the competent operator, the translation of sketch drawings into surface geometry is relatively straightforward, and facilitates the specification of component form with the capability to share the digital data. Whilst some industrial designers might argue that it is not appropriate to introduce CAID during concept generation, Warburton found the merits of employing CAID techniques during this phase of design activity as equivalent to those of more controlled conventional techniques. (Co Design, 04.05.06 1996 p24)

Black and Decker have recognised the difficulties experienced by some industrial designers in modelling complex 3D forms in CAD using solid modelling software. (ibid) They also identified a need to move towards the early representation of 3D geometry as a computer model to assist with the process of specification. To resolve this, Black and Decker started to translate the industrial designers sketches into CAD models relatively early in the design process. Significantly, the industrial designer was supported by a CAD operator in this task due to the complexity of the geometry and the fact that the solid modelling system used was not ideally suited to the generation of freeform curvature. Once created, the benefits of 3D model share became accessible, enabling the design team (design engineer, manufacturing engineer, tooling engineer, toolmaker, packaging engineer, industrial designer) to have controlled access to the 3D geometry. (ibid)

For Black and Decker, the benefits of the early integration of CAD have been:
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- “significantly reduced time in most phases of product development, including tooling and manufacture,

- clear and accurate interpretation of the design intent,

- first-time-right accuracy via on-screen visualisation and the high-quality prototyping made possible by the computer model.”

(ibid p88)

When faced with a presentation at the end of concept generation, it is important for the client to be satisfied (if not impressed) with the work undertaken. Indeed, for consultants, the progression to the next stage of the project is dependent on client approval of a concept, with commercial contracts usually allowing either party to withdraw at the end of a particular phase. The impetus to introduce CAID is therefore strong, and is summed up by Desbarats when he states that “the classic role of the visual is to sell, and without doubt the explosion of visualisation software has enabled design studios to turn dreams into stunning reality. It’s a very powerful tool for influencing opinion.” (C3 March 1999 p26).

Whilst dependent on the working practices of a particular organisation, the practice of using 3D geometry to produce digital renderings enables the same geometry to be used in the manufacture of production components. Desbarats sees this as “like linking your mouse direct to a milling machine. Here’s where designers frown and engineers - who have been known to say they’d rather die than take responsibility for data supplied by designers - faint or throw up their hands in horror”. (C3, March 1999, p26) However, the sharing of digital data does foster a more cohesive translation of design intent, avoiding the problems identified by Sharbaugh:

I’ve seen a change in the way new products are designed. Traditionally, concepts were born as subjective hand sketches and subjected to a lot of interpretation. And, the quality of the interpretation often drove the quality of the design. Whether done
by the designer when converting sketches into 2D data, or by engineers or manufacturing in converting the 2D data into a 3D product, interpretation often introduced undesirable changes.

(C3 March 1999 p23)

The application of CAID during concept generation therefore has the ability to produce photo-realistic renderings and ensure that forms are geometrically viable. However, its use depends on the nature of the project and the capabilities of individuals. In terms of digital design techniques, some industrial designers may prefer to employ 2D digital drawing techniques, and others CAID.

**Design development**

When CAID is used towards the end of concept generation, the 3D component geometry is available for use during design development. If the design development requires minor modifications such as colour changes or revised badging, this could be undertaken almost immediately. The undertaking of such changes when using conventional techniques necessitate the drawing being completely re-rendered. A more typical requirement is the modification of form and detail following client feedback. Again, being able to utilise geometry that has already been produced during concept generation can streamline this process significantly.

With a fully resolved industrial design solution, the CAID system can be used to render the proposal with photo-realism, put the product in some form of environmental context, and if appropriate (and within the capabilities of the system) provide an animated sequence.

**Specification**

CAID models used to produce renderings also mathematically specify the surfaces of a product, enabling the precise communication of design intent as 3D geometry. This geometry can be used to specify product form in several ways.
Elevational views can be printed to give an outcome identical to that of the manual GA drawing. An advantage of this approach is that minimal effort is required to produce the GA drawings. This contrasts with the considerable time invested in the preparation of GA’s produced via conventional techniques (including 2D CAD). However, under Desbarats “master model paradigm”, no GA is required as the surface data is passed directly to the CAD system of an engineering designer. (C3, March 1999, p26)

The application of GA drawings produced via CAID enables the production of appearance models using conventional workshop based techniques. This strategy was employed during the production of the appearance model for the chain hoist seen in Figure 12. The direct extraction of GA drawings from the CAID geometry has the capacity to save considerable time and ensure their exact compliance with the proposal renderings.

“Communicating geometry” is seen by Cunningham and Hughes as the responsibility of the design engineer, and requires the precise CAD definition of all component parts for the product. Originally the role of the engineering drawing, “the complex form of modern power tool designs has led to a digital model in the computer becoming the authoritative definition of the design.” (Co Design 04.05.06 1996 p87) In terms of product form, the key challenge is seen as ensuring that the CAD model reflects the intentions of the industrial designer.

As an industrial design consultancy established in the 1960’s, London Associates have witnessed the integration of 3D modelling into their practice. Whilst they still use conventional sketching, 3D CAID has enabled the consultancy to “produce better, fully resolved products quicker and it can also create forms, even organic ones, in the knowledge that they can be made. In short, you get products faster and more accurate.” (from O’Halloran in C3 February 2000 p27)

Whilst CAD and CAID offer a potential route for the digital specification of product form, it is not the only option. It is feasible to capture design intent by
laser scanning a physical model that was produced using conventional model making techniques. The resulting data can then either be refined within a CAD or CAID system, or used directly by a rapid prototyping system.

Hamilton identifies the benefits of modifying a form by hand to achieve the desired result, and then 3D scanning the model to produce digital geometry. (Dickens 1994 p300) He alludes to instances where this may be more effective than updating the CAD model, or is the preferred route due to the nature of the product e.g. with specific ergonomic or acoustic properties. (ibid p301) The contribution of this strategy is also acknowledged by Lazar et al when they state that “often enough, a new product is first created as a physical part either in a designer’s studio or by tests, optimising its streamlined shape. (Dickens 1995 p106)

During a review of 3D scanning technologies, Hamilton has identified contact and non-contact systems. (ibid p301) Whilst being accurate, contact probes are slow and require master models to be produced in relatively hard materials. A key shortcoming of contact systems is that the master model must be constructed from a material that can withstand the probing force applied. Lazar et al also note the complexity of compensating for the touch probe radius using sophisticated analysis software. (ibid p302)

Non-contact measuring systems that utilise a scanning laser do not have the problems associated with the contact method’s touch probe radius. The process is also faster and capable of scanning the form of soft materials. Drawbacks have been identified as inferior accuracy to mechanical touch techniques, and difficulties experienced with reflective materials. (Lazar et al in Dickens 1995 p107)

In summing-up their research findings, Lazar et al make a significant comment with respect to the potential of utilising 3D scanning during the industrial design of products. They state that “in general, experienced CAD operators obtain surfaces of better quality in shorter time with established methods.” (op cit p110) However, this does not reflect the fact that industrial designers may wish
to be more actively involved in the definition of form by actively working a material by hand which would then need to be translated into a digital format.

When a product has been fully specified as 3D CAD or CAID geometry, Pankhurst summarises the benefits for engineering designers when he states that, “once products have been defined it is possible to review tolerance build-up of the entire assembly. Using predictive analysis tools contained in these engineering packages, it is possible to simulate failure modes, examine performance under load, predict component weight, moulding characteristics and so on.” (C3 November 1998 p28) He sees this seamless transition from the visual to the technical as being an essential driver in the quest for a “design right first time process” (ibid p28)

Physical models and prototypes
Despite the capability to produce photo-realistic renderings and animation, there is still a need to verify the appearance of a product with a physical model. In achieving this, CAD and CAID geometry can be used to produce components using computer numerically controlled (CNC) machining and rapid prototyping: “I can easily download the geometry from my CAD system and make stereolithography or CNC parts. The combined technologies give designers a new sense of confidence that new designs will match their vision and meet or exceed their clients’ expectations.” (C3 March 1999 p24)

CNC machining is a subtractive process, using CAID or CAD surfaces to control a milling machine and produce components. Its efficiency depends on the complexity of the part being produced, usually requiring cutters to be changed and the component to be re-orientated to gain access to all surfaces. Rapid prototyping requires no operator intervention once the process has started. CNC machining and rapid prototyping will be discussed further in Chapter 2.

Digital industrial design methodological approach
The constant evolution of digital design techniques (both 2D and 3D) and their integration with conventional techniques makes it impossible to identify a
The integration of digital design techniques will therefore be discussed during the identification of the draft CAID/RP methodological approach in Chapter 3.

Summary

- The distinctive remit of the industrial designer is the definition of product form.
- The three generic phases of industrial design practice are concept generation, design development, and specification.
- Drawing represents a key skill for an industrial designer.
- Appearance models are an essential output from industrial design practice.
- Appearance models embody exterior form only. Appearance prototypes embody both form and functionality.
- 3D CAD or CAID modelling is not appropriate during the early stages of concept generation.
- Surface modelling software is more suited to the form-based activities of industrial design than solid modelling.
CHAPTER TWO: Rapid prototyping

Definition of rapid prototyping

Rapid prototyping is a relatively recent technological development, with the publication of research in this area starting in 1982, and the first commercial system being launched in 1989. (Kochan 1993 pv) Rapid prototyping has been defined as “those activities and processes which significantly reduce the time between concept and the production of high quality prototype parts or tools”. (Bennet 1995 Foreword) What this definition fails to identify is the pre-requisite of a 3D computer model that fully defines the form to be produced. This requirement is noted by Wood who states that rapid prototyping “is the creation of three dimensional objects directly from CAD files, without human intervention”. (1993 p1) The integration of these definitions and the nature of the build process enables rapid prototyping to be described as the use of 3D computer geometry in the production of components using a layer-based build process in condensed time-scales.

Kai and Fai have identified the generic operating principles of rapid prototyping systems, categorising them as: liquid-based e.g. stereolithography (SLA) and solid ground curing (SGC); solid-based e.g. laminated object manufacture (LOM) and fused deposition modelling (FDM); powder-based e.g. selective laser sintering (SLS). (1997 p11) Jacobs’ more descriptive system identifies layer-additive laser point by point fabrication (SLA and SLS); layer-additive
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non-laser point by point fabrication (FDM); layer-subtractive laser fabrication (LOM); layer-additive non-laser fabrication (SGC). (1996 p231)

Kai and Fai regard rapid prototyping as quite different to the majority of systems used to produce physical components as it employs “additive” techniques to manipulate a material and combine it to produce the required form. This contrasts with subtractive techniques where material is removed to produce the required object (e.g. machining), and formative processes where mechanical forces or restrictive forms are used (e.g. forging, injection moulding). (op cit p17)

The speed at which complex physical objects can be built from 3D computer geometry is a key issue, as computer numerical control (CNC) machining can fit within some definitions of rapid prototyping. Kochan identifies the key differences between the two systems as being that rapid prototyping is “highly automated, and unattended operation is normal. Additional tools, chucks, and specific equipment for material handling and transportation between machining stations and so on are not necessary. Complicated operations are automated in a one-stop procedure.” (op cit p10) Despite the complexities of CNC processes, these do have the flexibility to employ any material that can be machined, thereby having the potential to produce components that closely simulate those used in production processes.

Four primary areas in the development of rapid prototyping have been identified by Kai and Fai, these being “input, method, material, and applications”. (op cit pp5 - 7) “Input” refers to the geometry of the component, being either a physical object that must be digitised, or a 3D computer model. “Method” is the technique used to produce the component, be it photo-curing, cutting and glueing/joining, melting and solidifying/fusing, and joining/binding. “Material” can be supplied as solid, liquid or powder. Applications can be diverse, but Kai and Fai have identified groupings based around design, engineering, analysis and planning, tooling, and manufacture. (op cit p5 - 7)
Prerequisites for rapid prototyping

As a prerequisite to any rapid prototype build, a 3D computer model of the component must be generated. This may be produced using a CAD or CAID system, or via the digital scanning of a physical object. Whilst the computer model may be produced using either solid or surface modelling software, it is essential for the latter to be a closed volume, although some repair is possible using software such as MAGICS produced by the Belgian company Materialise N.V..

Kochan sees the requirement for a 3D computer model at the input stage as “the basic prerequisite for the new developments in rapid prototyping”. (op cit p1) He goes on to acknowledge that the most effective methodology for the use of rapid prototyping is to directly employ 3D computer modelling as opposed to the preparation of 2D drawings followed by 3D modelling (op cit p10).

The effort required to produce the 3D computer geometry required for rapid prototyping should not be underestimated. Indeed Kai et al consider this as being “the most time-consuming part of the entire process chain”. (op cit p19) The time scales required to produce the 3D computer geometry will of course vary according to part complexity, capabilities of the modelling system, and competence of the operator.

Although rapid prototyping systems can accept 3D computer geometry in a variety of file formats such as the International Graphics Exchange System (IGES), stl has evolved as the industry standard. The stl file format was originally created by 3D Systems for their SLA process (hence the stl abbreviation), and involves the conversion of the 3D computer geometry into a series of interlocking polygons that form an enclosed volume. Whilst simple rectilinear forms may require relatively few polygons to define the shape, highly curved organic forms require many thousand and can result in extremely large data files e.g. 55 Mb for the communication device case study in Chapter 6 (pp221 – 234).
Developments in 3D laser scanning are now enabling the translation of a physical object into an STL file. Kwan et al have developed a methodology that enables STL files to be produced directly by reverse engineering geometric data from a physical component that was copied by laser scanning. (Campbell 1999 p46) Three strategies are proposed by Kwan et al:

- Point cloud data acquired, manipulated in CAD, converted to STL and then to rapid prototype slice format. This strategy allows the manipulation and use of the CAD model for other applications e.g. design modifications, engineering analysis etc.

- Point cloud data directly to STL and then rapid prototype slice format.

- Point cloud data directly to rapid prototype slice format.  
  *(ibid)*

Whilst the second and third strategies may appear simple and efficient, Kwan et al acknowledge that difficulties may be encountered. These can include the point cloud data not representing a complete object, the presence of gaps, overlapping triangles, and reversed normal vectors. *(ibid p47)* Kwan et al undertook research into the development of an algorithm to reduce the amount of point data by eliminating the need for some cross sectional information, thereby significantly simplifying the process. *(ibid p47)* This technology is still in its infancy and is not considered an effective process for the translation of an industrial designer’s physical model into the STL file format required for rapid prototyping.

Prior to the advent of digital design techniques, the transmission of design information to a remote location was restricted to the use of fax machines and delivery of drawings and physical models by post or courier. As a digital data format, an STL file can be immediately transmitted to a remote location via the Internet. It is therefore possible to send an STL file to the other side of the World within seconds, making it available for immediate rapid prototyping. For those
organisations that operate as a global enterprise, such capabilities offer dramatic improvements in design distribution time scales when compared with conventional techniques.

In preparation for a rapid prototype component build, the stl file must be digitally “sliced” to convert the model into a series of cross-sections or contours. The geometric information embodied within these slices then becomes the data that controls the build parameters of the rapid prototyping system.

**Production systems**

As a relatively recent technological development, rapid prototyping continues to evolve, and researchers continue to develop new systems. However, five systems have emerged as key players in the commercial exploitation of rapid prototyping for the production of components suitable for engineering evaluation. (Dickens 1992, Campbell 1998, Jacobs 1996, Wood 1993)

**Stereolithography (SLA)**

The first commercial SLA machine was marketed in 1989 by 3D Systems. The company now produce a wide range of machines, capable of build volumes of 508 x 508 x 600mm. Dimensional accuracy of SLA has improved dramatically over the course of its development, seeing the RMS error reducing from 9 mils in the early 1992 to 1.8 mils five years later. (Jacobs 1996 p149) In 1997, 3D Systems had more rapid prototyping machines installed world-wide than any other system. (Kai and Fai 1997 p28)

The SLA process involves the partial hardening of a photosensitive liquid polymer by a carbon dioxide laser. For the SLA 500 machine, the laser operates at 351 - 364nm with an initial delivered power of 2000mW. The maximum laser spot size over the working area is 0.025mm, with a spot location resolution of 0.025mm. The spot location repeatability is 0.05mm, and the typical drawing speed 2540mm per second. The laser “draws” a cross-
sectional slice of the component on the surface of the polymer, curing the resin as it scans. Part borders are drawn first, and the remaining area “hatched” to complete the layer.

The component build includes a support structure that is generated using software such as “Bridgeworks”. The role of the support structure is threefold: to prevent the re-coater blade striking the build platform; to provide an accurate base on which to commence the build; to allow ease of removal from the platform. On completion of the cross-section (including supports) the platform on which the build takes place descends into the vat to cover the hardened area with another layer of liquid photo-polymer that is equal to the designated build depth. For the SLA 500 machine the elevator has a vertical resolution of 0.00177mm with a position repeatability of 0.025mm. The minimum layer thickness is 0.127mm. Once the elevator has descended, a sweeper blade traverses the vat to remove any excess resin before the hardening of the next layer commences.

On completion of the build, the platform raises the component above the surface of the vat to allow excess resin to drain off. The part is placed in a solvent cleaning apparatus to remove the remaining liquid resin and then allowed to dry. Final curing takes place in a UV light source known as a post curing apparatus (PCA). Jacobs notes that most parts take between one and two hours to cure, although very large parts can take up to ten hours. (1992 p16)

Whilst 3D Systems remain the world’s largest producer of rapid prototyping systems, other organisations are now active in the development of SLA technologies. These include Aeroflex Inc. (USA), CMET (Japan), D-MEC/Sony (Japan), Denken Engineering (Japan), Fockele and Schwarze (Germany), Meiko (Japan), MicroTEC (Germany), and Optoform (France). (http://home.att.net/~castleisland/com_lks.htm#ij)

Laminated object manufacture (LOM)
The LOM process is based around the bonding and cutting of layers of paper. It was developed by the Helysis Inc. in the United States who manufactured the first production machine in 1991.

The build takes place on a moveable platform, above which a carbon dioxide laser is mounted on an X-Y plotter system. The paper-based build material is supplied via a feed roller positioned to one side of the moveable platform, with the surplus paper being removed via a take-up roller on the other side. One side of the paper is coated with a polythene film that is melted during the build process, bonding the layers of paper together.

A cross-section of the component is produced when the laser cuts through a layer of paper on the build platform. The build thickness is therefore determined by the thickness of the paper. When the cross section has been produced, the laser cuts a grid pattern to assist in component removal when the build is complete. In preparation for the next layer, the platform moves downwards to enable a fresh piece of paper to advance from the feed roller, and at the same time the surplus paper from the previous layer is carried onto the take-up roller. The platform is then raised, allowing a heated roller to move across the build area to melt the polythene film and apply pressure to bond the two layers of paper together. The laser then cuts the next layer of the component.

When the build is complete, post-processing is required to remove the component from the support material. This is assisted by the grid pattern cut during the formation of each layer. The component “break-out” starts with the removal of a frame that was cut by the laser to retain the cross-hatched grid material. These cross-hatched pieces can then be removed using woodworking and dentistry tools. The components should then be treated with a sealant to prevent water absorption and distortion, as Reece and Styger acknowledge that “problems exist with stress creation and moisture content due to environmental conditions”. (Bennet 1995 p101)

Components produced using the LOM process have the appearance and physical properties of a wooden material, with a build accuracy of 0.25mm. The
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The largest build is currently from a Helysis machine at 810 x 550 x 500mm. Similar processes to Helysis LOM have been developed by CAM-LEM Inc. (USA), Ennex Corporation (USA), Kinergy Pte Ltd. (Singapore), KIRA (Japan), Schroff Development Corp. (USA), Stratoconception (France) and Zimmermann Products Inc. (Germany). (http://home.att.net/~castleisland-commerce.htm#ij)

Selective laser sintering (SLS)

SLS is based on a technology patented at the University of Texas and developed by the DTM Corporation who produced their first production machine in 1992. The process involves the fusing of a powdered thermoplastic material with heat from a carbon dioxide laser. The Sinterstation 2500 is capable of building components measuring 381 x 330 x 457mm, and the German EOS system operates on similar principles with build volumes up to 720 x 380 x 400mm.

The process begins when a roller spreads a thin layer of the material (usually thermoplastic) onto a moveable piston that sits within a heated cylindrical build area. The temperature of the powder is elevated to just below its fusing or melting temperature to reduce the additional laser energy required to fuse the powder. The build chamber is also purged with nitrogen to minimise the residual oxygen to between 1% and 2%, thereby reducing the risk of explosion and contamination of bonding surfaces.

Computer controlled mirrors project the laser onto the build area, defining the shape of the cross-section. The laser heats the powder causing it to fuse together and form a solid material. When the layer is complete, additional powder is deposited. The powder “cake” that surrounds the component serves as a support structure, and secures unsupported “islands” until they are attached to the body of the product by subsequent sintering.

After the layers have been formed, the component is removed with around 25mm of powder attached to its surfaces. This insulates the component to prevent distortion caused by rapid cooling. When the component has been
removed, further cooling takes place, the time required for this being dependent on wall thickness.

When cool, the component is taken to a “rough breakout station” where excess powder is removed from around the component. During this post-processing, the powder can be removed with compressed air, a brush, and simple hand tools. A major advantage with SLS is that the unused powder can be reused.

As with all rapid prototyping systems, SLS components have a stepped surface finish due to the layered build process. However, SLS components have a further degree of roughness due to the fact that the particles of powder are relatively large and not completely transformed by the laser, resulting in a distinctive granular texture.

Materials used for SLS include polyvinylchloride (PVC), polycarbonate, investment wax, nylon and acrylonitrile butadiene styrene (ABS). (Jacobs 1996 p143) One of the advantages with SLS is that the wide range of materials available increases the likelihood of using a plastic that is relatively close to the production material. For investment casting, DTM’s Castform and EOS Polystyrene can be used.

The DTM Corporation offer a copper polyamide build material that can be used to produce injection mould tools capable of manufacturing several hundred components. For functional metal components, die-casting tools and injection mould tools, DTM’s “RapidSteel” 2.0 (stainless steel infiltrated with bronze) is used.

Electro-Optical Systems GmbH (EOS) and Soligen U.S.A. have developed machines with operating principles relating to those of SLS. (Kai and Fai 1997 p92)

**Fused deposition modelling (FDM)**

Stratasys Inc. have developed an FDM process whereby casting wax or thermoplastic material (e.g. ABS and polyamide) is extruded through a heated
delivery head onto a fixed base. Components of up to 450 x 450 x 600mm or 575 x 575 x 468 are possible, with an accuracy of plus or minus 0.127mm and build thickness between 0.051 and 0.762mm. (ibid p93)

The material is fed via precision volumetric pumps to the delivery head and then heated to a semi-liquid state. The material cools as it is deposited, forming a cross-section of the component via the x-y movement of the delivery head. When the layer is complete, the build platform moves downwards to allow the next layer to be fused onto it.

Overhangs and flat areas require a support structure that is automatically generated by the build software, these being broken off during post processing.

A key advantage of the FDM system is that components can be produced using materials that closely resemble production materials e.g. polypropylene. Kai and Fai state that a component produced by FDM in ABS will have 85% of the strength of a production item. (ibid p95) As an “on demand” process, it does not require large reservoirs of material at the outset, although Jacobs makes the point that the FDM materials are almost twice the cost of liquid photo-polymers. (1992 p407)

**Solid ground curing (SGC)**

The Israeli company Cubital Ltd have pioneered the development of the Solid Ground Curing (SGC) system of rapid prototyping, releasing their first production machine in 1991. (Jacobs 1992 p416) The SGC process builds components form photo-curable resins using some of the principles of SLA. The minimum layer thickness achievable is 0.06mm, and maximum build volume 500 x 350 x 500mm. (Kai et al 1997 p37). Instead of using a laser, a powerful UV light source is exposed onto the resin via a series of reusable masks.

The process begins when a layer of resin is spread onto the build platform and moved to the exposure station. Specific areas of the resin are cured by exposure to a powerful flood of UV radiation that is projected through a mask.
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The mask represents a cross-section of the component, being generated as a “slice” from the stl geometry using a process closely associated with photocopier technology. Once exposed, the toner is removed in preparation for the deposition of the next mask. Any resin not solidified due to it being protected by the mask is removed with an automated air knife, followed by the deposition of molten wax into the resulting cavities. A cooling plate solidifies the wax before a fly cutter mills the polymer and wax to the correct thickness in preparation for the next layer. As the intensity of the UV light-source is powerful enough to completely cure the resin, the only post processing required is the removal of the wax support structure with hot water.

Whilst being a relatively expensive and noisy system, SGC has several advantages over other rapid prototyping processes. As the resin is fully cured by the UV light source, the part immediately acquires its full mechanical strength thereby reducing the possibility of warpage. As there are no support structures, the build envelope can be filled with components to make the process as economical as possible.

A similar system to Cubital’s SGC process is design-controlled automated fabrication (DesCAF) which has been developed by Light Sculpting Inc. (Kai et al 1997 p35) Objet Geometries Ltd of Israel manufacture the Quadra process that is based on the photo-curing of a photo-polymer delivered by inkjet printing. (http://home.att.net/~castleisland/com_lks.htm#ij)

Comparative studies
As a relatively new technology, the various rapid prototyping system manufacturers are forced to actively promote their respective systems to establish a presence in the marketplace. Comparisons of design outcomes from the various systems are therefore essential if an objective overview of the merits and shortcomings is to be made. As an established digital build technology, CNC machining will be included in the comparative studies.
CNC machining is capable of producing complex components from 3D computer geometry, but distinct advantages have been identified in the use of rapid prototyping. Kochan (1993 p14) refers to the following advantages of rapid prototyping over CNC machining: feature-based designs are not required (only 3D geometry); no requirement for conversion from design to manufacturing features; no requirement to define blank geometry; minimal process and operational planning; the sequence of operation does not have to be defined; no need for clamping, jigs and fixtures; it is a tool-less process (no requirement to design specific moulds and dies).

In a comparative study between rapid prototyping (SLA and SLS) and CNC machining, Prioleu found major differences in the set-up time required for the two systems. (in Rapid Prototyping Systems 1994 p81) The set-up time required for SLS was 0.5 to 1 hour, and for SLA 0.5 to 2 hours. The CNC machining time was dependent on the complexity of the part, so times varied from 0.5 to 40 hours. For the more complex parts, time was required to select the surfaces to be machined; create rough and finishing cuts; select process parameters; generate the cutter paths; run the cutter paths through the verification programme. This sequence was then repeated for each side of the geometry that required machining.

Prioleu notes that for rapid prototyping, the set-up procedure for SLA involved orientating the stl file, automatically generating a support structure, selecting predetermined slicing and build parameters, slicing and converging the data. (ibid pp 81 – 83) The procedure for SLS was virtually identical, but with the exception of the slicing operation being undertaken automatically during the build. (ibid p82)

In Prioleu’s study, limitations in the definition of form for rapid prototype components were found to be a function of the width of the laser, enabling sharp corners and small features to be produced. (ibid p83) With CNC machining, internal square corners are not possible, and deep narrow cavities presented significant problems. In addition, rapid prototyping did not require special tools to create features specified in a part’s design.
For engineering applications where tight tolerances were critical, CNC machining was considered more suitable than rapid prototyping. Dimensional accuracies quoted by Prioleu were +/-0.05mm to +/-0.1mm for CNC machining, and +/-0.13mm to +/-0.38mm for SLS and SLA. (ibid p84)

In concluding his comparative study, Prioleu lists the following guidelines when producing prototype plastic parts:

**CNC is most suited when –**

- Geometries can be machined in two or three set ups
- Parts are larger than the building envelopes of rapid prototyping systems
- The tightest tolerances are required
- Exact production materials are required

**SLS is most suited when –**

- Complex geometry makes machining or building supports difficult
- Materials with greater toughness than other rapid prototyping materials are required
- Materials with higher heat resistance than other rapid prototyping materials are required
- Parts will be used for limited functional testing

**SLA is most suited when –**
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- Complex geometry makes machining difficult

- Feature definition and detail are important

- Parts will be finished for use as masters for RTV or epoxy tooling

- Parts will be used for design review  
  \( \text{(ibid p85)} \)

For the production of appearance models, the results from the study undertaken by Prioleu indicated that of the three systems examined, SLA would be most suitable. This was based on the component production speeds, complex component geometry, and ability to achieve a relatively high level of surface finish.

Cool et al (in Dickens 1995 p42) undertook a comparative study into the use of rapid prototyping for the tableware industry. The research focused on a coffee pot design that was used to evaluate the suitability of the five established rapid prototyping production systems (SLA, SLS, FDM, SGC and LOM) for the production of models as a prerequisite for production tooling. In common with the requirements for appearance models and appearance prototypes, a high level of surface finish was required. Costing for the rapid prototypes was based on a build thickness of 0.25mm. For SLA, FDM and LOM, component prices were similar, being £1100, £1150 and £1250 respectively. SLS and SGC were the most expensive at £2000 and £2380. \( \text{(ibid p44)} \)

In terms of their potential for use by industrial designers, the findings of Cool et al indicated that SLA was the most suitable, not only because it was the lowest cost, but because it was considered by the researchers as having the highest level of surface finish. \( \text{(ibid p45)} \) The surface of the FDM and LOM models required more finishing time than the SLA model, and it was found to be particularly difficult to remove the waste material from the spout on the LOM
model. (ibid p45) The findings by Cool et al indicated that all processes resulted in “a considerable time saving” when compared with traditional craft-based techniques. (ibid p47)

Cobb et al point out that the labour intensive finishing operations as identified with the LOM and SLA models in Cool’s study (ibid) are “inconsistent with the philosophy of RP which is intended to eliminate such labour intensive processes in the early stages of the design cycle.” (Dickens 1996 p61) They go on to identify the risk of removing surface detail via smoothing during the finishing process. This issue was also raised during an informal discussion with Mark Stratford, a senior industrial designer at Black & Decker UK.

Cobb et al conclude that:

in addition to being labour intensive, manual finishing is also detrimental to the accuracy of the RP model. It can be highly selective, with the finishing of fine details and re-entrant features often omitted, and, given that the model maker has little knowledge of the initial surface deviation, we can only assume that the final part finish and geometry is the result of luck rather than judgement. (ibid p68)

It is important not to underestimate the skill of specialist industrial design model makers who would be aware of such issues, especially as many enter the profession following formal industrial design training. With a high degree of model making skill, and an awareness of the subtleties of the component form, the potential for distortion could be significantly reduced (if not eliminated).

Despite the superior surface finish of SLA, this process does not appear to have the best performance in terms of its mechanical properties. Kimble undertook a comparative analysis of SLA and SLS components and his findings indicated that SLS had superior performance in terms of its flexural properties, heat distortion temperature, and impact resistance. (Rapid Prototyping Systems 1994 p19 - 27) However, as the role of the appearance model is to define form, this should not be a significant issue.
Childs et al used a benchmark component to assess the geometric and linear accuracy of SLA, SLS, LOM and FDM. (Dickens 1994 pp36 - 43) The testing was rigorous, with care being taken to store the components in a temperature controlled environment that would not adversely affect the test results. Their findings for the SLA components were identical to those of Cool et al (op cit p42) in that they found the process to produce “the best visual appearance and smoothest feel”. (op cit p39)

In Child’s study, the FDM component had the roughest finish, being considerably more flexible than those produced by SLA. (op cit p39) LOM and SLS were positioned between SLA and FDM for surface finish, with the SLS being granular around the edges, and the LOM showing signs of de-lamination. (op cit p39) The most successful process in defining details below 0.5mm was SLA. For a study investigating the use of rapid prototyping by industrial designers, this represents a significant finding as features of this size are within the capabilities of injection moulding and may be specified by industrial designers.

An evaluation of the major rapid prototyping systems was featured in ID Magazine, although no indication of the underlying research method was provided. (September/October 1997 p85) The study concluded that the granular nature of SLS components made them best suited to models “needing strength rather than looks”, that LOM process was suited to larger components of lower accuracy, and FDM was “unsuitable for anything aesthetic”. (ibid) SLA and SGC were considered most appropriate for form and surface studies, although only limited functional testing was possible. Once again, this study indicated the superiority of SLA for the production of appearance models.

**Rapid prototyping applications**

Kochan has identified three generic categories of use for rapid prototyping: “prototypes for evaluation of designs; prototypes for functional tests/evaluation; models for further manufacturing processes”. (1993 pp22 - 23) This
Rapid prototyping classification is similar to that given by Wood who refers to the use of rapid prototyping for aesthetic visualisation, form-fit-and-function testing, and casting models. (op cit p2) There is also significant overlap between the categories given by Kochan and Wood, and those identified by Kai and Fai who refer to applications in design, engineering analysis and planning, and manufacturing and tooling. (op cit pp204 - 208)

For industrial designers, the key advantage afforded by the use of rapid prototyping appears to lie within the design-related areas as identified by Kochan and Kai and Fai. However, recent developments imply a shift in its use as a design tool by moving “into the heart of the manufacturing process” via its use in the production of low volume injection mould tools. (Dickens 1995 p28).

**Design evaluation**

The first level of use for rapid prototyping is identified by Kochan as “prototypes for evaluation of designs” (op cit p22), and by Kai and Fai as “applications in design”. (op cit p204) Within this general category, Kai and Fai define the more specific roles as: “CAD-model verification; visualising objects; proof of concept; marketing and commercial applications”. (op cit pp205 - 206) These four applications will now be discussed in some detail.

“CAD-model verification” involves the translation of a virtual 3D computer model into a physical object to enable its approval by the designer. (ibid p205) Kai and Fai comment that this is particularly important “for parts or products that are designed to fulfil aesthetic functions or are intricately designed to fulfil functional requirements”. (ibid p205) Whilst this also reflects the position of Kochan on the significance of undertaking a visual evaluation with a physical model, the reference to functionality could be seen as extending its application to prototypes and appearance prototypes.

“Visualising objects” is more general than CAD-model verification, as the objective is the communication of design intent to all interested parties. (op cit p204)
“Proof of concept” appears to acknowledge the need to position the new design within an environmental context, and Kai and Fai use the example of a mobile telephone within a car. \( \textit{op cit} \) p204 They again refer to functional performance, thereby implying the integration of a high level of design detail within the rapid prototype components.

“Marketing and commercial applications” are related to the promotion of the product to support sales, and the significance of “presentation models” for inclusion within promotional literature is noted. \( \textit{op cit} \) p205 The entire area of design evaluation appears particularly relevant to the needs of industrial designers, with the role of appearance models fitting within all categories.

**Functional testing**

The second level of applications for rapid prototyping identified by Kochan are “prototypes for functional tests and evaluation”. \( \textit{op cit} \) p23 Prior to the commissioning of production tooling, it is necessary to verify that the fit and function of components is acceptable. Working with an exterior form defined by the industrial designer, an engineering designer would translate the form into a specification for production by adding internal details and manufacturing tolerances. As such, rapid prototype components with internal details and wall thickness may make a major contribution to NPD as the production of such components using conventional techniques is both expensive and time-consuming. \( \textit{op cit} \) p22

Kai and Fai expand Kochan’s definition to include “applications in engineering, analysis and planning”. \( \textit{op cit} \) p205 The contribution of rapid prototyping is in the provision of “the information necessary to ensure sound engineering and functional analysis of the product” \( \textit{op cit} \) p205, and as such the roles defined by Kochan and Kai and Fai are identical. This is extended by Kai and Fai when they identify a further eight sub-sets of activity: scaling; form and fit; flow analysis; stress analysis; mock-up parts; pre-production parts; diagnostic and surgical operational planning; design and fabrication of custom prosthesis and implant. \( \textit{op cit} \) pp205 - 207 These will now be discussed.
“Scaling” is the capability to manipulate the dimensions of the CAD model and produce components of any size. As an example, Kai and Fai make reference to the ability to scale perfume bottles to produce containers of different volumes, although it is possible to argue that such modelling is more relevant to the design phase. Kochan’s definition of functional tests and evaluation would not include such applications. (op cit p23)

“Form and fit” integrates both visual and technical elements, and the former is an unusual application to identify under engineering, analysis and planning as the visual element has already been categorised under “design”. Whilst the “fit” component of Kai and Fai’s application can be seen as an engineering-based application, form (in the visual/emotional sense) does not. It must be assumed therefore that the form being referred to is product geometry. Kochan makes no references to aesthetics or form in his exploration of the use of rapid prototyping for functional tests and evaluation. (op cit p23)

“Flow analysis” via a physical prototype is essential whenever an engineering component has air or liquid moving through it. The complexity of components such as inlet manifolds and exhaust pipes makes rapid prototyping an ideal application when compared with traditional manual build techniques.

“Stress analysis” applies photo-optical techniques to determine stress distribution within a component. Despite the fact that the materials and moulding technique used in a rapid prototype component would not be identical to those of the production item, useful results can still be obtained, particularly when design comparisons are made.

“Mock-up parts” are those components that are integrated into a working prototype to evaluate performance. Whilst not recognised by Kai and Fai, there is some overlap between mock-up parts and components produced to evaluate fit.

“Pre-production parts” are necessary to prove both product assembly techniques and performance following manufacture. When significant
component volumes are required, or material properties closer to those of the production components are specified, vacuum casting may be used.

“Diagnostic and surgical operation planning” and “design and fabrication of custom prosthesis and implant has no direct relevance to industrial design, but its application represents a significant contribution to the medical profession when integrated with body scanning technologies.

With the exception of diagnostic operation planning, the use of rapid prototyping under the “functional testing” heading embodies the functionality of prototypes and appearance prototypes.

Manufacture
The third level of applications for rapid prototyping are identified by Kochan as “models for further manufacturing processes” (op cit p23), and by Kai and Fai as “applications in manufacturing and tooling”. (op cit p208) In both cases, the principle involves the production of components via rapid prototyping followed by the manufacture of production tooling.

Kochan’s areas of application identify the specific production processes of investment casting, vacuum casting, metal spraying and electro-discharge machining, which broadly mirror those of Kai and Fai (op cit pp208 - 214) The related applications given by Kai and Fai will now be identified.

“Vacuum casting with silicon moulding” (also known as soft tooling) utilises rapid prototype components as master models for the low volume production of components using silicon moulds. The process is commonly utilised by engineering designers who need to produce prototypes using materials with mechanical properties as close to the production item as possible. Jacobs notes that some organisations require the production of components using soft tooling as a matter of company policy, the aim being to reduce the likelihood of unexpected failures. (1996 p274)

The vacuum casting process involves pouring liquid silicon over the rapid prototype, allowing it to set, and then cutting through the silicon material to
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Rapid prototyping

remove the part and produce a split-line. To produce the cast components, the silicon rubber “tool” is filled with polyurethane in a vacuum chamber, thereby increasing definition by significantly reducing the amount of trapped air. This process has the ability to produce moulds of very high resolution at a fraction of the cost of conventional metal tools. Vacuum casting is so effective that there are instances of its application for production components, for example the Chameleon 3 voice synthesiser. (C3 January 2000 p17)

“Metal spray” tooling techniques can be used to deliver droplets of molten metal onto the surfaces of a pattern that was produced via rapid prototyping. The metal used is usually a low melting alloy (lead/tin based) and is applied with a device similar to a paint spraying gun. When a layer of around 2mm has formed, a composite material is used to “back-up” the tool. These tools can be used for low volume runs of around ten components. Jacobs notes that a problem associated with the production of spray metal tooling is that high internal stresses can develop in the shell, although this can be reduced by shot-peening. (1996 p275)

“Casting” allows the reproduction of rapid prototype forms in metals. Investment casting involves the use of ceramic slurry to cast the form of a component produced using rapid prototyping. Materials used for the rapid prototype build are important, as this must be removed from within the casting by melting or burning. When the casting operation is complete, the ceramic mould is cracked open to remove the component.

“Electro-discharge machining (EDM) electrodes” can be produced in copper directly via SLS. Alternatively, a rapid prototype tool pattern can be used to create an abrading die using an epoxy resin with an abrasive component. The die is then used to abrade the electrode.
Benefits of rapid prototyping

Whilst it is possible to evaluate design proposals using the functionality of 3D CAD and CAID software (e.g. rendering, finite element analysis, clash detection), the need for physical models remains, being strongly supported by the likes of Dr Werner Pollmann of Daimler-Benz, who states that:

The purchase of a car depends strongly on subjective impressions. Next to technological properties like horsepower or security equipment, properties like noise, handling, or styling are key factors for a purchase decision. But these properties can only be evaluated by physical prototypes. For that reason, availability of high quality functional prototypes will remain an important element of product development and cannot be substituted by digital models and analysis.

(in Jacobs 1996 p1)

This is reiterated by Wimpenny et al when they state that “despite the improvements in CAD packages, virtual reality and finite element analysis, there is still a requirement to produce prototype parts for durability testing, assessment of manufacturing feasibility and for customer evaluation trials.”

(Dickens 1995 p33)

Accepting a need to produce physical models during NPD, any techniques that reduce costs and time-scales must be considered seriously, and the savings quoted following the use of rapid prototyping have been significant. A Department of trade and Industry (DTI) Overseas Science and Technology Expert Mission (OSTEM) to the USA reported that NPD costs “can be cut by 40 - 70% and time to market reduced by 60 - 90%. (Waterman 1993 pi) The significance of these findings led Waterman to state that “it is vital that UK manufacturing companies adopt these new techniques now if they are to remain in business.” (ibid pi)
Rapid prototyping has been identified as contributing to a reduction of NPD lead times, the benefits of which have been succinctly identified by Jacobs when he comments that:

It has been determined that being six months late to market relative to your competitor can sacrifice as much as 30% of the available profit from a given life-cycle. By speeding up the product development and commercialization process, rapid prototyping contributes to a faster product launch and potentially higher profits. (1996 p23)

Kai and Fai have identified both direct (design, development and production) and indirect (sales, marketing and the consumer) benefits of employing rapid prototyping. (1997 p7) The key direct benefits are seen as “the ability to experiment with physical objects of any complexity in a relatively short period of time.” (ibid) They go on to note that the cost and time savings of employing rapid prototyping can be from 50% to 90% (ibid). Whilst the 90% time-saving may appear extreme, Jacobs also acknowledges that both cost and time savings of 40% to 80% are achievable (op cit p24)

Jacobs is more specific in his summary of the benefits of employing rapid prototyping (op cit p3). Applications include its use for physical evaluation by designers and engineers; communication tool for simultaneous engineering; component form and fit tests; test samples for market research; production planning for tooling quotations; packaging development; functional testing; tool production. (op cit p3) He goes on to note that reductions in lead times afforded by the application of rapid prototyping can facilitate greater time for testing, the exploration of alternate designs, and an ability to finalise the solution later in the design process. (ibid p22)

Specific professional groups that can benefit from the direct use of rapid prototyping have been identified by Kai and Fai (op cit pp9 - 10). These include product designers, tool designers and manufacturing engineers. The term
“product designer” is not defined by Kai and Fai, but the professional responsibilities referred to encompass a higher degree of engineering responsibility than would be expected of an industrial designer. They also refer to the use of rapid prototyping as a means of manufacturing production components and possible benefits. In the future, the use of rapid prototyping as a production technique may be viable, but to comment that a current benefit to designers is the capability to undertake part design “without regard to draft angles, parting lines or other such constraints” does not reflect current capabilities (op cit p9)

The use of rapid prototyping as a production process has been investigated by Binnard, who developed techniques for the integration of electro-mechanical systems within the build process through the use of pre-defined components (1997 p23). Whilst the findings were based on research into the design of small mobile robots, the generic possibilities for large scale production exist, but not until build rate, material properties and finish are significantly improved. Use for the direct manufacture of production components is not identified in Kochan’s description of the applications for rapid prototyping, stating that “they are used mainly for prototypes, models, functional test parts or patterns for other procedures”. (op cit p11) for other procedures“. (op cit p11)

Hopkinson and Dickens have undertaken research into the use of rapid prototyping in the manufacture of production components, referring to this technology as “layer manufacturing technique (LMT).” (2001 p197 – 202) They predict that it may take another three years to develop rapid prototyping materials with the mechanical properties of those used in injection moulding, but once achieved, they consider the benefits to be significant: “zero tool costs, reduced lead times and considerable gains in terms of freedom of product design and production schedules.” (ibid p200) If the development of the required material properties can be achieved, Hopkinson and Dickens believe that the cost of LMT components will be lower than those produced by injection moulding for production runs of up to 7500 units on small, geometrically complex parts. (ibid p201)
Industry sectors benefiting from the use of rapid prototyping were identified in the DTI OSTEM report. (Managing Product Design Project 1992) These were found to be organisations with the following characteristics:

- “Time to market driven and fashion conscious - e.g. the automotive industry”
- “Technically constrained and governed - e.g. the aerospace industry”
- “Personalised products are required - e.g. the medical implant industry”

Having identified these somewhat narrow areas, the report goes on to include virtually all of manufacturing industry where complex models, castings or mouldings are required.

The number of bureaux offering rapid prototyping has increased enormously over the last eight years, with additional competition and improvements in build technologies helping reduce costs. In 1997, Bill Evans of the San Francisco consultancy Bridge Design, stated that the production of rapid prototype models now takes a third of the time and cost than it did in the early 1990’s. (ID Magazine, September/October 1997 p85)

Despite the widespread acknowledgement of the benefits to be afforded by the use of rapid prototyping, Phil Grey, a partner in the London-based industrial design consultancy Weaver Associates, has expressed reservations on excessive time-compression. Having managed industrial design projects for major UK and international manufacturers, Grey has considerable experience of the interaction between industrial designers and in-house engineering design teams. He warns of the dangers of introducing appearance prototypes too early when he states that: “the appearance of an ‘inside/outside’ model (appearance prototype) months earlier than a conventional block model telescopes decision making - and in a way design and engineering teams are just not ready for at first.” (Design, February 1994 pp36 - 38)
Published case studies

Relatively few detailed case studies on the commercial use of rapid prototyping have been published, with even fewer exploring its use by industrial designers. Of the 43 case studies identified by Kai and Fai, none make reference to its use for the production of appearance models. (op cit pp237 – 280) General strategies have been identified, but these tend to focus on engineering design. For example, Kai and Fai have identified three phases of prototyping in the order that they are undertaken during NPD. (op cit pp2 - 4) Phase one is “manual” or “hard” prototyping, involving fabrication techniques with a high craft content. Phase two is “soft” or “virtual” prototyping that encompasses the utilisation of computer models for testing, analysis and modification. The emphasis here is on a technical component, with no reference to industrial design. Phase three is rapid prototyping. Whilst this represents a useful descriptor for the classification of prototyping, these are not entirely accurate, as manual prototyping can take place throughout NPD, and virtual prototypes may be produced by industrial designers prior to any other physical models.

From the limited case study material available, six have been identified as having relevance to this study, although the quantity and quality of information is somewhat limited. The relevant outcomes from these case studies will now be discussed.

Automotive diagnostic tool

Manchester-based industrial design consultancy Buxton Wall McPeake undertook the industrial design of a hand-held diagnostic tool for use by garage mechanics. (Rapid News Volume 4, Number 3 1999 pp 30 - 35) The role of Buxton Wall McPeake was to design a product that was “attractive enough to the purchaser in terms of appearance, price, and functionality”. (ibid p32) Significantly for the project, the client’s in-house engineering design team were using the SDRC I-DEAS solid modelling system that was also used within the consultancy.
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Rapid prototyping

All internal components were modelled on I-DEAS before the industrial design proposals were produced, with Alias software being used for the CAID modelling. \textit{(ibid p32)} The paper contains no information on the method employed by the industrial designers.

The client’s in-house engineering designers produced detailed CAD models for the interior and exterior of the components, and SLA was used to produce a set of master components that were used to confirm the fit and function of the product and the electronics. Silicon moulding and vacuum casting of the SLA masters was used to produce 30 vacuum-cast cases (via silicon moulding) for fully working appearance prototypes. Following market evaluation of the appearance prototypes, production tooling was commissioned using the 3D CAD geometry.

This case study demonstrated an application for rapid prototyping towards the end of design development, but made no direct reference of its relevance to industrial designers. Its descriptions were general, giving no indication of the precise role of the client’s engineering designers, and how conventional, digital industrial design techniques, and rapid prototyping were employed during concept generation, design development and specification. It did however illustrate how rapid prototyping has been used to assist in the detailed evaluation of pre-production components.

Minimal access surgery products

During the development of minimal access surgery (MAS) products, Pearce et al have identified a contribution made by the use of rapid prototyping in terms of mechanical prototyping and ergonomic/aesthetic evaluation. \textit{(in Bennet G 1995 pp29 - 40).} In this case study the 3D geometry from the CAD models was used to produce the mould tools for volume manufacture.

The paper indicated that the majority of the ergonomic and aesthetic evaluation was undertaken using the conventional industrial design techniques of sketch models and conventional appearance models. \textit{(ibid p36)} Only when there was significant design direction did 3D CAD modelling begin, working from the form
defined by the appearance models. Stl files were then generated from the CAD geometry, enabling the production of SLA components for appearance prototypes. Following performance trials, design revisions were made, although these were undertaken by engineering designers, not industrial designers. (ibid p32)

Benefits to the manufacturer from the integration of rapid prototyping were savings in development time (from concept to market) of 40% (ibid p38), and “a significant reduction in tooling costs”. (ibid p29)

This case study again illustrated the use of conventional industrial design techniques at the beginning of NPD, with the introducing of 3D modelling and rapid prototyping by engineering designers once significant design direction had been achieved.

Lan access module
HDS Design, a UK based consultancy, undertook the industrial design of a local area network access module that integrated state of the art electronics in an injection moulded enclosure. Supported by the client’s in-house engineering designers, the industrial design strategy employed by HDS Design involved the production of design concepts (technique not specified); development of chosen concept and production of CAD renderings (using Varimetrix solid modeller); construction of a conventional appearance model for final approval by the client. (C3 June 1999 p20 - 21)

On approval of the appearance model, development was taken over by the client’s engineering designers who generated detailed solid models using a Varimetrix CAD system. SLA masters were produced from the CAD geometry and used to produce vacuum cast appearance prototypes. On approval of the appearance prototypes, production tooling was commissioned using 3D CAD geometry supplied by HDS Design to ensure compliance with the exterior form. Despite the fact that the necessary 3D geometry had been used to produce renderings, the reasons for not employing rapid prototyping in the production of the appearance model were not given.
Vacuum cleaners
Dyson integrate the use of 3D CAD modelling and rapid prototyping into the design of vacuum cleaners and other domestic products. (C3 February 2000 pp 14 - 15) Their strategy involves the design and modelling of components as 3D CAD geometry using Unigraphics software followed by the production of physical components from an in-house FDM system that runs 24 hours per day. Intended for engineering evaluation, FDM gives the material properties required for the evaluation of fit and function. (ibid p14)

Following the evaluation of component performance, any modifications are undertaken via the master model within the CAD system, and further FDM models produced if necessary. “In this way, product development at Dyson has become an interactive process between 3D modelling, rapid prototyping, physical testing and modification of FDM parts”. (C3, February 2000 p15) Pre-production parts are then produced using SLA components supplied by a rapid prototyping bureau.

Mills does not indicate why Dyson use SLA components for pre-production, although he does note that the components were painted prior to design approval. A reason for selecting SLA may therefore be due to its superior finishing properties.

Having ‘signed-off’ the design, mould tools are designed using component geometry from the CAD master model. A major advantage of this strategy is the capability for the toolmaker to identify any modifications, have these executed on the master model by a Dyson engineer, and then return this to the toolmaker, “in most cases, the same day”. (C3, February 2000 p15) Detailed 2D drawings are now virtually obsolete at Dyson, as toolmakers work with the 3D solid models that fully specify component geometry. 2D drawings with major dimensions are however used for checking tool design.

Whilst this case study demonstrates how Dyson integrate CAD and rapid prototyping from an engineering perspective, no reference is made to industrial
design. For a more complete overview of the strategy at Dyson, information would be needed on the specific strategy employed from concept generation through to the production of an appearance model.

Speech synthesiser
During the development of a child's portable speech synthesis computer, Rodd Industrial Design used rapid prototyping in both the design and manufacture of the product. The strategy for the integration of conventional industrial design methods with digital techniques was presented at the Solid Modelling Conference at the National Motorcycle Museum in Birmingham on 8 March 2000 at a session titled “Chameleon 3 - The Changing Face of Design”. Ben Davies, an industrial designer at the consultancy, described how the team utilised sketching and foam models during the concept generation. With a concept approved by the client, design development continued with more sketching and foam modelling, whilst the electronic components were modelled in 3D CAD using SDRC I-DEAS.

The concept was presented to a customer clinic before final approval by the client. The detail design was resolved using a conventional appearance model from which a CAD operator reproduced the final surface geometry. (C3 January 2000 p17) Having verified the CAD model, SLA components were produced to physically approve fit and function. There was a distinct division in the application of physical models at this stage, with conventional model making for appearance and interface design, and rapid prototyping for the engineering elements.

On approval of the final design, silicon moulds were created using SLA masters for the manufacture of production components. As the production volumes for the product were relatively low, injection moulding was not viable. During a question and answer session at the end of the presentation, the potential of rapid prototyping to produce appearance models was discussed. Ben Davies felt that the “rub-down tolerance” required a degree of caution as it was possible for important detail to be removed from some rapid prototype components. A solution to this was for the designer to become involved in this
Rapid prototyping phase of model-making or ensure their involvement in a briefing with the model maker.

This case study indicated that for relatively low production volumes, rapid prototyping has the capability to be used to produce complex but economical silicon mould tools.

**Instant Camera**

During the industrial design of an instant camera for Polaroid, London-based consultancy PDD undertook all initial conceptual work using conventional sketching and 3D sketch modelling. Jones et al comment that the consultancy did not believe that computers “do not encourage creativity in the early stages of design”, although his reference was to 2D digital drawing as opposed to 3D modelling. (Cooper 1995 no pagination)

During the commission, the industrial design commenced with conventional sketching, moving-on to the application of colour and tone using a 2D digital drawing package to produce renderings for client presentation. The renderings were therefore a combination of conventional sketching and digital enhancement. On approval of a design proposal, a conventional appearance model was produced. (*ibid*)

Having approved the industrial design solution, engineering design commenced with 3D CAD modelling using SDRC I-DEAS, followed by rapid prototyping using SLA. The SLA components were used to produce a working appearance prototype that enabled the evaluation of ergonomics/appearance in conjunction with the engineering design solution. Feedback from user trials resulted in modifications to the 3D CAD model.

A second appearance prototype that incorporated SLA and CNC machined components was produced for approval. On acceptance, twelve working prototypes were manufactured using SLA to create vacuum casting moulds. These appearance prototypes were required by Polaroid for dealer and distributor liaison, internal briefings and promotional literature.
As the product moved into production, the 3D CAD geometry was available for use by the toolmakers. 2D drawings were also produced as back-up information at the request of the toolmakers. As off-tool samples became available, a further set of 2D drawings were produced for quality assurance and inspection.

The accuracy and economic production of fully specified SLA components enabled vacuum casting to be used to supply pre-production prototypes in sufficient quantities for all parties involved in the design and promotion of the product, thereby facilitating maximum expert feedback.

**Summary**

- A 3D computer model is a prerequisite for rapid prototyping.

- Stereolithography is the rapid prototype build system most suited to the production of appearance models.

- The cost of a component produced using rapid prototyping is dependent on its volume, not complexity.

- Rapid prototyping can be used to produce appearance models and appearance prototypes.

- Sophisticated components can be produced in condensed time-scales via rapid prototyping.

- No methodological approach exists for the integration of rapid prototyping within the professional practice of industrial design.
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Rapid prototyping

- The use of rapid prototyping in the production of appearance models during industrial design practice has not been evaluated.
CHAPTER THREE:
Draft CAID/RP methodological approach

Draft CAID/RP methodological approach
With the exception of papers published by Cool et al (Dickens 1995 p42), Cheshire et al (Dickens 1994 pp181-190, Bennet 1995 pp1-10, Sobolewski 1995 pp 461-468) and Evans et al (Hillery 1996 pp 827-835, Dickens 1997 pp 1-7), no detailed research into the suitability of rapid prototyping for use by industrial designers was identified, despite extensive on-line searches. Reasons for this may be a consequence of both academic and commercial factors.

The lack of published material from academic sources within the UK may be related to the fact that prior to 1992, the majority of degree courses in art and design were delivered by colleges of higher education and polytechnics where the focus of activity was on teaching as opposed to research. In 1992, a change in government policy gave polytechnics and some colleges of higher education university status, providing an impetus for the development of a more extensive research culture in this field. This impetus increased as the amount of government funding awarded to the institutions became, in part, linked to the research activity quantified by the Research Assessment Exercise (RAE). As a result of the increased activity in art and design research, a number of new design-based conferences and journals emerged e.g. The Design Journal, Co-Design, National Conference on Product Design Education.
methodological approach

The lack of material published by manufacturers and consultancies is related to the highly competitive nature of new product development. As the disclosure of innovative practice in detail would reduce the competitive advantage of an organisation, there is no motivation to publish. Exceptions to this appear as articles that make general references to practice and techniques, but the aim is to promote the services of the organisation. This is particularly prevalent in C3, a popular professional magazine for CAD and CAID users.

The literature review into the nature of industrial design practice and rapid prototyping identified the potential for the integration of activities from these two areas. Appearance models form a key component of industrial design practice (Kojima et al 1991 p83, Powell 1990 p11, Pipes 1990 p58), and rapid prototyping has the potential to contribute to their production subject to the generation of an stl file. SLA has many of the properties (post-process finishing, definition of detail, mechanical properties) required for appearance models. (Dickens 1994 pp37 – 39, Dickens 1995 pp44 – 47, Dickens 1996 pp60 – 72) In addition, rapid prototyping has the potential to be utilised in the production of sophisticated appearance prototypes that integrate both the appearance and functionality of the intended production item. This arises from the fact that once defined as 3D computer geometry, rapid prototyping systems can produce component wall thickness at no additional cost. This is in sharp contrast to the expense and build times involved when producing appearance prototypes by conventional fabrication techniques.

In contrast with industrial design methods that do not employ digital techniques, the use of CAID facilitates the mathematical definition of surface geometry and immediate specification of form without the need for GA drawings or physical models. Even the most basic geometry, whether produced using a surface or solid modelling system, fully defines form and has the potential to be transferred and interpreted by others involved in the NPD process (e.g. engineering designers, manufacturing engineers). This principle of sharing computer models allows the utilisation of the master model paradigm as identified by Desbarats. (C3 March 1999 p26). Whilst modelling time will vary according to the expertise of the operator and software/hardware being
used, it cannot replicate the speed and spontaneity of the drawing techniques employed during concept generation. It takes literally seconds to visualise a complex form using pen and paper, although this does not produce a mathematical definition of the geometry. It is simply a 2D representation.

Desbarats refers to the need for industrial designers to embrace 3D digital modelling, integrating it into working practices that push forward the capabilities of the profession. (C3, March 1999 p26) To operate effectively, CAID skills must be developed that enable the translation of design intent from manual sketch to digital geometry. It is not an effective paradigm to sketch and translate design intent into a GA or appearance model, followed by its modelling by a computer operator to produce an stl file. The most effective methodological approach (as espoused by Desbarats) is for the industrial designer to produce conventional sketches, translate the selected design(s) into CAID geometry, and utilise the full range of applications available for the digital model: the capability to rapidly and realistically render the form; the knowledge that the form is geometrically viable; its representation as an exact translation of industrial design intent into a specification of form; the capability for model-share. (C3 March 1999 p26).

Having identified the conventional and digital techniques applied during professional practice, and the nature of rapid prototyping, a methodological approach for their effective integration can be proposed. A diagrammatic representation of this draft CAID/RP methodological approach can be seen in Figure 16.
The draft CAID/RP methodological approach is characterised by the retention of the conventional techniques of sketching in 2D and 3D at the beginning of the concept generation phase as they are acknowledged as the most effective means of externalising and manipulating emerging ideas. The potential to use rapid prototyping to produce sketch models was identified but dismissed as the build costs and time scales were considered excessive. (Dickens 1995 p42)

The use of digital drawing techniques such as scanning line work and applying tone and colour, or the use of a graphics tablet, could be employed during concept generation as they involve conventional drawing techniques and not the definition of 3D geometry. Having undertaken sketching in 2D and 3D to produce a product concept, it becomes appropriate to introduce CAID to model the form as 3D geometry.

To ensure that the capabilities of CAID are fully utilised, the CAID/RP methodological approach assumes that it is the industrial designer that undertakes the 3D digital modelling (as prescribed by Desbarats), thereby ensuring that their intent for the product form is not diminished. (C3 March 1999 p26). Problems of using a third party to undertake the modelling of the product form from material provided by an industrial designer have been identified by Potter who states that “not being an artist, and perhaps unaware
of some of the subtleties of shape, the engineer is likely to lose some of the designer intent”. (Potter 2000 pp21 – 28)

The commencement of CAID modelling facilitates the mathematical specification of form and the potential to share geometry with others involved in the NPD process considerably earlier than when employing conventional industrial design techniques. The ability to communicate design intent via 3D CAID geometry (model share) gives industrial designers the opportunity to become integrated within the practice of concurrent engineering that “involves all of the departments working simultaneously creating the product design, manufacturing processes, and marketing/sales plans”. (Floyd et al p89) This is in contrast with serial development that requires an individual or team to complete their work before passing it on to the next. As manufacturing engineers would not be in a position to conclude their detailing until the industrial designers had passed on their specification of form, the time-scales would be greater than if they had access to 3D geometry throughout the project. (ibid p90)

Having employed CAID during concept generation, the geometry can be rendered to produce realistic visualisations of the proposal(s), but it must be stressed that this does not necessarily require the full detailing of product components e.g. internal walls, ribs and bosses. For a presentation at the end of the concept generation phase, only details of the exterior form would be required. It is therefore only necessary to model the surfaces that would be seen in the rendered views, thereby simplifying the process significantly.

When the proposals emerging from concept generation have been presented, the client must make a decision as to which will be progressed during design development. When this decision has been made, the CAID geometry that was previously generated during concept generation would be available for design development, thereby providing a more advanced starting point for further modelling than would be the case with conventional techniques.
As design development progresses using a combination of CAID and conventional drawing techniques, the product would become more fully defined. Whilst the role of detailing components in terms of design for manufacture (DFM) would generally be undertaken by an engineering designer, CAID software has the capability to generate wall thickness on components, usually by off-setting the exterior surface and trimming the resulting gap to produce a closed volume. As industrial designers work extensively on products that are manufactured by processes that create internal cavities (e.g. injection moulding, rotational moulding, pressure die casting), walls can be modelled for such components.

On completion of design development, the final proposal would be presented to the client as a CAID rendering(s). If the design were not approved at this stage, further development would be required. A feedback loop has been included in the draft CAID/RP methodological approach to facilitate this. The client would again be required to approve the design presented via renderings before geometry was released as a formal specification of form.

In contrast with the conventional industrial design methodological approach, the use of CAID facilitates the precise mathematical specification of form for whatever surface is defined. Whilst the use of CAID would normally start during the latter stages of concept generation, the final specification of form would not be complete until the conclusion of design development and client approval. The CAID data would then be used to produce an appearance model or appearance prototype for final approval by the client. Once approved, the CAID component geometry would be formally released as a specification for the preparation of production tooling.

**Questionnaire**

The literature review of Chapters 1 and 2 identified a correlation between the modelling requirements of industrial designers and the capabilities of rapid prototyping, but no published data were available on the extent to which
industrial designers were using rapid prototyping and detailing how they were using it. A survey of practitioners was therefore initiated to resolve this issue and obtain feedback on the CAID/RP methodological approach.

The questionnaire invited responses on the number of models produced using rapid prototyping; systems used; a judgement comparing rapid prototyping with conventional fabrication techniques; who undertook the computer modelling; the computer modelling strategy employed. In addition to questions that focused on appearance models and appearance prototypes, responses were also sought on any other applications for rapid prototyping and 3D computer data. The concluding section of the questionnaire invited comment on the proposed CAID/RP methodological approach.

Prior to the survey, the questionnaire was piloted with industrial designers from Flymo and Black and Decker, leading to minor modifications in the layout of the form to increase clarity. The revised questionnaire was sent to all industrial design consultancies registered with the UK’s Chartered Society of Designers. 173 questionnaires were posted to the senior industrial designer within each consultancy. The questionnaire employed in the survey can be seen in Appendix 1.

In an attempt to secure the highest possible return, the questionnaires were posted in a hand-written envelope with a covering letter and postage paid envelope for its return, this having been identified by Burns as a means of securing the best possible response rate. (Burns 2000 p580)

Of the 173 questionnaires posted, 35 were returned, representing a response rate of 20%. Burns indicates that a typical response rate for a postal questionnaire is between 15% and 50%. (ibid p581)

The questionnaire was divided into seven sections. Section A identified whether or not industrial designers were using rapid prototyping. Section B focused on the use of rapid prototyping in the production of appearance models, asking whether industrial designers were using rapid prototyping to produce such models and which systems were employed. A comparison with
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conventional fabrication techniques was requested, with the opportunity for further comment. Who was responsible for the computer modelling, software used, and the degree of difficulty in generating the stl file was also asked. Section B concluded by identifying how the computer modelling was undertaken and why that particular strategy was employed.

Section C addressed questions identical to those of section B, but focused on appearance prototypes as opposed to appearance models. Section D was to identify if rapid prototyping was being used for any other forms of physical model/prototype, and Section E any downstream CAD/CAID data applications other than rapid prototyping. Strengths and weaknesses of rapid prototyping were requested in section F, followed by feedback on the CAID/RP methodological approach.

**Questionnaire responses**

**Use**

Question A1 asked “Have engineers in your organisation used rapid prototyping during the development of products?” and sought to identify which professional group was using this technology. The question addressed general use, making no reference to who was producing the 3D geometry. Responses to question A1 indicated that 69% of the consultancies had experience of engineers using rapid prototyping (see Figure 17), and from question A2, that 83% had experience of industrial designers using rapid prototyping (see Figure 18).
Figure 17: Response to question A1: Have engineers in your organisation used rapid prototyping during the development of products?

Figure 18: Response to question A2: Have industrial designers in your organisation used rapid prototyping during the development of products?
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Appearance models

The appearance model represents a key outcome from industrial design practice as it plays an essential role in the specification and approval of product form. Responses to question B1 indicated that 58% of the consultancies had used rapid prototyping to produce appearance models (see Figure 19), with 43% of these using it for two to five projects, and 50% for five or more projects (see Figure 20).

Figure 19: Response to question B1: Have industrial designers in your organisation used rapid prototyping to produce non-working appearance (block) models?
Figure 20: Response to question B1(ii): For how many projects (have industrial designers used rapid prototyping to produce non-working appearance (block) models)?

Findings from the literature review on rapid prototyping systems indicated that SLA was the build system most suited to the needs of the industrial designer. This was confirmed by the results to question B2 indicating that this process was used most by the consultancies in the production of appearance models (62%). 19% had used LOM, 14% SLS, 5% FDM and none had used SGC. A bar graph representation of the findings can be seen in Figure 21.
Figure 21: Response to question B2: Which rapid prototyping system was used (by industrial designers to produce non-working appearance (block) models)?

In question A3, those consultancies that had experience of more than one rapid prototyping system were invited to comment on which they felt was most suitable for the production of appearance models. The responses concurred with the published material on the capabilities and limitations of the build techniques: SLA gave good detail and general quality of components; LOM was appropriate for large components; SLS was suitable for components with hinges and snap-fits (e.g. engineering applications).

When asked to comment on how the outcome compared with conventional fabrication techniques (question B4), the reaction to rapid prototyping was overwhelmingly positive, with 79% regarding it as being superior. 14% saw it as being about the same, and 7% as worse. (see Figure 22).
Figure 22: Response to question B4: How did the outcomes (using rapid prototyping to produce fully working appearance prototypes that combine product appearance) compare with conventional fabrication techniques?

The two key reasons for its superiority were due to the reduced lead times and the fact that the models were an exact reproduction of the 3D computer geometry. Other reasons given were that it cost less than conventional techniques, did not require the preparation of engineering drawings, and gave confidence in the fit and tolerances of components. The level of hand-finishing required for SLA components was considered to be about the same as that for conventional fabricated components, although the stepping was considered to be a disadvantage.

As a precursor to a rapid prototype component build, a 3D computer model must be generated. This would typically be produced using a CAD or CAID system, although other techniques such as cloud-point scanning could be used.
The rigorous modelling required to generate an STL file suitable for rapid prototyping necessitates a competency in the use of CAD or CAID. For industrial designers with limited skills in this area, or consultancies without an in-house 3D computer modelling capability, a third party would undertake this task. Responses to question B5 indicated that in 86% of the consultancies, an industrial designer produced the 3D computer model for rapid prototyping (see Figure 23).

Figure 23: Response to question B5: Was the computer modelling for the rapid prototypes undertaken by the industrial designer of the product?

Question B6 identified the software used by the industrial designers to produce the STL file for rapid prototyping. Of the systems used, only two were CAID packages (Alias and Form Z), with the majority being solid modelling CAD software such as Pro-Engineer and IDEAS. The bar graph representation of the findings to question B6 (Figure 24) uses the following abbreviations: Pro-E (Pro-Engineer), Acad (Autocad), Mdesk (Mechanical Desktop), Uni-g (Unigraphics) and S-work (Solidworks).
There were no significant problems in the industrial designer producing the STL files, with 92% of the consultancies indicating that it was straightforward, and only 8% finding it moderately difficult (see bar graph in Figure 25). However, it must be noted that the majority of these industrial designers were using solid modelling software that, whilst making the production of STL files relatively straightforward, are acknowledged as being less suitable for the generation of the freeform geometry required by industrial designers. It would have been a useful addition to the questionnaire if those who found the production of STL files moderately difficult had been asked to indicate which software they were using.

Figure 24: Response to question B6: What software was used by the industrial designer?
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Figure 25: Response to question B7: How difficult was it for the industrial designer to generate the STL files (for the appearance (block) model)?

Question B8 was directed at the 14% of consultancies that did not use an industrial designer to produce the 3D computer models for rapid prototyping. Of these, 100% employed a CAD/CAID operator who worked from engineering drawings produced by the industrial designer (see Figure 26).

Figure 26: Response to question B8: How was the CAD modelling undertaken?
Appearance prototypes

Appearance prototypes made using conventional fabrication techniques are notoriously time consuming to produce, and as a consequence relatively expensive. (Kochan 1993 p5) As rapid prototyping has the capacity to produce components in reduced time scales, and cost is based on volume as opposed to complexity, they have the potential to make a significant contribution to the production of appearance prototypes. This was confirmed in the response to question C1, indicating that 100% of those consultancies using rapid prototyping had used it to produce appearance prototypes. Experience of using rapid prototyping for appearance prototypes was less than that of appearance models, with 29% of the consultancies having used it for one project, 29% for between two and five, and 42% for five or more. A bar graph representation of the findings can be seen in Figures 27 and 28.

![Bar Graph](image)

Figure 27: Response to question C1: Have industrial designers in your organisation used rapid prototyping to produce fully working prototypes that combine product appearance?
Figure 28: Response to question C1(ii): For how many projects (have industrial designers used rapid prototyping to produce fully working prototypes that combine product appearance)?

The rapid prototyping systems used reflected the findings from the literature survey, with SLA being the most popular at 76%. The poor definition of detail obtained from LOM may have contributed to only 3% using this process. A bar graph representation of the findings can be seen in Figure 29.
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Figure 29: Response to question C2: Which rapid prototyping systems were used (by industrial designers to produce fully working prototypes that combine product appearance)?

As with appearance models, those consultancies with experience of more than one rapid prototyping system felt that SLA was the most suitable due to its material/finishing properties.

Question C4 asked “How did the outcome compare with conventional fabrication techniques”? 88% of the consultancies using rapid prototyping for the production of appearance prototypes found it superior to conventional fabrication techniques, 4% found it to be about the same, and 8% found it worse (see Figure 30).
Figure 30: Response to question C4: How did the outcome (using rapid prototyping to produce fully working appearance prototypes that combine product appearance) compare with conventional fabrication techniques?

In offering an explanation for the response to question C4, the most consistent reasons given for its superiority were identical to those for appearance models i.e. exact reproduction of the 3D CAD model and faster build time. Other reasons given were accuracy, lower cost, and high level of detail.

A similar number of consultancies that employed an industrial designer to undertake the 3D computer modelling for the appearance model (86% in Figure 23) did so for the appearance prototype (88%). A bar graph representation of the findings can be seen in Figure 31.
Figure 31: Response to question C5: Was the computer modelling for the rapid prototypes undertaken by the industrial designer of the product?

Software used for the 3D computer modelling of the appearance prototype was similar to that used for the appearance model, with Pro-Engineer again being most popular with a response of 27% (question C6). Two packages that had not been used for the modelling of the appearance model had been employed in the production of the appearance prototypes, these being X-CAD (Xcad on bar chart) and Varimetrix (Vmet on bar chart), both of which are solid modelling CAD systems (see Figure 32).
When asked to comment on the effort involved in the generation of the stl files, their production for appearance prototypes was considered to be more difficult than for appearance models. This was not entirely unexpected as additional modelling effort is required to produce the internal details required for an appearance prototype. The results from question C7 indicated that 81% found the modelling straightforward for appearance prototypes (compared with 92% for appearance models), and 19% found it moderately difficult (8% for appearance models). A bar graph representation of the findings can be seen in Figure 33.

Figure 32: Response to question C6: What software was used by the industrial designer?
Figure 33: Response to question C7: How difficult was it for the industrial designer to generate the stl files (for the appearance prototype)?

Those consultancies that did not use an industrial designer to produce the stl files were asked to identify how the modelling was undertaken. As with appearance models, 100% used a computer modeller who worked from engineering drawings supplied by the industrial designer (see Figure 34).

Figure 34: Response to question C8: How was the CAD modelling undertaken?
Reasons for using a computer modeller to produce the stl file instead of an industrial designer were provided by question C9. The predominant reason was being that they did not have the necessary skill to undertake the task.

Other Models
Findings from the literature review indicated that the construction of appearance models and appearance prototypes could benefit from the use of components produced via rapid prototyping. 88% of those industrial designers using rapid prototyping had used it for appearance models and appearance prototypes. Question D1 identified any other applications for rapid prototyping, the most popular of which being for the production of prototypes to evaluate mechanical function only. The complexity of such prototypes would be dependent on the industrial designer's capabilities both as an engineering designer and computer modeller. A bar graph representation of the findings can be seen in Figure 35.

![Figure 35: Response to question D1: Have industrial designers in your organisation used rapid prototyping to produce any other type of model?](image)

Figure 35: Response to question D1: Have industrial designers in your organisation used rapid prototyping to produce any other type of model?
Data generated through the use of 3D CAD and CAID has applications other than for rapid prototyping, and question E identified the extent to which this was applied (see Figure 36).

![Bar graph](image)

**Figure 36: Response to question E: Have industrial designers in your organisation produced 3D CAD models (surface or solid) that were used in applications other than rapid prototyping?**

From the responses given, 20% had used 3D computer modelling for rapid prototyping only, and of the remaining 80%; 26% had used it for product visualisation; 18% for tooling; 16% for promotional packaging/graphics; 14% for surface definition for engineering development; 14% for CNC machining; 12% for finite element/mould-flow analysis. No other applications were identified. A bar graph representation of the findings for question E1, can be seen in Figure 37, with abbreviations for product visualisation (visual); promotional packaging/graphics (promo); CNC machining (CNC); engineering development (eng. Dev); finite element/mould-flow analysis (FEA).
Figure 37: Response to question E(ii): How were the data (3D CAD models that were used in applications other than rapid prototyping) used?

Strengths and weaknesses

General comments on the strengths and weaknesses of rapid prototyping were sought in question F. The reduced lead times for models and components was considered the most common strength of rapid prototyping. Accuracy was considered another important characteristic, this being related to the fact that the rapid prototype component was an exact copy of the design as seen on the computer monitor (within build tolerances). Cost effectiveness also featured as a significant strength, along with the continuity of the 3D CAD data when used for other applications such as rendering.

The overall reaction to rapid prototyping appeared positive, but weaknesses were identified. The major disadvantage was the requirement for additional surface finishing to remove the stepping. This was of course a function of the layer-based build process which was directly related to the build time and ultimately cost. An inability of some rapid prototyping systems to closely represent production materials was also considered to be a disadvantage.
Draft CAID/RP methodological approach feedback

A key finding from the questionnaire was that whilst rapid prototyping appeared to have the potential to make a significant contribution to the production of appearance models, 42% had not used it in their production. It is relevant to note that industrial designers have access to some form of model-making resource, varying in sophistication from simple sketch modelling in card with a craft knife to a full prototyping capability. It is also significant that from the 58% of consultancies that had used rapid prototyping, only 50% of these had employed it on 5 or more projects. Use and experience was therefore relatively low.

The use of rapid prototyping for the production of appearance models was greater than that for appearance prototypes, with only 42% using it for 5 or more projects. However, it must be acknowledged that the production of physical models and prototypes has a commercial function within many consultancies where investment has been made in the capital equipment for their fabrication. It is therefore necessary to question the benefits of employing rapid prototyping from a financial perspective as its use necessitates the bulk of the cost being sub-contracted to a bureau due to the high capital expenditure required for an in-house rapid prototyping machine. If consultancies with an established conventional workshop generate revenue by undertaking model making, profits may be reduced if a significant shift to the use of rapid prototyping through sub-contractors is introduced.

Feedback on the CAID/RP methodological approach was positive, with comments concurring with the overall rationale. Comments included an acknowledgement that the cost of rapid prototyping would be prohibitive during concept generation, and a confirmation of the importance of the model-share capability for engineering and production design.

A useful comment from the head of a leading industrial design consultancy referred to the need to have a feedback loop from the appearance model/appearance prototype back into design development, as the evaluation
of physical models/prototypes may result in a requirement for remedial design work. This loop had not been considered when devising the draft CAID/RP methodological approach, and its addition was considered to be a significant enhancement, particularly when the use of rapid prototyping would enable modifications to be executed in shorter time scales than when employing conventional fabrication techniques. A diagrammatic representation of the revised CAID/RP methodology with the additional feedback loop can be seen in Figure 38.

Figure 38: Revised CAID/RP methodological approach

Whilst the findings from the practitioner survey indicated that industrial designers were actively using rapid prototyping, and confirmed the significance of the revised CAID/RP methodological approach, it could not provide detailed information on its use or offer a direct comparison with conventional fabrication techniques. As this information was not available through published sources, a design-based case study was initiated to resolve the lack of knowledge in this area. Details of the case study are discussed in Chapters 4 and 5.

Summary

- Industrial designers are using rapid prototyping in the production of appearance models and appearance prototypes.
• The experience of industrial designers in the use of rapid prototyping to produce appearance models and appearance prototypes is limited.

• SLA is the most popular rapid prototyping technique for the production of appearance models and appearance prototypes by industrial designers.

• The outcome from the use of rapid prototyping is superior to that of conventional fabrication techniques.

• It is more difficult for industrial designers to produce stl files for the production of appearance prototypes than appearance models.
CHAPTER FOUR:
Case study – concept and modelling

Case study structure
The structure and content of the revised CAID/RP methodological approach was based on findings from the literature review (Chapters 1 and 2), and feedback from the practitioner survey (Chapter 3). To fully evaluate the effectiveness of this methodological approach and identify any shortcomings, it was necessary to apply this during an industrial design case study.

The case study was divided into two phases. The first (discussed in this Chapter) involved the origination of the product concept, its modelling using a variety of techniques, and concluded with the production of STL files for components to be produced using rapid prototyping. In the second phase (discussed in Chapter Five), physical models and prototypes were produced to fully evaluate the capabilities and limitations of rapid prototyping. This involved a direct comparison between an appearance model produced using rapid prototyping and one produced using conventional fabrication techniques. To achieve this, two identical appearance models were produced for the product proposal using both construction techniques. In addition, an appearance prototype was also produced as the literature review and practitioner feedback indicated the effectiveness of using rapid prototyping in their production.

The physical models/prototypes produced as outcomes from the case study were therefore:
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• Appearance model produced using rapid prototyping

• Appearance prototype produced using rapid prototyping

• Appearance model produced using conventional model making techniques

Details of the comparative evaluation between the models and prototype is discussed in Chapter 5 (pp 159 – 194).

Product origination

Prior to becoming a member of academic staff at Loughborough University, the author was employed as the principal industrial designer for a major manufacturer of powered garden products. After joining the University, a competitor had offered a consultancy commission to undertake the ergonomic evaluation and associated industrial design for a new nylon line trimmer. The consultancy did not proceed due to corporate restructuring, but the previous experience in this product sector coupled with a commercial need for design improvements, resulted in a nylon line trimmer being selected for the case study.

It would have taken less time to design a product that required a simple enclosure to house electronics, or a product requiring no electro-mechanical components, but it was considered essential for the product used in the case study to be relatively demanding in terms of form and function. The fact that the appearance prototype for a nylon line trimmer would be subjected to high frequency vibrations and flying debris was considered particularly appropriate in the evaluation of the capabilities of rapid prototyping.

The configuration of the nylon line trimmer could have been based around that of an existing product, but to ensure that the revised CAID/RP methodological approach closely followed a commercial design exercise, a complete re-design was undertaken, involving the analysis of existing products in the identification
of opportunities for improvement. (Archer 1963 p6) This strategy provided the potential to include a degree of functional innovation as opposed to appearance alone, thereby adding significant design and modelling challenge to the case study.

**Analytical phase**

**Market survey**
A survey of the nylon line trimmers available at retail point of sale in large DIY multiples (e.g. B&Q, Do It All) and independent retailers was undertaken. The dominant brands at point of sale were Black and Decker and Flymo, with the occasional McCulloch, Bosch, Ryobi, and Qualcast product.

The majority of machines were powered by mains electricity, but battery and petrol products were also available. Prices ranged from £22.00 to £103.00 for mains and battery products, and £85.00 to £300.00 for petrol. As the petrol machine price range was considerably higher than that of the electric, and the underlying operating principles were quite different, these were excluded from the case study. The re-design was to be based around an electric product.

The in-store evaluations and manufacturer’s literature enabled the key features of the products to be identified for inclusion in a user questionnaire.

**Questionnaire.**
A questionnaire was devised to establish general patterns of use and opinions on features prior to more detailed observed user trials. The questionnaire provided specific data on patterns of use and product features. Of particular interest was the handle configuration as several machines had some form of secondary device for additional support. The questionnaire can be seen in Appendix 2.

The questionnaire was distributed at random using the internal telephone directory to two hundred staff on the Loughborough University Campus. As a means of economically targeting potential users of nylon line trimmers, this
strategy was adopted as the group represented a broad mix of occupations (e.g. skilled manual, clerical, managerial, professional) that were in employment (with the associated likelihood of being homeowners with gardens). There was also considered to be a high probability of this group participating in the survey, which was confirmed when a response rate of 38% was achieved.

Key findings from the questionnaire indicated that 94% of users with products that had a rotating motor housing for lawn edging felt that this feature was useful. In addition, 55% of the products used had some form of secondary handle for additional support, and 100% of the users with this feature felt that this was useful.

The responses to the list of features identified in question 15 were between average and excellent for weight, length, balance, handle, and switch. This was in contrast to a predominantly average response (with a bias towards average and poor) for comfort. There was therefore a perception that whilst users regarded the individual features as being above average, when viewed as a whole they were in some way deficient as the products were generally regarded as being uncomfortable during use. A means of improving the comfort of the nylon trimmer was therefore identified as a key objective and a specific focus of the industrial design.

Home Accidents Surveillance ID System (HASS) data
HASS data on nylon line trimmers was used to establish if any of the accidents correlated with product features. (HASS ID System 1990, 1991, 1992) The majority of incidents involved material being thrown-up by the rotating line and hitting either the user or bystander, implying inadequacies in the design of the cutter guard or misuse. Some of the incidents were only tenuously related to line trimmer use, such as “Patient was bitten by a horse fly while using a trimmer to cut lawn”. (ibid 1992 ref. 8704)

With the exception of the potential to integrate the design of an improved cutter guard on some products, the HASS data proved to be of limited relevance.
Product user trials

Four products were selected for detailed evaluation during product user trials. The Flymo Mini-Trim (250 Watt) was priced at £24.50 and selected because of its unusual wrist support. This was a mains operated product with a 200mm cutting width. The construction was based around a plastic handle, steel stem, and fixed plastic cutting head. The centre of gravity was 590mm from the switch (Figure 39).

![Figure 39: Flymo Mini-Trim and centre of gravity](image)

The Black and Decker GL565C cost £44.75 and was of a similar construction to the Flymo but differed in its positioning of a secondary support in front of the main handle. Whereas the secondary support on the Flymo Mini-Trim gained leverage from its contact with the user’s wrist, for the GL565 it was necessary to grip a secondary support at 90 degrees to the main handle. There was also the capability to adjust the distance of the secondary handle from the main handle. The GL565C had a 260mm cutting width, 340 Watt motor, and the switch was located 695mm from the centre of gravity (Figure 40).
The Ryobi RCT425B was the most expensive and most powerful of the products. It cost £102.95 and had a 500 Watt motor with a 300mm width of cut. It was selected for evaluation in the user trials as it was the only electric machine available with the motor positioned behind the handle. It was of similar construction to the Mini-Trim and GL565C, and had a flexible drive to take the rotary motion from the motor to the cutter head. Like the GL565C it had an adjustable secondary handle, but the main handle was orientated in line with the steel stem. The centre of gravity was 220mm from the switch (Figure 41).

The Black and Decker GLC400 was the only battery operated product selected for the user trials. It cost £78.49, and had a 230mm cutting width. The construction was based around two large plastic injection mouldings, and had a centre of gravity 290mm from the switch (Figure 42).
The user trials were devised to identify general merits and deficiencies of the four products, and as relatively detailed studies that included observations and interviews, a sample size of sixteen subjects (with previous experience of using a nylon line trimmer) was considered sufficient for this purpose. The conduct of the trial involved each subject being advised of the procedure, instructed in the use of the machine, and given an opportunity to use the product before the trial began.

The subjects were informed that they would be asked questions on the following attributes after using the products: comfort of handles; general handling and control; balance; comfort of switches; noise/vibration; safety, appearance.

The trial was undertaken in a three metre square frame, with the subjects cutting grass and weeds on the inside and outside edge, and around five plastic tubes (to simulate trees). The average height of grass for the user trial was 70mm. The user trial test area is shown in Figure 43 and user trial taking place with the Ryobi RCT425B in Figure 44.
Figure 43: User trial test area

Figure 44: User trial with the Ryobi RCT425B
Following the use of a product, the user immediately moved on to the next. The order of use for each machine was systematically changed for each user to avoid anomalies due to order effects. On completion of the trials with the four products the users were asked to comment on product features and use.

Results from the questionnaire indicated that the Black and Decker GLC400 had the preferred handle configuration (69%), balance (44%), shape (69%), ease of use (56%), and comfort in use (44%). The Black and Decker GL565C had the preferred switch system (50%), and the Ryobi RCT425B the preferred length (50%). Black and Decker green was the preferred colour (88%).

Key conclusions from the user trials were that the perception of comfort when using nylon line trimmers had a correlation with the balance of the product. Whilst the Ryobi RCT425B was the heaviest product it was rated as the second most comfortable, with a response of 31%. This was due to the machine being relatively well balanced, having the centre of gravity closer to the switch than any other machine.

In terms of identifying an innovative feature for the design-based case study, the issue of user comfort represented a key issue. This was to be addressed by designing a product that had its centre of gravity either on or as near to the handle as possible. In addition, as the cordless product made a major contribution to the perception of ease of use (GLC400 56%), that used in the case study was to be battery powered.

Product Proposition
The market survey, questionnaire, accident study, and product user trials provided an insight into nylon line trimmer design and use. The product user trials were particularly productive as they identified specific features for which improvements could be made.

In moving the centre of gravity to the handle, a fundamental rethink of the mechanical configuration was required as both the dc motor and battery would have to be positioned behind the handle so that their combined weight would
balance the components used on the stem and cutter. This configuration would require a flexible drive shaft to take the rotary action of the motor to the cutter.

The design would be manufactured using techniques similar to those of existing products, with the basic production methods incorporating injection moulded housings connected by a metal stem. Whilst the Black and Decker GLC400 required only two structural injection mouldings, the size of these components was at the limits of the production process and larger sizes would be required as the user trials indicated that the larger Ryobi machine had the preferred length. As the GLC400 was considered to be too short, the metal stem construction would allow the product to be of greater length.

Prototype
Before commencing the industrial design it was necessary to prove the viability of the product configuration that involved the cutter being driven by a motor positioned behind the handle. A prototype was produced to identify and resolve any problems. As the industrial design of the product had not yet been undertaken, the prototype could not embody appearance. It was simply an engineered assembly of functional components that could be used to evaluate performance and weight distribution.

To ensure that the weight of the prototype did not exceed that of the production item, aluminium was used for the bulk of the structure. The assembly techniques allowed access to the battery and motor, enabling any adjustments to be as straightforward as possible.

The flexible drive shaft was inserted through an aluminium tube with bends at the base and top, and the motor and battery supported on an aluminium frame. A nylon bush housed the bearing on the flexible drive shaft where it was attached to the spool for the nylon line. Expanded foam was used to increase the diameter of the handle.

The prototype proved to be an effective means of evaluating the basic ergonomic and engineering principles, and gave considerable confidence in the viability of the overall concept. It was particularly important to explore the
improvements in user comfort afforded by positioning the centre of gravity at the handle. Figure 45 shows the prototype undergoing technical evaluation.

![Prototype evaluation](image)

**Figure 45: Prototype evaluation**

**Concept generation**

Whilst it would have been possible to undertake some form of concept generation using CAID, at a time when form is being rapidly developed conventional sketching remains the most effective tool available. (Pipes 1990 p88, Co Design 04.05.06 1996 p22) Simple pen and pencil line-work was employed to generate the basic industrial design concept of the line trimmer, with the occasional use of sketch rendering (Powell 1990 p70). An example of a sketch rendering produced during concept generation is shown in Figure 46.
Much of the early sketching was in perspective, but as the design progressed this evolved into increasing numbers of elevational views that were necessary to ensure that the components could be housed within the exterior profile.

A total of twenty five hours of conventional sketching was required to generate the basic product concept, concluding with the production of simple elevational information that could be used to produce a sketch model in Styrofoam. Whilst the sketch model was needed for the physical evaluation of form, its production involved more than simply translating information embodied within the elevational drawings. Having been presented with an opportunity to sculpt and manipulate the form by hand, changes to the appearance of the product emerged through the direct interaction with material and the 3D foam. Specifically, the handle diameter was reduced towards the rear, the chamfer on the battery/motor housing increased, and the doming of the air intakes became more pronounced.

The production of sketch models for the handle and cutter guard took four hours of workshop time, requiring the use of a band-saw, sanding disc and abrasive pads. The sketch model for the handle can be seen in Figure 47.
With the basic product configuration defined using 2D sketching and confirmed using conventional sketch modelling, a high-level CAID system was used to translate the concept into 3D digital geometry and the addition of further detail. Having previous experience in the use and capabilities of the Finish DeskArtes system, and specialist technical support available through David Cheshire, a lecturer at Staffordshire University, this software was selected for the CAID modelling.

As the CAID modelling involved the interpretation of a form that had been defined using sketching and sketch modelling, it was necessary to identify the engineering reference points. This was achieved by modelling the battery and motor in CAID prior to the definition of any exterior surfaces. This was necessary to prevent any clashes of components with the exterior surfaces and to define a volume around which the industrial design surfaces must fit.

During the modelling of the exterior it was not intended to copy the shape of the sketch models exactly, but recreate the general form and allow emergence as defined by Edmonds and Soufi during the CAID modelling. (Design Studies Volume 2 Issue 2 1998 pp451 – 463)
3D modelling using the DeskArtes CAID system involves the input and manipulation of projection curves, cross sections, and secondary projections. The basic projection curves produced for the battery compartment/motor housing are shown in Figure 48, and for the cutter in Figure 49.

Figure 48: Projection curves for battery compartment/motor housing of line trimmer handle

Figure 49: Projection curves for line trimmer cutter
When sufficient projection curves had been produced to define the 3D form, surfaces were “built” as wire-frame or shaded surfaces. The 3D wire-frame views had the benefit of allowing the designer to see right through the model and were relatively economical in terms of computer processing power. The production of shaded views required greater processing power, but enabled the visualisation of the form as an exterior surface and its rotation in real time. Having defined the exterior surfaces of the concept, they were rendered using the functionality of the DeskArtes software (see Figure 50).

Figure 50: Renderings of the concept proposal

Concept evaluation
The key outcomes of concept generation activity were introduced to users that had been involved in the product user trials. As a period of fifteen months had passed since the user trials, some of the individuals had either retired, graduated, or were unavailable for an additional interview. It was therefore only possible to undertake the concept evaluation with nine of the original sixteen participants, but as an opportunity to receive detailed feedback on the concept
proposal, the exercise was still considered as representing a valuable opportunity to receive user feedback.

The Outcomes of the concept generation exercise were presented in a format that enabled the users to understand specific features of the concept proposal, consisting of renderings to define product appearance, foam models to give an indication of physical form, and the prototype for the assessment of performance and weight distribution.

Before the concept proposal was evaluated, the users were invited to re-familiarise themselves with the products that had been used during the user trials. This involved handling the products, switching them on, and cutting grass for one minute. On completion of the re-familiarisation exercise, presentation of renderings, interaction with the sketch model, and use of the prototype, the participants were invited to comment on the proposal. This involved answering questions on key features such as handle orientation, length/balance, appearance, handle comfort and overall dimensions.

Without exception, the major features of the prototype received a positive response, indicating that the balanced weight distribution was an improvement on existing configurations. Six out of the nine users felt that the effort required to maintain the correct cutting position was acceptable, and five believed that the prototype required less effort than the best of the products from the previous trials. As the concept proposal was balanced at the handle, no secondary handle was required. This proved to be a positive feature as six of the users felt no need to use their other hand to support the product.

Responses to the CAID renderings were generally in favour of the concept proposal. The only feature that received a negative response was the colour, for which six felt it was poor.

Whilst both the prototype and renderings enabled the subjects to gain an indication of what it would be like to hold the design concept, they were by no means complete. In providing additional design information, the foam sketch model was extremely useful in communicating the physical form of the handle,
although it could not give the user feedback on product balance. Seven of the nine users found the comfort good, and six did not want any of the dimensions to be changed.

By giving the users an opportunity to provide "any other comments", a mismatch in the orientation of the handle on the computer renderings and prototype was discovered. The angle on the renderings was steeper and pointing more towards the ground. This was not liked, and cross referencing with the product user trials indicated the same result for the products evaluated with a similar configuration. Modifications were therefore required to ensure that the handle orientation of the prototype was depicted in the renderings.

The users were also asked if they felt that the design concept was an improvement on the product that they preferred in the product user trials. Only two out of the nine felt that the design concept was not an improvement.

**Design development**

Design development of the line trimmer involved the implementation of the handle modification (as identified during user feedback) and attention to visual details on the cutter guard and handle. Development work was also undertaken to explore alternatives to the colour that had been presented during the concept evaluation.

The modifications to the form were undertaken using conventional sketching followed by CAID modelling and rendering. A rendering of the handle for the developed proposal can be seen in Figure 51, and for the cutter guard in Figure 52.
Figure 51: CAID rendering of handle produced on completion of design development

Figure 52: CAID rendering of cutter produced on completion of design development
Specification

As the modelling of the components had been undertaken using the DeskArtes CAID system, 3D geometry was available at the outset of this activity, thereby providing (if required) a full specification of the surface geometry. Had conventional industrial design techniques been employed, it would have been necessary to specify the developed proposal with GA drawings.

The CAID system modelled in 3D, but the surfaces generated had been used primarily for rendering. As no internal detail had been modelled, the surfaces were unsuitable for the direct translation to the stl file format required for rapid prototyping. Further CAID modelling was therefore needed to give the components the required wall thickness.

To generate the wall thickness, the basic build curves used to produce the rendering were copied and off-set (moved) by 3mm. This gave an open volume that could be trimmed with the relevant projection curves. On several occasions the stl verification software within DeskArtes identified errors due to surfaces that were not completely enclosed. Additional corrective remodelling was therefore required. In contrast with the production of the CAID renderings, the additional modelling time required to generate the walls for rapid prototyping was significant, taking a total of four hours.

The CAID modelling required for the two outputs of rendering and stl files were quite different. Whilst rendering can be relatively crude, with a focus on the visual outcome, the generation of stl files necessitates far more rigour. A means of resolving this issue would be to have some form of functionality within the CAID software that could translate the component surfaces used for rendering into walls and ultimately an stl output. Unfortunately, the automatic definition of such complex geometry is not at present possible.

Having completed the additional modelling required for the production of stl files for the line trimmer components, the surfaces were rendered to confirm their suitability. A rendering of these components can be seen in Figure 53.
Many CAD and CAID software packages have the capability to translate the fully specified component geometry directly into an stl file format. Those without this functionality may use the services of a rapid prototyping bureau. As the DeskArtes software had this capability, the procedure was immediate, and no errors in the components identified.

**Summary**
A systematic evaluation of existing products resulted in a proposition for an innovative nylon line trimmer.

Prior to commencing the industrial design it was necessary to ensure the viability of the proposal through the production of a prototype.

Simple sketching and sketch rendering was required to generate the industrial design concept.

Sketch modelling was required to illustrate the suitability of the basic 3D form.

Rapid prototyping could not contribute to the production of the physical sketch model.

Simple CAID modelling enabled the production of renderings at the conclusion of the concept generation phase.

Significant additional effort was required to produce the stl files required for rapid prototyping.
Rapid prototype components

Findings from the literature review (Chapter 2) indicated that SLA would be the most suitable rapid prototyping build technology for integration into industrial design practice. This was based on component cost, post-process finishing, surface definition, and structural integrity. Results from question B2 of the practitioner survey (Chapter 3) indicated that SLA was the most popular system for the production of appearance prototypes, with 62% of those consultancies that used rapid prototyping having experience of this process. The second most popular was LOM at 19%.

SLA was therefore used in the comparative evaluation of physical models and prototypes, and as the practitioner survey indicated that LOM was the second most popular process, a decision was made to compare and contrast this with SLA. To achieve this, a full set of line trimmer components were produced using both SLA and LOM rapid prototyping systems.

LOM Components

A complete set of components were produced by the Advanced Technology Centre at the University of Warwick using a Helysis LOM machine with a 0.1076mm paper thickness (see Figure 54).
The total build time for the components was 31 hours, and the commercial price for the components £2157. This cost did not include the component break-out during which surplus material was removed. Figure 55 shows the break-out of the convex surfaces on the cutter guard that proved to be a relatively straightforward procedure.
In contrast, the concave surfaces on the underside of this component proved to be significantly more difficult due to problems gaining access with the break-out tools (see Figure 56).

![Figure 56: Break-out of the concave surfaces of cutter guard](image)

Difficulties were experienced with all components that had concave surfaces or cavities such as the battery housing, cutter guard release and motor housing. Figure 57 illustrates the difficulties experience of gaining access to the relatively deep cavity of the battery cover.

![Figure 57: Removal of waste material from battery cover](image)
The total break out time for the LOM components was four hours. A photograph of the complete set of LOM components can be seen in Figure 58.

Figure 58: Complete set of LOM components

SLA Components

SLA components for the rapid prototype appearance model were produced by 3D Systems using an SLA 500 machine. The components took 10 hours to produce at a build thickness of 0.1mm. The commercial cost for a complete set of components was £1500.

On completion of the build, support structures and excess resin were removed and components cured in an ultraviolet cabinet for one hour. After delivery of the components it was necessary to remove the stepping that resulted from the build process. A smooth finish was achieved using wet and dry paper, taking care not to distort the form as specified in the CAID geometry. This operation required an additional two and a half hours of workshop time.
Comparative evaluation between LOM and SLA components

Following the removal of the stepping, the definition and material properties of the SLA components was considered to be comparable with that of conventional plastic fabrication techniques. In contrast, surfaces of the LOM components were less well defined and in places extremely fragile or starting to de-laminate. The finish and material properties of the SLA components were well suited to the application of a high definition paint finish, but it was evident that the LOM components would require considerable finishing time in the workshop.

To more fully evaluate the differences between the LOM and SLA components, a comparative evaluation was undertaken. As there were so few deficiencies in the SLA components, this tended to focus on the shortcomings of those produced by LOM.

Battery housing

The battery housing protects and supports the six nickel cadmium cells that provide power for the motor. It also forms a point of attachment for the battery housing closing panel. The LOM and SLA battery housings can be seen in Figure 59.

Figure 59: Battery housings produced using LOM (left) and SLA (right)
The LOM component was starting to de-laminate on the exposed 3mm wall around the rim. This was due to the relatively long layers of 3mm wide build material that had a narrow surface area with which to bond onto the layer below. There was also evidence of de-lamination on the outer surface of the base.

Battery housing closing panel
The battery closing panel retains the batteries, forms a support structure for the release mechanism and prevents user access.

Again, delamination was evident on this component which would require considerable effort to correct. For an appearance model with the battery permanently attached, this component would not be seen, and as such the LOM component would be satisfactory.

The LOM and SLA battery closing panels can be seen in Figure 60.
Motor housing

The motor housing represents a key component, performing several functions. It supports the motor, retains the aluminium stem, forms an air inlet, and acts as a location point for the battery, air outlet and handgrip. To prevent water ingress it has a 0.5mm wide lip around the point at which it connects to the handgrip.

Considerable de-lamination was present on the LOM model, particularly around the 0.5mm lip. There was also excessive flexing on the walls towards the rear of the motor housing. The structural integrity of this component for use on an appearance model was in doubt. No industrial designer would wish to undertake the time and effort required to finish such a component if there was a risk of it failing in during client evaluation.

The LOM and SLA motor housings can be seen from above in Figure 61, and from below in Figure 62.
Figure 62: Motor housings seen from above produced using LOM (left) and SLA (right)

Handgrip
As a production item, the handgrip would be manufactured as a two-shot injection moulding, with a soft rubber layer over an ABS core. The surface that attaches this moulding to the motor housing has a 0.5mm wide groove to prevent water ingress.

The removal of unwanted material from the LOM model during break-out was extremely difficult inside the 0.5mm groove, and some damage to the surface could not be prevented. On the sides of the groove, the 0.5mm walls were prone to de-lamination.

The LOM and SLA handgrips can be seen in Figure 63.
Air intake

The air intake closes the rear of the motor housing and allows air to flow around the motor. Crisp corners connected by flat sides form the slots for the air intakes. On the LOM component the flat sides were relatively rough and corners contained areas of paper that had not been cleanly cut. The LOM and SLA air intakes can be seen in Figure 64.
Cutter guard

The cutter guard acts as a mounting point for the attachment of the aluminium stem, houses the universal joint/cutter guard release mechanism, and protects the user from flying debris.

The quality of the LOM component was generally good, although excessive stepping was apparent around the exterior of the stem mounting point. Problems experienced during the break out of the concave inner surface had left some damage that would require significant attention for its restoration. The LOM and SLA cutter guards can be seen in Figures 65 and 66.

Figure 65 Cutter guards seen from above produced using LOM (left) and SLA (right)

Figure 66: Cutter guards seen from below produced using LOM (left) and SLA (right)
Chapter Five                                      Case study – comparative physical
models/prototype

Cutter guard release

The function of the cutter guard release is to provide a surface that can be
gripped by the user whilst the cutter head is unlocked and rotated, thereby
making the product suitable for cutting grass on the edge of lawns. The
dimples and colour change help communicate this functionality to the user.

As a production item, the cutter guard release would be a twin-shot injection
moulding in which the majority of the component appeared as a dark grey soft
rubber with a small turquoise conical end in ABS. For model/prototype making
purposes, this component was produced as two separate pieces to enable a
realistic colour break between the grey and turquoise.

The concave surfaces of the 4mm diameter dimples for both the LOM and SLA
components were found to contain unwanted material that would need to be
removed.

As relatively simple forms, these components worked well in LOM, and the
unwanted rippled effect on the cylindrical section would be easily corrected by
sealing and light sanding. The LOM and SLA cutter guard release components
can be seen in Figures 67 and 68.

Figure 67: Cutter guard release handgrip produced using LOM (left) and SLA (right)
Summary of evaluation between LOM and SLA components
The LOM process produced components for which it would not be economically viable to convert into either an appearance model or appearance prototype, and a decision was made not to proceed with further model making. This was based on poor surface quality and de-lamination in many areas of fine detail. In addition, there were concerns over the structural integrity of these components. The correction of these deficiencies would have been difficult and time-consuming, and in terms of commercial industrial design practice would not justify the effort required, especially when SLA provided a satisfactory alternative.

SLA component finishing
The removal of the stepping on the SLA components required two and a half hours of workshop time. The finish of the concave surface for the cutter guard was improved by the use of high-build spray putty followed by light sanding when dry. The complete removal of this stepping necessitated this operation to be repeated five times (see Figure 69).
Figure 69: Removal of stepping from underside of cutter head with spray putty

The stepping on the dimples of the cutter guard release was located on a concave surface, and as such difficult to sand as they were of only 4mm diameter. To produce the high level of surface definition required, the component was sprayed with a high-build primer, allowed to dry, and sufficient cellulose knifing putty introduced into each dimple to fill the steps. A dentist’s cavity preparation tool with a rounded end was then used to return the dimple to its correct size. This technique proved extremely effective, producing a smooth dimple with excellent dimensional accuracy. Figure 70 shows the dimples on the cutter guard release after filling and re-shaping.

Figure 70: Reworked dimples on the cutter guard release prior to final priming
With the exception of the cutter guard, all other surfaces were either convex or only slightly concave, presenting an ideal surface orientation for the removal of the stepping. Two coats of primer followed by rubbing down with 600 and 800 grade wet and dry paper was adequate to prepare these surfaces for the top-coat of paint that would simulate the colours of the injection moulded plastics.

To represent the spark-eroded surface finish of the production item, a cellulose automotive aerosol paint with a matting agent was used as the colour coat. The paint was applied, left to dry overnight, and rubbed down with 800 grade wet and dry. A final coat was applied and allowed to dry overnight.

The total amount of time required to apply a high quality paint finish on a single set of SLA components with a high-level paint finish was three hours.

**SLA appearance model**

As with an appearance model produced using conventional fabrication techniques, the SLA appearance model was required to have a quality of surface finish that matched that of a production item. Fortunately, with the exception of the removal of the stepping, the majority of SLA components for the nylon line trimmer required relatively little or no additional preparation prior to painting. In addition to the SLA components, several items were produced using conventional techniques: the aluminium stem that connected the cutter guard to the battery housing and foam inserts for the air intakes. The stem was shaped by bending annealed aluminium tube on a former, and the foam inserts cut from a sheet of black expanded PVC foam. The production of the additional components took three hours.

3D Systems, the supplier of the SLA components, expressed an interest in using the SLA appearance model to promote the capabilities of their process. As this would involve exhibiting the model at trade fairs around Europe, a base on which the model could be displayed was produced. To present the product
in a realistic orientation, an aluminium peg was inserted through the base and into the stem via the cutter spool.

**Assembly**

Before finishing and painting, the SLA components were assembled without adhesives to check for fit. It was also necessary to confirm the rigidity of the aluminium peg that was to support the model on the plinth. The unpainted appearance model can be seen in Figure 71.

![Unpainted SLA appearance model](image)

**Figure 71: Unpainted SLA appearance model**

The components were painted and the form evaluated in some detail. As expected, the rigid, high definition components of the SLA appearance model
had quite different material properties to those of the Styrofoam sketch model used to evaluate form during concept generation. In particular, on the sketch model the join between the motor housing and handgrip had been defined by a line as opposed to two separate components (see Figure 47). On seeing and feeling these components in resistant materials (SLA) it was felt that the curved join line in front of the switch was too severe and the angle needed to be reduced. When using conventional workshop techniques this would be relatively straightforward, involving the direct manipulation of material to resolve the mismatch. The modification would then be interpreted by an engineering designer when detailing components for production.

In this instance, the component geometry was to be defined by the 3D CAID surfaces (thereby facilitating effective data transfer), making it difficult to modify the form through direct physical manipulation by the industrial designer as any modifications created using such techniques would then have to be precisely re-modelled as 3D CAID surfaces. In addition, to ensure that the CAID modifications had been accurately executed, additional SLA components would need to be produced and integrated into the appearance model.

As there was no budget for the production of additional SLA components, the modification was not implemented, but the difficulties encountered in the direct manipulation of the rapid prototype components was seen as a significant shortcoming that would require further consideration.

Having checked the components for form and fit they were primed, painted, and assembled using epoxy and cyanoacrylate adhesives.

No significant problems were encountered and the assembly operation took two hours. Figures 72, 73, 74, 75 and 76 show the high level of surface finish achieved on the SLA appearance model.
Figure 72: Front view of cutter guard on SLA appearance model

Figure 73: Rear view of cutter guard on SLA appearance model
Figure 74: Handle of SLA appearance model

Figure 75: Air intake of SLA appearance model
Figure 76: SLA appearance model on display plinth

**Time-scales**

The time-scales for the production of the SLA appearance model were as follows:

- SLA component build by 3D Systems (including curing) - 11 hours
- Removal of stepping – 2.5 hours
- Additional components – 3 hours
- Painting – 3 hours
- Assembly – 2 hours

The total production time for the SLA appearance model was twenty one hours and thirty minutes.
Conventional appearance model

Having produced an appearance model using SLA, it was necessary to undertake a comparative evaluation of the time-scales required to produce a model of identical specification using conventional fabrication techniques. This comparative analysis would give an indication of the costs and time scales required for each strategy.

An appearance model was produced by Mr Les Pickstock, the model making technician for the Department of Design and Technology at Loughborough University. Mr Pickstock has a diploma in Commercial Model Making and Technical Illustration from Hertfordshire College of Art and Design (now the University of Hertfordshire) followed by twenty years of commercial and educational experience.

As the appearance model was not required to house any electronics or motors (it was non-working), a block method of construction was employed for the majority of components which involves the shaping of solid material to form accurate external surfaces. In keeping with commercial practice, all individual mouldings were to be produced as separate components to enable the accurate definition of split-lines.

Component production

GA drawings were generated using the DeskArtes wire-frame models and printed out as full-size plots. These were used in an identical way to drawings produced via a drawing board or 2D CAD.

The majority of the components were made by shaping medium density fibreboard (MDF) blocks by hand using standard workshop equipment such as the band saw, sanding disc, and hand-tools. The construction methods employed in the production of the components were as follows:

- Motor housing/handle - Overall shape cut from glued sheets of MDF using GA drawings as guide and formed with sanding disc and hand tools. Two
internal cavities produced, one to accept peg on battery housing, the other to locate top of the stem. Front air intake cut out with fine-bladed saw and sanded to finish.

- Handgrip - Shaped as motor housing/handle.

- Switch - Shaped as motor housing/handle.

- Battery housing - Shaped as motor housing/handle with peg for attachment.

- Battery release button - Due to the relatively small scale, marked out by hand onto acrylic sheet and sanded by hand.

- Air intake - Overall shape cut from urethane modelling material using GA drawings as guide. Slots machined and curved exterior profile sanded by hand.

- Foam for air vents - Cut from sheet material with craft knife.

- Stem - Annealed aluminium tube bent around wooden former and adjusted to required profile.

- Cutter guard release end cap - Turned acrylic bar.

- Cutter guard release - Urethane modelling material turned and dimples drilled with bull-nose milling cutter.

- Cutter guard release button – Shaped as battery release button.

- Cutter guard - Main guard area vacuum formed over turned pattern of MDF. “Teardrop” moulding sanded by hand from urethane modelling material.
Cylindrical section turned from urethane modelling material. Components bonded together with epoxy resin. Radii added to join between main guard and teardrop-shaped moulding with plastic body filler.

- Cutter spool - Purchased as spares item.

The unpainted motor housing with the battery housing and handgrip attached can be seen in Figure 77, and cutter guard assembly in Figure 78.

Figure 77: Unpainted motor housing/handle with battery housing and handgrip for conventional appearance model
Figure 78: Unpainted cutter guard assembly for conventional appearance model

Unlike the layer-based rapid prototyping system that produced a stepped effect on the entire surface of the SLA components, the cutter guard for the conventional appearance model was vacuum formed from a sheet material. This resulted in negligible deformation of the concave underside of this component, requiring minimal preparation prior to painting (only light sanding and priming). In addition, the concave dimples on the cutter guard release for the conventional appearance model were produced by milling urethane modelling material. Again, as this process left a smooth surface finish, only priming was required prior to painting. The additional effort required to produce a satisfactory surface finish on the SLA components with a concave surface demonstrated that in some areas of model making, conventional techniques may have a distinct advantage over rapid prototyping.

The designer maintained close contact with the model-maker during the fabrication process. At one stage, whilst evaluating the emerging form of the motor housing/handle, the designer wanted to redefine the transitional radius
and chamfer that occurred at the front of the battery compartment and motor housing. This was a spontaneous reaction to seeing and feeling the components as physical objects in a resistant material, and could be viewed as a natural extension of the manual form-giving process that occurred with the foam sketch model. However, as the conventional appearance model was to be an exact copy of the SLA appearance model and SLA appearance prototype, such changes were not implemented.

This opportunity illustrated how components produced via rapid prototyping may tend to be accepted at face value as the production of further components would incur increased project costs and delay the completion of the appearance model or appearance prototype. The implementation of such changes when employing conventional techniques would be immediate and straightforward, although modifications to the GA drawings would ultimately be required.

Production of the components for the appearance model took thirty seven hours.

**Finishing**

MDF components were sealed with a cellulose shellac. This involved the application of the sealer with a cloth, and when dry, rubbing lightly with wire wool. Three applications of shellac were applied. MDF components were then primed with an aerosol-based filler primer and plastic components with a standard grey primer. After a light rubbing-down with fine wet and dry paper, any blemishes were filled with cellulose knifing putty. Once dry this was sanded and the component sprayed with a grey primer. Blemishes still present were removed by repeating this process.

When all surfaces were paint primed to a satisfactory level, a colour paint coat was applied. When dry this was rubbed down with fine wet and dry paper. A second coat was applied to complete the painting of the components.

Finishing of the components took six hours.
Assembly
The techniques employed in the production of components for the conventional appearance model included features that would assist in assembly. Following paint finishing, the assembly of the model was relatively straightforward, involving the bonding of components with either epoxy or cyanoacrylate adhesive.

Component assembly took four hours.

Time-scales
The time-scales required for the production of the conventional appearance model were as follows:

- Manual component build by - 37 hours
- Painting- 6 hours
- Assembly – 4 hours

The total production time for the manual appearance model was forty seven hours.

SLA appearance prototype
The distinction between appearance models and appearance prototypes is that the latter integrate both form and functionality. As such, appearance prototypes are significantly more complicated, requiring the inclusion of internal cavities and components.

The appearance model represents a key outcome from the industrial design activity, embodying the definition of product form. Whilst it must be acknowledged that industrial designers may become involved in the detailed design of components, (particularly if they have an engineering background) this role is typically undertaken by an engineering designer.
The cost and time involved in the production of appearance prototypes generally excludes their use to the latter phases of NPD. Indeed it is only then that the design has evolved to a sufficient level of detail to make the production of appearance prototypes viable.

A significant feature of rapid prototyping is that an increase in component complexity does not attract a corresponding increase in production cost, making it viable to produce components with a wall thickness that closely represents the production item. This is in contrast with the conventional techniques used to produce appearance prototypes that typically involves the time consuming operations of vacuum forming and fabrication to produce components with internal cavities.

Rapid prototyping has the capacity to reduce both the costs and time scales involved in the production of components with internal cavities, and extending the use of an appearance model to that of an appearance prototype would involve the inclusion of functional parts such as motors, batteries, circuit boards. However, it is unlikely that the rapid prototype components would embody the internal details of the production item as the definition of such features would not necessarily have been completed and may well be outside the remit of the industrial designer. However, by using rapid prototyping to produce components with a wall thickness, simple model-making techniques can be used to provide supports for the inclusion of the functional parts.

To identify the potential for such practice, an appearance prototype for the line trimmer was undertaken. As a relatively complicated electro-mechanical product, the nylon line trimmer represented a significant challenge for such a strategy, and would enable a comparative analysis to be made with the SLA appearance model.

**Component production**
A second set of nylon line trimmer components were produced by 3D Systems. These were identical to those used for the appearance model, requiring ten
hours of build time plus an additional hour to cure. Two and a half hours were required for the removal of the stepping.

**Pre-assembly of electro-mechanical components**

Prior to any paint finishing, the motor and drive system were positioned within the rapid prototype components and tested. As the electro-mechanical components (motor, battery, flexible drive and bearings) had been modelled on the CAID system and used as a template for the 3D modelling, there were no problems of fit. Checking the fit for the batteries and terminals can be seen in Figure 79, and for the motor, stem, and flexible drive in Figure 80.

![Figure 79: Checking battery and terminal fit using unpainted SLA components](image-url)
The only problem that arose from the pre-assembly was that the rear of the motor housing had distorted due to the unsupported wall being exposed to excessive heat whilst stored in an office. This was easily corrected by using a hairdryer to re-heat the affected area and applying slight pressure to correct the distortion. To ensure that the original shape was achieved, the air intake that attaches to this area was used as a template.

Paint finishing of the SLA components for the appearance prototype was identical to that of the appearance model (three hours), although an additional hour was required to fill and paint two countersunk holes used to attach the drive mechanism onto the cutter guard.

Assembly
The electro-mechanical components were either bonded (using epoxy adhesive) or mechanically attached to the SLA components. The only problem encountered was due to an excessive build-up of paint around the hole through
which the aluminium stem was attached to the motor housing. This was corrected by lightly sanding with wet and dry paper.

With the battery pack in position, the battery housing closing panel was fixed in place with epoxy adhesive as access was not required for charging. The motor was also permanently bonded into position using the two supports on the motor housing as guides (see Figure 81).

The angle at which the flexible drive entered the cutter guard was too severe to allow the cable to be bent and directly inserted into the spool housing. To allow such a dramatic change in the orientation of the drive system, a universal coupling was mounted on the spool housing. This universal coupling was retained by a Delrin bearing surface bolted onto a mounting plate (see Figure 82)
The relatively high levels of vibration generated by the universal coupling necessitated the mounting plate to be attached to the cutter guard with mechanical fixings as opposed to adhesive. As adjustments may be required in this area, bolts were considered to be the most appropriate option. The mounting plate was secured in position with countersunk bolts inserted through holes in the cutter guard (Figure 83).
The upper surface was reinstated by filling the countersunk holes with epoxy adhesive, filling, priming and painting.

On completion, the appearance prototype met the same specification of form and surface finish as the appearance model. However, the workshop time was considerably higher, requiring seventeen hours to produce additional components, four hours for paint finishing, and six hours for assembly.

Compared with the SLA appearance model, the production of the SLA appearance prototype required an additional twenty five and a half hours of build time.

Testing
As a representation of design intent that enabled the evaluation of form, user interface and performance, the appearance prototype was of enormous benefit. The weight distribution was almost identical to that of a production item, and the key feature of its balance at the handle was illustrated without ambiguity (see Figure 84).
The appearance prototype embodied the performance of the previously constructed prototype, with the added features of a fully defined handle, working switch, correct weight distribution, and the embodiment of the form of the production item. The differences between the prototype and an appearance prototype can be seen in Figure 85.
Detail of the cutter system can be seen in Figure 86, the motor mounting in Figure 87, and cutting grass during the performance trials in Figure 88.

Figure 86: Detail of appearance prototype cutter system

Figure 87: Detail of appearance prototype motor mounting with air intake removed
Figure 88: Performance trials with appearance prototype

After two trials of ten minutes duration, the motor started to accelerate and the rotation of the cutter became erratic. On removing the universal joint mounting plate, the flexible drive was found to be slipping inside the bush that connected it to the cutter. The bush was discarded and replaced with a component that had been machined with a closer tolerance between the mating surfaces. The joint was also bonded with an engineering cyanoacrylate adhesive. The necessity for such a feedback loop at the appearance model/prototype stage had been identified by one of the consultants responding to the rapid prototyping questionnaire and included in the revised CAID/RP methodological approach. The significance of this amendment was effectively demonstrated through this need for design modifications.

On completion of sixty minutes of trials (with battery charging every ten minutes), the main problem with the appearance prototype was due to the lack of durability of the paint finish, particularly on the cutter guard. Such damage was inevitable, and identical to that expected from an appearance prototype produced using conventional techniques.
As an appearance prototype that was subjected to relatively high levels of vibration, the mechanical properties of the SLA components proved to be adequate, and after a total of three hours of use no failures were evident.

**Time-scales**

The time required to produce the appearance prototype was as follows:

- SLA component build by 3D Systems (including curing) - 11 hours
- Removal of stepping – 2.5 hours
- Additional components – 17 hours
- Filling/painting – 4 hours
- Assembly – 6 hours

The total time required to produce the appearance prototype was forty hours and thirty minutes.

As the focus of the comparative evaluation of the physical models/prototypes was to compare the two forms of appearance model, and the use of rapid prototyping to produce an appearance prototype as an extension of this exercise, no appearance prototype was produced using conventional fabrication techniques. However, the professional opinion of Mr Les Pickstock was that it would have taken 80 – 90 hours to produce an appearance prototype of the line trimmer using conventional fabrication techniques. Component costs for the appearance prototype were £235, which when added to the model making time (costed at the Loughborough University consultancy rate for technical staff of £35 per hour) gives an estimated cost for a conventional fabricated appearance prototype of between £3035 and £3385.

**Comparative evaluation**

Findings from the line trimmer case study indicated that the use of rapid prototyping could have a significant impact on the time scales required for the production of appearance models. As an injection moulded product requiring the integration of electronic and mechanical components, the line trimmer case
study can be regarded as being representative of a wide range outcomes from professional practice. In addition, this outcome from the line trimmer case is supported by findings of the practitioner questionnaire in which reduced lead times for the production of appearance models was identified as the most common strength of rapid prototyping (Chapter Three p135).

Whilst the costs for the SLA appearance model and conventional appearance model were similar at £1898 and £1750 respectively, the time scales required for the production of the appearance model were reduced by 54% through the use of rapid prototyping. This equated to forty seven hours for the conventional appearance model, and twenty one and a half hours for the SLA appearance model. In addition, the reduced time scale for the production of the SLA appearance prototype was close to that for the non-working conventional appearance model.

The estimated time savings for the use of rapid prototyping in the production of the appearance prototype were similar, at between 49% and 55%, but as the overall time scales were greater, this equated to around an entire working week.

A summary of the findings from the comparative evaluation can be seen in Table 1, with modelmaking labour being costed at £35 per hour.

<table>
<thead>
<tr>
<th>Build system</th>
<th>Component cost (RP)</th>
<th>RP Build time (hrs)</th>
<th>Removal of stepping (hrs)</th>
<th>Manual component build time (hrs)</th>
<th>Fill &amp; paint time (hrs)</th>
<th>Assembly time (hrs)</th>
<th>Modemaking costs (labour/materials)</th>
<th>Total time (hrs)</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOM (appearance model)</td>
<td>£2157</td>
<td>51</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SLA (appearance model)</td>
<td>£1500</td>
<td>11</td>
<td>2.5</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>£398</td>
<td>21.5</td>
<td>£1898</td>
</tr>
<tr>
<td>SLA (app. prototype)</td>
<td>£1500</td>
<td>11</td>
<td>2.5</td>
<td>17</td>
<td>4</td>
<td>6</td>
<td>£1268</td>
<td>40.5</td>
<td>£2768</td>
</tr>
<tr>
<td>Conventional (appearance model)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>37</td>
<td>6</td>
<td>4</td>
<td>£1750</td>
<td>47</td>
<td>£1750</td>
</tr>
</tbody>
</table>

Table 1: Comparison between costs and build times

**Summary**
• LOM components are not suitable for the efficient production of appearance models and appearance prototypes.

• SLA components are suitable for the efficient production of appearance models and appearance prototypes.

• It is more difficult to achieve a high level of surface finish on rapid prototype components with concave surfaces than convex surfaces.

• The use of CAID and production of stl files did not facilitate any tactile interaction with the product form either before or during the rapid prototype component build.

• A significant reduction in build times can be achieved when SLA (as opposed to conventional fabrication techniques) is used to produce appearance models and appearance prototypes.
Outcomes from line trimmer case study

The line trimmer case study demonstrated the effectiveness of using rapid prototyping during professional practice through the adoption of the revised CAID/RP methodological approach. Through its use, the benefits of 3D computer modelling (model share, rendering, precise geometry) were integrated with the advantages of rapid prototyping (faster than fabrication techniques, exact translation of 3D geometry). However, it also identified two issues with the revised CAID/RP methodological approach: significant effort was required to produce the stl files for rapid prototyping; the integration of CAID and rapid prototyping removed the opportunity for the industrial designer to be actively involved in the direct definition of form during the production of the physical model/prototype.

In an attempt to resolve these issues, emerging technologies were examined and potential solutions identified. These involved the export of an industrial designer’s CAID model into an engineering designer’s CAD system to resolve the issue of stl file generation, and the use of a haptic feedback device to resolve the inability to engage in the physical interaction with material when employing rapid prototyping.

In addition, the emergence of faster and lower cost concept modelling rapid prototyping systems during the late 1990’s was identified as an opportunity to
Case study issues enhance the revised CAID/RP methodological approach through the integration of this technology. This was regarded as the exploitation of an emerging opportunity as opposed to the resolution of a problem. The potential to further enhance the revised CAID/RP methodological approach was therefore identified through the use of rapid prototyping concept modelling to produce sketch models.

Provision existed within the research methodology for an additional case study, and this was extended to cover the three issues of stl file generation, sketch modelling via rapid prototyping, and physical interaction. The inclusion of the additional case studies within Phase 4 of the amended research methodology can be seen in Figure 89.
Stl file generation

A conventional marker rendering is defined by the application of lines and colour to produce a representation of design intent. If a conventional rendering was produced as a series of orthographic views, it may be possible to use the dimensional information to generate a physical model or give basic information on component geometry to an engineering designer. A rendering produced using a CAID system is also a representation of design intent, but the underlying geometry fully defines the exterior surfaces of the 3D components. Whilst this may not include internal detail, a full geometric specification of the surfaces would be available.

Advances in the ability to translate 3D geometry from one 3D CAD or CAID system to another have facilitated a strategy that enables the industrial designer to define the external surfaces of a product and pass these on to an engineering designer for detailing (tolerancing, internal walls, draft angles). The resulting geometry is then available for the generation of stl files for rapid prototyping.

This strategy not only removes the need for the industrial designer to become involved in the additional modelling required for the production of stl files, it also allows the engineering designer to add internal details that had been specified up to that moment in time. Potter acknowledges the theoretical viability of this strategy, but highlights the potential difficulties when she states that “in an ideal world, the CAID surface model is imported into a CAD system, where an engineer turns it into a solid model, then adds the features necessary to turn the conceptual design into a real, manufacturable product. But that ideal process often falls apart at the point where the surface model converts to a solid model”. (Potter 2000 pp21 – 28)
This strategy is dependent on the ability of CAID and CAD systems to share data, but if such a procedure could be demonstrated as being effective, the possibility exists to bypass the appearance model and progress immediately to an appearance prototype that embodied engineering detail. Such a strategy would of course be dependent on any internal components being available and the underlying technology (electronics/mechanics) fully resolved.

During an industrial design commission from a major car manufacturer, the author was given the opportunity to evaluate such a strategy under commercial conditions. The rapid development of the product was the key feature of the commission, and the opportunity to remove the need for an appearance model was seen as a significant enhancement to the project through a reduction in design lead times.

**Industrial design**

The commission involved the industrial design of an in-car binnacle that would allow the driver to control the mobile communications and audio/navigation systems. Key elements of the proposal were to be based around features that had been defined by a team of consultant ergonomists at the Human Sciences and Advanced Sciences Research Institute (HUSAT) at Loughborough University.

The concept generation phase of the project was undertaken using conventional techniques with dimensions supplied by HUSAT. This involved the use of fine line fibre tip pens and marker paper. The conventional sketching techniques employed at the outset of the concept generation can be seen in Figure 90.
The product proposals were presented to the consultant ergonomists as simple line drawings, an example of which can be seen in Figure 91.
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Following discussions with the ergonomists, a single proposal was selected for design development, with the outcome presented as a CAID rendering.

The industrial design proposal took the form of an elliptical cross-section that moved out from the steering column and then cranked at 135 degrees, ending in a rounded user interface. The wire frame surface geometry for the proposal can be seen in Figure 92.

![Figure 92: Wireframe CAID geometry for control binnacle](image)

The complexity of the form necessitated extensive use of the shading functionality of the DeskArtes CAID software as the wire-frame representation was not always adequate for the evaluation of form. The shaded surfaces can be seen in Figure 93.
Text specified by the ergonomists was added to the DeskArtes surfaces prior to rendering. A total of five renderings were produced: three elevational views showing the front, rear and end; two perspective views as front and rear. These were produced as hard-copies using an A3 inkjet printer. The CAID rendering for the proposal can be seen in Figure 94.
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The CAID modelling of the surfaces had been undertaken using techniques that focused on the development of the product exterior and need to generate rendered views. The proposal focused on an optimum interface and form for the product, and whilst wall thickness and internal details (electronics/mechanisms) were considered by the industrial designer, they were not addressed in detail as this was to be undertaken by the client’s engineering designers.

The proposal was approved by the client and an appearance prototype commissioned.

Engineering design and rapid prototyping

Arrk Formation, a design and model-making bureau based in Gloucestershire UK, were commissioned to undertake the engineering design and produce the appearance prototypes. To ensure that the form complied with the industrial designer’s proposal (as approved by the client), the DeskArtes surface geometry was forwarded to Arrk Formation as an email attachment in an IGES file format. This enabled the geometry used for the renderings to become the specification for the exterior form and transmitted as a digital data file to others involved in the design process, thereby adopting the “Master Model Paradigm” approach as defined by Desbarats (C3, March 1999 p26).

The DeskArtes CAID data was imported by Arrk Formation into their in-house Pro-Engineer solid modelling CAD system as surface data. The main body was translated into a single surface by the CAD operator, and the buttons copied and cut through to create individual elements. A split-line was produced and the two halves of the main body cored out to produce walls. The internal mechanism was designed and bosses and supports added. Movement and clearances for the articulating components were checked using the movement tolerance capability of the Pro-Engineer software.

The finished 3D solid model was translated into an stl file format for rapid prototyping and a single set of SLA components produced at a 0.1mm build thickness. These were lightly sanded to remove stepping and used to produce
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A silicon mould for vacuum casting, as a total of ten appearance prototypes were required. Polyurethane was used for the vacuum castings to simulate ABS.

The finished components were sprayed with a matt black textured paint finish before the inclusion of internal electronic components. The final appearance prototypes were supplied with 0.5m of wiring and a mounting bracket for the column of the car steering wheel. An appearance prototype can be seen in Figure 95, and internal details/components in Figure 96.

Figure 95: Appearance prototype of control binacle
The success of the appearance prototype was due to the virtual and physical modelling capabilities of the CAD operators and engineering designers at Arrk Formation. Had the project been undertaken using a conventional industrial design methodological approach, a significant number of drawings would have been required to specify the exterior form to the engineering designers, and compliance with the intent of the industrial designer could not have been guaranteed.

During the project debriefing, the Arrk Formation Project Manager, Mr Mike Gilmour, commented that such a methodology was not the norm at Arrk Formation. It was more typical to be supplied with either fully specified stl files or create the 3D geometry from engineering drawings using Pro-Engineer. He did however feel that the methodology had been successful in achieving the required project outcomes.
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**Sketch modelling via rapid prototyping**

The literature review for rapid prototyping that was undertaken as a precursor to the line trimmer case study indicated that SLA was the most appropriate rapid prototyping system for the production of appearance models. Rapid prototype concept modelling systems were not commercially available, and their emergence during the late 1990’s as a lower cost, less robust build system, offered the potential for their integration within the revised CAID/RP methodological approach as an alternative to sketch modelling in foam and card.

Five commercial concept modelling systems were identified: 3D Systems’ Thermojet, Sanders’ Model Maker, Ballistic Particle Manufacture, Genisys system and the Z-Corp process. ([http://home.att.net/castleisland/home.htm](http://home.att.net/castleisland/home.htm)) The capabilities of these concept modelling systems will now be discussed.

**Concept modelling systems**

The 3D Systems Thermojet uses what the company describes as Multi-jet Modelling (MJM), employing a 300 dpi inkjet-based printing process to deliver a thermo-polymer compound onto a build platform. Thermojet 88 and Thermojet 2000 are the build materials used, both being available in neutral, grey and black. 3D Systems claim that Thermojet 88 has “superior model quality and surface workability that is best suited for the producing communication models and patterns for casting and moulding operations”. ([http://www.3dsystems.com](http://www.3dsystems.com)).

The build process involves the “print” head moving in the x - y plane to deposit a layer of material. This is followed by the descent of the build platform in the z-plane in preparation for the next layer. Where cavities and undercuts are encountered, fine support structures are automatically generated. Component sizes of 250 x 190 x 200 can be produced.

The product aims to deliver “high speed, low-cost, convenient, office-based concept modelling capability for use early in the product development cycle”. 

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(The Edge Volume V Number 1 p3) The publicity provided by 3D Systems does not refer to the rougher surface finish on the downward facing surfaces that results from the remains of the support structure.

The Sanders Modelmaker was developed by Sanders Prototype Inc. U.S.A.. It is suitable for use in office environments and is based around ink jet printing technology. Components are built on a platform using two piezoelectric print heads, one of which deposits a wax build material, and the other a supporting wax. The print-heads deposit 0.003 inch diameter droplets that spread out to a 0.004 inch wide bead 0.0025 inch high. The platform is then lowered on the completion of each layer. The system has good part accuracy at 0.05mm over 152mm, building in 0.08mm layers. (Kai and Fai 1997 p111) Build volumes of 300 x 150 x 220 are possible with a layer thickness of 0.013mm to 0.076mm. (http://www.solid-scape.com/mmii.html) The Model Maker system has some similarities with SGC in that the build material is embedded in a wax material which is levelled via a cutter.

Ballistic Particle Manufacture (BPM) involves the deposition of molten droplets of thermoplastic material (12 000 per second) which immediately solidify. The component is formed as the droplets deform and spread on impact. During the build process the ejector head moves in the x - y plane, and build platform in the z - plane. (http://www.solid-scape.com/mmii.html)

The Genisys system is manufactured by Stratasys Inc., and based on a 3D printing principle that was developed by IBM. The process is similar to FDM in that molten polyester is extruded through a computer-controlled nozzle. Unlike the majority of rapid prototyping systems, increments in the z -axis are produced by a gantry on which the extrusion nozzle is located.

The system software automatically generates a support structure that can be broken-away when the build is complete. Part accuracy of +/- 0.356mm is possible, with build volumes of 300 x 200 x 200mm. (http://www.solid-scape.com/mmii.html)
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The Z-Corp system uses an operating principle that was developed at the Massachusetts Institute of Technology (MIT). (http://www.zcorp.com/azc.html) The system is based around a layer building process that produces components from a powder composed of corn starch and sugar. The process involves the deposition of powder over the build area, followed by its selective hardening using a binder solution sprayed from a moveable printer head. On completion of a layer, the build platform is lowered and new powder spread over the surface. When the component is complete it is removed from the surrounding loose powder and cleaned using air tools and a soft brush. Improvements in the mechanical properties of components can be made by their infiltration with wax or viscous cyanoacrylate adhesive.

The Z-Corp Z402 3D printer has a 203 x 254 x 203mm build volume and is capable of producing layers of 0.076 to 0.254mm. (http://www.zcorp.com/azc.html) The equipment is relatively portable and compact, with overall dimensions of 740 x 910 x 1070mm.

System selection
Whilst the surface definition of components produced on concept modelling rapid prototyping systems is not as high as those of production systems, they have the advantage of lower component costs and faster build times, thereby providing the potential to contribute to the production of sketch models during industrial design activity. To evaluate the potential of a rapid prototype concept modelling system to contribute to this essential activity, the Z-Corp process was identified as being the most appropriate, as the tactile and visual properties of the build material were closest to those of Styrofoam, a conventional sketch modelling material.

Concept Generation – 2D physical/3D virtual
The use of the Z-Corp concept modelling system was integrated into a commercial industrial design exercise involving the design of children’s cutlery. The handles for the cutlery were to be manufactured by injection moulding, with forms suitable for manipulation by young children.
As a prerequisite to concept generation, user trials with six children (aged two to five) were conducted to evaluate patterns of use and any merits or shortcomings with current products (see figure 97).

Conventional sketching in crayon, pen and marker was used during concept generation to produce a range of ideas. The speed and spontaneity required of this activity did not lend itself to the use of 3D CAID modelling, as forms could not be generated with sufficient speed. An example of the 2D concept generation using pencil crayon can be seen in Figure 98.
As concept generation progressed, design direction emerged and mixed media were employed to achieve greater definition. An example of early mixed media renderings can be seen in Figure 99.

As can be seen from Figure 99, the application of media was relatively loose, enabling a degree of spontaneity and emergence. As concept generation progressed and the design proposals became more defined, it was appropriate to model components using the DeskArtes CAID system. The rigorous modelling methods of 3D CAID resulted in key design decisions being made during the translation of the concept from a conventional 2D sketch rendering.
to a 3D CAID model. Whilst both decisions arose from the modelling methods of CAID, they differed in that one resulted from the modelling limitations of conventional 2D sketching, and the other being a direct result of emergence. These two issues focused on:

- The ability of CAD/CAID modelling to identify limitations in 2D drawing.
- The facilitation of emergence when using CAID.

As the process of CAID modelling is a precursor to rapid prototyping, these two issues will be discussed.

Whilst resolving details of the design, the limitations of conventional concept generation became apparent when modelling the pimples on the handle using CAID. As a conventional sketch rendering in mixed media, there appeared to be no problems in the placement of pimples on the surfaces of the handle. This can be seen in the detail of the mixed media concept generation in Figure 100.

Figure 100: Positioning of pimples using conventional sketching and sketch rendering drawings
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Only when the pimples and handle were accurately modelled on the CAID system did a problem with this configuration emerge due to an incompatibility between the diameter of the pimples and the curvature of the handle. Whilst there was no problem with the desired pimple diameter on the flatter surfaces of the handle, on the area of tightest curvature an unacceptable amount of cylindrical body of the pimple became exposed. This can be seen within the white circle in Figure 101.

Figure 101: Cylindrical body of pimple exposed at top of handle (within white circle)

The two pimples on the flatter sides do not experience the same problem as the curvature on the handle is much less. This issue was resolved by reducing the diameter of the pimples so that the cylindrical base was not exposed (see Figure 102).
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Figure 102: Reduced diameter of pimple to produce desired effect at top of handle

The ambiguity embodied within conventional drawing demonstrated how the more rigorous modelling methods of CAID offered tangible benefits, even at the concept generation stage. Having produced an acceptable elevational configuration for both the handle and pimples, the surfaces were modelled in greater detail to produce full 3D CAID geometry.

Results from the consultancy questionnaire (discussed in Chapter 3) indicated that in some instances, the 3D CAD or CAID modelling of a product was undertaken by someone other than the industrial designer. In such cases the CAD/CAID modeller translates GA’s, engineering drawings or physical models supplied by the industrial designer. However, CAID systems allow a high degree of interaction with the product geometry, and when modelled directly by the industrial designer, opportunities of emergence are still possible. This was illustrated when designing the raised collar for the front of the handle on the children’s cutlery. The function of the collar was to prevent the child’s hand slipping off the handle, and consisted of a raised lip with a series of regularly spaced domes. Figure 103 shows the definition of these details during concept generation using conventional mixed media.
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Figure 103: Pen and marker concept generation showing details of the doming on raised collar

The doming on the raised collar was the preferred option for this detail, and progressed to CAID modelling. As the DeskArtes CAID system required the industrial designer to define 3D form by specifying elevational curves followed by the projection of cross sections, the form was viewed from several angles. The 3D wire-frame drawings produced for the collar can be seen in Figure 104.

Figure 104: CAID wireframe geometry of collar
Figure 104 illustrates the difficulties in visualising the detail of a form using a 3D wire-frame model, but by utilising the capability of the software to generate a shaded view of a surface, the detail of the form can be seen with greater clarity (see Figure 105).

![Figure 105: Shaded view of collar looking towards handle](image)

When viewed from the front (as in Figure 105) the form was exactly as envisaged. However, due to an error in the modelling of the projection curves, the rear view was quite different. Instead of repeating the form on the front, it was more rounded, creating a series of raised ripples (see Figure 106)

![Figure 106: Shaded view of collar (with ripples) looking away from handle](image)
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Such a form had not been considered during the 2D concept generation, and emerged only as a result of a modelling error when using the CAID system to visualise the outcome. Whilst it would have been straightforward to correct the error, this form was considered an improvement on that originally proposed and immediately integrated into the proposal.

Concept generation - rapid prototype concept models

Having produced CAID geometry for the design proposal, stl files were generated for the production of rapid prototype concept models that were to be used to evaluate variations in handle size. Three sets of components were produced, with one set being the size of the components modelled on the CAID system, one set 10% larger; and one set 10% smaller. The components were produced on a Z-Corp 2402 concept modelling machine using a ZP11 material (modified corn starch). The 2B4 binder emulsifies the powder at a build thickness of 0.175mm.

The component build took twenty minutes, after which the components were left for a further twenty minutes to allow the build material to harden. The commercial cost of the components was £20. Figure 107 shows one handle of each size scaled at 10% increments.

![Figure 107: Z-Corp concept model components scaled at 10% increments](image)
The durability of the Z-Corp components was assessed both with and without post process finishing. The post process finishing involved the impregnation of components with viscose cyanoacrylate adhesive. Whilst this made the components more robust, the procedure took thirty minutes, with a further one hour of drying time. At a time when the industrial designer needs to interact with the components, such a delay was considered excessive, and the unfinished components proved to be surprisingly robust and considered adequate for evaluation by both the industrial designer and users (young children). The components treated with cyanoacrylate adhesive can be seen in Figure 108, and untreated in Figure 109.

Figure 108: Components treated with cyanoacrylate adhesive

Figure 109: Components with no post-process finishing
User trials with eleven children aged from two to five were undertaken. The principal objective of this exercise was to identify which of the three handle sizes most suited the needs of the target user group (children aged from two and a half to five) as the size of products on the market varied between 85mm to 100mm. In addition, as part of this study, it was also seen as an opportunity to evaluate the capability of Z-Corp concept models to contribute to the decision making process during the concept generation and design development phase of professional practice.

Of the eleven subjects recruited for the user trials, four were between two and a half and three years old, three were between three and four years old, and four were between four and five years old. To avoid the effects of an unfamiliar environment on the child, the user trials took place in their homes. The children were also known to either the client or industrial designer (observers), and as it was necessary to have one observer present during the trial, it was always the one known to the child.

In preparation for the user trial, the observer set-up the room and briefed the parent on the procedure. A Mini-DV video camera was set up to record the trials for further analysis when all eleven had been undertaken.

The management of the user trial was undertaken by the parent, and involved a period of play to get the child familiar with the presence of the observer (who was known to them). The trials coincided with meal times, and the children were given an opportunity to use the knife and fork followed by the spoon. For the knife and fork trials, the children were given either four chicken nuggets, two sausages, or two fish fingers according to preference. For the spoon trials they were given either a half bowl of spaghetti hoops, chocolate coated Rice Crispies with milk, ice cream, or yoghurt. The food types were selected to provide a suitable challenge of dexterity for the item of cutlery being evaluated.

The child was allowed to use each of the three sizes of knife and fork handle for two minutes before being distracted by the parent and these replaced with
another size. The procedure was then repeated with the three sizes of spoon handle. As with the line trimmer user trials discussed in Chapter Four (page 151), the impact of order effects were reduced by the rotation of the size of handle used first by each child. An observed user trial can be seen in Figure 110.

![Observed user trial for cutlery with three year old child](image)

After the first two trials, it became apparent that a further two sets of components would be required as the handles had started to become discoloured through contact with food. Whilst this did not affect structural integrity, it was felt that the handles would not look particularly appealing or hygienic as the number of trials increased.

On completion of the eleven user trials, the video footage was reviewed simultaneously by both observers. Having watched the footage for the use of the knife, fork and spoon by a particular child, a consensus decision was
reached as to which size appeared most suitable based on confidence and dexterity in use. This was by no means an easy process, but was assisted by the capacity to review the video footage whenever required.

The results from the user trials indicated that the mid-size handle was most suited to the needs of the target market, being used with greatest dexterity and control by eight of the eleven children. The handles that were increased and decreased in size by 10% were most suitable for the smallest and largest children respectively, these being at the extremes of the target market.

The results from the user trials provided the client with sufficient evidence to confirm that the size of handle as originally modelled on the CAID system was that most suited for the particular market and proceed with the project. Without access to accurate and low cost physical models produced using the Z-Corp rapid prototype concept modelling system, it would not have been financially viable to undertake an evaluation of this kind as the cost of producing components using manual techniques, or a production rapid prototyping system such as SLA, would have been prohibitively expensive.

Whilst the rapid prototype concept models of the cutlery proved extremely useful, they could only be a direct translation of the form as modelled by the CAID system. A function of conventional sketch models is the capability for them to be used in the definition of form by directly shaping material. Whilst the rapid prototype concept models could have been subject to further modifications by hand, any changes would then have to be precisely modelled on the CAID system to ensure compliance of the 3D geometry. This issue appeared during the line trimmer case study and an attempt at its resolution will be discussed in the section on physical interaction.
Having identified what was considered to be the most suitable handle size through the use of concept models, the CAID surfaces were rendered to produce realistic images of the cutlery for client approval. The number of colour options was potentially unlimited, and CAID proved to be an extremely effective means of presenting a wide variety of options. In addition, the software could be used to render different material properties, allowing translucent materials to be added to the range. The colour options for the knife, fork and spoon can be seen as elevational renderings in Figure 111, and as a perspective view in Figure 112.

Figure 111: CAID rendering of full colour range for knife, fork and spoon
Design Development
The presentation of the design proposal via the concept renderings resulted in positive feedback from the client. Having approved the basic concept, the orange/green colour scheme was preferred, and renderings produced to illustrate the final proposal. (see Figure 113)
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Specification

The mathematical specification of the component geometry commenced when the design was first modelled using CAID, and updated via the various modifications as the proposal progressed. Having used the CAID geometry to generate the final renderings of the proposal, this data was utilised in the production of an appearance prototype using a 3D Systems SLA-250. The layer thickness was 0.157mm, and the production time for all components was two hours.

On receipt of the components, the stepping was removed by light sanding and the fit of the parts checked. The components were primed and sanded before applying two coats of coloured matt cellulose paint. Epoxy adhesive was used to bond the components together. The total finishing time (excluding paint drying time) was four hours. The finished appearance prototypes can be seen in Figure 114.

![Figure 114: Appearance prototypes of children’s cutlery produced using SLA](image-url)
Once approved by the client, the component geometry was available for use by engineering designers and toolmakers.

**Physical interaction**

During the production of the rapid prototypes for the nylon line trimmer, control binnacle and children’s cutlery, it was impossible for the industrial designer to engage in any direct physical interaction with either the virtual CAID model or the rapid prototype components during the build process. This inability to be fully involved in the physical shaping of material has been identified by Mahoney, who states that “there’s no question that computer graphics has had a tremendous impact on the business and practice of artistic expression. And while the consequences have been largely positive, a significant casualty of the digital revolution has been the sensory deprivation the technology imposes on the user”. (Mahoney 2000 pp13 – 14) She goes on to note that “artists and designers are a notoriously touchy-feely lot to whom the ideal creative process is a multi-sensory one that supports direct, physical control of the artistic media. Traditional computer graphics don’t allow this. By adopting a 2D mouse or stylus as their design implement, artists have had to stifle their natural impulse to tactically explore and manipulate their creations”. (ibid)

When using conventional model making methods, industrial designers have the opportunity to use their hands to physically interact with a form as it emerges. This tactile interaction with material has the potential to guide the designer’s decision making and direct, to varying degrees, the evolution of the design. On a more fundamental level, McCullogh identifies the inability of computer systems to allow the user to more fully engage in the task being undertaken: “What good are computers, except perhaps for mundane documentation, if you cannot even touch your work? The fact that traditional craft endures at all is because it satisfies some deep need for direct experience – and most computers are not yet providing that experience.” (McCullough 1998 p25)

Such interaction is not possible when rapid prototyping is employed. The physical object is a copy of the CAD or CAID data from which it was produced,
and as such cannot be subject to any tactile manipulation by the industrial
designer. As an activity that can be closely associated with sculpture, its
removal may not be in the best interests of the product outcomes. However, it
is also necessary to acknowledge the commercial need to develop products
efficiently, which increasingly means moving towards digital design techniques.

In an attempt to re-establish the manipulative control of form that is afforded by
the production of physical models by hand, the use of a haptic feedback device
was identified as a potential solution. Haptics have been defined as “the
technology that provides sensing and control via touch and gesture”, and a
haptic feedback device translates these characteristics to the operator.
(Hodges 1998 pp48 – 58)

A haptic feedback device provides the operator with a form of physical
interaction with a virtual model by applying force feedback when manipulating
the component surface. It achieves this by giving feedback to the user through
a control arm.

Whilst the promotional literature for haptic feedback devices may appear
convincing, the sensory information delivered is limited. These limitations are
summed up by Salisbury, the Principal Research Scientist at the MIT Artificial
Intelligence Laboratory, when he states that “to sense the shape of a cup we do
not take a simple tactile snapshot and go away and think about what we felt.
Rather, we grasp and manipulate the object, running our fingers across its shape
and surfaces in order to build a mental image of a cup”. (ibid) This is reiterated
by McCullough: “Touch technology is underdeveloped, and few interaction
devices provide force or tactile feedback. Without touch, currently the most
common complaint about computers is not about overload, but deprivation. It is
about the inability to touch one’s work. Being out of touch is considered an
occupational hazard: regular sensory deprivation turns you into a nerd.” (op cit
p130) Salisbury acknowledges that the use of haptic feedback devices in the
fields of medical simulation (for surgical procedures), animation and computer
games, but their contribution to CAD and CAID has yet to develop. (op cit pp48 –
58)
Having identified the absence of tactile interaction with the emerging product form when using rapid prototyping, the resolution of this issue was evaluated through the use of a haptic feedback device. This was undertaken via an entry by the author for the 2000 Ngoya International Design Competition. The Ngoya International Design Competition is a global design event open to designers aged forty and under. For the previous competition in 1997, 839 designers from 53 countries submitted entries. ([http://www.idcnagoy.co.jp/compe/top.html](http://www.idcnagoy.co.jp/compe/top.html))

The only haptic feedback device to achieve worldwide commercial use has been the Phantom input device and Freeform software developed by SensAble Technologies in Woburn USA. (Oshiba in Bullinger and Zeigler 1999 pp1075-1079, Penderson in Bullinger and Zeigler 1999 pp1070-101074, Kameyama in Bullinger and Zeigler 1999 pp1035-1039, Dachille et al in Proceedings of the 1999 Symposium on Interactive Computer Graphics 1999 pp103-110)

To assist with the case study, the Phantom input device, Freeform 2 software and technical support (via Christopher Dean) were made available by SensAble Technologies. The Phantom input device can be seen in Figure 115.

![Figure 115: Phantom haptic feedback device](image)

**Concept generation**

The Ngoya International Design Competition offered a totally open design brief, with a requirement for visual and conceptual innovation. The specific product to be designed was to be based on a small communication device that would
cross the boundary between conventional consumer product and an item of jewellery. The aim of the communication device was to be a departure from the current over-specified transient products.

Concept generation was undertaken using conventional sketching in pencil, examples of which can be seen in Figure 116.

The proposal was for a small brooch-type product that would have limited functionality compared to a typical mobile telephone. A large elliptical button would be used to answer calls, with smaller buttons for dial/send, memory, and on/off. Recesses on the outer surface would give access for the microphone/speaker. As jewellery produced using craft-based techniques can have an irregularity of surface finish that adds to the visual quality of the artefact, such elements were explored during concept generation.

Use and evaluation of haptic feedback device
In preparation for modelling with the haptic feedback device, it was necessary to become familiar with the hardware and software. Using the device for the first time was quite awkward as the feedback to the hand was some distance away from the virtual model. It also took time to orientate the tools of the input device on the surfaces of the virtual model. Within two hours, and with the support of the SensAble consultant, confidence grew and the modelling method became more intuitive. The additive and subtractive modelling techniques were explored, along with smoothing operations and manipulation of material density. One of the test models produced during this familiarisation process can be seen in Figure 117.

![Test model produced whilst exploring the capabilities of haptic feedback modelling](image)

Figure 117: Test model produced whilst exploring the capabilities of haptic feedback modelling

After a period of use and evaluation, it became apparent that the hardware and software could be used on two levels. The first involved techniques closely associated with CAD/CAID modelling, whereby forms could be generated by non-haptic input e.g. using the keyboard to create a form and numerically lengthening it in one or more planes. This functionality provided by the Freeform 2 Software was relatively crude when compared with the DeskArtes CAID system, and for the communication device it was considered more appropriate to undertake such modelling using CAID. The second technique,
that of haptic interaction, had the potential to produce forms by physically interacting with the virtual model.

On using the haptic feedback device to interact with the virtual model, it became apparent that the software and hardware were capable of producing forms that would be impossible to model using any other digital tool such as CAD, CAID, or optical scanning. Techniques such as bump-mapping a texture from a greyscale image onto a CAD/CAID model may recreate similar freeform surfaces, but their orientation and depth could not be directly controlled by the designer.

**Digital concept generation**

At the start of the modelling process for the communication device, the basic outer form of the product was modelled using the Freeform 2 software without the use of its haptic feedback capabilities. It was generated from a sphere and distorted to produce the required flat, curved form. Several attempts were made to model the speaker/microphone notches with the haptic feedback device, but it was not possible to generate the smooth forms required. The stepping effect produced by the motors that controlled the feedback resulted in a slightly distorted surface that could not be resolved using the smoothing operations available within the software. Such limitations were not entirely unexpected, although Hodges noted the technical and sensory limitations of current haptic feedback devices, stating that “today’s haptic interfaces provide only a bare approximation of a human’s sensitivity for touch”. (Hodges 1998 pp48 – 58)

In developing an alternative haptic feedback device to that of SensAble Technologies, the California Institute of Technology (CalTech) has produced a research system called “Surface Drawing” that involves the use of an 18 sensor CyberGlove within a 3D interactive tabletop display. (Mahoney 2000 pp39 – 46) As with the SensAble system, Surface Drawing is not suited to the generation of crisp, clean forms characteristic of industrial design requirements. *(ibid)*
In attempting to produce the clean scoops for the speakers, it would have been possible to use the more controlled modelling techniques available within the software, such as using a guide to control the path of the cut. However, this would have represented a significant departure from tactile haptic feedback modelling, emulating the more controlled techniques of CAD and CAID. It was therefore considered more appropriate to use CAID for the modelling of the basic form followed by the use of the haptic feedback device for specific surface effects. The basic form of the communication device was modelled using the DeskArtes CAID software in 20 minutes. As the body of the product was to be modified using haptic feedback modelling, it was imported into Freeform 2 as an stl surface. The imported surface (modelled using CAID) can be seen in Figure 118.

![CAID stl file imported into Freeform 2 modelling system](image)

Figure 118: CAID stl file imported into Freeform 2 modelling system

The elliptical step in the centre of the component is the cavity into which the answer button would be positioned at a later stage. The three notches at the lower left of the model in Figure 118 are for the speaker/microphone outlet, these being the features that were impossible to model using the haptic feedback device.
The surface finish of the communication device was not rigorously defined at the concept generation stage as it was intended to explore the capabilities of the haptic feedback device to produce techniques related to conventional craft-based interaction. Adjustments to the density of the virtual modelling material and shape of tool resulted in the development of the required hammered effect. This result was achieved by using a rounded tool to hammer a relatively hard surface. The initial hammering can be seen in Figure 119.

![Figure 119: Haptic feedback modelling of hammered effect](image)

As when working with physical materials, the virtual model was rotated to ensure that the hammer blows were in the correct orientation. When complete, the surface was smoothed to soften the edges of the hammer blows. A second series of hammer blows were then applied to give a more irregular effect. On
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Completion this was again smoothed to achieve the finish as seen in Figure 120.

The hammered surface was saved as an STL file and imported into the CAID system for additional rendering. The rendered product can be seen in Figure 121, and as a photo-montage on a user in Figure 122.
Design development
Following the concept generation and rendering of the communication device, it was apparent that other creative forms would be possible if the capabilities of the Freeform 2 software and Phantom input device were exploited. The design development phase involved the exploration of additional opportunities based on a common generic form.

During the introduction to the use of the haptic feedback device, the capability to mask surfaces to avoid deformation by subsequent operations was demonstrated. This not only created a mask, but could also be used to define a cut on a surface to enable its removal. Whilst exploring the use of this functionality to produce a rim around a scored section of the surface, the potential to create a distinctive random transition between two surfaces became apparent (see Figure 123).

With the mask applied, it was possible to extract the inner surface and leave the outer section as a separate element. The surfaces were then imported into the CAID system for rendering and the addition of the remaining components. The final rendering was defined with a silver outer section and purple plastic inner. A rendering of the product that was produced using the masking
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technique can be seen in Figure 124, and as a photomontage on a user in Figure 125.

Figure 124: Rendered masked product

Figure 125: Photomontage of user with masked product
Specification

As all of the design modelling was undertaken using CAID and the haptic feedback device, the specification of the component geometry was embodied as digital data. As such, engineering designers and manufacturers with digital design capabilities would have the potential to import this data as a full specification of the industrial designer's proposal (as with the control binacle).

To conclude the modelling of the communication device, the major component for the hammered product was translated into a sketch model via a Z-Corp rapid prototype concept modeller (see Figure 126).

On delivery of the sketch model, it became apparent that the use of the haptic feedback device had resulted in a form that could not have been produced using any other means. The control over the material properties had enabled the specification of a virtual material that would not be possible under conventional workshop conditions. In a matter of minutes the designer had created the material resistance that was required to produce the desired effect.
In addition, during the hammering procedure, any blows that fell in the wrong place could be erased.

Having explored the capabilities of the haptic feedback device, limitations were identified, although it must be acknowledged that the use of the system also opened up creative possibilities that would not be possible without the use of such technology.

**CAID/RP methodological approach**

The issues of STL file generation, use of a concept modelling rapid prototyping system, and physical interaction were identified during and after the line trimmer case study and their resolution evaluated through the three additional case studies. The outcomes necessitated modifications to the revised CAID/RP methodological approach (see Figure 127).
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The CAID/RP methodological approach commences with the production of concepts using conventional 2D sketching and simple 3D sketch modelling during the concept generation phase. Having established a design direction for one or more concepts, digital surface modelling is employed through the use of CAID, a haptic feedback device, and a rapid prototype concept modeller. The specific applications for these three modelling techniques would vary from project to project, but the potential to use all three would enable digital industrial design techniques to be used to maximum effect.

The core of the modelling process is the use of CAID to facilitate the effective generation and manipulation of freeform surfaces and rendering of concept proposals. Where appropriate, a haptic feedback device may be employed to facilitate a degree of physical interaction with product form (as takes place in a conventional workshop). This may utilise an imported CAID surface or generate form entirely through the use of the haptic feedback device (hence the arrows point in both directions on the diagram in Figure 127). On completion of the haptic feedback modelling, the surface data is imported into the CAID system for additional modelling and rendering.

Whilst not a precise replication of all conventional sketch modelling operations, the use of a haptic feedback device as a precursor to the production of components using a rapid prototype concept modeller would enable the production of physical representations of form that had been modelled, at least in part, through tactile interaction.

Industrial designers may use conventional 3D sketch modelling during concept generation, and the production of 3D sketch models via rapid prototyping necessitates the definition of component geometry as an stl file. The CAID/RP methodological approach provides options for the stl files to be produced by the industrial designer using the CAID system or through modifications to the geometry by an engineering designer (adding wall thickness).

The three activities of physical interaction, CAID modelling, and stl file generation produce digital design data, and as such this can be made available
to others involved in NPD (such as engineering designers) through ‘model share’ (see dotted lines with arrow in Figure 127). In addition, as these three activities produce a mathematical definition of surface geometry, their use also signifies the commencement of the specification phase.

Having undertaken the design element of the concept generation phase (physical interaction, CAID modelling, sketch modelling, stl file generation), the 3D geometry is available for the production of concept rendering(s) for client presentation. In addition, the model share capability gives the potential for the transmission of the renderings for marketing activities such as customer/user feedback.

Progression from concept generation to design development is dependent on the decision of the client, but as the possibility exists for the concept(s) to be rejected, a feedback loop to the start of concept generation has been included (see Figure 127). The entire concept generation phase can therefore be undertaken as many times as required.

The basic techniques employed during design development are almost identical to those of concept generation, involving the potential to employ 2D/3D conventional techniques, CAID, a haptic feedback device, a rapid prototype concept modeller, and the expertise of an engineering designer. They differ, however, in that these activities now focus on the refinement and detailing of the outcome(s) from concept generation. Again, the digital outputs from a haptic feedback device, CAID, and an engineering designer are all available for use by others involved in NPD through model share.

Having completed the detailing of the proposal(s), CAID is used to produce proposal renderings for client presentation that can again be distributed through model share for activities such as user/customer feedback. Should the proposal be rejected or require further modifications, a feedback loop within design development has been included.
When the client has approved the output from design development, the final specification of the proposal can take place as 3D computer geometry and a physical appearance model and/or prototype. The definition of product form would be available as an output from the CAID system, but the production of an appearance model/prototype using rapid prototyping would require the generation of stl files. This can be done either directly by the industrial designer or by exporting the CAID surface geometry to an engineering designer.

Having produced stl files for product components that mirror the design as approved through proposal renderings at the conclusion of design development, a physical appearance model/prototype can be produced using rapid prototyping and workshop-based finishing techniques. Having presented the appearance model/prototype to the client, a decision must be made to either proceed to production (using the CAID geometry or stl files to define form), or employ additional design development through the feedback loop.

**Summary**

- CAID surfaces can be effectively imported into an engineering designer’s CAD system for stl file generation.
- The use of appearance prototypes can remove the need to produce appearance models.
- Rapid prototype concept modellers can be used as an alternative to the production of conventional sketch models.
- The use of a haptic feedback device can provide useful tactile information during the definition of product form.
- The use of a haptic feedback device has the capability to produce forms that are impossible to generate using any other means.
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- The state of the art in haptic feedback devices is not sufficiently advanced to undertake the full range of modelling functions required during industrial design practice.
CHAPTER SEVEN: 
Appraisal framework

The comparative evaluation of the two appearance models during the line trimmer case study demonstrated that the use of rapid prototyping was effective in the reduction of lead times. This case study also identified modelling issues that were addressed via further case studies, resulting in modifications to the revised CAID/RP methodological approach and the definition of a the CAID/RP methodological approach. Having evaluated all elements of the CAID/RP methodological approach through the four case studies, it was necessary to validate this proposal using an appraisal framework.

The appraisal framework employed the rating/weighting method, using responses generated during interviews with practitioners. (Pugh pp92 – 99 1991) The rating/weighting method involves the allocation of a weighting factor (based on judgement) to specific criteria, followed by the rating of alternative concepts against these (again based on judgement). (Ibid) The values arrived at for the weighting are then multiplied by the rating values, giving a score for each alternative. The resulting numeric value provides an indication of the relative merits for each alternative, and “the concepts having the highest scores are those that appear to best satisfy the criteria”. (Ibid p93) The use of the rating/weighting method provided an indication as to whether or not the CAID/RP methodological approach could facilitate an improvement in existing practice based on the relative numeric values of the two strategies evaluated, with the difference indicated as a percentage.
To validate the contribution of the CAID/RP methodological approach for practitioners with access to varying resources for the production of appearance models, it was necessary to reflect this diversity in the profile of the interviewees. To achieve this, at one extreme was a recent graduate who was just starting out on a freelance career, with a model making resource that consisted of basic power and hand tools. At the opposite end of the scale was a multinational white goods manufacturer, with a capability that consisted of twenty model makers with access to a fully equipped workshop (including three-axis CNC machining). Between these extremes were a rotational moulding company with a basic model making facility (including band-saw, lathe and pillar drill); a consultant within a university industrial design department with one model maker and well equiped workshop; and a consultancy with four model makers and fully equiped workshop (including vacuum casting). Whilst this group consisted of practitioners with access to a broad range of resources, they could not of course represent every model making capability. However, as the elements of the CAID/RP methodological approach had been partially evaluated through the four case studies, a positive consensus on its effectiveness from all five practitioners would provide verification of its validity.

The interviewees were: Chris Taylor, industrial design manager for General Domestic Appliances, a major manufacturer of white goods with 10000 employees; Stuart Wright, industrial designer for Rototek, a rotational moulding small to medium sized enterprise (SME) with 50 employees; Ian Storer, senior industrial designer for consultants Hodges and Drake with 12 employees; George Torrens, academic member of staff in the Department of Design and Technology at Loughborough University, with 380 undergraduate industrial design students; Andrew Thompson, 2001 graduate (BA Industrial Design and Technology, Loughborough University.

The conduct of the rating/weighting exercise followed the format identified by Pugh, commencing with the interviewees being presented with objectives for the production of appearance models and given the option to remove some of these or add others as required. (ibid pp92 – 93) The objectives focused on the
generic requirements for appearance models as discussed in Chapter 1, with
the addition of objectives that had specific relevance to the capabilities and
opportunities that arise from the use of the CAID/RP methodological approach.
The pre-defined objectives were:

1. Efficient translation of design intent.
2. Designer interaction during definition.
3. Efficient build technique.
4. Lowest possible cost to specification.
5. Effective integration of components.
6. Exact translation of design intent.
7. Requires minimal workshop resources.
8. Previous use of rapid prototyping for sketch models.
9. Immediate deletion of errors (editing).
10. Efficient paint finishing.
11. Use of digital 3D surface data in build.
12. Efficient conversion to appearance prototype.
13. No on-cost for additional complexity.
14. Possible to specify density of material.
15. Interactive definition of texture (digital).
Chapter Seven

Appraisal framework


The rationale behind these objectives will now be discussed.

The “efficient translation of design intent” (objective number 1) referred to the ease with which a design proposal could be translated into an appearance model. The proposal could take the form of renderings, GA’s, digital geometry or a sketch model, but the interpretation of this and its effective translation into an appearance model was the focus of this objective.

“Designer interaction during definition” (objective number 2) enables form to be manipulated and specified through the physical shaping of material. Whilst form may be defined through 2D, 3D sketch modelling, and 3D digital geometry, the interaction with material that becomes a specification of product form is an acknowledged industrial design technique. This objective refers to both physical materials and the use of a haptic feedback device.

Appearance models can be produced from a wide variety of materials, but the objective of “efficient build technique” (objective number 3) gives an indication of the significance of specific production methods. Whilst certain materials may give a high level of surface definition (e.g. acrylic), considerable effort may be required to achieve this. This objective focuses on the significance of an effective fabrication process.

“Lowest possible cost to specification” (objective number 4) indicates the significance of cost in the production of appearance models.

Production components may form part of an appearance model to avoid the need to re-make them (e.g. the petrol engine on a lawn mower), or to enable the accurate evaluation of balance (e.g. motors within power tools). The inclusion of components within mouldings can be problematic when employing ‘block’ modelling techniques in the fabrication of appearance models. “Effective integration of components” (objective number 5) sought to identify the importance of this capability.
In contrast with “efficient translation of design intent” (objective number 1), “exact translation of design intent” (objective number 6) sought to establish the designer’s requirement for the appearance model to precisely reproduce the proposal (as embodied through drawings, renderings, sketch models, digital geometry etc.) as an appearance model.

The resources available to the industrial designer for the direct production of appearance models vary from cutting card to full prototyping. “Requires minimal workshop resources” (objective number 7) focused on the significance of the lowest possible capital investment.

The ability of rapid prototyping to deliver low cost sketch models is a relatively recent development, with its significance being demonstrated through the children’s cutlery case study. “Previous use of rapid prototyping for sketch models” (objective number 8) sought to identify the weighting of this capability in terms of actual use or potential application.

By integrating the use of a haptic feedback device within the CAID/RP methodological approach, during the interaction with form it is possible to undertake the “immediate deletion of errors (editing)” (objective number 9). This is analogous to shaping a piece of resin or wood in a workshop, deciding that the operation was unsuccessful, and seamlessly replacing that material. Clearly this is impossible with a physical material, but the Freeform software of the SensAble haptic feedback device enables this to be undertaken for up to 25 operations when working the virtual material. It was therefore necessary to receive a weighting for this capability through objective number 9.

Some resistant materials are more suited to the efficient application of paint than others. For example, whilst Jellutong can be readily shaped, as a wood it requires sealing before paint can be applied. In contrast, Perspex is significantly harder, but once formed does not require sealing. “Efficient paint finishing” (objective number 10) focused on the suitability of the base material for painting.
When using digital design techniques that generate 3D computer geometry, the use of such data in the production of appearance models and prototypes through rapid prototyping ensures that the intent of the industrial designer is accurately translated from the virtual to the physical. The significance of this capability was addressed in objective number 11: “use of digital 3D surface data in build”.

When an industrial design proposal has been approved via an appearance model, for those products that house electronic and mechanical components it is then necessary to produce an appearance prototype. Whilst an appearance model produced from solid materials in wood or plastic would be difficult to translate into an appearance prototype, this would not necessarily be the case if hollow components had been used (e.g. vacuum formed fabrications or rapid prototype parts. The significance of the “efficient conversion to appearance prototype” was identified in objective number 12.

The costing of rapid prototype components is dependent on volume, not complexity. As such this process offers a potential advantage over conventional workshop-based fabrication techniques. To assess the significance of this capability, “no on-cost for additional complexity” was identified in objective number 13.

A unique attribute of the CAID/RP methodological approach was the facility to identify the density of the virtual material that was manipulated by the industrial designer. This capability was the focus of objective number 14: “possible to specify density of material”.

When employing injection moulding or die casting, the application of texture to a product surface is generally under the control of the toolmaker through the use of shot blasting and etching. The communication device case study indicated the potential for the industrial designer to be directly involved in this process through the use of a haptic feedback device. In presenting this
capability for appraisal, “interactive definition of texture (digital)” was addressed via objective number 15.

The significance of removing the need for physical models to define form (as opposed to communicating it) was addressed by objective 16: “entirely digital specification of form”.

Whilst no requests were made to remove any of the prescribed objectives, additional ones were added by the interviewees. The “resolution of engineering detail” (objective 17) and “maximum use of sketch models” objective 18) were added by the consultant. The “earliest possible marketing buy-in” (objective 17), “earliest possible technical buy-in” (objective 18) and “maximum material realism” (objective 19) were added by the major manufacturer. “Reliability of development chain” (objective 17) and “tutorial support” (objective 18) were added by the academic. “Durability” (objective 17) was added by the SME, and no additions were requested by the graduate. Rating/weighting forms with the sixteen prescribed objectives and the blank variant for additional objectives can be seen in Appendix 3.

During the appraisal, the interviewee was asked to weight each objective from 1 (least important) to 5 (most important), with 3 being neutral. On completion of the weightings, the responses were covered to prevent the interviewee from referring to these during the rating exercise.

The rating exercise involved the identification of a numeric value for the effectiveness of the strategy employed by the interviewee for the production of appearance models. This was rated against each objective with a value from 1 (very poor) to 5 (very good) with 3 being neutral. The responses were again covered before progressing to the second rating exercise.

Interviewees were fully familiarised with the implementation of the CAID/RP methodological approach. This included a slide presentation with images of the activities and outcomes from the four case studies (line trimmer, control binnacle, children’s cutlery and communication device), the physical models
produced during the line trimmer case study, and the rapid prototype sketch and appearance models for the children's cutlery. The tabular results from the comparative evaluation of appearance models and prototypes were also presented and discussed (Table 1). When the interviewee was content that they understood the nature of the CAID/RP methodological approach they were asked to rate its effectiveness in achieving the objectives for appearance models as previously specified.

Having completed all five interviews, it was necessary to ensure that the outcome provided an indication of the degree of change (improvement or worsening) that would arise from the use of the CAID/RP methodological approach. This was achieved by normalising the values generated during the weighting exercise by adding the values for each interviewee together, dividing the total into 100, and multiplying this figure by the value given for each objective (producing an outcome out of 100%). For example, for the academic the total figure for the weight factors when added together was 65. When divided into 100 this gave 1.54 which was then multiplied by the response for every weight factor. A response of 5 therefore became 7.7, 4 became 6.2 and so on. The values for the rating were also converted to a figure out of 1 by dividing by the maximum value of 5. A response of 5 therefore translated into 1, 4 to 0.8, and so on. The responses given for each of the five interviewees can be seen as raw data in Appendix 4, and as normalised data in Appendix 5. Figures 128 to 132 show the normalised weighting/rating responses for the objectives from each interviewee as bar graphs.
Figure 128: Bar graph of normalised weighting/rating responses for academic

Figure 129: Bar graph of normalised weighting/rating responses for consultant
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Figure 130: Bar graph of normalised weighting/rating responses for graduate

Entirely digital spec. of form
Interactive definit. of texture
Specify density of material
No on-cost for complexity
Efficient conversion to proto.
Use of 3D surface in build
Efficient paint finishing
Immediate deletion of errors
Prev. use of RP sketch models
Requires minimal resources
Exact translation of intent
Effective integration of parts
Lowest possible cost to spec.
Efficient build technique
Designer interaction
Efficient translation of intent

Figure 131: Bar graph of normalised weighting/rating responses for major manufacturer

Maximum material realism
Earliest technical buy-in
Earliest marketing buy-in
Entirely digital spec. of form
Interactive definit. of texture
Specify density of material
No on-cost for complexity
Efficient conversion to proto.
Use of 3D surface in build
Efficient paint finishing
Immediate deletion of errors
Prev. use of RP sketch models
Requires minimal resources
Exact translation of intent
Effective integration of parts
Lowest possible cost to spec.
Efficient build technique
Designer interaction
Efficient translation of intent
When the normalised weigh factor \((w)\) was multiplied by the normalised rating \((r)\), and the totals added, the resulting figure could be evaluated against 100% effectiveness which would be the perfect solution. For example, for the academic, the in-house strategy for the production of appearance models was 51.1% effective, whilst the CAID/RP methodological approach was considered 72.6% effective, resulting in an improvement of 21.5%. A summary of the % change for the normalised weighting/rating responses can be seen in Table 2.

### Table 2: Summary of responses to weighting/rating exercise

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>Normalised rating/weighting score (%)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current strategy</td>
<td>CAID/RP</td>
</tr>
<tr>
<td>Major manufacturer</td>
<td>56.2</td>
<td>75.3</td>
</tr>
<tr>
<td>SME</td>
<td>61.0</td>
<td>75.4</td>
</tr>
<tr>
<td>Consultant</td>
<td>73.1</td>
<td>92.2</td>
</tr>
<tr>
<td>Academic</td>
<td>51.1</td>
<td>72.6</td>
</tr>
<tr>
<td>Graduate</td>
<td>59.6</td>
<td>89.9</td>
</tr>
</tbody>
</table>

Figure 132: Bar graph of normalised weighting/rating responses for SME
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The responses to the CAID/RP methodological approach were overwhelmingly positive, with an average 21% improvement over the interviewees current strategy for the production of appearance models.

In addition to the rating/weighting method, interviewees were invited to provide feedback on the perceived disadvantages and advantages of the CAID/RP methodological approach. In terms of disadvantages, a response shared by all five interviewees related to the limitations of the haptic feedback device in delivering sensory information that was close to that of conventional workshop techniques. For advantages, the one feature of the CAID/RP methodological approach cited by all interviewees related to the reduction in overall lead times for NPD.

The final question asked whether or not the CAID/RP methodological approach would reduce lead times for the production of appearance models. All interviewees felt that this would be achieved, with reasons for this being given as: the speed of rapid prototyping; immediate progression from visualisation to appearance model; the effectiveness of digital techniques; and its adoption as a single process.

Summary

- Improvements afforded by the use of the CAID/RP methodological approach were validated by practitioners.

- The limited tactile response of the haptic feedback device was considered to be a limiting factor for the CAID/RP methodological approach.

- All interviewees believed that the CAID/RP methodological approach would reduce lead times for NPD.

- All interviewees believed that the CAID/RP methodological approach would reduce lead times for the production of appearance models.
• The average improvement achieved through the use of the CAID/RP methodological approach was 21%.

• A positive response was received to the CAID/RP methodological approach when presented at UK and overseas seminars.
CHAPTER EIGHT: Conclusions

This Chapter identifies the achievements and limitations of the project with respect to the objectives as stated in the introduction, future research and development, and potential future changes in the field.

To undertake a literature review with respect to the nature of industrial design and rapid prototyping so as to illuminate the research field and determine parameters for the methodological approach

The contribution of the literature review into the nature of industrial design and rapid prototyping was two fold. Firstly, and relatively rapidly, it identified a major shortcoming in the quantity and quality of published material on the use of rapid prototyping by industrial designers. Secondly, it provided evidence to suggest that this technology had the potential to make a significant contribution to professional practice through the production of appearance models and prototypes. The identification of a correlation between the modelling requirements of industrial design practice and the capabilities of rapid prototyping represented a key outcome. The documentary evidence provided a convincing case for its efficacy.

Despite these positive outcomes, as an investigation into practice, it could be argued that there was an over-dependency on published material and an opportunity to undertake primary research into the methods and needs of practitioners missed. However, survey methods were subsequently employed
through the use of a practitioner questionnaire that identified the extent to which industrial designers were using rapid prototyping. Whilst the response rate of 20% may appear relatively low, this was within the 15% to 50% range expected for such activity. (Burns 2000 p.580)

The questionnaire focused on the use of rapid prototyping, and there was potential for the results to be skewed if only those practitioners using this technology had responded. However, 17% of the responding consultants had not used rapid prototyping. In addition, further validation was provided by the close correlation of the questionnaire responses with the findings of the literature review.

Although practitioner opinion was not sought during the definition of the draft CAID/RP methodological approach, it was ultimately validated via positive feedback through the subsequent questionnaire.

To evaluate the methodological approach through its application during the industrial design of a new product

Having defined the revised CAID/RP methodological approach following practitioner feedback, its evaluation during a design commission undertaken by a practising designer was considered. Whilst this had the potential to validate the revised methodological approach, significant problems were identified with this strategy. These involved: identifying a commission in which rapid prototyping was guaranteed to take place; monitoring and recording the conduct of the consultancy at all relevant stages; identifying a commission in which the product to be modelled would comprehensively evaluate the properties of the rapid prototype components; and agreeing to academic freedom in openly reporting the outcomes. There was also the low probability of a commercial commission resulting in the production of two identical appearance models using both conventional fabrication techniques and rapid prototyping.
The production of the identical appearance models using contrasting techniques was considered an essential feature of the study as it would facilitate an evaluation of strengths and weaknesses. It was also required as there was no published material on such activity. Had this been evaluated during a commission undertaken by a commercial consultant or in-house designer, this strategy would have concurrently evaluated and validated the CAID/RP methodological approach.

Having considered the problems associated with the evaluation of the CAID/RP methodological approach within a consultancy or in-house environment, these were resolved by the application of an equally valid strategy of reflective designing (involving the author). This involved a project that had its origins as a commercial industrial design commission. Whilst the amount of commercial activity undertaken by the author was less than that expected of an active full-time consultant, the design of approximately two products per year using the generic techniques of professional practice (as identified in the literature review) ensured that professional skills were maintained. The author was also in a position to record all relevant events, this representing a key advantage of reflective designing.

Despite a high degree of confidence in the fact that the line trimmer case study had emulated commercial industrial design activity, a key area where this was not achieved was in the overall time scales during which it was conducted. Whilst the elapsed time for the individual activities was comparable with a commercial commission, the overall project duration was significantly greater. This was due to the necessity for the designer to undertake other duties (teaching, admissions, other research). There was also no pressure for a specified completion date from a client. However, whilst the process of designing may have taken place over an extended period of time, the key outcomes were reliable, and time-scales for the production of the appearance models/prototype meticulously logged.
To compare and contrast models produced using rapid prototyping with those of workshop-based fabrication techniques

Whilst the execution of the line trimmer case study emulated commercial practices, a significant deviation existed in the necessity to produce two identical appearance models. Under commercial conditions, only one appearance model would be required to facilitate the evaluation of form and interface, but a key element of the case study was the necessity to compare and contrast the capabilities and limitations of both rapid prototyping and conventional fabrication techniques. This involved recording not only the time involved in the production of each appearance model, but an evaluation of the associated model making operations.

As a computer controlled process, the SLA component build time could be accurately recorded and repeated if required. Time scales for the finishing and assembly operations that followed this, plus the fabrication of the appearance model using conventional techniques, was recorded to the nearest minute through the use of a log book. Unlike the SLA build, it must be acknowledged that the replication of the time scales for the operations undertaken by the model maker could not be guaranteed. Even if repeated by the same model maker, the capacity for improved performance due to previous experience would exist, as would the potential for reduced performance due to error. Should a different model maker be employed to undertake the same task, their level of skill may be higher, lower, or different fabrication techniques used to produce an identical visual outcome.

In defence of the time scales that were recorded for the conventional model making activities, for a professional model maker, the operations undertaken would be relatively straightforward and could confidently be carried out by a suitably qualified individual with workshop facilities. Whilst it is accepted that some deviation may occur with the results for the time scales if the exercise was repeated, it is not anticipated that these would have a significant impact on the final outcome. This arises from the fact that the difference in time scales
was significant, with 21.5 hours required for the production of the appearance model using rapid prototyping, compared with 47 hours for that produced by conventional fabrication techniques. In addition, of the 21.5 hours required for the production of the appearance model using rapid prototyping, 10.5 hours of this (49%) involved the use of conventional model making techniques for the finishing and assembly operations. There is therefore a high probability that a reduction or increase in time scales that may arise from the differing levels of skill of another model maker would be transposed to both forms of appearance model.

In addition to the identification of reduced time scales achieved through the production of the appearance model using rapid prototyping, other significant outcomes from the comparative evaluation related to specific model making issues, the extension of the role of the appearance model to that of an appearance prototype, and the more general interaction with physical material.

In terms of specific model making issues, the necessity to remove stepping from rapid prototype components to produce a representation of the original computer geometry had been identified in the literature review and practitioner survey. Difficulties associated with this became apparent when a high definition concave surface was required for the SLA appearance model. In the production of the appearance model using conventional fabrication techniques, the concave surfaces of the cutter guard and cutter guard release handgrip were produced by vacuum forming polystyrene and machining urethane respectively, and as such required no post-processing smoothing. However, identical surfaces on the SLA components required significant model making effort to rectify the disruptions to the surfaces caused by the removal of stepping on the cutter guard and reworking of the dimples on the cutter guard release handgrip.

The capacity of rapid prototyping to economically produce complex parts with internal detail was effectively demonstrated by extending the use of the SLA components for the production of an appearance prototype of the line trimmer. Whilst appearance models are more representative outcomes from industrial design output, the potential to produce fully working appearance prototypes in
comparable time scales represents a significant enhancement to the capabilities of professional practice.

Issues relating to the more general interaction with physical material involved the lack of tactile feedback when employing rapid prototyping, this being limited to sanding, painting, and assembly. It must be acknowledged that the physical interaction with form during the production of an appearance model may not be required during all industrial design commissions, but its absence within the rapid prototype build represented a significant omission. As an alternative strategy, the laser scanning of a physical object to produce point cloud data was identified in Chapter Two (p83). This technology was found to be not only unreliable, but if integrated within the CAID/RP methodological approach would still require a high definition physical model to be produced by hand, scanned, the geometry manipulated, and rapid prototypes produced. Such a strategy would therefore require an additional physical model that would increase, not decrease lead times.

To identify any issues with the methodological approach and devise a strategy for their resolution

The evaluation of the revised CAID/RP methodological approach via the nylon line trimmer case study employed methods of action research and reflective designing. Through these activities, two significant deficiencies were identified: the additional effort required to produce the stl files required for rapid prototyping, and lack of physical interaction during the component build. In addition, having noted that rapid prototyping could not contribute to the production of sketch models within the revised CAID/RP methodological approach, the subsequent emergence of commercial rapid prototype concept modelling systems on completion of the line trimmer case study challenged this notion. Having identified these issues, it is necessary to consider that if the nylon line trimmer case study been undertaken by a different industrial designer, would these outcomes have been replicated?
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The issue of STL file generation involved the additional computer modelling required to translate the geometry used for rendering into a format suitable for rapid prototyping. Had the line trimmer case study been entirely based around conventional industrial design techniques, it would have been necessary to specify the product form as GA drawings in preparation for the production of an appearance model. As the case study employed rapid prototyping, it was possible to extend the use of the CAID geometry for the production of STL files. This involved the definition of interior walls, requiring an effort and rigour in modelling exceeding that for both CAID rendering (where only an exterior surface is required) and the definition of exterior form for a conventional appearance model (using GA drawings). As a significant departure from the practices as identified in the literature review, and a generic requirement for the production of rapid prototypes, the likelihood of this issue being identified by another industrial designer is considered to be high.

Having noted that the activity of STL file generation may be considered as being outside the industrial designer’s distinctive remit of defining product form, it has also been acknowledged that the working practices of this group may need to change if the opportunities afforded by the use of digital design techniques are to be fully exploited. It is therefore possible to regard the additional effort required to generate STL files as a necessary part of professional development, especially as the benefits of employing rapid prototyping are significant. This additional effort may not therefore be regarded as a problem, but an extension of professional practice. The potential for this becomes more apparent when considering the relative ease with which the appearance prototype was produced. By becoming increasingly involved in the definition of internal product detail, and exploiting the capacity to produce appearance prototypes, industrial designers will be in a position to become increasingly responsible for engineering design. The potential for this has greater significance if the capabilities of design automation increase, thereby reducing the engineering knowledge required to undertaking such activity.

To ensure the validity of the CAID/RP methodological approach for those practitioners who do not feel it appropriate to move into this more detailed area
of product specification, the option to utilise the modelling capabilities of an engineering designer for the production of the stl files remains. This strategy was demonstrated and validated through the automotive control binnacle case study and is included within the CAID/RP methodological approach.

During the course of this project, design technologies have continued to develop, and the first commercial haptic feedback device (SensAble Phantom) became available within twelve months of completing the line trimmer case study. Having employed a haptic feedback device during the industrial design of the communication device, its use as an alternative to interacting with the rapid prototyping build process (which is impossible) was found to have shortcomings in the level of feedback delivered. However, some operations were very close to the interaction undertaken using conventional workshop-based techniques, demonstrating that a haptic feedback device could effectively reproduce areas of this activity.

Despite limitations of the haptic feedback device, the creative opportunities afforded through the functionality of the FreeForm software were significant. Of particular relevance was the ability to edit the digital model by deleting operations that were considered unacceptable. In the context of working with a physical material, this was analogous to delivering a hammer blow to a piece of metal, deciding that it was in the wrong place, and removing it at the press of a button. The FreeForm software enabled this to be undertaken for up to 25 previous operations. In addition, the software could perform operations that could not be conceived of when working a physical material, such as the specification of material density and the production of a precise mask that protected areas from deformation.

Whilst the full range of physical interaction available within a conventional workshop could not be reproduced using the haptic feedback device, some could. In addition, this technology provided the capability to perform operations on a virtual material that could not be undertaken in a conventional workshop.

During the fabrication of the SLA appearance model, the perceived need to interact with form was relatively subtle, involving minor changes to the
curvature of the handgrip and motor housing. Had the line trimmer case study been undertaken by another industrial designer, the proposal for the exterior form would have been different, and a desire to manipulate form through the physical interaction with material at the rapid prototype stage may or may not have been required. Another scenario could have involved a different industrial designer undertaking the case study and accepting the inability to interact with form during the rapid prototype build process as an inherent limitation of this technology. However, having acknowledged the validity of defining form during the interaction with physical material (Chapter 1 pp62 – 63), the probability of this issue being raised in an interview with a different designer is considered to be high. Whilst both situations are hypothetical, the findings of this study have been enhanced through the identification of the inability to interact with form during the rapid prototype build process. Having sought to rectify this through the use of a haptic feedback device, the scope of this research project has been extended and the findings have indicated the creative possibilities afforded by this approach.

Commercial rapid prototype concept modellers were not available when devising the draft and revised CAID/RP methodological approaches, and the component cost and build time for production systems such as LOM and SLA made them unsuitable for the production of sketch models. Again, emerging technology caught up with the research project through the development of lower cost systems with faster build times. The issue of sketch modelling via rapid prototyping was investigated through the children’s cutlery case study, and the ability to produce low cost components with speed and accuracy made a valuable contribution to the resolution of design issues that could only be achieved through the use of physical models.

The integration of rapid prototype concept modelling within the CAID/RP methodological approach did not arise from the process of action research or reflective designing, but an opportunity brought about by on-going research into the emerging capabilities of rapid prototyping throughout the project. Its evaluation during the design of the children’s cutlery demonstrated how it might contribute to professional practice. Had another industrial designer undertaken
this commission and been given the opportunity to use rapid prototype concept models to support the evaluation of product size, it is difficult to predict a scenario where the use of this technology would not contribute to the decision making process. Whilst this assumption involves a degree of speculation, confidence that the proposal had been optimised through the use of Z-Corp concept models provided evidence of its validity.

Despite the fact that rapid prototype concept modellers can produce a derivative of the conventional sketch model, the lack of physical interaction during the build process remains. However, on those occasions when the industrial designer perceives a need to undertake interactive physical modelling, this can be achieved to some degree through the use of a haptic feedback device. The key difference with this strategy, as opposed to that of conventional workshop techniques, is the time delay between the 3D digital modelling and production of the component. With conventional techniques this takes place concurrently, but with a haptic feedback device and rapid prototype concept modeller, the build must take place after the component has been defined.

**To validate the methodological approach through the use of an appraisal framework**

Whilst the key elements of the CAID/RP methodological approach had been evaluated through four case studies, it had not been validated as an integrated strategy. As the project had made extensive use of action research and reflective designing, one option under consideration was to initiate a further case study. For the final validation, it would have been necessary for this to be undertaken by at least one practicing industrial designer. However, the difficulties identified in the use of such a strategy for the nylon line trimmer case study remained. In addition, there was the further problem of identifying a commercial commission that would require the full range of techniques as identified in the CAID/RP methodological approach, including the use of a haptic feedback device. As with the nylon line trimmer case study, such a
strategy was considered problematic, and an alternative method devised that would enable practitioners to comment on the capabilities and limitations of the CAID/RP methodological approach.

The appraisal framework involved the validation of the CAID/RP methodological approach using the normalised rating/weighting method. This enabled five practitioners to compare their existing strategies for the production of appearance models with the CAID/RP methodological approach. The resulting numerical values gave an indication of how close each strategy came to 100% effectiveness.

Every effort was made to ensure that the practitioners understood the process and outcomes of the CAID/RP methodological approach through the use of diagrams, models, prototypes, images and data. The material presented was comprehensive, and as all practitioners were capable designers, the level of understanding of the concepts being presented appeared high. However, this could have been enhanced further had all processes and outcomes to been described through a single case study as opposed to four.

All five interviewees were unanimous on the capacity of the CAID/RP methodological approach to reduce NPD time scales and enhance professional practice. The outcomes indicated that the CAID/RP methodological approach represented an improvement on their current techniques ranging from 14% to 30%, with an overall average of 21%. In addition, the practitioners also confirmed the capability of the CAID/RP methodological approach to reduce NPD lead times, although concerns were expressed about the effectiveness of the haptic feedback device.

To propose a methodological approach for the use of rapid prototyping by industrial designers

It is significant that the resolution of two of the three issues identified at the conclusion of the line trimmer cases study (stl file generation and physical
interaction) were not directly related to the rapid prototyping build process, being dependent on the prerequisite digital modelling. The issue of STL file generation necessitates the definition of component thickness by either an industrial designer or engineering designer, and is independent of the rapid prototype build system. The issue of physical interaction using a haptic feedback device cannot be concurrently transferred to the rapid prototype build process, and again must take place in isolation. A third issue, that of the use of a rapid prototype concept modelling system, is directly related to the build process, and for enhanced effectiveness this could be combined with a capacity for tactile interaction which is only possible through previous modelling via a haptic feedback device.

This study has demonstrated that the CAID/RP methodological approach is capable of reducing lead times for the production of appearance models, thereby providing industrial designers with the potential to contribute to the reduction in NPD time scales. In addition, the application of the methodological approach has been shown to offer enhanced professional performance in terms of both visual and engineering outcomes.

The definition of a methodological approach for the effective integration of rapid prototyping within industrial design practice is an idea that was originated within this research project. The direction and conduct of the research arose from a lack of published material in the field, and on-going requirements and opportunities for the use of emerging technologies. Through the use of literature review, case study, action research and survey methods, the study represents a substantial body of work that has been devised to produce an original contribution to knowledge by systematic enquiry. The findings are generalizable in that the CAID/RP methodological approach is relevant to generic industrial design activity, and has been validated through case study and practitioner feedback.

The research makes an original contribution to knowledge and understanding in the area of professional practice through the definition and validation of
The key elements of this are represented in the research by the following:

- The identification of a problem in terms of the commercial need to reduce NPD time scales and an acknowledgement of the extensive lead times required for the production of appearance models.
- A literature review and practitioner feedback leading to the definition of the revised CAID/RP methodological approach.
- An evaluation of the revised CAID/RP methodological approach through an industrial design case study.
- A comparative analysis of physical models/prototype produced using conventional fabrication techniques and rapid prototyping.
- The identification and resolution of issues arising from the case study.
- The validation of the CAID/RP methodological approach through an appraisal framework.

The original contribution to knowledge is of relevance to the following groups:

- Industrial design practitioners and students: the methods employed in the CAID/RP methodological approach have direct relevance to the process and output of professional practice.
- Design educators: the CAID/RP methodological approach identifies a rationale and strategy for the progression from conventional to state of the art digital techniques, making a contribution to design pedagogy.
- Researchers: the research methodology demonstrates the contribution of case study methods and reflective designing in doctoral study, and identifies opportunities for further research and development.
- Commercial hardware and software developers: the evaluation of existing and emerging design tools contributes to the identification of opportunities for future development.
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Future research and development

The validity of the CAID/RP methodological approach using commercially available resources has been demonstrated. However, the limitations of the only commercial haptic feedback device have been identified, and its contribution to the CAID/RP methodological approach discussed. The extension of the CAID/RP methodological approach to more fully replicate the manipulation of physical material through the use of a haptic feedback device is dependent on the resolution of these limitations through future research and development.

As a commercial organisation, specific research and development being undertaken at SensAble Technologies remains confidential, but the limitations of the Phantom haptic feedback device are acknowledged, and it is not unreasonable to speculate that effort is being applied in their resolution. During a meeting at SensAble Technologies Research Centre on 22 May 2001, their Marketing Director, Mr Andrew Hally, confirmed that the development of the next generation of the FreeForm software (version 4) would focus more closely on meeting the specific needs of the industrial designer.

As the originator of the Phantom haptic feedback device, the MIT Touch Lab continues to undertake research into the development of this technology through its Machine Haptics Group. Of relevance to the evolution of a more intuitive haptic feedback device for industrial design modelling is the development of linear and planar graspers by Professor Srinivasan. (Stanley 2002 pp142 – 153) Through on-going research, these devices are facilitating the simulation of the mechanical properties of objects during haptic interaction i.e. compliance, viscosity and mass. (ibid) A more realistic sensation of form and modelling will be essential if the use of haptic feedback devices is to make a significant contribution to industrial design practice.

On a more fundamental level, a change in the speed and additive nature of rapid prototyping systems is required to exploit any enhanced capabilities of haptic feedback devices. Specifically, a rapid prototyping system that facilitates
a concurrent build during the tactile manipulation of digital geometry would produce physical models and prototypes in real-time (as achieved using conventional workshop techniques). Such a system would of course have the major advantage of maintaining a record of the shape-giving operations as a digital 3D model. However, the challenge for the development of such systems lies in the accommodation of the capability of haptic feedback devices to delete operations through the editing facility. For example, if a detail were produced using a haptic feedback device and concurrently modelled via rapid prototyping, should the designer wish to delete the feature, it would have to be concurrently removed from the rapid prototype component. The removal of material from any part of the build is at present beyond the capabilities of current rapid prototyping systems. However, for the full exploitation of the potential demonstrated through the CAID/RP methodological approach, such functionality would ultimately be required.

**Potential future changes in the field**

Despite increases in the capabilities of virtual reality and haptic feedback modelling, the realism of the visual and tactile experience does not yet come close to the sensation of seeing and physically interacting with a complex physical object. However, with the exponential increases in computing power over the past decade, the emerging capabilities of this technology should not be underestimated. It is therefore possible to predict a scenario towards the end of the next decade where the form and interface of an industrial design proposal could be effectively evaluated through the use of virtual reality and haptic feedback, without the need for a physical artefact. If this can be achieved, its integration with more sophisticated virtual prototyping and testing would result in a complete virtual product development system capable of modelling the entire range of operations that are at present undertaken using a combination of digital and conventional modelling techniques. Whether or not this replaces the appearance model or appearance prototype is a matter of conjecture, as the signing-off of an industrial design proposal for production may continue to require its embodiment in an analogous form, i.e. a physical
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artefact. The sophistication of product evaluation through virtual reality will therefore evolve, but this does not necessarily imply the future demise of the appearance model and appearance prototype.

With a continuing need for appearance models and appearance prototypes, the relevance of this study will remain, particularly as rapid prototyping continues to evolve through the provision of additional capabilities. For example, its use as a layer manufacturing technique for production components removes the need for tooling, with dramatic savings in NPD time scales and costs. The removal of tooling costs will enable manufacturers to use common internal components for low volume production runs of products targeted to distinctive or even niche markets. The implications of this for the industrial design profession are significant, as a greater number of product iterations would result not only in more work, but increased creative activity as the number of markets for a generic technology would increase. A requirement for products that are more closely associated with niche markets can at present be seen in the consumer demand for customised mobile telephone covers.

With a continuing requirement for appearance models and appearance prototypes, and the potential for increased professional activity resulting from the commercial use of layer manufacturing technique, it is necessary to consider the way in which the industrial designer’s intent is translated from a digital model (CAID or virtual reality) into a rapid prototype production component.

Having identified the range of techniques employed during industrial design practice, the impact of 3D computer modelling is starting to render some of the conventional media obsolete. This was demonstrated through the redundancy of the GA drawing and conventional appearance model within the CAID/RP methodological approach. In contrast with this is the additional requirement to produce stl files for a rapid prototype component build.

The CAID/RP methodological approach has validated two strategies for the production of the stl files, demonstrating that this can be undertaken by either
an industrial designer or engineering designer. In the future, an opportunity to reduce the time and effort required in their production may be afforded by the use of design automation. Neural networks and genetic algorithms are being developed to facilitate the automatic generation of industrial design proposals and engineering detail. Whilst this technology is still in its infancy, it is reasonable to predict that the automatic generation of wall thickness may be viable once the side on which it is to be built has been specified. Extending this further still, a capacity to use design automation to define the internal walls required to support components and perform all necessary production testing (e.g. mould flow, finite element analysis) would significantly extend the modelling capabilities of the industrial designer.

The potential future changes in the field would enable industrial designers to produce sophisticated products for a wide variety of niche markets using the rapid prototyping system of layer manufacturing technique. Through the use of virtual reality, haptic feedback, and design automation, products would be modelled and engineered by the industrial designer in preparation for a single pre-production layer manufacturing technique build for final client approval. Production would then follow immediately as no tooling was required.

Whilst no profession is immune to change, the impact of digital technologies appears to be having a significant impact on the industrial designer. It is apparent from this study that the profession must critically appraise the perceived opportunities afforded by such developments and be receptive to their integration into practice.
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Appendix I

Questionnaire used to investigate the use of rapid prototyping by industrial designers
Appendix II

Nylon line trimmer questionnaire
This questionnaire forms part of a research project investigating the design and use of nylon line garden trimmers (‘Strimmers’). Please answer the questions as appropriate, with either a number, or a tick, or enter your comment in the boxes provided. Thank you for your assistance - Mark Evans, Lecturer.

1. What is your age?
   - Under 26
   - 26 - 35
   - 36 - 45
   - 46 - 60
   - Over 60

2. Are you male or female?
   - Male
   - Female

3. What is your height?

4. When did you last use a trimmer?
   - Up to 6 months ago
   - 6 to 12 months ago
   - 1 to 2 years ago
   - More than 2 years ago

5. What make of trimmer was it?
   - Black & Decker
   - Flymo
   - Bosch
   - Other - please specify

6. How was the trimmer powered?
   - Battery
   - Mains electric
   - Petrol

7. On average, how long was the trimmer used for?
   - Up to 5 minutes
   - 5 to 15 minutes
   - 15 to 30 minutes
   - 30 minutes to 1 hour
   - Over 1 hour

8. Please indicate the main cutting use of the trimmer with a 1, and its secondary use (if any) with a 2.
   - Grass around obstacles e.g. tree, wall
   - Weeds
   - The edge of a lawn
   - Other - please specify

9. Is it possible to rotate the motor housing on the trimmer for edging lawns?
   - Yes
   - No

10. If yes, do you find this useful?
    - Yes
    - No

11. Does the trimmer have just one main handle, or is there a second for extra support?
    - One
    - Two

12. If two, did you find the extra handle useful?
    - Yes
    - No
13. Have you experienced any discomfort during, or after, use of the trimmer?
   
   [ ] Yes  [ ] No

14. If yes, what is the nature of the discomfort?
   
   [ ]

15. How satisfied were you with the various features of your trimmer?
   
   Please put a tick in a box to indicate how effective that particular feature was. If you feel that the feature could not be improved, put a tick in column 1. If you feel that the feature was totally inadequate, put a tick in column 5. Tick column 2, 3 or 4 if your opinion falls between these extremes.

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16. If you would like to comment on any other aspect of trimmer design, or indicate how you feel that the design could be improved, please do so in the space below.

[ ]
Appendix III

Weighting/rating forms
## APPRAISAL FRAMEWORK

Objectives for the production of appearance models

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Objectives for the production of appearance models

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Appendix IV
Rating/weighting responses
## Interviewee: Academic

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Appendix V

Normalised rating/weighting responses
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