FUTUREFACTORIES: THE APPLICATION OF RANDOM MUTATION TO THREE-DIMENSIONAL DESIGN

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A thesis submitted to the University of Huddersfield in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

The University of Huddersfield

September 2009

Abstract

The title of the project, ‘FutureFactories’, describes an exploration of direct digital manufacturing and the use of this technology in creating new models for consumer product design practice.

In additive fabrication itself, there is no economic advantage in producing identical artefacts: given this, and the free-form potential of a technology that can deliver almost any form imaginable, the project examines the possibility of modifying the design with every artefact produced. The aim is to create automated systems capable of volume production, establishing mass individualisation: the industrial scale production of one-off artefacts.

This work explores the potential to combine parametric CAD modelling with computer programming to create animated meta-designs that change in real time. These scripts introduce a random computer generated element into each physical product ‘printed out’ using direct digital manufacturing. The intention is to combine qualities normally associated with the vagaries of the hand-made with the technical resolution of industrial mass-manufacture; whilst at the same time maintaining a coherent design and identity.

The outputs from this practice-based research project consist of inspirational products ranging from gallery pieces to commercial retail products and, alongside the real-world artefacts, the scripted meta-designs from which they are created.

The use of such software processes and real-time networks as generative tools, questions existing transient boundaries of practice, and exposes the irrelevance of conventional definitions of role. It is clear that the outcomes of such a new model of creative production cannot be thought of as traditionally conceived pieces. The outcomes of the research suggest that the resulting artefacts can be considered both functionally useful and as art. Outside of that, existing definitions convey little of the reality of their production, as they lie in some new, as yet unspecified, arena of production.

Contents

11.0 Appendices

List of Figures

Acknowledgement

Throughout the period of this research I have had a huge amount of encouragement and support……

I am grateful to the School of Art, Architecture and Design and The University of Huddersfield for their ongoing support. In particular I would like to thank Ertu Unver for his patient supervision and guidance over virtually seven years of study and Paul Atkinson for commissioning the initial residency and supporting the project throughout its early development.

I would like to express my gratitude to Katie Bunnell, John Fieldhouse and David Swann for examining this thesis and for their insightful comments. I would also like to thank Dave Tancock and Ray Anable for their supervision and Ian Pitchford and his staff at the Research Office.

Finally I would like to express my gratitude to my wife and family for their love, support, patience and understanding.

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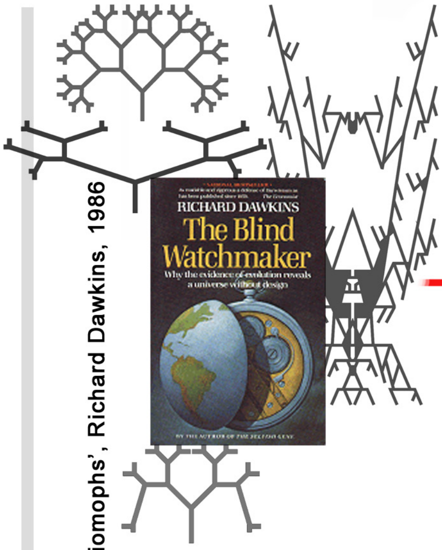
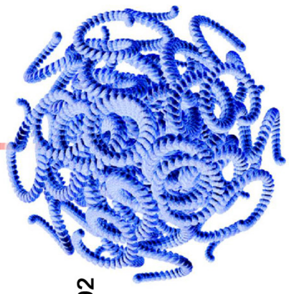


'Biomorphs', Richard Dawkins, 1986

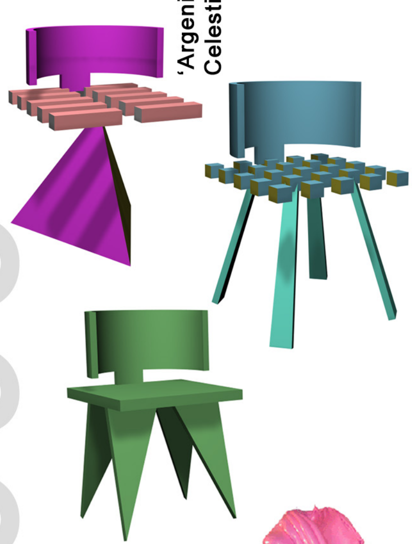
William Latham, 1989
Hand Drawn 'Formsynth' Trees

1990



'Mutator', Todd and Latham, 1992

1995



'Argenic Design'
Celestino Soddu, 1997

'Schmak' Auto Sculpture Maker
Roxy Paine, 1998

Digital Practice Timeline
Part 1 (gatefold in printed document)

Digital Practice Timeline
Part 2 (gatefold in printed document)

1.0 Aims and Objectives of the Thesis

The aim of this thesis is to demonstrate the potential for mass individualisation: the industrial scale production of one-off artefacts. In order to achieve this, the research should:-

Combine CAD techniques with computer programming;

Create automated systems that need no further creative input to achieve unique outputs;

Create unique variants without repetition;

Achieve an obvious visible difference between iterations while maintaining a coherent design identity;

Result in artefacts manufactured direct from computer data with the minimum of post processing; and

Generate desirable and functional consumer products.

1.1 Key Terminology

The creative use of digital technologies is central to this thesis. These technologies are developed by various rival commercial entities each trying to establish their own process and come with a bewildering list of names and acronyms. These are detailed a Technical Glossary 9.0. However, in the context of this project certain key terms, and their definition, require introduction from the onset.

The term Direct Digital Manufacturing (DDM) as used in this thesis refers to the automated production of artefacts from CAD data. This may be shortened to Digital Manufacturing or Direct Manufacturing depending on the context. Direct Digital Manufacturing most often refers to additive manufacturing processes where material is added, where required, rather than cut away from an oversize billet. Whilst the rise of these additive or so called Rapid Prototyping processes was the trigger for this project, it is the principal of using computer data rather than fixed tooling (moulds, dies, patterns and the like) that is important and this applies equally to computer numerically controlled (CNC) subtractive machining.

The practice considered in the thesis is design for industrial manufacture which is referred to as Product Design. The term Product Design is used rather than Industrial Design simply because the desired outputs are consumer products, rather than any of other activities a practicing designer might become engaged in. Product Design in the context of this thesis is defined as the specification of an artefact, which enables its subsequent commercial manufacture without further creative input from the designer.

1.2 Chapter Summary

Section 1: Introduction. This section describes the project, the ideas behind it and the technology that underpins it. Previous work across art design disciplines that has informed project thinking is considered in a literature review.

Section 2: Project Overview. This section describes the projects' origins as a Design Residency and its contribution to the undergraduate teaching program

Section 3: Mass Individualisation. This section examines retail manufacturing and mass consumption in the digital era considering where the impetus for such a mass individualisation and/or customisation concept might originate.

Section 4: Computer Generation of Variants. This section examines, through case studies, the creation of meta-designs which combine computer scripts with CAD models. The design implications of Differing methodologies are compared and evaluated.

Section 5: Design Work and Exhibitions 2003-2006. This section documents the designs created at the end of the residency period, the dissemination of these outputs and public reaction to them. It describes how the plausible retail finishes were obtained from budget visualisation processes and how, towards the end of this period, the option of more exotic manufacturing processes allowed a fuller realisation of the projects potential.

Section 6: Commercial Retail Products. This section documents commercial retail design opportunities that developed from the early research outputs demonstrating the commercial viability of the project ideas.

Section 7: Later Works. This section examines project outputs to-date, charting design developments as the computer programming underpinning the work becomes more sophisticated and, from a manufacturing perspective, an increasing palette of materials and finishes become available. The section culminates with Icon, an edition of 100 jewellery pieces, 25 of which are produced effectively proving the project ideas.

Section 8: Summary and Conclusions. The work is summarised and conclusions drawn in this section.

1.3 Introduction

The title of the project, ‘FutureFactories’, describes a creative exploration of digitally technology-driven design and manufacture. Rapid Prototyping (RP) technologies were developed to compress product development cycles and are now well established. The new frontier is Direct Digital Manufacturing or Rapid Manufacture (RM); Rapid Prototyping technologies applied to the production of end-use artefacts. These technologies essentially allow functional real-world objects to be ‘printed’ out in a series of fine layers direct from virtual Computer Aided Design (CAD) data. The need for significant tooling investment, such as moulds and dies dedicated to a particular job, is gone. This allows flexibility in production, unprecedented in the industrial era as the mass-production economics of standardization and uniformity cease to apply. Through Direct Digital Manufacturing a revolution is underway in 3D Product Design that is likely to be as radical as that brought about by digital technologies in 2D Graphic Design. Layer-build manufacturing costs are principally governed by the build height i.e. the number of layers built. They are largely independent of the part’s geometry. There is no economic to producing repeats as there are no physical tools or mould dedicated to producing a particular form that can be reused. The question is therefore, why not produce something unique every time? There are clearly design implications as a unique specification has to be generated somehow and these will be discussed. From a purely manufacturing point of view however, the economies of scale rationale of mass-production need not apply. There will be benefits to volume manufacture in the bulk ordering of material, shared plant costs and the like, but these advantages would apply equally to volumes of differing artefacts. Each time CAD information is entered into the build process there is a degree of data processing which would be reduced or eliminated in repeat builds, this however is the work of minutes as opposed to the builds themselves which take several hours.

In 2002, the researcher presented to Huddersfield University, an embryonic concept for the industrial scale production of one-off artefacts. In essence the project proposed an inversion of the mass production paradigm to one of individualised production; mass-individualisation. Rather than defining a discrete form, the designer would create a meta-design capable of random, automated change. This design template would yield a string of unique outcomes, each of which would be constrained to remain true to the designers’ intent and the desired product identity. The concept involves combining high-end parametric CAD (in which geometry is defined by relationships rather than absolute numerical values) with computer scripting.

The variance in form may encompass a variety of design criteria including the relative positioning of features, shape, scale, proportion, surface texture and pattern. These variations may be multiple and interrelated. The intention is to achieve changes in the 3 dimensional form itself rather than scaling the existing geometry or by the use of surface treatments such as texture or colour. In this way, FutureFactories aims to overcome the split between the technological and the aesthetic, between artistic creativity and mechanised production. While designs for mass production are regularly highly creative and have strong aesthetics, their impact is diminished by familiarity. They are by definition commonplace. In hand worked artefacts there will be differences at some level in every piece. This allows for diversity within a design type and emotional responses to individual outcomes. A future is envisaged in which virtual reality (VR) boutiques are filled with 'living' products. At any given moment a product of choice is frozen to create a unique design that may be ordered on-screen, digitally manufactured, and delivered to the door. An original… A one-off... A work of art?

1.4 The Technological Landscape

The possibility of creating computer based virtual representations of three dimensional forms has existed since the first Graphic User Interfaces appeared in the 1960's. The use of comtemporary computational power to animate such virtual objects can be seen as a logical extension of that capability. As the computer has increased in speed and power, the possibilities for manipulating form have become ever more complex and visualisation of the virtual realm increasingly convincing. However, until recently, computer generated forms existed purely in the virtual world as graphics or computer art. It is only the advent of additive layer-build fabrication referred to as Rapid Prototyping, or more importantly the wide spread availability of the technology, that has enabled these forms to be realised as real-world products.

It is only the advent of additive layer-build fabrication referred to as Rapid Prototyping, or more importantly the wide spread availability of the technology, that has enabled these forms to be realised as artefacts. Initially additive manufacture was limited to visualisation models whose mechanical performance and longevity bore no relation to the functional parts they were simulating. Increasingly, materials and processes have been developed that allow the assessment of functional criteria to the point where certain high-end processes can yield artefacts suitable for retail sale.

Additive layer build Rapid Prototyping, RP is a relatively recent phenomenon. The first patents where granted in the mid-1980's and commercial service providers began appearing towards the end of that decade. The term RP however, can also be applied to computer controlled subtractive processes, where material is removed from a blank, such as milling. Computer Numerically Controlled (CNC) milling has been available as an industrial process for decades. The principles can be traced back as far as the Jacquard Loom and Babbage's mechanical computers in the 1800's. Generally however, Rapid Prototyping refers to additive fabrication in which forms are created by the addition of material only where required with no waste. It is the rise of this technology that has made Direct Digital Manufacture not only possible but commonplace. In addition to developments in additive fabrication technology itself, parallel and more general digital advances have facilitated uptake including:

- powerful affordable computing;
- developments in design software;
- the ability to visualize though powerful graphics; and
- the Internet and rapid digital data transfer.

It is now possible to manufacture almost any 3D form direct from an on-screen model allowing virtual graphics to be 'printed-out' as functional artefacts with the properties expected of mass-market consumer products. This can effectively remove manufacturing criteria from the creative process and potentially allow freedoms normally open only to those manufacturing their own work.

A timeline of technological developments considered relevant to this project can be seen in Figure 1 on gatefold pages 9 and 10.

1.4.1 Computer Aided Design (CAD)

Even with the advent of Direct Digital Manufacturing the computer art of previous decades would defy production. For successful manufacture three-dimensional models need levels of definition and integrity not present in the visualisation models of computer art and games. It is common for example for surfaces in the virtual world to be infinitely thin, for them to pass through one another, or for a regular surface to give the appearance of having a complex texture via linked two-dimensional reference data. Computer Aided Design data by contrast, in particular that of high end packages with an engineering rather than a visualization bias, offer robust models with more watertight data. CAD packages, running on personal computers (PC) rather than industry mainframe based systems, have evolved from the basic drafting packages introduced in the mid-1980's to sophisticated 3D design systems capable of producing complex irregular forms with the necessary integrity for production. These packages allow the parametric definition of models. Parametric CAD models enable the designer to set-up relationships that define the character and function of a design; rather than identifying a single, discrete, design solution. Parametric design defines relationships between degrees of freedom rather than specifying absolute dimensions. This allows the whole form to update in reaction to the modification of a single element. In the context of this project parametric CAD potentially allows the morphing model to be run within the CAD package driven by external script data.

1.4.2 Rapid Prototyping, RP

It is primarily the advent, and the availability, of Rapid Prototyping (RP) that makes the physical production from on-screen models a realistic proposition. It was this technology that formed the basis for the FutureFactories concept. Rapid Prototyping is a catch-all term that applies to the digital manufacture of prototypes directly from CAD data. The focus for this project is additive fabrication, as the limitations of manipulating a physical cutter means that subtractive manufacture can never offer sufficient flexibility for the reproduction of 'freeform' models. It is the appearance of additive RP that has allowed the unfettered production of virtual forms. In additive RP, software 'slices' the CAD model into thin layers (down to 0.05mm). The model then 'grows' one thin layer at a time with the machine 'forming' the build material only where it is required. Each data 'slice' is replicated in three-dimension (3D) from the bottom up. The layers are built on a moving platform, each built on its predecessor as the platform steps down in layer thicknesses. There is no tooling or cutting away of material. This allows unlimited geometry. Forms may be produced that would be almost impossible to mould or machine.

a) 'High-End' RP Processes

The high-end processes require industrial scale capital equipment. The equipment can cost between £200K and £500K. They require skilled operators and ancillary processes/stations.

- Stereo Lithography, SLA (Stereo Lithography Apparatus)
  Stereo lithography was the first of the modern layer build systems. Developed by 3D Systems in the Eighties, it accounts for 45% of new machine installations (Wohlers 2003). In this process each layer is 'drawn' by laser in a photosensitive liquid polymer; the laser energy solidifies the liquid. The advantage of this process is the surface finish; the disadvantage is that delicate features and overhangs require thin supports that must be removed post-production. A 3DSystems SLA machine can be seen in Figure 2.

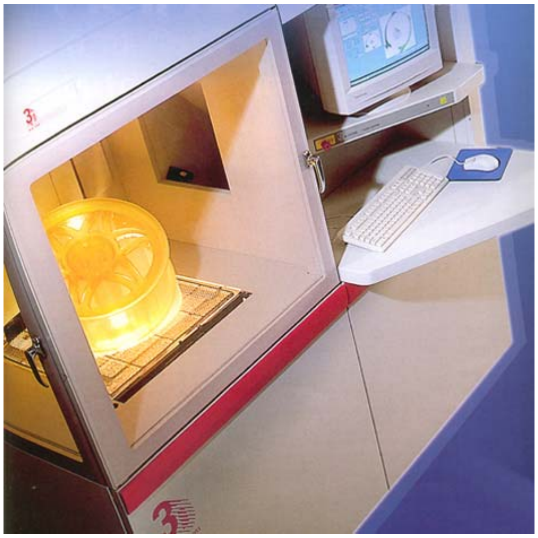


Figure 2
A 3DSystems SLA machine

- Selective Laser Sintering, SLS

  Selective laser sintering is powder based. The production chamber is maintained just below the melting point of the build material. The layers to be built are then ‘drawn’ on the fusible powder which is sintered by the laser. The finished part is formed within a cake of un-fused powder which supports the features. The final step is to remove the loose powder. SLS components are much more than appearance models, they have sufficient durability to be considered functional. A wide range of powder based materials are available to the process including nylon, stainless steel, synthetic rubber and ceramics. An SLS machine from EOS, Germany, can be seen in Figure 3.

Figure 3
The EOS P390 SLS machine

- Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM)

  Metal sintering has been available since the start of the project, but high cost, limited availability and poor surface finish proved a barrier to its use. Improvements in the process and increased availability have brought them within reach for the later stages of the project. DMLS is marketed by EOS of Germany, SLM by MCP in the UK. Both systems offer production in titanium, stainless steel and cobalt chrome. Unlike the sintering of plastics, where geometry is supported by loose powder, metal sintering involves the forces of contracting metal which requires firmer anchorage. Geometry must be attached to the build platform by support structure at the base. If material is built with overhangs of anything more that 45 degrees to the vertical then additional support is required. Any support structure requires manual post production removal and is not the light ‘snap off’ material of the resin processes such as SLA and the like.

b) Mid Range RP Processes

Processes such as 3DSystems Envision offer similar quality photo curable resin parts to SLA only with the Laser replaced by a UV light source. This greatly reduces the capital cost to around 25% that of SLA. A Further advantage is that any support structure can be built in a second soluble build material rather than the primary resin itself automating support removal.

c) Budget RP Processes

Three-Dimensional Printing (3DP) is at the budget end of the RP spectrum. The processes use inkjet printing technology and the equipment costs are around a tenth of those for STL/SLS. Each layer is formed by a jet of material or binder from a multi-nozzle piezoelectric print head. 3DP tends to be used for visualisation rather than functional models.

Fused Deposition Modelling (FDM) is another budget process that uses a two axis extrusion head (X,Y), over a vertically moving platform (Z) to deposit material. This is a relatively inexpensive process that can yield components with good mechanical performance. Experimental projects such as Fab@Home (Malone 2008) have produced entire robotic devices including batteries and actuators using this technology. As a commercial process however it is slow and the material expensive (including a separate soluble support structure material), these factors drive up build costs in spite of a relatively low capital cost. The finishes are inferior to those of the high end processes.

1.4.3 Direct or Rapid Manufacture

Rapid Prototyping (RP) as a bureau service exists to provide models and prototypes in advance of high volume industrial production. It enables complex forms to be prototyped and trialled without the delay or cost of machining production tools. Disregarding the technologies' current expense; designers, artists and commentators have experimented with, and speculated on, the use of RP for end-use manufacture, this project among them. In 1997 Professor Celestino Soddu wrote that, *"Digital manufacturing technology allows one to realize, at the same operational cost, unique objects or repeated objects. We have examples of this before us every day: a printer costs the same to run whether it prints ten identical pages or ten different pages"* (Soddu 1997). In 2003, less than one year after the start of this project, the first Direct Manufacture consumer products went on sale. The RP industry, having reached a sales plateau as the prototyping market reaches saturation, has been keen to foster embryonic Direct Digital Manufacture or Rapid Manufacture; the use of RP technologies for end use manufacture. In 2006, Time Compression Technologies, an RP industry journal, dedicated its annual conference to ‘Rapid Manufacture’. At the conference Rapid Manufacture was defined as, “*The use of a CAD based automated additive manufacturing process to construct parts that are used directly as finished products or components*” (Hopkinson et al 2006).

1.5 Computer Generated Art

Computer generated art is limited only by the ability to render images on screen rather than any physical manufacturing restrictions. The technology to computer-render 3D graphic images has been available around twenty years longer than rapid prototyping. Of particular relevance to this project are works involving the creation of 3D forms, albeit virtually, and systems for the automated or semi-automated generation of 'art'.

1.5.2 William Latham

The Artist, William Latham, was inspired by natural systems and how they often relied on the repetition of simple, small, steps (Todd and Latham 1992). He sought to create art systems going beyond two dimensional drawing systems, such as Russian Constructivism, to create 'synthetic organic forms'. His first system, FormSynth, was hand drawn. It featured an evolutionary tree of sketches, Figure 4. Starting with a parent generation of regular forms, a series of children would be created from each parent sketch by combining the form in some manner with other parents of the generation. Highlighted in Figure 4 are two children from the cone parent, one with the addition of the cube, the other with it subtracted. The children of this first generation would in turn become the parents of the next and so on, creating an exponential growth in 'solution space'.

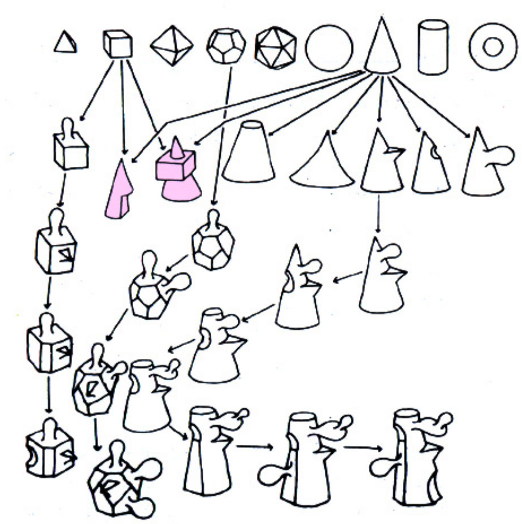


Figure 4
Small Hand-Drawn FormSynth Tree, William Latham 1992

These hand drawn FormSynth 'trees' could run to 10m in length. Interestingly the artist sculpted some of the 'more aesthetic' results in wood and plastic, indicating that the sketches were seriously considered as 3D objects. The artist refers to the sketches, which were the hand drawn equivalent of virtual models, as ghosts of sculptures.

1.5.3 Richard Dawkins' Biomorph

Dawkins is a scientist and author rather than an artist: however, the 'Biomorph' system he created to illustrate the principals of evolution and natural selection, is significant both as a work in itself and for its influence on Todd and Latham. The Biomorph program was developed to point out the power of micro-mutations and cumulative selection. The Biomorphs are simple line drawings, 2D graphics made up of a series of straight line vectors. They are generated by a recursive subdivision algorithm. The recursive function calls on itself during its execution allowing the repetition of features. The program begins with a simple line or, in Dawkins' natural world analogy, a 'trunk' (Dawkins 1986). Subdivision allows the initially simple graphics to grow ever more complex with vectors being divided and divided again by intersecting 'branches'. A generation of alternatives is produced by adding these 'branches' according to differing rules. From the range of alternatives generated, one 'child' is selected by the user to be the subsequent parent and the process repeated, Figure 5.

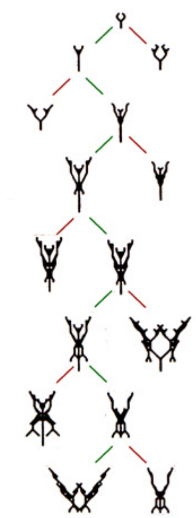


Figure 5
Generations of the Dawkins' Biomorph, 1986

The subjective aesthetic judgment of the user thus plays the role of natural selection. Dawkins expected trees to develop in a form reminiscent of the various species seen in the natural world. He was surprised to see insect like forms emerging after only a few generations and described these ‘creatures’ as ‘Biomorphs’: the name coined by Desmond Morris for the vaguely animal-like shapes in his surrealist paintings, Figure 6. Starting from the ‘trunk’, there is a sub-branch corresponding to each iteration. Each sub-branch is defined by a vector. Dawkins likened these vectors, cumulatively, to a genetic code.

Figure 6
The Visitor, Desmond Morris, 1949
Featuring the “Creatures” He Termed “Biomophs”

1.5.4 Latham and Todd

For Artist William Latham, it was a logical step to employ computational power to drive art systems such as his FormSynth (1.5.2). In the late 1980’s he began collaboration with mathematician and computer graphics expert Stephen Todd. Using what was considered then to be the extensive computational resources of IBM’s UK Scientific Centre in Winchester USA, Todd developed FormGrow, a system that arranged geometric primitives, such as spheres and torii, to create computer based virtual forms (Todd and Latham 1992). A system called Mutator was then developed to explore the ‘solution space’ created using FormGrow. Mutator in concept was a combination of Latham’s FormSynth and the two dimensional ‘Biomorph’ system of Richard Dawkins (Dawkins 1986, as detailed in 1.5.3). *“Biomorph demonstrates, in zoological terms, the power of natural selection. Mutator harnesses this power, and extends it to make a fast and effective exploration tool”* (Todd and Latham 1992). The result is a ‘survival of the most aesthetic’ evolutionary development. From each new generation of mutations, Figure 7, one ‘child’ could be selected by the artist. This subjective selection would be used to ‘steer’ the next generation of evolutionary mutation.

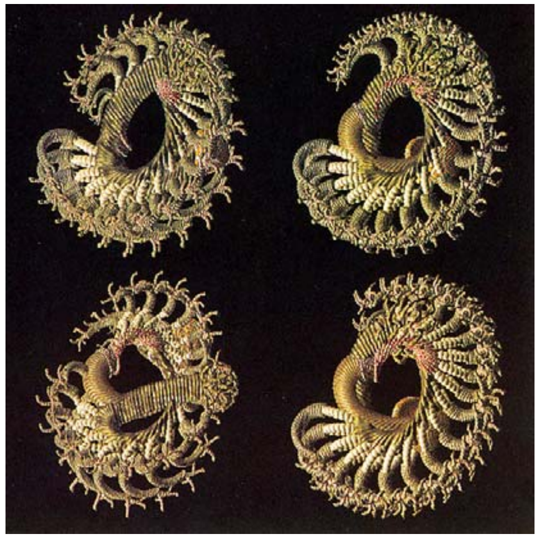


Figure 7
A Set of “Children” from Mutator
Todd and Latham 1992

The similarities of this process to natural evolution have led to Latham being referred to as a ‘Digital Darwin’ (Cook 1996). The driving force behind ‘Mutator’ was the creation of art. As Todd and Latham stated, *“Some artists feel that it provides a genuinely new way of working, and it has certainly led to the creation of forms that would not have been created by other methods”* (Todd and Latham 1992). Although the resulting ‘sculptures’ were only ever intended to be seen as 2D representations of complex 3D models, presented as art in a gallery context, the principle behind it can just as easily be used to create variations on ‘usable’ forms to produce designs for *“anything from buildings to shampoo bottles”* (Computer Artworks 2003).

1.5.5 Karl Sims

Karl Sims studied computer graphics at the MIT Media Lab, and Life Sciences as an undergraduate at MIT. For several years, in the early nineties, Sims was artist-in-residence at ‘Supercomputer’ Manufacturer Thinking Machines Corporation, Cambridge, Massachusetts.

In his 'Panspermia' series (Sims 1990), Sims created scenes with 3D ‘vegetation’ controlled by genetic parameters. ‘Plant’ forms were 'bred' together with 'survival of the prettiest' determining the evolutionary direction. Sims uses a similar approach to Todd and Latham, with comparable selection criteria. In this work however, there is an attempt to create plausible structure in terms of human experience resulting in realistic yet alien landscapes. The results are quite different to Latham's work with plausible organic vegetation and an air of realism, Figure 8.

Figure 8
A Still from Panspermia, Sims 1990

In his research 'Evolved Virtual Creatures' (Sims 1994) he created simulated Darwinian evolutions of virtual block creatures. The form of these 'creatures' was represented by a hierarchy of rigid primitives. Elements of the creatures' genotype code determines firstly the particular primitive employed and secondly the constraints placed on the relative motion between this primitive and its neighbour. In this work, evolutionary optimisation methods where used to develop pseudo-physical skills, walking, swimming, jumping and the like.

1.5.6 Digital Sculpture, Digital Art Practice and Design Art

The work of Todd and Latham, Dawkins and Sims in which computation is employed to create 3D forms capable of change over time, is of obvious direct relevance. There are many other artists experimenting with digital techniques aspects of whose work are of interest and relevance.

Geoffery Mann graduated from the Royal College of Art (RCA), London, in 2005. He describes himself as a 'Product Artist'. Mann uses motion capture to record movement and reproduces it digitally in a 3D artefact. Examples of his work include 'Attracted to Light', in which the path described by a moth circling a light bulb is captured and produced as a physical form, as detailed in Figure 9.

Figure 9
Attracted to Light, Geoffrey Mann 2005

Another piece by Mann is 'Blown' from the 'Natural Occurence Series'. This is a cup and saucer digitally distorted by a cooling breath on a liquid surface, Figure 10.

Figure 10
Blown, Geoffrey Mann 2005

Mann's Blown is reminiscent of New York Artist Robert Lazzarini, who works with commonplace objects such as a violin, a telephone and a skull. These objects are scanned, deliberately distorted, and then reproduced digitally, Figure 11.

Figure 11
Teacup, Robert Lazzerini 2003

Belgian Artist/Designer Marcel Wanders, used motion capture to record the 3D form or airborne mucus. The forms obtain where digitally manufactured as a series of vases, Figure 12.

Figure 12
Snot Vases, Marcel Wanders 2001

1.6 Commercial Examples of Digital/Direct/Rapid Manufacturing

At the inception of this project, direct digital manufacture was limited to a few niche examples. RP processes were expensive and not widely available. The materials employed by these processes were intended for short term visual representation and limited in terms of functionality. There were examples of the Direct Manufacture of high value/ultra low volume components used in specialised industries such as aerospace and motorsport. There were also examples of mass customisation in the medical field, such as hearing aids built to precisely fit a particular patient's inner ear. Over the period of this study, developments in this area have seen digitally manufactured products available in the high street, to the extent that there is now scarcely a need to present a case for the viability of direct manufacturing itself in a retail context. The processes themselves remain relatively expensive compared to conventional mass-manufacturing. However, the increasing availability is producing more competitive pricing and within the RP bureau industry there is talk of adopting 'production' rather than 'prototyping' pricing structures. It is a growing awareness of the capabilities of the technology and the value that can be added to a product, in terms of complexity and functionality, that provides a justification for higher production costs. The emphasis placed on speed by service bureaus, which is such an asset to prototyping, often hinders the development of Rapid Manufacture. The bureau industry is often characterised by feast/famine workloads and large amounts of overtime. This does not lend itself to rapid manufacture where efficiency is vital and profits are made over a longer term. Exotic new materials are being developed all the time; the reality is however that these take time to filter though to the mainstream bureaus. They are often expensive, having been developed for engineering performance, rather than to be cost effective. Switching materials can be extremely costly often necessitating the replacement an entire reservoir of material.

1.6.2 Materialise

Materialise was founded in 1990 as a joint venture with the University of Leuven, Belgium, and became one of the first European rapid prototyping service bureaus. Materialise now has four divisions. Three established divisions cater for software development, SLA technology, and medical applications. The fourth and youngest division, Materialise.mgx, is engaged in direct digital manufacture.

The manufacturing capacity of Materialise places them at the forefront of the bureau industry. Materialise has developed its own SLA machines, the Mammoth, with a build volume of 2100x650x780mm. They have a unique, competitive, advantage amongst service bureaus therefore, in that they use their own technology. This applies only to SLA production; however, for other process such as SLS, third party machines are used. Currently SLS technologies tend to be favoured over SLA for Direct Manufacture, as it uses more functional, durable materials and does not require a support structure.

In 2001 Materialise began participating in an annual Dutch initiative, "Young Designers and Industry", forging links between design students and manufacturing. Students were encouraged to explore the potential of Rapid Prototyping techniques with the offer of Materialise building the most successful projects. In the summer of 2003 Materialise formed its own design division, Materialise-MGX, to market a collection of lampshades, manufactured using SLA and SLS techniques: these designs were the result of the Young Designers and Industry collaboration. Among the designers were Alex Gabriel, Vince Vijsma, Koen Koevoets, future MGX Art Director Naomi Kaemfer, and Freedom of Creation duo Janne Kyttanen and Jiri Evenhuis. The collection gained considerable attention in the design press first at the Milan Furniture Fair, April 2003 and then under the MGX brand at 100%Design London, October 2003, Figure 13.

Figure 13
Lilly, Janne Kyttanen 2003

Early MGX designs focused the aesthetic possibilities of the process and early designs were simple lamp shades simply placed over a halogen bulb. Materialise had no experience of engineering development in an industrial design sense. Several of the designs could even have been made conventionally with development and really only exploited the cache of an exotic new technology. Later collections began to exploit the technical possibilities of the process as well as the freedom in form.

1.6.3 Freedom of Creation, FOC

Fin Janne Kyttanen and Dutchman Jiri Evenhuis both graduated from the Rietveld Academy in 2000. During the course of their studies they developed and filed a patent for 3D printable 'fabric'. The fabric consists of interlocked loops forming a chain-mail like structure. In 2002 they formed Freedom of Creation. They have designed and produced artefacts for the Materialise-MGX lighting collection and fashion items using their 'fabric' including handbags, mobile phone poaches, and a sleeveless lady's blouse, Figure 14. Their publicity material promotes the notion of mass customisation with the concept of garments being built to fit, this service has not however been offered commercially as yet.

Figure 14
Freedom of Creation V-bag 2004

1.6.4 Patrick Jouin

Patrick Jouin is an independent French designer. In 2004 he presented the 'Solid' furniture collection, a chair and a stool produced by SLA and SLS techniques respectively, Figure 15. This collection is notable for the sheer scale of the pieces. The full size dining chair was produced in one piece using Materialise's Mammoth SLA machines. The chairs are in effect, gallery art objects being extremely costly and in the case of the SLA chair, too fragile for effective use. The chair requires a substantial amount of finishing as it is produced by Stereo Lithography (SLA) which required support structures. It is hand finished and painted with a price tag around 30,000+ Euros (Milan Furniture Fair 2005). The stool is a more practical proposition for direct manufacture. It is produced by Selective Laser Sintering (SLS). It is robust and requires no post finishing. The largest laser sintering machines at the current time, limit the build volume to 700 x 380 x 580mm; hence a stool rather than a chair.

Figure 15
Chairs – Solid Collection, Patrick Jouin 2004

1.6.5 Bathsheba Grossman

Grossman studied sculpture and metalwork with Erwin Hauer and Robert Engman, mathematical sculptors who were both trained by Josef Albers. In the late nineties, after several years practicing traditional sculpture, she experimented with CAD/CAM and began designing sculpture digitally for production by 3D printing. Grossman describes her work as *“exploring the region between art and mathematics”* (Grossman 2005), her work features pure, mathematically derived, surfaces achieved via computational design. Grossman is an artist rather than a designer. Materialise, however, manufacture lighting designs produced by her, Figure 16. These tend to be examples of sculpture that have been lit rather than designed lighting products suggesting that function has been an afterthought and perhaps indicative of differences in practice between the artist and the more holistic approach required of the designer. The work is nevertheless extremely significant as an example of computational design and algorithmically derived form.

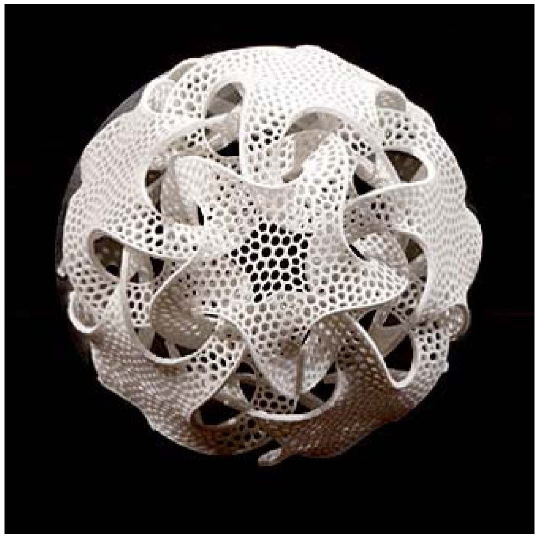


Figure 16
Quinse, Bathsheba Grossman 2005

1.7 Mass Customisation and Individualisation

Mass production itself is a relatively recent concept. Prior to mechanised production artefacts would be produced by craftsmen whose individual skills would be reflected in the product. Mass production depends on uniformity. Since the worldwide adoption of the mass production model, the goal of manufacturing has been accurate repeatability. Mass production has made desirable objects affordable. The size of the market allows levels of design development and the use of sophisticated processes not possible at lower volumes. There is however a perception that something has been lost. In today's consumer world we are surrounded by every conceivable product for every possible application, all at affordable prices. This availability, and the omnipresence of mass-merchandise, fosters within us a desire for something personal and unique.

The term, 'Mass Customization', was coined by Stan Davies, in his book 'Future Perfect' (Davies 1987). The term is deliberately paradoxical: 'Mass Customisation' can be defined as *"a delivery process through which mass-market goods and services are individualised to satisfy a very specific customer need at an affordable price"* (Davies 1987). Based on the, *"Public's growing desire for product personalisation, it serves as the ultimate combination of custom made and mass produced"* (Fu 2002). There are many different models for mass customisation; suiting different products and market sectors. They are all, by definition, consumer driven. Customisation may be achieved through the combination of options; for example, selection from an extensive but finite range of colours and finishes. Alternatively, the consumers may provide data on personal preferences or accurate measurements of body parts, to enable the production of a 'tailor made' product. Consequently, examples of mass customized products range from genuine medical 'needs', such as perfectly fitting hearing aids (Fu 2002), to desired product differentiation in a kitchen stove or better-fitting bespoke jeans (Marsh 1997).

1.7.2 Ron Arad

Ron Arad, in collaboration with Geoff Crowther, Yuki Tango, and Elliot Howes, presented, 'Not made by hand, Not made in China" in 2000. This collection featured a range of artefacts manufactured using RP techniques. The project publicity spoke of 'growing' products as a new, fifth way, of manufacture after:-

subtractive methods, such as carving or machining;
moulding;
forming, such as bending or pressing; and
assembly.

One of the projects was “bouncing vases”, using Maya, 3D software aimed at the video animation industry. A helical vase form was created, that was expanded and compressed in an animation clip, Figure 17. *“We can take a model, throw it in the air, let it drop, animate and calculate the distortions, thus producing hundreds of frames, each a mature model ready to be “grown” into a real object”* (Arad 2000).

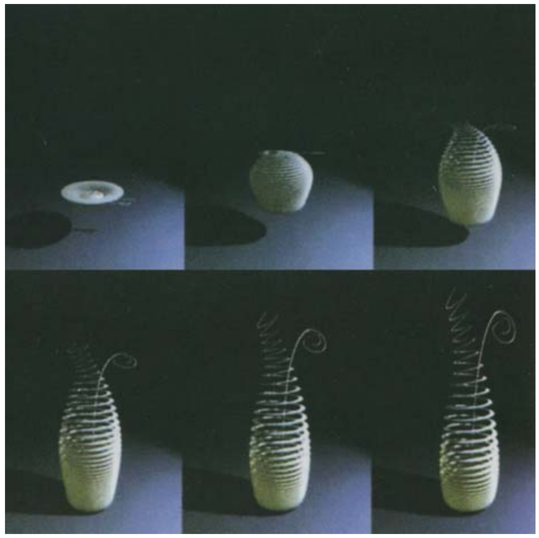


Figure 17
Bouncing Vases, Ron Arad 2000

The impression in the work is of a fixed model that is acted upon by external forces that impose deformation. The model is ‘thrown up’ and then ‘bounces’: it is being virtually customized. The subsequent changes are predictable, albeit they may be complex. The bouncing vase itself is designed in the form of a helical spring, to deform in a particular way as with a spring or bellows. The range of possibilities is readily apparent and is little different to scaling the overall form. The concept of designs generated from an animated model is non the less highly significant.

1.7.3 Professor Celestino Soddu

Professor Celestino Soddu has written extensively on the use of generative design in product design and architecture, since the 1980’s. From 1998 he has organised the annual international conference ‘Generative Art’.

In the late 1990’s, Professor Soddu recognised the potential of emergent rapid prototyping techniques to facilitate the Direct Manufacture of artefacts directly from computer based data. In a paper given at the European Academy of Design Conference Stockholm, Sweden, in 1997, Soddu spoke of a return to unique products in a post-industrial era; made possible by a combination of generative computer models and rapid prototyping techniques (Soddu 1997). In 2001, as Professorial Research Fellow at Hong Kong Polytechnic University, he claims to have created software that enabled the direct output of unique objects via Rapid Prototyping equipment. In his Stockholm paper, Soddu points out that, *"Before the industrial era every object was unique, unrepeatable, and strongly connected to the identity of its maker or user"* (Soddu 1997). He put forward the notion that in the post-industrial era the values of mass production were no-longer valid and that mass production would no-longer be more cost effective than individualised computer-driven manufacture. This prediction on cost was, and remains, over optimistic. It is extremely unlikely that in the near future Direct Manufacturing will be viable in high volume applications. Although it is already proving viable in low volume niche applications and is likely to become competitive in medium volume applications in the years to come (Wohlers 2004).

Soddu points out that design optimisation need not necessarily lead to a single solution and that the 'quality' of a design is not the final result in itself. He discusses the subjectivity of both designers and consumers in regard to what is considered 'necessary' and 'optimal' and the impoverishment that has resulted from a disregard for the quality of uniqueness. Soddu describes how 'idea-products' could create a new market with industry buying into an '*endless sequence of automatically generated 3D models'* (Soddu in Bentley & Corne (Eds) 2002).

The work is fascinating and ground-breaking. From a product design perspective however it is only the start. The computer generated 'product' forms that illustrate Soddu's publications are figurative, Figure 18. They collections of primitive volumes representing for example, the lid, body, handle and spout of a coffee pot. These elements are then transformed and configured in different ways. Soddu's stated goal of a 'recognisable design' does not seem to be achieved in product design terms.

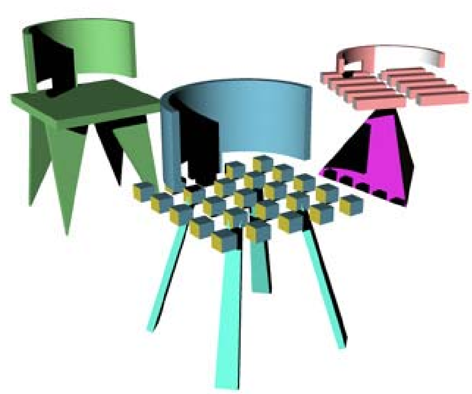


Figure 18
Computer Generated Chair Designs, Celestino Soddu 2001

There would not appear to be little difference between the results shown and those that would be expected from random configurations. The chair examples shown are recognisable as a ‘species’, only by virtue of a common chaotic make-up of random primitives. There appear to be few technical rules and little guidance or targeting. Functionality beyond the conceptual does not appear to have been a consideration in the work. In an example of coffee pots, there is little regard to function beyond the provision of an appropriate volume and spout. These are virtual designs. They potentially could be translated into real-world artefact but this would require substantial post-processing prior to any build. These are virtual designs The digitally manufactured output produced by Soddu in 2001, are small scale, appearance models, Figure 19. It is of interest and significance that theses pieces were generated automatically. They are however, ‘proof of concept’ rather than any form of prototype and are considerably less sophisticated than the vases and lamps presented by Arad in 2000 (Arad et al 2000). The lack of design in perhaps borne out by the absence of any functional outputs in the intervening years. The technical resolution of the output however does not detract from the significance and prescience of Soddu’s work at a concept level which is clearly ahead of its time.

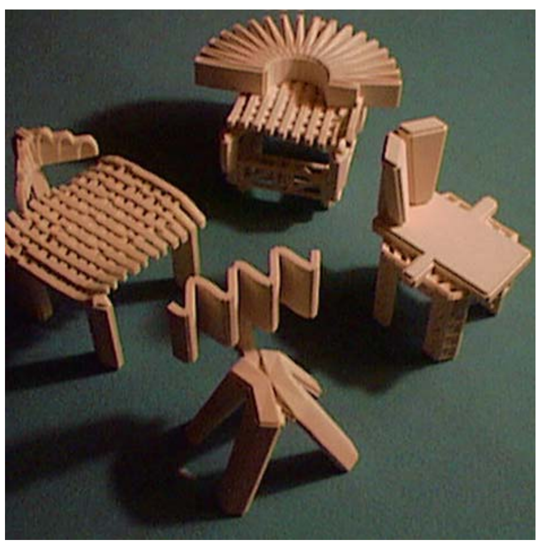


Figure 19
Digitally Manufactured Chair Models, Celestino Soddu 2001

1.7.4 Fluidforms

Austrian Fluidforms describe themselves as a fusion between designers, artists and programmers. Fluidforms offer the consumer the opportunity to create household items (vase or salt/pepper grinder), *"according to his own visions"* (Fluidforms 2005). This is achieved via an interactive web based experience. The user is able to adjust, via on-screen click and drag, the cross section of an axi-symmetric form. Control points on a cross section curve can be displaced in 2D modifying the form. Figure 20 shows two iterations, the pink control points may be dragged in both X and Y, the green in x only. The limited number of control parameters and their restricted range (14mm on the radius) limits creative expression. The artefacts are built in CNC cut wood laminate and hand finished. The customised element is essentially a decorative sleeve that houses a proprietary grinder mechanism or glass vase. This limits, to a large extent, the scope of what can be achieved. Despite these limitations, Fluidforms is an example of true mass customisation. The design can be customised and ordered over the internet for a cost of 90 Euro (2008). The company passes the creative role to the consumer, *"Fluidforms hands this role over to the customer. Thus, everyone can become a designer"* (FluidForms 2005). There are set limits to the individual parameters but no relationships between them and hence no design intent is maintained beyond overall dimensions and a sacrosanct inner volume. This is an intriguing step forward in mass customisation as it is web based and allows interactive adjustment of form, rather than merely selecting options. From a design perspective however, it is reliant on the consumer for creative decision making. It is only the limited scope of adjustment that prevents 'undesirable' outcomes.

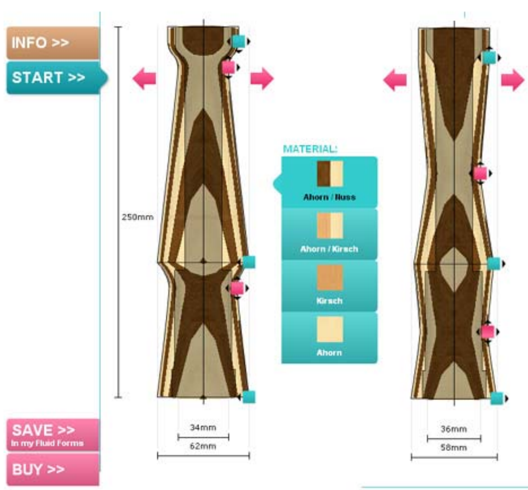


Figure 20
Serene Pepper Grinder, Fluidforms,
Customisation Screen Shots, 2008

1.7.5 Front

An extreme example of Customisation is the Sketch Furniture project by Front, a Swedish Design Collective formed in 2005. Front have a reputation for subverting the norms of the design process with 'products', like wall paper, made by the gnawing of rats, Figure 21.

Figure 21
Rat Wallpaper, Front, 2006

At Tokyo Design week in 2006 the group showed the Sketch Furniture Project with furniture 'drawn' by motion of the hand in 'thin air', Figure 22.

Figure 22
"Sketch" Furniture Creation Video, Front, 2005

The movement is captured digitally and used as geometry to define an extruded surface. The virtual form created can then be built by RP technology, Figure 23.

Figure 23
Chair - Sketch Furniture Collection, Front, 2005

The video is extremely engaging; the 3D output however is extremely crude. There is no control: the 'designers' work blind, unable to see where their hand is in relation to what has gone before. The work is in essence similar to the work of glass and ceramic artist Tavs Jørgensen. In his Motion in Form project Jørgensen uses a data glove, Figure 24, to describe artefact features, such as the lip of a glass vessel, in space.

Figure 24

Jørgensen's Data Glove

The results have been produced in glass and ceramic via CNC (Computer Numerical Control) milled tooling. Ironically, the 'artist' in this case puts considerably more control and constraint into his work, Figure 25 , than do the Front 'Designers' whose work is essentially performance. It might be expected that a design process would put greater emphasis on functionality and allow less freedom. Jørgensen however is using digital technology to capture the authentic momentary gesture of the artist rather than as a development tool to refine and perfect his ideas towards some notional ideal. The significance is that the vessel rims bear witness to discreet acts of the maker. The usual meaning of the word "craft" opposes high-technology processes in which the hand plays a diminished role (McCullough 1996). Digital technology is to the fore in this project yet the 'hand of the maker' is evident and celebrated despite the physical separation of action from the manufacture.

Figure 25
One-Liner Glass Bowls, Tavs Jørgensen, 2008

Sketch furniture, with its crude extrusions, is also reminiscent of artist Roxy Paine's Scumak No.2. In this experimental automatically generated art, plastic was extruded via a randomly controlled CNC (computer numerically controlled) nozzle. The extrusion would be deposited onto a conveyer, which periodically would index along to begin the next piece, Figure 26.

Figure 26
Scumak No.2, Roxy Paine, 1998

1.8 Software Developed for Generative Design

1.8.1 Genometri – Generative Design Software

Genometri is a Singapore based design technology company which markets generative design tools to the design industry, principally product design and architecture. Genometri was a start up company in 2005, a commercial technology spin-off from the National University of Singapore, which received funding from the Singapore Government.

Genometri developed a plug-in for the SolidWorks solid modelling package called Genovate. The idea behind Genovate is that it generates any number of random variants from a given parametric CAD model. The premise being that a busy design studio does not have the time to consider every possible permutation. According to the founder, Dr Sivam Krish, *"It allows the rapid generation of a vast number of designs based on a generic model. It is able to explore a larger set of design possibilities than what is manually possible today"* (Krish 2005). Significantly, Genometri uses the kernel of a parametric CAD package to control the geometry of the model, as has been proposed with FutureFactories (Unver et al 2003 Appendix 1) (Dean et al 2005 Appendix 2). The Genometric software has been developed as a plug in specifically for Solidworks CAD software. Theoretically it could be developed to suit any parametric package. The fact that it is only available on a single platform currently is something of a limitation. While it is common practice to export geometry from one package to another, with varying degrees of success, Genometry works with variables contained in a construction history. This effectively requires that geometry be built in Solidworks rather than use imported elements. A reasonable level of competence in a specific software package is therefore required. The idea is that a Solidworks file can be imported directly into Genovation and 'Genovation' can begin immediately. All named dimensions are reassigned random values. The range of variance can be controlled via a slider bar that specifies a maximum percentage change (relative to the original parameter value) across all variables or by manually setting limits for individual dimensions. The iterations are wild, random jumps contrasting sharply with the subtle changes over time envisaged by the researcher. Seismic changes bring issues of control and stability which will be discussed, 4.3.4 p81. There is also an issue of presentation. Genovate is aimed at generating design options in the commercial context. Output is all important and there is little need to engage the user with the generative process or to reassure them that control is in place since they themselves have established the parameters. It is interesting to note that the pop-up screen for setting limits manual is named 'live-DJ' with the connotation of 'remixing' creative output.

Genovate avoids issues of functionality: it is a plug-in which adjusts parameter values within a pre-defined model. There is nothing to constrain the form beyond the geometry limitations of the input Solidworks model which when exceeded, as frequently happens on a model of any complexity, causes the iteration to fail. The generative software operates purely on the CAD model's data set and is blind to the significance of particular features. Each parameter is treated independently. There is no provision for linking features as has been considered necessary in this project to maintain control over the form (Atkinson et al. 2003, Appendix 3). The character of a design often centres on proportional relationships. If for instance, a feature 'X' is small, the possibilities for feature Y might be restricted. Should this feature X be larger this in turn might offer more freedom in feature Y.

Genovate proves the virtue of using a parametric CAD kernel to control an animated 3D model and proves that applying mutation to such a model can be relatively straight forward. The only control the designer has over the character of the design is via range limits. The greater the range, the less likely a random change will be acceptable. It is interesting to note that the extreme end of the range slider bar is labelled 'creative', this implies that cruder adjustments are equated with increased creativity. Provision for setting relationships between parameters would enable greater control of the design's character.

In 2005, the researcher established links with Genometri and undertook beta-testing. As a result Genometri developed a dedicated version of the software, that allowed the storing and modification of parameter ranges in a Microsoft Excel file. Cornuta (8.1) was produced using this software: in this work relationships between parameters were introduced via formulas set in the CAD package.

1.8.2 Bentley Systems, Generative Components, and the Smart Geometry Group

Bentley Systems is a software developer. The company has developed Generative Components, released for beta testing in 2005, a software package for exploratory architecture that combines CAD (Bentley's own Microstation) with computer scripting. Large numbers of architectural firms are experimenting with scripting options to embed mathematical models within CAD packages, to digitally re-shape a form in response to loads for example (Hesselgren 2004). The Smart Geometry Group is a non-profit organisation promoting computational and parametric approaches to design, principally in architecture. Lars Hesselgren architect, researcher and founding member of the

Smart Geometry Group comments that, *“It moves the decision as to what is “architecture” versus what is “engineering” from the software vendor to the user. Just as with the adoption of spreadsheets 20 years ago, it is again the user who creates meaning, not the software.”* (Hesselgren, 2004). In a presentation to the SmartGeometry Conference, January 2006, Lars Hesselgren spoke of Computational Design, design practice driven by rules and relationships, as a development of Digital Design. Digital design was compared to digital word processing, computational design to the spreadsheet such as Microsoft Excel. In the case of the spreadsheet, the importance is not the initial values entered, but the relationships into which they feed. The SmartGeometry group, founded by four key industry experts; Robert Aish (Bentley Systems), Hugh Whitehead (Foster and Partners), Lars Hesselgren (KPF) and Jay Parish (Arup Sport) is in the process of registering itself as an educational charity, sponsored by Bentley Systems, with the aim to further advance education and research in the area of advanced 3D CAD applications.

Generative components aim to offer parametric modelling at a much more sophisticated level than is found in conventional parametric CAD packages. Conventional CAD functions are combined with scripting, to achieve more complex parametric relationships in what Bentley Systems terms ‘Programmatic Design’. Robert Aish, Director of Research, for Bentley states that the software can be used to capture design rules in a logical form and that, where programming skills are available, these can be harnessed to create additional programmatic components, without requiring a complete application to be written (Aish 2004). As with Genometri, much emphasis is placed on the rapid generation of variants. *“In real-terms that could provide a practice with the ability to come up with 20 or 30 designs simply by moving sliders within a Generative Component model”* (Day 2005). The suggestion is that project specific parametric rules can be set down to define architectural details and that these details can be rapidly applied in widely differing formats all bearing the same ‘character’. This is maintaining the designers’ intent as discussed in this thesis. It is easy to see that, disregarding focus on architectural applications, rules could be set to carry the visual language or the ‘genes’ of a product ‘species’. It is interesting to note the importance attributed to the interface. The need for an intuitive set-up interface was identified in this project (Unver et al 2003 Appendix 1)

1.9 Literature Review Summary

The Literature review examines work in generative art and design and direct digital manufacturing. The generative artwork of Todd and Latham includes speculation on the automated generation of 3D designs. Soddu goes further predicting emphatically the concept of individualised production brought about through the combination of generative computation and direct digital manufacturing He demonstrates extensive families of computer generated virtual products albeit that they are rather random and technically unresolved. If Soddu's output lacks functionality this addressed in Arads 'Not made by Hand, Not Made in China' which yields functional product iterations from CAD animations.

Different levels of consumer interaction are explored. Soddu states that his works are *'not tools for designers'* (Soddu in Bentley & Corne (Eds) 2002) where as at the other extreme Fluidforms would like the user to create products *'according to his own visions'* (Fluidforms 2005)

The concepts and predictions of the generative research considered are given weight by the emergence of digitally manufactured retail products documented in this section. These products produced in respectable volumes for retail sale indicates the commercial viability of such scenarios.

Examples of work from artists and designers demonstrate how virtual artefacts can be manipulated virtually and physical and 3D artefacts generated from the data. These works highlight to possibilities for 'living' products free from rigid specification.

2.0 Project Overview

In 2002, The School of Design Technology at the University of Huddersfield, took the decision to allocate an amount of research funding to provide an 'Artist-in-Residence' to work alongside Fine Art students, and a 'Designer-in-Residence' to work alongside Product and Transport Design students for a period of one year. Project proposals were invited, in April 2002, for the post of Designer in Residence. The researcher presented an embryonic proposal 'FutureFactories' for product manufacturing, using the then relatively new technology of Rapid Prototyping, and was subsequently appointed Designer is Residence for the Academic Year 2002/2003.

2.1 Design Residency Program

The concept of an 'Artist-in-Residence' has been part of the international art world for over a century. Residency programs may serve as a kind of patronage, offer a utopian seclusion, or facilitate an engagement with a possibly aesthetically impoverished public or business. Their presence in institutions, business and the arts is familiar. In art education the benefits of following an experienced practitioner is recognised and valued. A Designer in Residence working within design education is however somewhat unusual.

Fine art and craft traditions often feature specific manual skills which are accessible and can be readily observed even if more profound aspects of the practice remain elusive. Craft practice is usually workshop based and therefore placing a working professional practitioner alongside students is relatively straight forward. In design for industrial manufacture, the practitioner's skills tend to be wide ranging and encompass managerial activity as conflicting design criteria, for example mechanical function, user interaction, industrial production, environmental impact and aesthetics, are balanced against each other. Product design can involve a variety of activities from manual skills such as sketching and model making, to knowledge based activities such as CAD and calculations. Whilst the design is progressively refined in the course of a project, this is only visually evidenced at key presentation stages: there is rarely the continuous refinement of a physical piece. Development issues and decision making may be opaque requiring detailed explanation, rather than being apparent from observation alone. Accommodating a practicing designer is therefore potentially more of a challenge. Digital design practice is particularly difficult as the majority of the work is screen based. There may be no manually based practice beyond the use of a computer mouse. There may be test-rigs, printouts and diagrams but there need not be and in the researcher's practice such physical evidence of the creative process is increasingly unnecessary and rare.

The potential impacts of digital manufacturing, and the opportunities it presents, were considered to have sufficient significance to outweigh presentational barriers to the work. Paul Atkinson commented that, *"The (FutureFactories) project was fresh, exciting and potentially stimulating for students to see unfolding, the approach to design was particularly suited to the school as it combined theory and practice in a balanced way"* (Atkinson 2006). For the academic year commencing Autumn 2002 the researcher was based part-time at the University of Huddersfield, working alongside Product and Transport Design students in an open plan studio space. An open sided booth was provided with CAD workstation and wall space for flatwork. In addition to the day-to-day presence of the work, a series of presentations were arranged to allow a fuller communication of project thinking. One aim of the project was to encourage students to consider the implications of digital manufacturing within design practice and education. In addition to stimulating this theoretical and philosophical debate, the residency project aimed to benefit students at a more pragmatic level, by providing an insight into contemporary professional practice, highlighting the project management and time planning required.

The Design Residency program was for a fixed period of one year. Target outputs for the project were outlined at the proposal stage; these included culminating the residency with a public exhibition. This exhibition would include digital displays of the 'system' in action and a collection of physical products generated from it. It was considered important that actual artefacts be displayed to distinguish the work from virtual computer art and to engage a wider audience beyond the digitally aware. The focus of the project was the creation of design systems rather than discreet product design types. The exhibition would therefore feature a range of different consumer products. Presenting a range of designs would also enable exploration of alternate approaches, geometries, processes and materials. Early in the residency period it was decided that the concept was generating sufficient interest to merit a small touring exhibiting; taking the material beyond the University and opening up debate to a wider Art and Design community.

As well as the practice based elements of the project, the researcher was involved with research activity in collaboration with Huddersfield academic staff. During the residency period this academic activity was reported on in a paper to the 5th European Academy of Design Conference, Barcelona, April 2003, which considered cultural and pedagogic aspects of the project (Atkinson et al 2003 Appendix 3). A second paper presented to the International Conference on Advanced Engineering Design, Prague, May 2003, considered the technical CAD modelling and programming elements (Unver et al 2003 Appendix 1).

2.2 Expansion of the Project into a PhD Study

As the residency program developed it became clear that the work was of a significance that both merited and required investigation beyond the one year program. The project's first presentation outside the University, at the European Academy of Design Conference, Barcelona, April 2003, demonstrated a significant level of academic interest in the work. In the same month the Belgian Rapid Prototyping service provider, Materialise (1.6.2), unveiled a collection of lighting design prototypes. In September 2003, these designs where launched as commercial retail products under the company's own brand Materialise.mgx. This proof of the economic viability increased the relevance of the work and created an imperative to complete and disseminate the study. In Spring 2004 the researcher formally enrolled on a practiced based PhD study. Project outputs have been exhibited regularly, both nationally and internationally, since the conception to-date. There has been increasing overlap with the researcher's professional design practice. A number of commercial retail products have directly or indirectly stemmed from the work and limited edition gallery pieces have been created under the FutureFactories 'label'. The researcher's work is now focussed exclusively on Direct Digital Manufacturing.

2.3 Justification of the Practice Based Elements of the Project

Contemporary consumer products are almost invariably mass produced, and are visually identifiable as such through consistent detailing, regular surfaces and high quality surface finishes. Craft practice has an altogether different aesthetic. It is perhaps easy to imagine individualised craft output, as variations are often inherent in hand making: industrial processes are required to achieve standardisation and uniformity. Mass produced articles, by contrast, are expected to be exact facsimiles with variation considered a flaw. The broader 'systems design' element of the study can be illustrated and discussed through comparison and analogy. Comparisons can be made with the natural world, pre-industrial production and contemporary craft. It would remain difficult however to imagine the impact of variation on artefacts hitherto defined by their uniformity. For instance, when the project considers 'variation in form', what degree of difference would be involved? High-end Rapid Prototyping equipment can achieve a resolution of 0.05mm. Minute variations could be introduced that would not be visually apparent. This would technically be in line with the concept but would not be in the spirit of it. Artefacts and a practice-based element to the work is required to fully explore the implications of the concept.

Additive manufacture will remain an expensive process compared to the conventional moulding processes of mass manufacture for the foreseeable future. The commercial viability of individualisation using this technology depends on the premise that variation brings some form of added value. This is likely to require more than a technical difference; at some level even 'identical' mass-produced artefacts will exhibit differences as a result of manufacturing tolerance. Would differences in chemical composition, for example, hold any cache? It would seem unlikely. What degree of change then would be required to capture consumer interest and can this need for obvious change be accommodated while retaining a brand or design identity? Value and appeal are abstract concepts that can only be effectively examined through experimentation and dissemination. Technically a system can be defined on paper: the practicality, desirability and likely impact of such a production model can only be effectively debated through practical testing.

2.4 The Researcher's Established Practice

The researcher had 15 years of experience as a professional industrial designer prior to this thesis. He trained and practiced as an automotive designer before developing a specialism in the design of lighting objects. Computer Aided Design was not widely available during the researcher's training although systems were demonstrated. An undergraduate training in automotive engineering however and in particular the Cartesian referencing practiced in the automobile industry, made for an east transition to desktop CAD when it arrived.

The researcher's practice, in common with standard practice in the Industrial Design industry, would be to commence a design project with concept sketchwork. Loose drawings would become increasingly defined to the point where dimensionally accurate orthographic projections could be drawn and scale models made. The researcher's technical background always favoured accurate definition and complex curvature would habitually be defined by orthographic cross sections: a practice that has relevance in the CAD techniques developed in the thesis. In general terms the methodology would be to set out loose ideas that captured a desired aesthetic and then to iteratively refine the concept making it increasingly viable.

3.0 Mass Individualisation: Industrial Scale Production of One-off Artefacts

3.1 Why Individualise?

Mass production is a relatively recent concept characterised by the production of large quantities at low cost per unit. Rather than dictating low budget inferior products, mass production can allow precision manufacture and quality control. The size of potential markets allows intense design development and the use of sophisticated processes not economically viable for lower volumes. Mass production has made desirable objects affordable. Standardisation, rationalisation and uniformity are used to achieve a level of repetition that allows both affordable pricing through economies of scale and quality through technical refinement.

The economics of mass production is dependent on high volume manufacture, supported by mass-consumption. To be appropriate for mass-production therefore, products must have mass market appeal. Since the worldwide adoption of the mass production model, the goal of manufacturing has been for accurate repeatability. By definition, mass-market designs become commonplace and unexceptional.

Pre-industrialisation artefacts would be produced by craftsmen whose individual skills would be reflected in the products. Products would have a strong connection with the user and maker. The artefacts produced would be bespoke interpretations of a design 'type', recognisable yet not facsimiles. Each artefact produced could be more or less faithful to this original 'specification'. A level of variation would be inherent in the process with makers often working 'by eye'. The design specification itself might be ill defined and open to interpretation, organic, developing and mutating over time. The material stock employed in the design might be non uniform and adaptation might be required to work around a flaw or blemish. The manufacturing process may not be consistent with many craft processes being a balance between the demands made of the process and the control of it, for example, hand-blown glass.

Such discrepancies in interpretation, material or process, rather than resulting in scrap, might produce an interesting variation on a familiar theme. This lack of uniformity, this uniqueness and un-repeatability, far from being seen as a negative by the consumer, is often valued. Mass production has made desirable objects affordable. The size of the market allows levels of design development quality and technical sophisticated processes not possible at lower volumes. There is however a perception that something has been lost. In today's consumer world, we are surrounded by every conceivable product for every possible application, all at affordable prices.

The availability and omnipresence of mass-merchandise fosters within us a desire for something personal and unique, something we can imbue with a soul or character of its own.

An aim of this thesis is to deliver the technical resolution and affordability of mass market products, combined with the idiosyncrasies of craft production: to reintroduce the individuality inherent in hand manufacture whilst still exploiting the economic and technical benefits of a mass-production.

3.2 Industrial Production Versus Craft Making – The Need for Automation

The distinctions between craft and design can be complex. Perhaps simplistically and for the purposes of this discussion, 'Craft' will be defined as production dependent on the skills of an individual and 'Industrial Design' as a process in which artefacts are defined for production by any "appropriately skilled workers", usually employing automated equipment.

CAD software is a production tool that can be used to effectively hand-craft one-off artefacts, albeit indirectly with a mouse or similar input device. Virtual three dimensional models can be manipulated and edited with relative ease. Systems can be envisaged in which a creative practitioner would manually adjust a virtual model in response to each and every order received. The aim of this project however is an automated design and manufacturing system. If a designer is required at the point of production, then the outcome becomes dependant on a particular individual's skill and the production capacity limited by the time they have available. This is in contrast to the industrial design model, in which the designer's skills are required only to define an article and its manufacture. Once the design is complete, manufacture becomes mechanistic, perhaps requiring skills and training, but not dependant on an individual's creativity. If the CAD manipulation can be automated, production becomes viable on an industrial scale, and therefore not dependant on individual skills. The aim of this project is a design process with the capacity to run on an industrial scale and an automated process is therefore essential. Within the context of this project, mass-individualisation is defined as the automated industrial scale production of one-off artefacts.

3.3 Mass Individualisation Distinct From Mass-Customisation

The term 'Mass Customisation' was coined by Stan Davies, in his book 'Future Perfect' (Davies 1987). Mass customisation offers personalisation though the use of flexible manufacturing systems without losing the economic advantages of mass production; *"Producing goods and services to meet individual customers' needs with near mass production efficiency"* (Tseng and Jiao 2001). Kaplan and Haenlein define mass customisation as, *"A strategy that creates value by some form of company-customer interaction at the fabrication/assembly stage"* (Kaplan and Haelein 2006). This interaction normally involves a level of specification by the consumer; either passively through the use of body scan data for example, or actively through some form of configuration.

In contrast, FutureFactories derives only limited input from the consumer. The user can merely arrest an ongoing development, or initiate a new one. Crucially, the nature of the form generated is independent of any consumer interaction other than this crude stop/start. There is no attempt to configure an artefact to specific requirements or taste. The aim is merely to generate, on an industrial scale, a series of unique design iterations and thereby to give each customer the satisfaction of owning a one-off artefact. The FutureFactories model is therefore more correctly termed 'mass individualisation,' defined in this context as, "the production of unique product variants with near mass-production efficiency."

3.4 Consumer Input to the Individualisation

FutureFactories achieves individualisation by introducing elements of random variance at certain stages in the design process. Crudely, certain parameters and sets of parameters are allowed to 'float' within their own predetermined range. It might seem logical to allow the consumer to make these adjustments via a 'slider-bar' style interface? The researcher, however, has sought to avoid this. The desire for customised merchandise can be a search for something unique, in a mass market culture. It does not necessarily result from dissatisfaction with contemporary product design. Indeed it is the very success of particular designs, their proliferation and omnipresence that fosters the desire for something more personal. The desire is not necessarily for something designed by oneself personally, dependant on whatever skills and experience one has, but for something individual and personal. The intention of this research is to introduce individuality into "off the shelf" mass produced artefacts rather than to empower the consumer as a designer/maker themselves. Such an empowerment would be worthy of study and there are several projects and companies working in this direction, for example Genometri (1.8.1) and Fluidforms (1.7.4). FutureFactories is concerned with the boundaries and nether ground between industrial repetition and the bespoke. Practitioners are often commissioned to work to a client's individual instruction and a case could be made for some element of co-design. However, for the sake of clarity, and to draw a clear distinction between FutureFactories and mass customisation, the decision was made not to allow consumers into the design process, other than to initiate or halt its development.

3.5 Random Morphing, Control or Happenstance

FutureFactories requires adjustments to the design specification for each and every artefact produced. Individual variants cannot be created by the designer as an automated, industrial system is required. There is also is no desire to assign a creative role to the consumer. The solution is to introduce an element of computer generated variance; a random element. Central to the project is that this computer generation remains only an element within a controlled, recognisable, design form. The aim is coherent, identifiable designs rather than random objects; artefacts comparable in style and design to mass produced consumer products. Rules are required to ensure that each and every solution maintains a desired aesthetic and is therefore designed, rather than randomly generated.

The notion of there being a single optimal solution and unique physical specification for any given design concept is something of a myth. Often design is the management of compromise, trading off different factors against each other. This is particularly true where product aesthetics are a driving factor and there are arbitrary decorative elements; taking the FutureFactories Holy Ghost chair as an example, Figure 27.

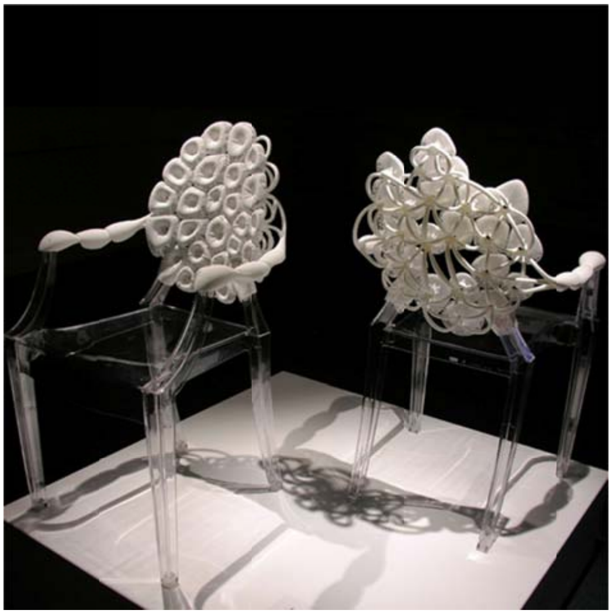


Figure 27
Holy Ghost chairs, 2006

The Holy Ghost chair back is made up of a number of 'buttons'. The weight of the occupant is shared between these buttons and there has to be a sufficient number to share the loading from a structural perspective. From a visual perspective, however, the aesthetic is not dependant on a fixed number of buttons although clearly there would be limits. The exact number of buttons is an arbitrary design decision. Accordingly the computer script underpinning the Holy Ghost design has been developed to generate a range of between 20 and 26 buttons. As designer, the researcher considered that the character of the design was effectively maintained throughout this range.

3.6 Meta-designs

In the FutureFactories model the designer creates what has been termed a design template (Atkinson et al 2003 Appendix 3). Rather than specify a discrete design solution, the designer sets up a series of rules and relationships that define desired aesthetic and functional criteria over a potentially infinite range of outcomes. This meta-design is equivalent to the organic design specification of artisan making. It allows a certain freedom in form whilst maintaining an overall design intent. The template should allow a balance between freedom and control. Whilst maintaining a coherent design identity there should be obvious difference between iterations and even the potential for a surprising twist.

4.0 Computer Generation of Variants

FutureFactories began as a one year residency, which was to culminate in a series of exhibitions in the Yorkshire region. One of the key demands in disseminating project thinking was the creation of real-world consumer products to illustrate what could be achieved. There were, and are, few close precedents in the commercial realm. Creating 3D outputs from the project required both product designs and software solutions to drive and control the generation of variants. The need to exhibit 3D outputs after a comparatively short period of development meant little time was available to develop the underpinning computer scripts. As the potential of the project to develop beyond the blue-skies residency became clear the demands for dissemination increased. In order to exploit interest in the work, communication was considered key and prioritised producing presentable artefacts over writing lines of code. As the project has become established the software development has gradually caught up. In the later design examples the project aim of real-time individualisation is achieved and developed.

In FutureFactories, meta-design templates maintain design criteria over potentially infinite numbers of outcomes. This is achieved using a computational design approach that combines parametric CAD software with computer scripting. Three dimensional CAD models are defined by geometry, usually a set of curves, and relationships between them.

Taking a tuboid form similar to the 'limbs' that make up the Tuber lamp, the form is defined by a series of circles. Three operations define each circle, a translation from the origin (in Cartesian space), a rotation relative to global axes and a scale. Each of these three operations is then sub-divided into X, Y and Z components. Each element in the CAD geometry therefore has nine discrete parameters that can be adjusted, Figure 28.

The overall model is defined by a string of listings, nine for each geometric entity. Such listings defining 3D form have been compared to the DNA genotype in nature. Richard Dawkins uses geometric parameters to represent genes in a graphic growth structure illustrating evolution (Dawkins 1986). The virtual CAD model is the phenotype or observable morphology, the embodiment of the genotype data. The genotype listing carries the mathematical instructions required to build the phenotype form. Parameters within the list can be modified and, providing values remain within certain bounds allowed by the geometry, a new variant of the same design will result.

Each FutureFactories model is defined by a list of geometric features and associated parameter values. It is by operating on this genotype list of parameter values, that the morphing of design variants is achieved. The CAD meta-design describes the features: the computer script, via the genotype parameters, defines a particular configuration of those features.

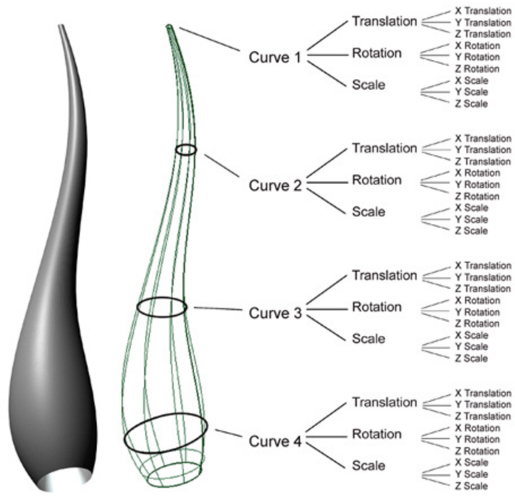


Figure 28
Phenotype Form and Genotype Data List

4.1 Key Frame Animation

Design variants in the work discussed so far have been achieved by modifying parameters. A project aim was to avoid a series of staccato jumps, as one random value is replaced by another. Instead the model should appear to ‘grow’ with one mutation flowing seamlessly into the next. In the early work this was achieved using CAD package based key-frame animation. In key-frame animation an entity is created along with a series of developmental stages for that entity between the start and end states. CAD software then extrapolates between these key stages creating a series of transitional models between them. This results in an extended sequence of model states each differing only slightly from its neighbour. Rendered images of these model states can played sequentially to produce a seamless video animation.

Key-frame animation was employed to create the design variants of the ‘First Collection’ Lampadina Mutanta, Nautilus, Twist, Let’s Twist Again and Tuber exhibited at the end of the residency period. At that point the generative designs created were limited to test sections like the tubular volume, in Figure 28. In the more complex design examples produced, the key frame states were derived manually.

Creating a key-frame animation can be an intuitive process with the development assessed at regular intervals. The end state is fixed and pre-defined. In extrapolating between the key stages, the software generates a discreet model at every frame. A vast number of models can be created from even a short clip of animation (30 frames a second is typical). The collection of Tuber variants was derived from a two minute animation clip offering a potential 3600 discrete forms, one for every frame of the animation. The difference between neighboring frames however is almost imperceptible, a level of subtlety necessary to achieve a smooth animation. Five distinct Tuber variants were created from the animation, Figure 29. If a greater number had been produced from the clip, the separation of the frames produced would be reduced and there would be greater similarity between the variants.

Pre-defined key-frame animation offers potentially large numbers of unique variants for relatively few key-frame inputs. The scope is nevertheless limited however, and falls short of the project's fully automated production aims in which there should be no limit to the potential variants.

Figure 29
Tuber variants

4.2 Procedural Animation: Rules, Ranges and Relationships

Each solution generated is intended to be unique and not repeated in a cycle, however long. The second stage of software research was to develop procedural animations. In a procedural animation, entities are modified by a procedure or algorithm to create successive keyframe states. A set of developmental rules and relationships are established along with an initial condition for the entity. Solutions are then generated automatically. In contrast with the standard key-frame approach, procedural animation is abstract. 'Control' of the development is attempted via indirect inputs which can be multi-layered and interrelated. The results, while being determined by the algorithms (as apposed to truly random), can be unpredictable, with experimentation required to achieve the desired results. Once created, however, a procedural animation can yield a potentially infinite series of solutions, given an appropriate script.

4.2.1 Procedural Animation Principles as Applied in FutureFactories

The procedural animation work began with setting variables, to cycle independently through specified ranges. Different variables were set to cycle at different rates. The fact that variables changed out of phase provided the computer generated random element.

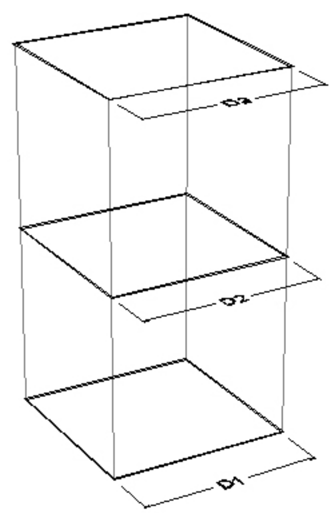


Figure 30
A Solid Formed by Lofted Square

To understand the principles a simple box can be considered, Figure 30: this could be, for example, the leg of a piece of furniture. A simple solid model is created by 'lofting' three square sections. 'Lofting' is the creation of a 3D transitional form between 2D profiles (usually) and is a common feature in high-end CAD. The form defining 2D profiles are termed control curves. The size of each square control curve, defined by dimensions D1, D2 and D3 respectively, is allowed to cycle independently 100% - 30%. Figure 31, shows the effect of this applied to the uppermost control curve only.

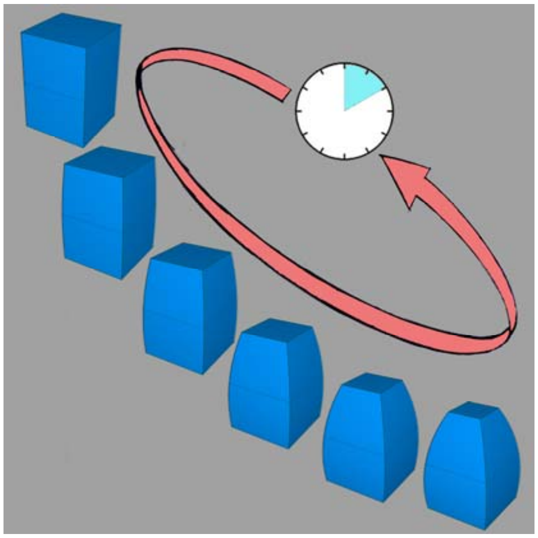


Figure 31
The Effect of Scale Variance

Now all the scale of all three control curves is allowed to cycle through the range but at different rates. The cycling of the variable D3 is set at a given rate. The other two variables, D1 and D2 are now also set to cycle though the same value range but at different rates. The effect of this is illustrated in Figure 32. In this example D1 cycles at twice the rate of D2 and D3 at five times the rate of D2.

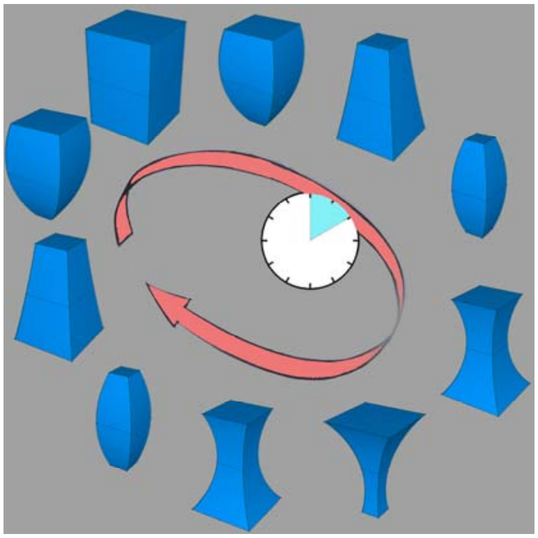


Figure 32
The Effect of Differing Scale Variance on all Three Lofted Profiles

With only three variables that cycle through relatively narrow ranges, the chances of similarity are high and similar pairs are evident. Another element of variance that could be considered is the addition of a twist about a vertical axis formed by rotating the horizontal profiles in Z, as illustrated in Figure 33.

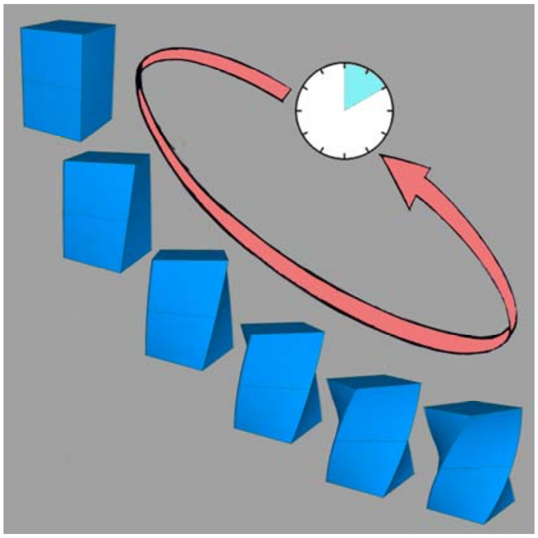


Figure 33
The Effect of Rotating One Lofted Profile

So far the three control curves have been evenly spaced with the mid-profile of the loft construction located mid-way up the form. This control curve can be allowed to rise or fall, Figure 34.

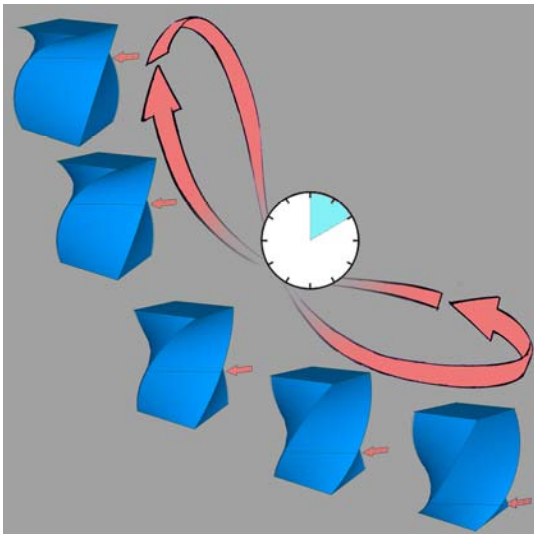


Figure 34
The Effect of Altering the Height of the Central Profile

The rotation about the vertical axis and the asymmetric placement of the mid profile are assigned ranges and independent rates of change. These transformations are overlaid on the earlier Figure 32 model, and the resulting forms illustrated in Figure 35. There are now five variables and, in spite of the similarities in the scale transformations, there is a reasonable difference between all iterations.

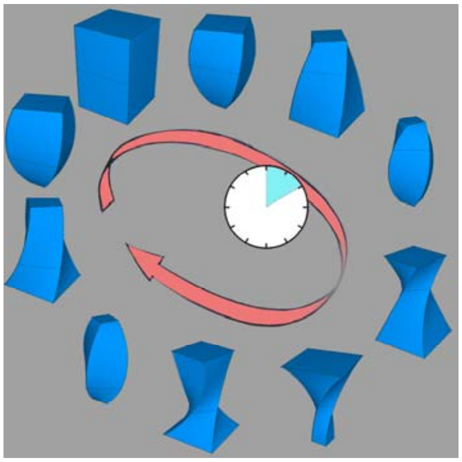


Figure 35
Effects of combined transformations

The Twist candlestick, Figure 36, was developed using these principles. The design has three leg volumes which meet at the top. Each of the legs has elements of variance similar to those used in the box example. The three legs morph independently, but with a constraint to ensure the upper control curves of each leg volume match (Section 6.1.5).

Figure 36
Twist Candlestick

4.2.2 The Nature of Morphing: Micro Changes, Macro Changes and Alterations of the Geometrical Structure

In the process described in 4.2.1 parameters are considered in isolation. In design terms this is simplistic. When manipulating a model a designer will often choose to apply the same operation to a group of features, moving an entire leg for example. It may be desirable therefore to group features in order to apply operations to the set as a whole.

Another manipulation strategy common in digital animation is to spread an operation over a number of features, blending out its effects progressively. Taking the control vertices (CVs) on a surface for example, Figure 37: a single central CV could be displaced deforming the surface locally (left) or the displacement could be spread over neighbouring CVs with diminishing amplitude (right). An operation can be given a 'sphere of influence', such that it affects all entities within spherical bounds: this has diminishing intensity with increasing distance from its centre.

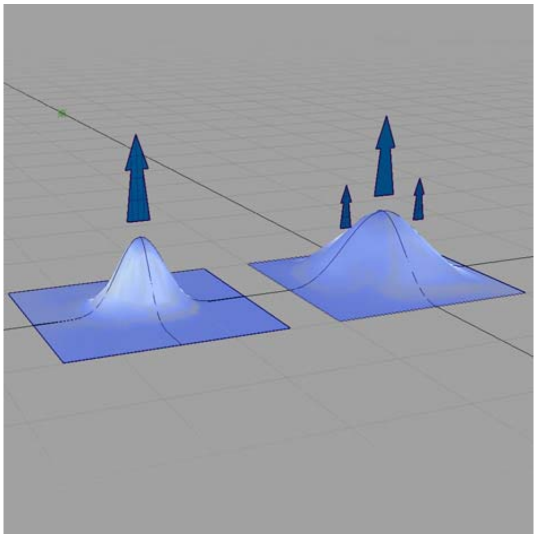


Figure 37
Sphere of Influence

The table leg in Figure 38a may have a translation applied locally, Figure 38b, creating a kink in the form. Using a sphere of influence, the effects of the same translation can be spread over the entire leg producing a flowing bend, Figure 38c.

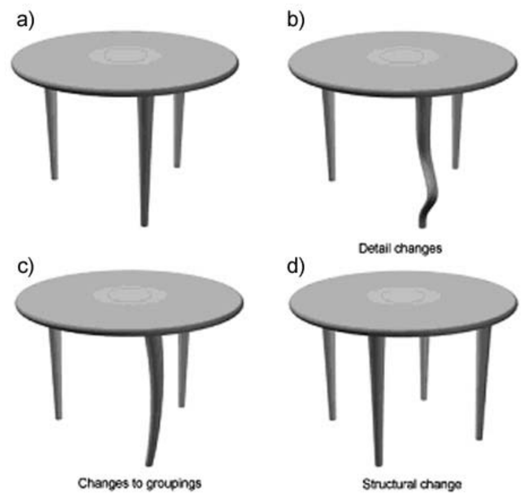


Figure 38
Modes of Mutation

4.2.3 Structural Changes to Geometry

Sometimes the desire for change goes beyond the mere adjustment of existing geometry. Some modifications, the addition of a whole new leg in Figure 38d for example, requires changes to the fundamental geometric structure of the CAD model. This type of change proved difficult to accommodate in the early FutureFactories models, due to their surface based geometry and the requirement that each iteration produces a potentially viable product. The parametric models could not support the creation of new geometry or the removal of existing features whilst maintaining construction history.

In the natural world complex systems have evolved from crude beginnings. The human eye perhaps evolved from something akin to the light sensitive spots processed by some single celled animals (Dawkins 1986). With a pre-defined design template the design remains constrained, however long the development period. An LED, for example, has fixed physical parameters and is either there or it is not. It cannot evolve for example from, in a parallel to the natural world, a slightly glowing protuberance.

A degree of structural evolution is desirable, if not essential. Structural changes to the geometry can be achieved by breaking the design down into an assembly of separate sub-models. Tuber consists of four limbs that intersect. These can be separate CAD models joined in an amalgamating Boolean operation (Technical Glossary page 267). Each of the four volumes has its own geometry whose integrity must be maintained; the links however, need not be pre-defined. The links are created indirectly by physical interference between the limbs and are only created if a particular iteration is manufactured. As the links are not pre-defined the format of the assembly can change during the evolution as long as all four limbs remain linked. A link can pass from one limb to another, in the manner of a baton being passed in a relay race, Figure 39. A direct link between two volumes can be broken as long as they remain indirectly linked and all four volumes remain joined.

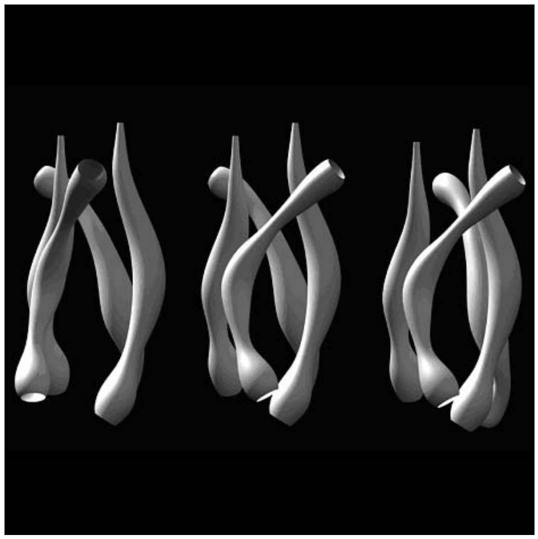


Figure 39
Changes in Model Structure

4.3 The Use of Evolutionary and Genetic Algorithms: The Introduction of Selection

To this point it had been considered necessary to define a complete envelope of parameters. The envelope defined a 'solution space' covering every possible mutation of the form. Each individual parameter required specified ranges that considered both the effects of that parameter alone and its effects in combination with others. If there are more than a handful of parameters and their effects interrelate to any significant degree, then the task of specifying such an envelope becomes extremely long and complex. An aim of FutureFactories is to explore generic systems of commercial potential. For commercial viability, it should be possible to introduce new designs with reasonable ease. Ideally one would be able to apply mutation rules to a conventional 3D model via an intuitive on-screen process: the system was initially seen as a 'plug-in' addition to high-end parametric CAD systems. The complexity of specifying a parameter envelope could be reduced by severe restriction of the permissible parameter ranges and by isolating their effects where possible. However this would lead to uninspiring, predictable changes in the form, repeated oscillations, for example.

A way of simplifying the generative rules had to be found. Evolutionary design principles offered a potential solution. Genetic algorithms permit virtual entities to be created, without requiring a full understanding of the procedures or parameters used to generate them. Instead of incorporating expert systems of technical knowledge into the programming, evolutionary design systems rely on utilitarian assessments of feasibility and functionality (Sims 1999, Funes and Pollack 1997). The parameter envelope specified in this research is designed to perform two functions; to ensure that manufacturability be maintained and that the mutated form retains the 'designer's intent'. If the degree of success in meeting these requirements can be assessed and quantified, then selection can potentially guide the design towards acceptable solutions rather than having to identify every possibility.

4.3.1 A Model for Mutation and Selection

The procedural animations created had been driven by a series of algorithmic steps. Introducing evolutionary algorithms, each key-frame step becomes a generation with a single parent and an arbitrary number of randomly mutated offspring. Each of these offspring would have a single randomly selected parameter modified by a predefined step. The iterations would then be ranked for 'fitness' and the most successful selected as the parent of the next generation. The scoring for fitness is based on the 'desirability' of the last transformation with reference to the designer's intent. Before becoming the parent of the next generation the selected iteration is tested against functional criteria such as fitting the production machine volume. This ensures that after mutation the design is no less manufacturable. If the parent fails this assessment the next best offspring is selected. Only selected offspring are tested against the failure criteria to reduce computation. Animation is then employed to provide a flowing transition between one generation key frame step and the next, as illustrated in Figure 40.

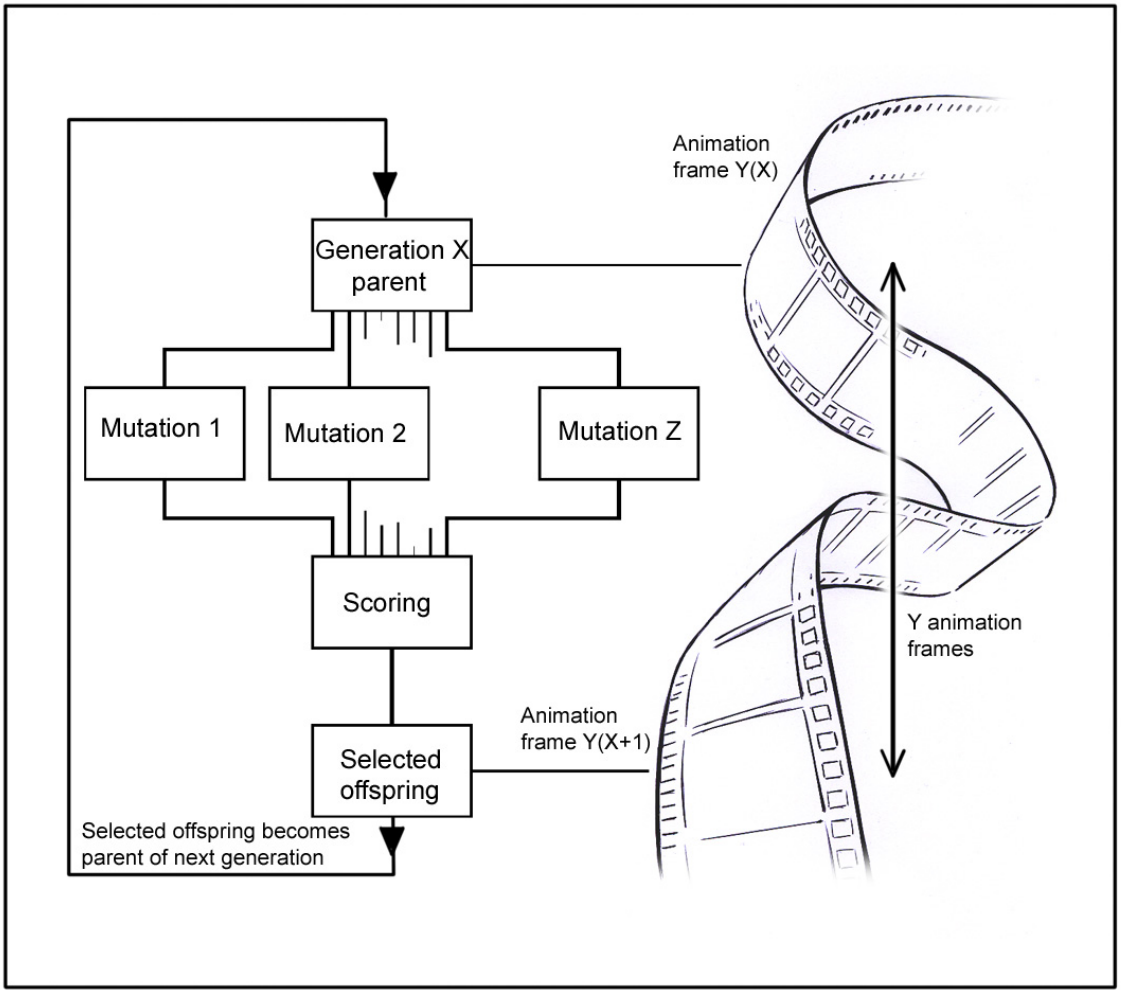


Figure 40
The Mutation, Selection and Animation Process

4.3.2 The Introduction of an Evolutionary Pressure: Aesthetic Evolutionary Design

Evolutionary principles were introduced to simplify control; the aim is not the functional optimisation of the designs through evolutionary computation. The suitability and functionality of the design are present in the initial seeded product form. These qualities are then maintained by the selection process, rather than their being improved. It is hard, however, to avoid creating evolutionary pressures by virtue of the 'fitness' scoring. Public reaction to the early stages of the project also pointed to the inclusion of an evolutionary element. There was a desire to see the form evolve in a direction. Creating this type of intrigue is obviously important from a marketing perspective. A level of evolutionary development is seen as a way of stimulating interest and engagement. One possibility is that designs would be available and evolve for a limited period. Different periods of the evolution process may achieve different levels of desirability. The value of an artefact would vary according to its position in the evolution. There may be 'good' and 'bad' evolutionary periods as there are good and bad vine harvests. The introduction of evolutionary pressure creates what has been described as Aesthetic Evolutionary Design (Bentley 1999), an area that borrows from Evolutionary Design Optimisation and Evolutionary Art, Figure 41.

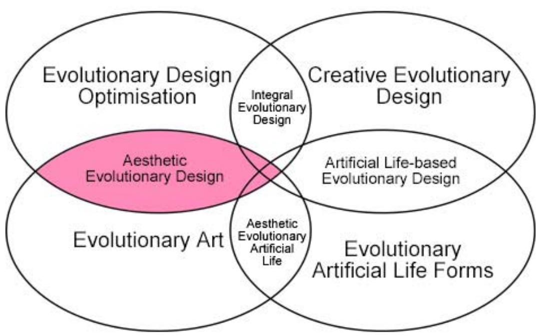


Figure 41
Aspects of Evolutionary Design by Computers, Bentley 1999

4.3.3 Ranking

Evolutionary pressure is introduced to evolve increasingly visually interesting designs. The designer creates both an initial form and the evolutionary pressure that will guide changes in that form over its evolutionary lifespan. The use of digital manufacturing favours forms of geometric complexity as these justify the costs of the processes. It made sense therefore to equate desirability with geometric complexity.

In order to score geometric complexity, one option considered was to measure surface area divided by volume. Dividing by volume prevents simple expansion. Experiments were carried out on a simple pendant lamp form based on one of the Tuber volumes. The effect after 200 generations can be seen in Figure 42, the initial form is on the left, the form after 200 generations is on the right.

Figure 42
Initial State and the Form after 200 Generations

4.3.4 Micro-Mutation, Macro-Mutation and Achieving a Balance in Transformation Step Size

Evolution in the natural world is the result of accumulated small changes. Dawkins points out that in nature small change is crucial, *"Even a small random jump in genetic space is likely to end in death. But the smaller the jump the less likely death is, and the more likely is it that the jump will be in improvement…….The chance of improvement resulting from a transformation tends to zero with increasing step size and to 50% as it decreases"* (Dawkins 1986). Similarly, if the parameter values of a CAD model were re-assigned at random there would be a strong possibility that the geometry would fail. The larger differential between old and new values, the greater this possibility will be. In addition, the more operations that are occurring simultaneously, the lower the probability that any particular one will be successful as effects overlap. For this reason each 'child' generated from the 'parent' form has only one parameter adjusted at random +/- one 'small' step. The step size is a value arrived at through experimentation and is relative to the operation and feature in question. The steps must be balanced so that they each achieve a comparable degree of change to the form.

4.3.5 Assessing Functionality and Manufacturability

Assessing the children for manufacturability is relatively straight forward to envisage, even if difficult to implement. The validity of the CAD models created can be assessed through the ability to export a suitable digital file for manufacture. Problems, such as overlapping surfaces, either prevent successful export, or are flagged up by error messages. The manufacturing limitations of the intended digital manufacture process can be imposed, minimum material section thickness and the machine build envelope for example. Functionality may be harder to evaluate. Stability may be assessed via the centre of gravity. The space to house internal components can be examined with an interference check. Practical assessments of this type are used to impose absolute limits rather than for relative scoring and are a separate check in the generative cycle, Figure 43. The aim is not technical refinement. It is not the intention to select the quickest to manufacture or the most stable; merely to assure that each generation conforms to a minimum functional standard.

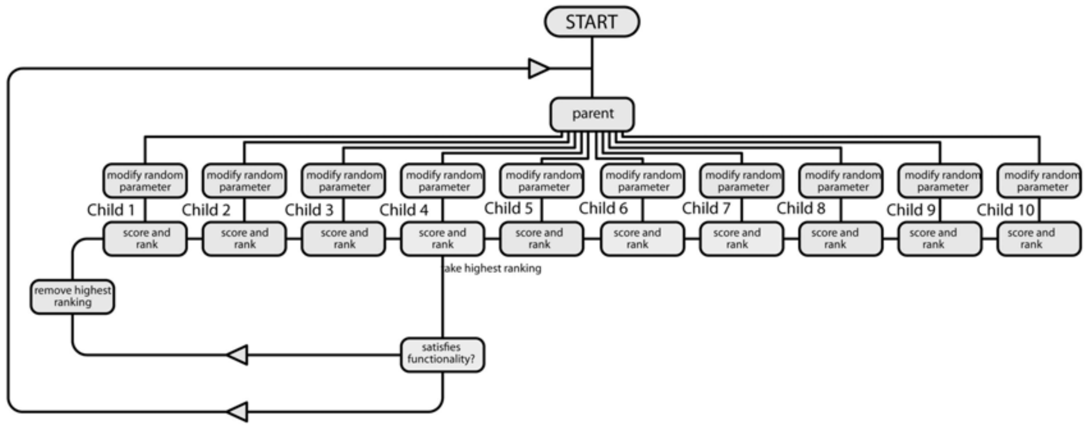


Figure 43
Scoring and Functionality Check

4.3.6 Scoring the Aesthetic

Maintaining the designer's intent requires a more abstract, relativist approach than does assessing functionality and manufacturability. Selecting designs based on a relative scoring of specific geometric criteria, allows the designer to express a general image for the design rather than absolute limits. The notion of 'slightly twisted', for example, might translate to a high probability of rotation, followed by an exponential decrease in the probability of further rotation following each rotation selected. As in evolutionary 'survival of the fittest', the designs with the highest 'fittest' scoring will prevail. This less rigid form of definition simplifies the set up of the model and also allows the possibility of new unexpected forms (although the possibility of dramatic change has to be balanced against maintaining a coherent, identifiable design). The effects of the rules are 'softened' by the use of probability: a high fitness score can be allocated a higher probability of selection rather than assured success. This again broadens the possibilities, allowing the occasional success of a less 'optimal' and therefore potentially surprising solution.

FutureFactories focuses on a single mutating parent. Evolutionary algorithms are usually much more sophisticated. They usually feature populations of solutions, and two parents, both of whom contribute to the offspring's 'genetic' make up. This 'crossover' combines characteristics and provides stability.

4.3.7 The Constructive Solid Geometry, CSG 'Building Block' Approach

Exhibitions following the initial residency period yielded valuable feedback on the concept. Would-be consumers, in the form of exhibition attendees, expressed a desire for more dramatic, fundamental changes than the gently writhing designs presented. At the same time, it became clear that the number of variables involved and the need to achieve a reasonable balance between freedom and control made scripting an onerous task; a design investment that would mitigate against widespread uptake of any system. The adoption of an evolutionary algorithm approach had helped simplify set-up to a degree, this however works best when limited to gradual subtle changes. Simplifying the designs and achieving stability in morphing was proving difficult; it was also at odds with the demand for more visual excitement. A fundamental change of methodology was needed. The approach to this point had been to take complex CAD models made up of mathematically defined surfaces and to apply modifying scripts. An alternate, more script centred, building block methodology was now considered. Rather than the script redefining geometry, it would more simply re-configure pre-defined geometric building-blocks or primitives (Technical Glossary).

The building-block approach was explored using Virtools, a software development tool aimed primarily at video game creation. Virtools was selected for a number of reasons:-

- Scripts developed using this software can run on a freely available web browser plug-in, the '3D life' player;
- Software is created within Virtools using an intuitive block diagram method rather than hard scripting;
- Custom software building blocks can be written if required;
- Designed for web applications, Virtools allows the easy creation of flexible interfaces;
- Virtual 3D entities can be rendered with realistic materials comparable to the CAD environment;
- 3D mesh data can be imported into Virtools from a range of CAD software, including 3DStudiomax;
- It has a strong user community with active forums providing problem/solution sharing; and
- It supports the management of data and attributes, via 2D arrays, with the capacity to import and export data files.

A simple example of a Virtools code is illustrated in Figure 44. In this script an 'Iterator' building block cycles though each entity in a data set. Each entity in turn is given a translation, rotation and scale operation by respective blocks. These operations loop back to the Iterator. When the data set cycle is complete, the 'finish' output is triggered. The trigger path can be seen in black. The dotted green lines represent the input of information, in this case the selected entity to operate upon. This is a simple example and in practice the schematics become significantly more complex. The principles, however, remain intuitive with actions tracked through a schematic path. This intuitive approach, coupled with the software's suitability for web based 3D operations, made Virtools an effective tool for the project.

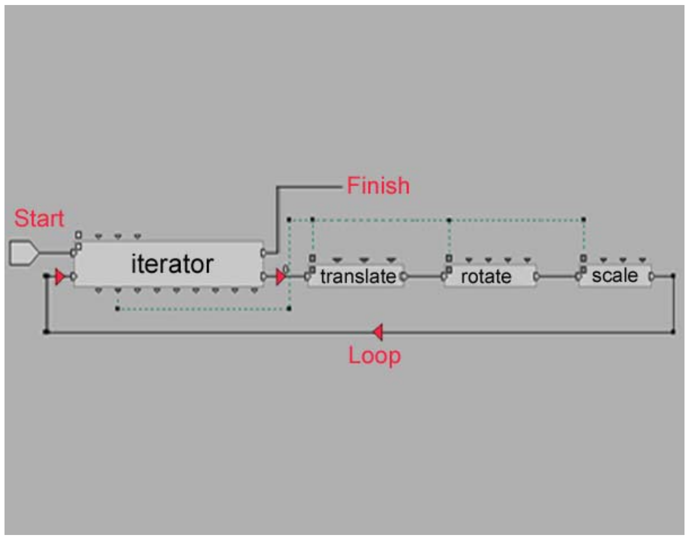


Figure 44
Example of Virtools' Script

The Grasshopper plug-in for Rhino CAD software, RhinoScript, a more sophisticated Virtual Basic scripting option for the same package, and Generative Components that works with MicroStation architectural CAD were considered as alternatives. Being CAD system based, these options all offered more flexible links with the model geometry. It was freely available web player however that made Virtools the preferred solution. This would allow 'customers' to run scripts on their own PCs in the manner envisaged for a commercial system without the need for specialist software.

4.4.1 DNA: Design Case Study of a Constructive Solid Geometry 'Building-Block' Approach

A simple, modular design was considered comprising a network of multi-coloured lenses arranged around a standard GLS incandescent light bulb, Figure 45.

Figure 45
DNA Luminaire

This design was titled 'DNA'. In this design a series of linked rims, rather like spectacle frames, are built one after another around the light bulb starting from the bulb holder. The sequence begins with a simple open rim which attaches to the bulb holder, via the industry standard threaded clamp provided for lampshades. There are three different lens sizes: small, medium and large, 20, 25, and 30mm respectively, and six colour options; amber, blue, green, purple, red and yellow. The linked rims are built into a self supporting framework, which is digitally manufactured in a single piece. The lenses are punched from polypropylene sheet and are clipped into the rims as a post production process.

Each rim may have three branches, evenly spaced 120 degrees apart, around its circumference. Links between rims may be straight or twisted with rotations in two axes, Figure 46.

Figure 46
DNA Components

In Constructive Solid Geometry, CSG (Technical Glossary), geometric primitives are combined using the Boolean operations of union, subtraction and intersection, to form a more complex whole. In the DNA design, rim elements pre-exist as a library of CAD models that are assembled via Boolean union, Figure 47. Sets of angled links are pre-created and assembled as required rather than geometry being manipulated to the requisite angles. This ‘building-block’ approach simplifies the Virtools script, avoiding the manipulation of geometry within the package. Translation of the virtual representation, through to a manufacturable model, is also simplified. The design is defined by the configuration of sub-models within it. As the virtual model is made up of pre existing CAD entities, the ‘production’ CAD model is likewise a configuration of pre-defined CAD sub-models. Hence computationally ‘light’ visualisation models can be used within the script, these are then mirrored in a set of technically robust equivalents used for production.

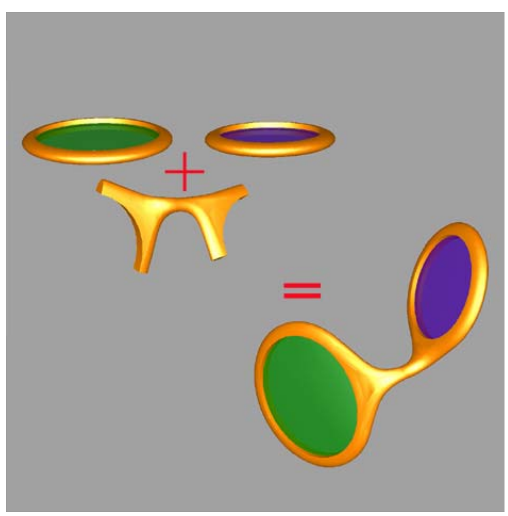


Figure 47
Boolean Union

DNA was created to explore a simpler approach to generative design, with as few rules as possible. Design rules were created to:

- Maintain sufficient clearance around the bulb as a thermal constraint;
- Restrict the overall form to a practical, easy to build and saleable size;
- Restrict the number of lenses in the assembly to define the 'size' of the design; and
- Prevent physical interference between the lenses.

To resolve the size and clearance issues in the structure as a whole, inner and outer boundary spheres were created with the design allowed to grow in the intermediary space. The structure builds in steps with subsequent rims, their positions and orientations selected at random. Determining the step's 'success' is comparatively simple; if it does not clash with boundary volumes (inner and outer) or its lens does not clash with any others present in the structure, the step is allowed. Clashes between the post production fitted lenses are not allowed as this would prevent assembly. Interference between the surrounding rims is permitted however, as it is visually interesting and adds strength. A degree of interference between the rims is judged essential; the minimal nature of the rims means loads must be spread around the structure. Where rims overlap in the virtual design, they are built structurally united. If DNA were to build itself as one long coil with no inter-linkage, the resulting structure would potentially not be self-supporting. In spite of this imperative, no assessment of structural cross-linkage was attempted in the programming. Structural integrity would be extremely difficult to assess across a randomly generated network in which intersections have varying degrees of structural merit. In practice intersections proved plentiful without any scripted provision for them and the issue was set aside. The structure can in practice be assessed with a quick visual check of the virtual design. The DNA I Virtools' script was developed in collaboration with supervisor Ertu Unver. A schematic of this code can be seen in Figure 48. Subsequent scripts are the work of the researcher alone.

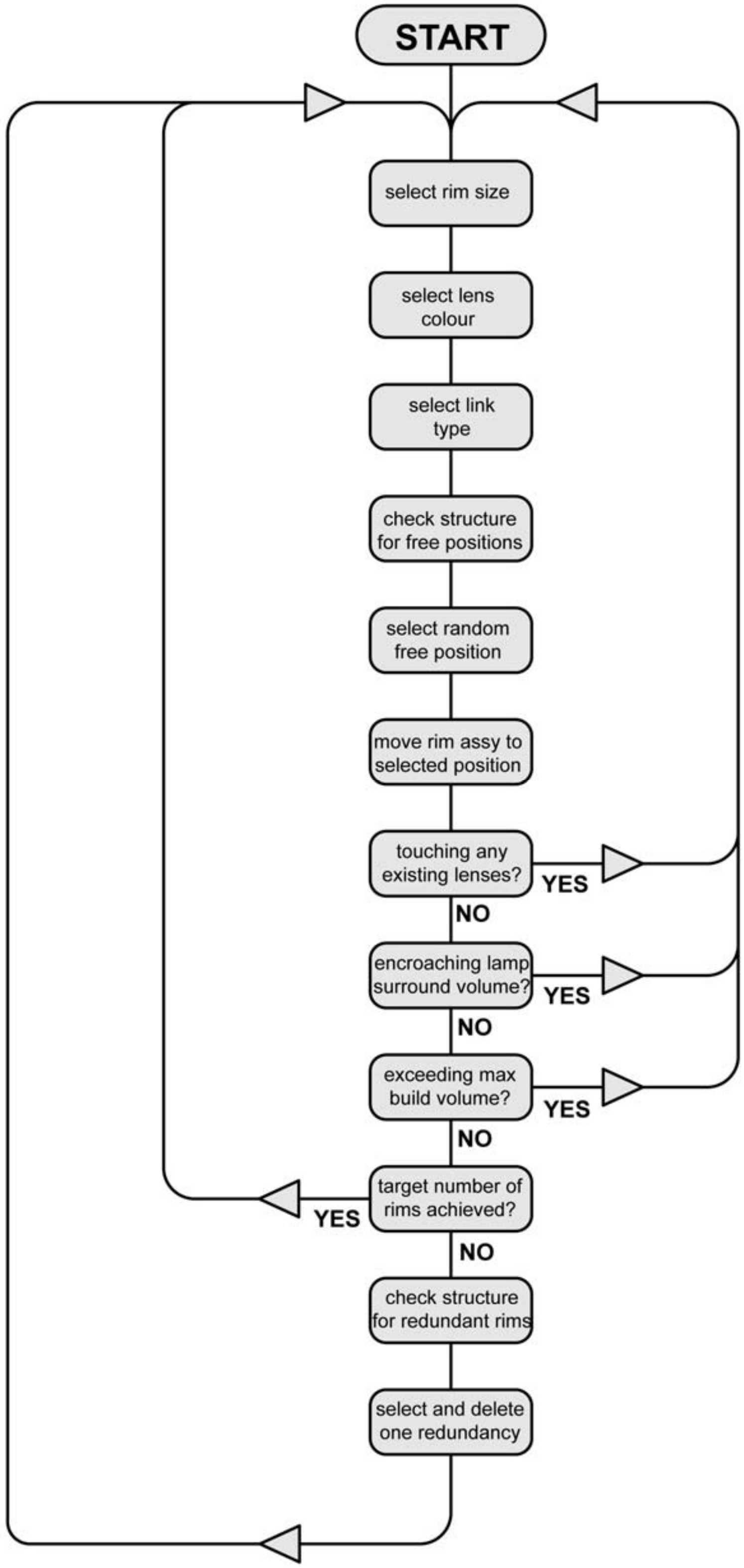


Figure 48
DNA Schematic

The structure grows until it reached a predetermined number of elements. After this point the addition continues in the same manner but for every addition an existing rim is removed. The rim to be removed is selected at random from the set of all redundant rim positions in the framework; those without child branches, whose removal has no effect on the remainder of the structure. Once built up to the preset rim density, the design will theoretically continue to modify itself ad infinitum.

Once the basic build methodology of the concept was established, the design could be refined. In order to influence the character of the design, restrictions were placed on particular features. The smallest, 20mm lens would be a dead end from which no further branching would be possible. The most prevalent lens in the structure would be the medium 25mm lens followed by the large 30mm with the small lens being the rarest. The probability of selecting each lens size is as follows:-

20mm lens – 10%
25mm lens – 60%
30mm lens – 30%

This probability is established using Random Switch building-blocks within Virtools, Figure 49

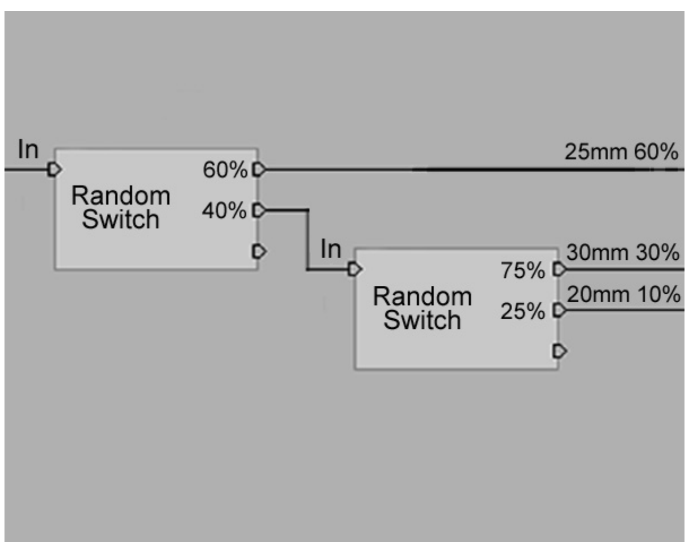


Figure 49
Lens Size Section within the Virtools Script

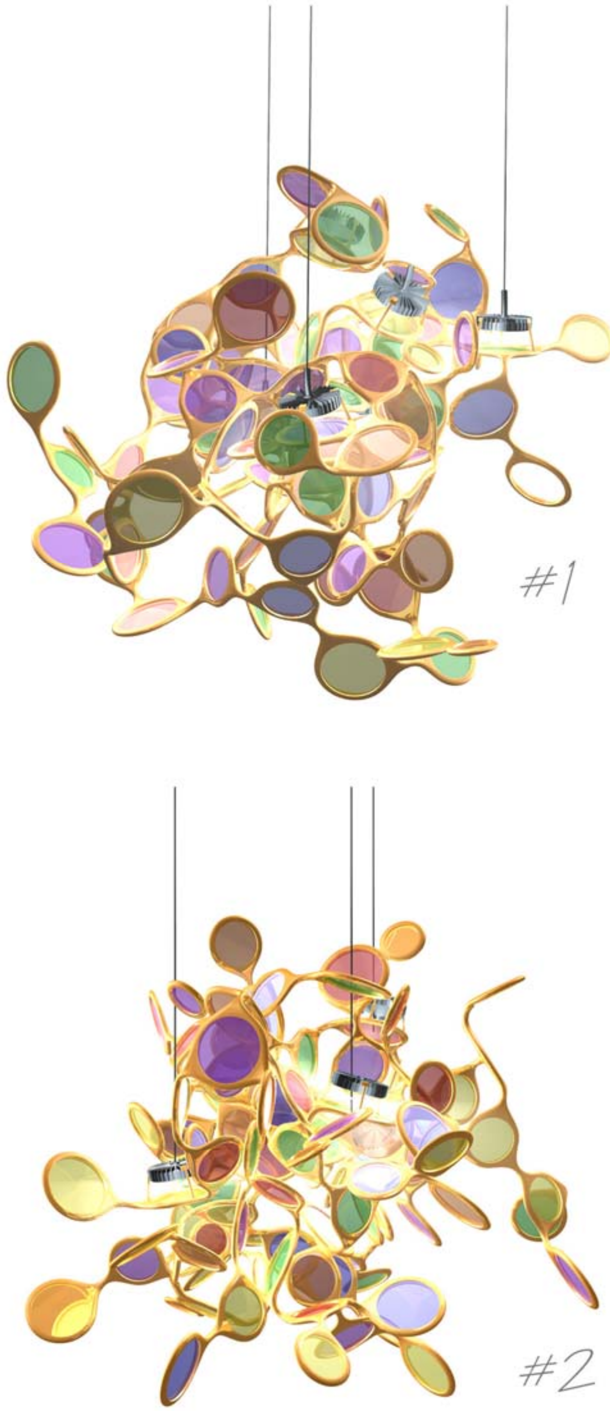


Figure 50
DNA II iterations

4.4.2 DNA II

Unrestricted by boundary interference rules, the DNA script would build structure randomly in all directions out from a point. The ‘natural’ form of the growth in clusters is very different from the hollow shade form required. Forcing the structure to grow in a spherical skin around the light source requires considerable computation with many rejected steps for each successful one. As the structure grows the steps become progressively slower. It became evident that the script created would lend itself better, both computationally and structurally, to creating a ‘solid’ rather than a hollow form. In a separate issue, the GLS light bulb on which the design is based is becoming obsolete for environmental reasons. A voluntary UK retail phase out began in 2008.

To address these issues an evolution version of the design, DNA II, was developed with the GLS light bulb replaced by six high intensity LEDs, Figure 50. The LEDs are attached to 30mm lenses within the structure and do not interfere with the branching, Figure 51. Side-emitter LEDs are used which spread light out into the surrounding structure rather than producing a focused beam.

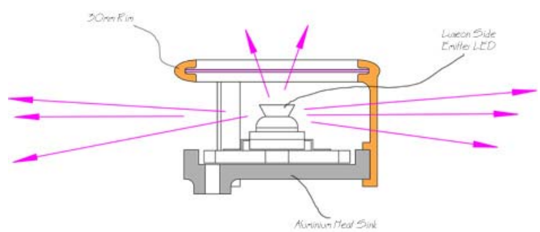


Figure 51
Side emitter LED fitted to 30mm rim

The rim elements were re-modeled with the links formed in two halves. This allows the X rotation to be achieved via a rotation operation between the halves rather than by the selection of a pre-modelled angle. Added to this flexibility, the Y rotation range was extended to cover 5 degree intervals between 0 and 120 degrees. The ‘Link type’ selection operation of the DNA script, schematic Figure 47, was therefore replaced by two operations, Figure 52:

1 - Select Y rotation +/- 0-120 degrees (nearest 5 degree interval); and
2 - Select X rotation +/- 0-90 degrees (any whole number).

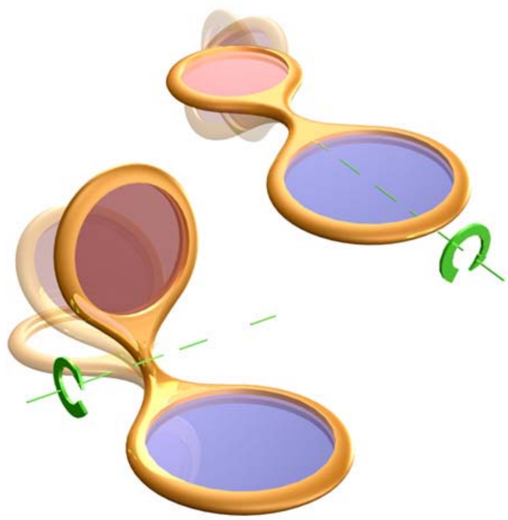


Figure 52
Rim Link Rotations

The structure builds in the similar manner to DNA I but without the inner boundary sphere. The difference is the six LEDs. The first rim, which is always 30mm, houses an LED. Each 30mm lens selected thereafter has a percentage probability, initially 20%, of housing an LED until the six LEDs of the design have been allocated. The exterior boundary is the maximum permissible build volume. This is the XY plane area of the machine by a proportion of the chamber height (determined by permissible cost), Figure 53.

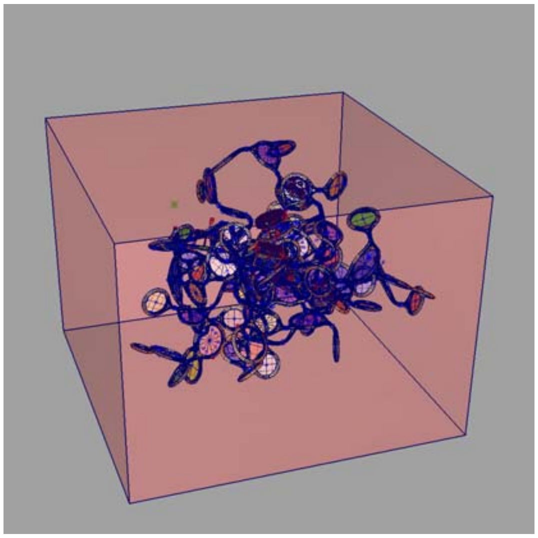


Figure 53
DNA II Build Volume Restriction

Iterations #1 and #2 of DNA were built to 100 lenses. The aim would be that after this point development would continue with subtraction and addition. In practice this addition/subtraction phase has not yet been implemented. The component makeup of #1 and #2 can be seen in Figure 54.

DNA II Iterations								
	% 20mm	% 25mm	% 30mm	% Amber	% Blue	% Green	% Purple	% Red
#1	10	63	27	11	15	18	24	20
#2	6	73	21	16	11	19	17	17

Figure 54
Component make up of DNA II iterations

The development of DNA II #1 can be seen in Figures 55 and 56.

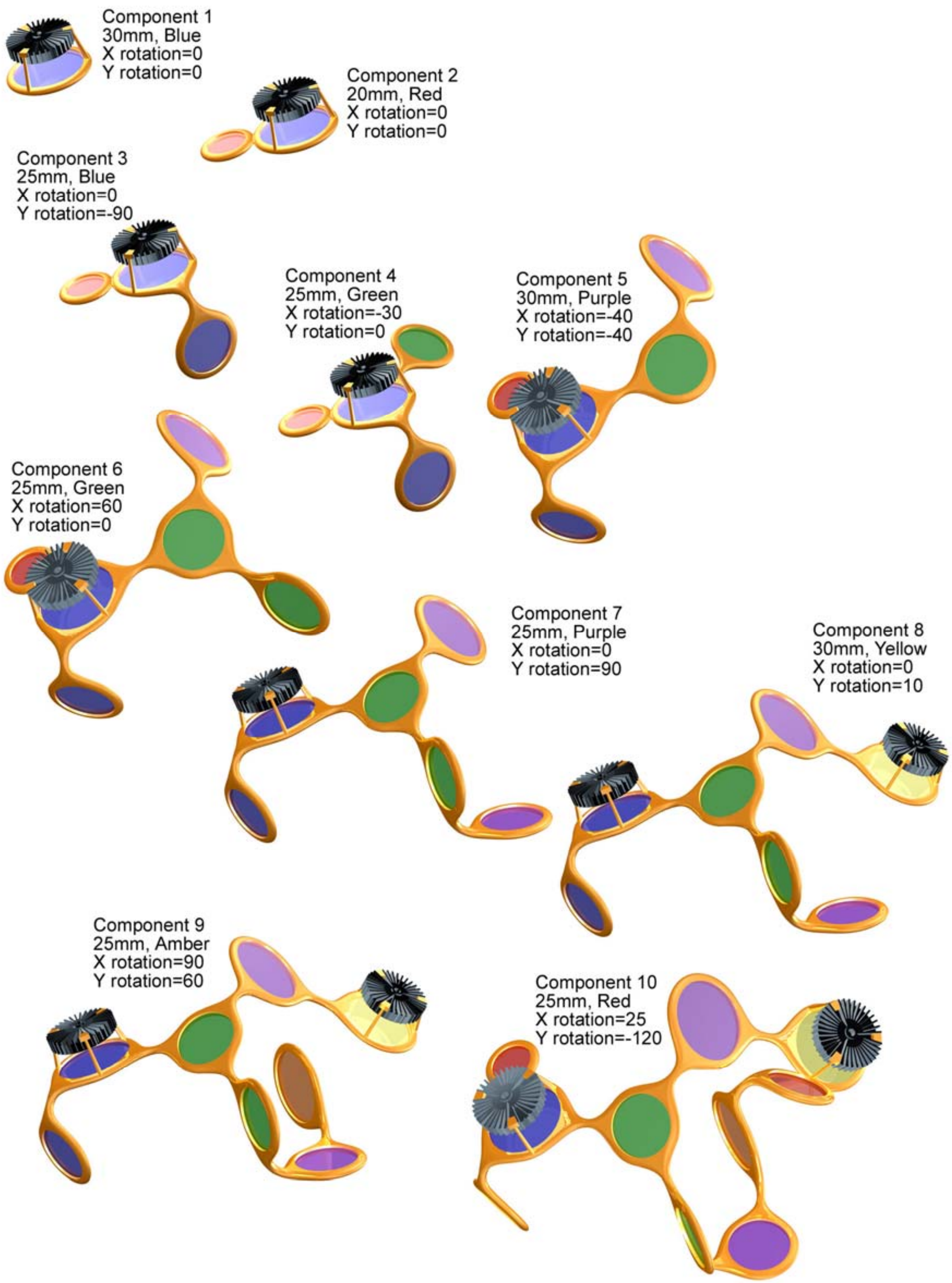


Figure 55
DNA II #1 'Growth' iterations 1 - 10

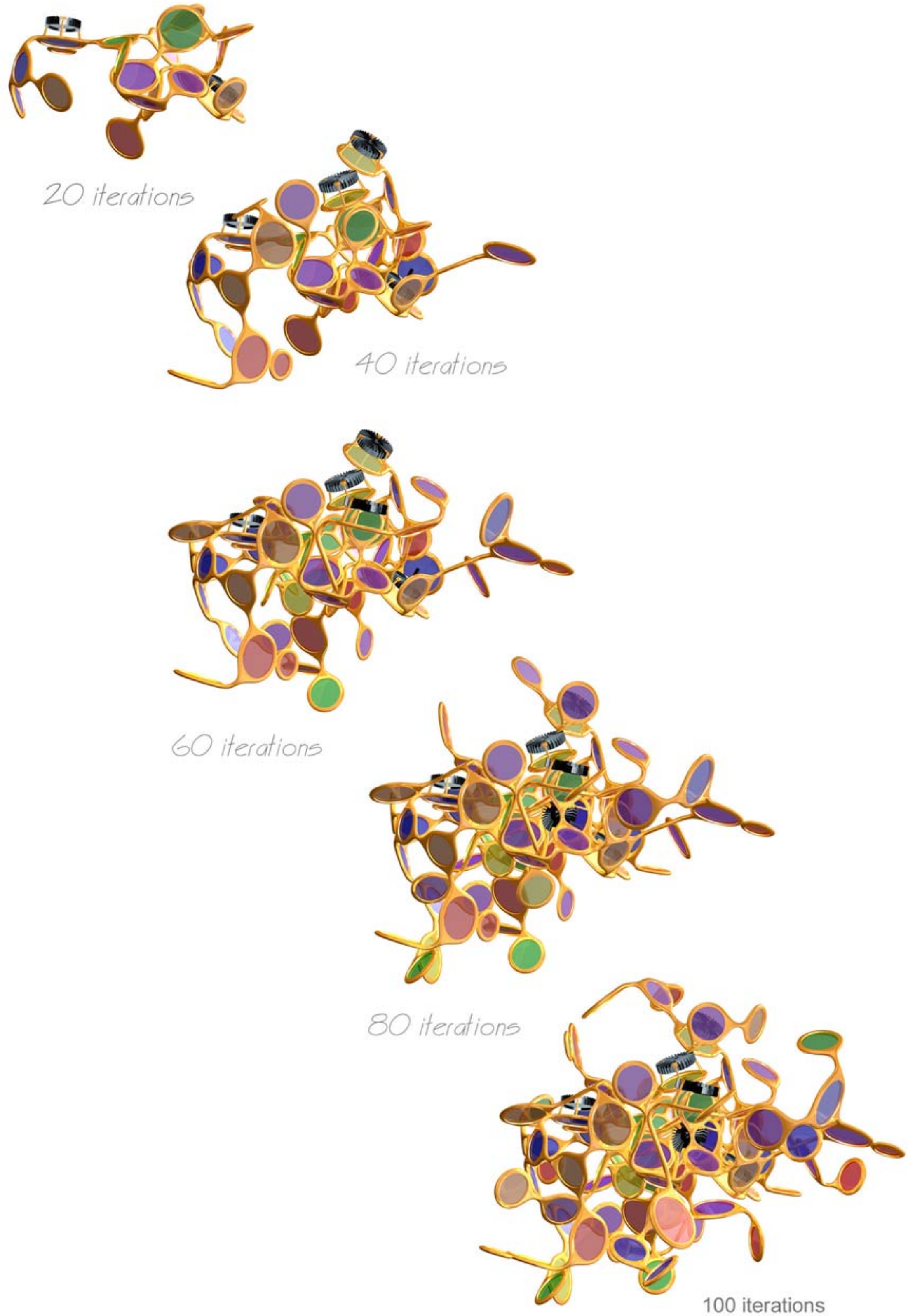


Figure 56
DNA II #1 'Growth' iterations 20 – 100

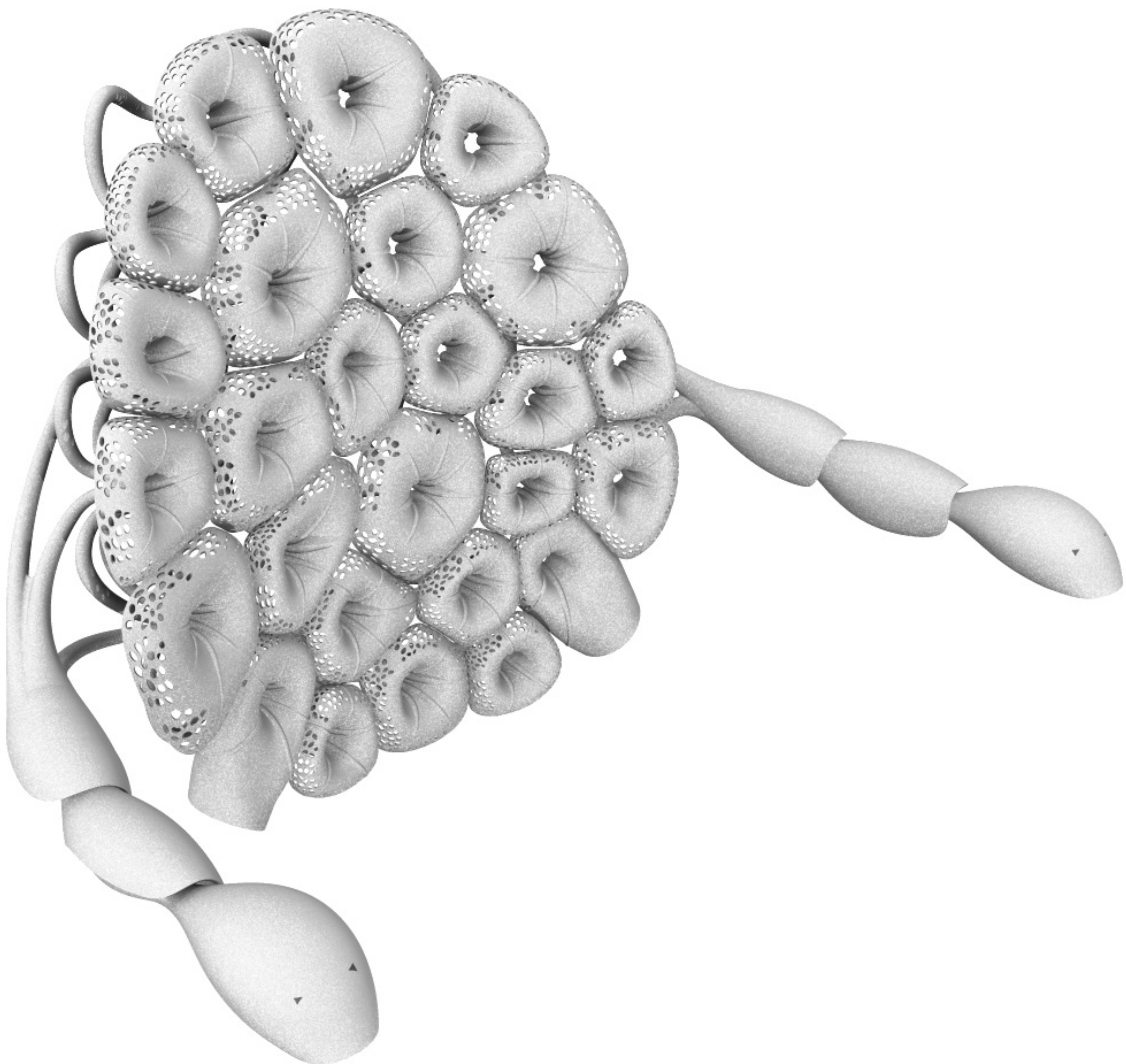


Figure 57
Holy Ghost

4.4.3 Holy Ghost: Design Case Study - Combining the Building Block Approach with Morphing

DNA is fairly basic in product design terms. The next step was to apply the building block strategy to a more demanding form closer to the designs of the First Collection, Lampadina Mutanta, Nautilus, Tuber and Twist. A chair was selected as the subject as this offered significant opportunities for a large scale sculptural piece whilst having a simple, well understood function. Given the cost of Rapid Prototyping (RP) services and the restricted build volume of available equipment, it was decided to build only the back and arms of the chair, taking the rest from the iconic Stark/Kartell Louis Ghost Chair as unwitting collaborator.

The 'Holy Ghost' generative script was again created in Virtools, only this time the build block approach is combined with the morphing strategy of earlier works. The form would be assembled from pre-existing geometric entities but, rather than these pre-defined entities remaining fixed, once placed they would be manipulated by the script.

In the Holy Ghost design, the back support of the standard Kartell polycarbonate Louis Ghost chair is cut away and replaced by a laser sintered nylon component. This SLS piece is an assembly of standard building block elements termed buttons (as introduced in Section 3.5). Collectively, the faces of these buttons form the back support of the chair. Development takes place in three phases, Figures 58 to 60.

a) In the first phase, the number of buttons that will form the back support is determined. This set of units is then placed one at a time on a virtual 3D surface pre-determined by ergonomics i.e. a back support surface positioned to accommodate an appropriate anthropometric range.
b) In the second phase, the placed buttons expand in a uniform manner (whilst maintaining the ergonomic envelope) until they almost touch.
c) In the third and final phase the buttons expand in a non-uniform manner as individual control vertices (CVs) on the geometry are pulled to close up the gaps in the back form.

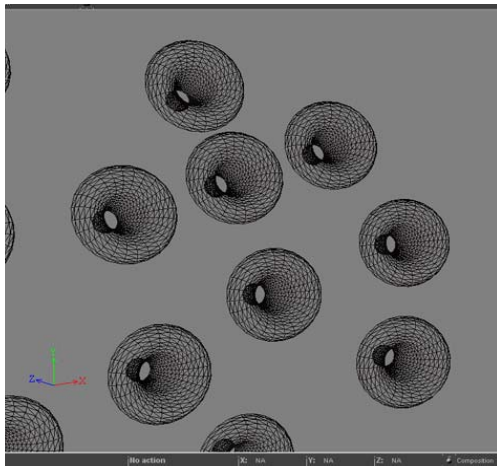


Figure 58
Virtools Holy Ghost Script: Phase 1, Placing ‘Buttons’

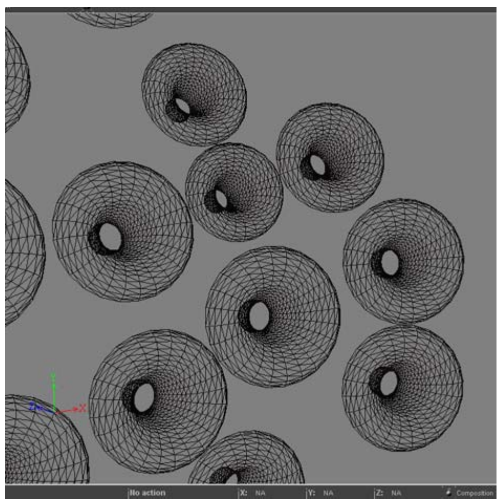


Figure 59
Virtools Holy Ghost Script: Phase 2, Uniform Axial Expansion

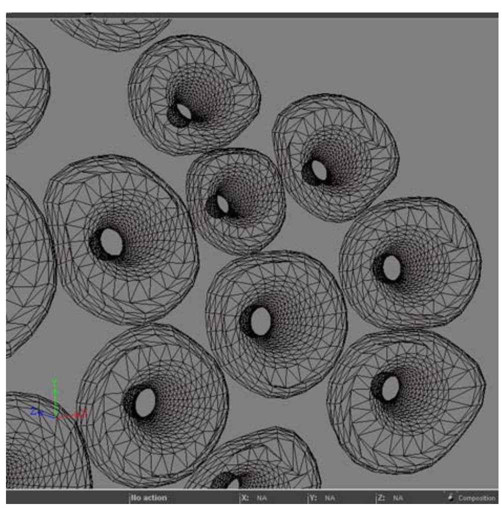


Figure 60
Virtools Holy Ghost Script: Phase 3, Irregular Expansion

Rather than call up 3D elements from a resource library, the buttons are modelled from a 2D curve on demand from a custom written building block within the script. This was necessitated by the requirement to manipulate entities in a controlled fashion. The models are manipulated by moving mesh vertices. When geometry created in a separate CAD modelling package is imported into Virtools, it is difficult to control the numbering of vertices and hence to index them appropriately. Creating the geometry in the script itself provided a 'cleaner', more logical, mesh.

In the expansion phases, the operations take place in small steps across each button in turn, with an associated collision check. This step by step methodology increases computation but prevents the first few buttons dominating as they take up the available space and leave little room for subsequent expansions. Step by step expansion, compared with a full expansion to the limits, can be seen in Figures 61 – 63.

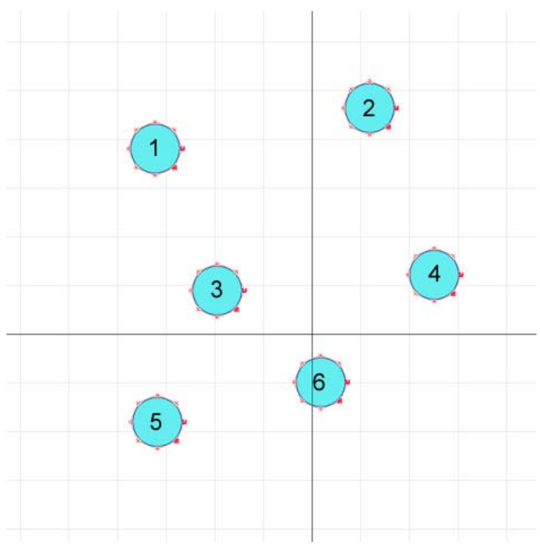


Figure 61
Placed buttons

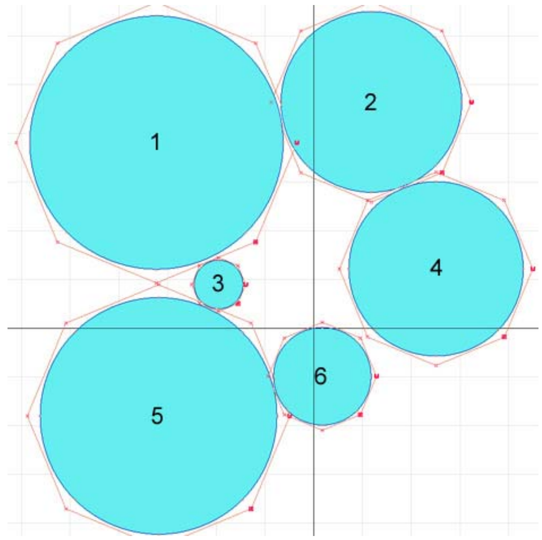


Figure 62
Sequential full expansion

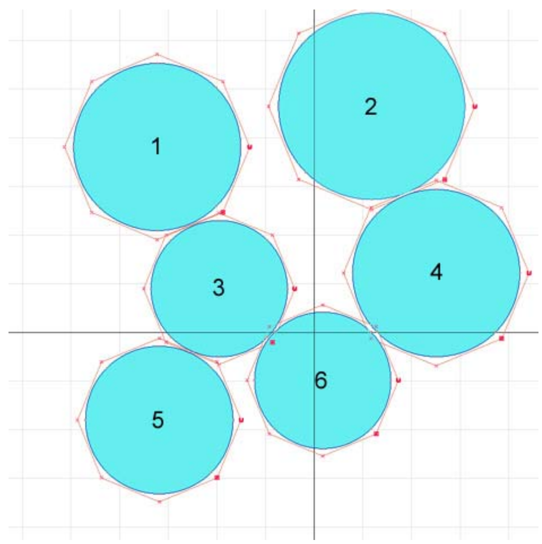


Figure 63
Balanced results from step-by-step expansion

Expansion is applied to the ‘head’ of the button, while the base (the hole in the centre) remains unchanged. The Expansion is ‘blended out’ with a diminishing amplitude applied to vertice groups down the form, Figure 64.

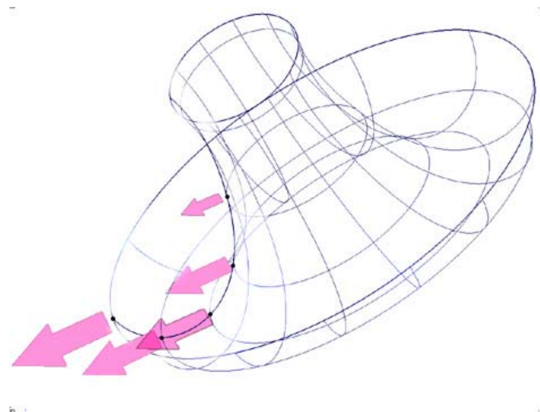


Figure 64
Blending Out of Expansion Amplitude

The expansion is in two phases. The first is a uniform expansion (x,y,x) in which the forms remain axi-symmetric. The second phase of expansion is non-uniform, in which the form distorts to fill the available space, Figure 65.

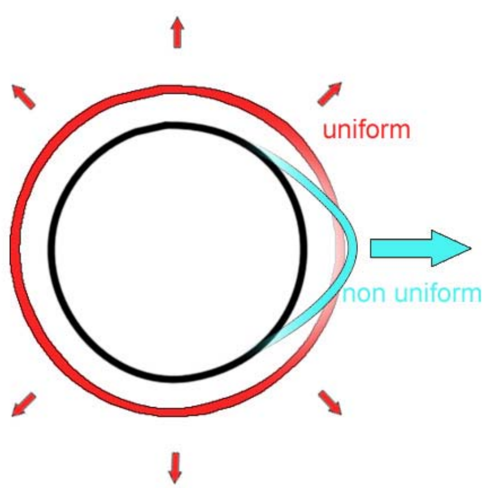


Figure 65
Uniform Compared with Non-Uniform Expansion

To avoid ‘spikes’, a vertex group is not allowed to expand more than two expansion steps beyond its neighbours, Figure 66.

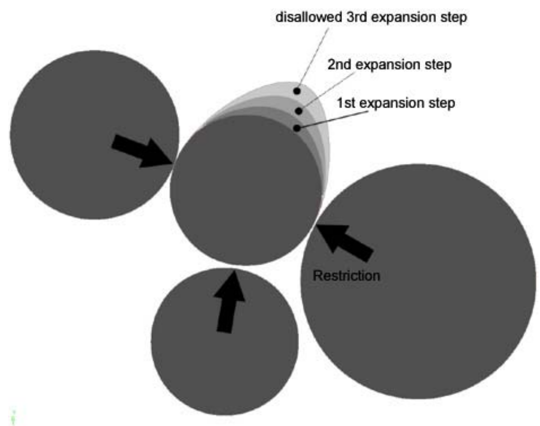


Figure 66
The prevention of ‘Spikes’

The Holy Ghost Virtools’ script generates only the button forms. In the built product, the buttons are connected by a matrix of curved links which, built in SLS Polyamide, act as live springs and allow the whole back to flex like a sprung mattress, Figure 67. The addition of these links is a manual mapping process. The modelling of the links could have been automated in the software with further programming investment. A decision had to made concerning the amount of time to spend on the computer script given that only two were to be produced for the original commission. As the links had little effect on the individual character of iterations and that the effectiveness of the script could be judged without their inclusion; these features were omitted from the programming and modelled manually on the two iterations physically produced. The perforations around each button are also a manual mapping process though this again could be automated. Currently, the position and shape of the holes is generated automatically by mapping a 2D pattern onto the form transposing the 2D X/Y co-ordinates onto the u/v isopharms of the virtual model. Each hole is then ‘trimmed’ from the forms manually.

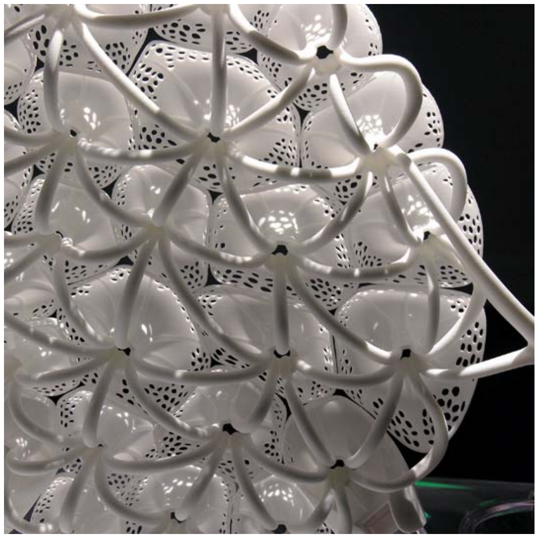


Figure 67
Holy Ghost Polyamide Link Springs

The mapping approach adopted in Holy Ghost with the computer script working on a simplified model is one common amongst computational evolutionary systems. The scripts need not in themselves produce the final phenotype output but merely the genotype code or configuration which can be transposed, manually or automatically, into the intended outcome. 'Mapping' operations are often employed to translate primitive blocks which allow for efficient computation, into more sophisticated models. A 'trade off' found in the fields of artificial life and computer animation is that of complexity versus control. Sims points out that it is often difficult to build interesting or realistic virtual entities and still maintain control over them (Simms 1999). A balance can be achieved by removing operations from the generative script itself and performing them only when a 'finished' design is required. The viewer, or in this case consumer, is presented with a 'stripped down' version of the design, whilst some of the detail is lost; the computational burden of building these features at every iteration is avoided. In Tuber, for example, the animation shows four separate 'solid' volumes. The script ensures that each volume has an intersection with at least one other. There is no attempt in the programming to unify the four volumes into a single hollow volume and thus avoid intersection surfaces which cannot be exported additive fabrication. To physically manufacture an iteration, the surfaces of respective volumes must be intersected, trimmed and filleted in a mapping operation, Figure 68. With the resulting single volume 'shelled' to create a hollow form. A balance must be achieved between the accuracy of the visualisation and the complexity of computation. An over-simplified visualisation would be open to misinterpretation. If the mapping operation makes significant changes to the model, then too much is left to the imagination.

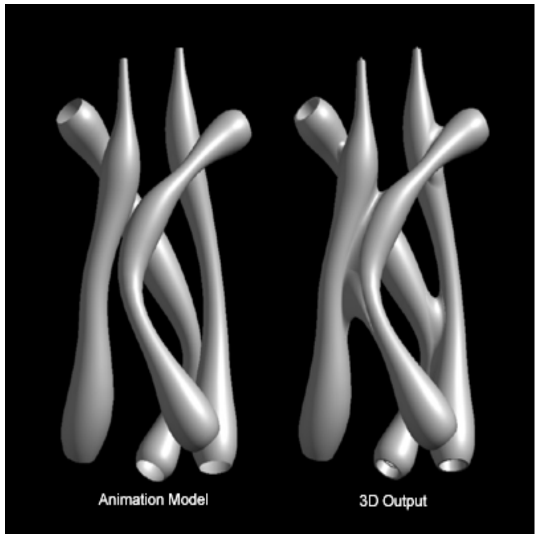


Figure 68
'Mapping' in the Tuber animation

Including the link elements within the Holy Ghost generative script would required significant additional development and would have made the computer file larger and slower to run. Its omission, however, means that a significant manual operation is required after the script has been run. The most significant factor in balancing level of mapping against scripting investment is the anticipated volume of sales. Holy Ghost is intended as a gallery edition of ten pieces; there is little point therefore in huge investments in productivity.

4.4.4 SuperKitsch Bangle Case Study

The SuperKitsch bangle takes as its theme, the commonplace, banal, charm bracelet. Charm bracelet elements are stored as 3D models in a virtual library. These elements are then assembled at random to form a rigid loop around the wrist leaving a slight gap for it to be slipped on, Figure 69. The number of elements that make up the bangle form depends on the particular elements selected but is in the order of 30 pieces.

The library of models is pre-defined Figure 70. All that is needed to fully define a particular iteration of the design is a list of elements, their positions in 3D space and their orientation. This information is automatically stored in an array each time the script is run. When a design is ordered, therefore, there is no need to up-load the built 3D model back to the server.

The 3D entities stored in the host CAD system and those in the user-end script are not the same. The user-end models are merely for visualisation and for some relatively crude interference checks. These are simple polygon meshes which, although they lack the refinement and integrity, in RP build terms of their NURBS (Non Uniform Rational Basis Spline) surface model parents, they have sufficient detail to render convincingly. These meshes are far smaller in file size than their NURBS counterparts. In essence NURBS surfaces are mathematically defined and maintain their character at any level of resolution whereas polygon meshes are faceted approximations.

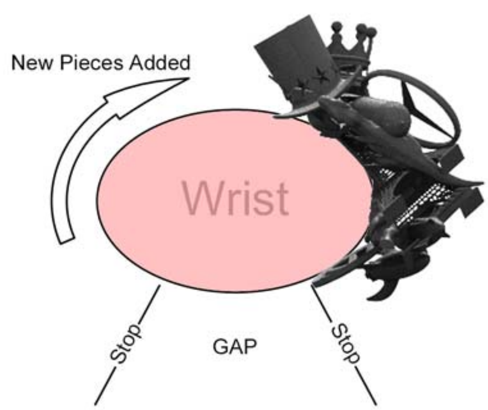


Figure 69
SuperKitsch Bangle Configuration

Figure 70
Superkitsch Library of Charm Elements

The SuperKitsch script runs as follows; a charm piece is selected at random from the pre-defined library of models, it is scaled, orientated and placed on a path curve around the virtual wrist. Further charm elements are then selected, at random, and swept around the path curve until they butt up against the existing assembly. The band of elements builds in this way around the wrist until it forms a complete loop, less a gap for fitment.

The path curve is not static: it translates and scales within certain bounds to create a broad band. Control is achieved through collision detection, which ensures that there is appropriate contact between the pieces. There should be enough interference to build a structurally united piece but visually, the pieces should not overlap unduly. If the requisite level of interference is not achieved the part is repositioned. An interference check, with start and stop planes, forms the gap in the loop.

Individual charm elements should not be repeated in the bangle. Currently there are only sufficient pieces to complete the loop, with little margin. The library will be added to in the future providing opportunity to tune the design. Certain key elements may be 'seeded', with an increased probability of selection. There may be restrictions placed on similar elements, the VW and Mercedes bonnet badges, for example: these may be prevented from appearing next to each other or barred from the same bangle iteration. There is potential for users to submit their own pieces for inclusion. These contributed pieces could be offered to others with an incentive given back to the creator, in the manner of content sharing websites such as Turbosquid.

A schematic of the SuperKitsch script can be seen in Figure 71 and images of a generated example in Figures 72-74.

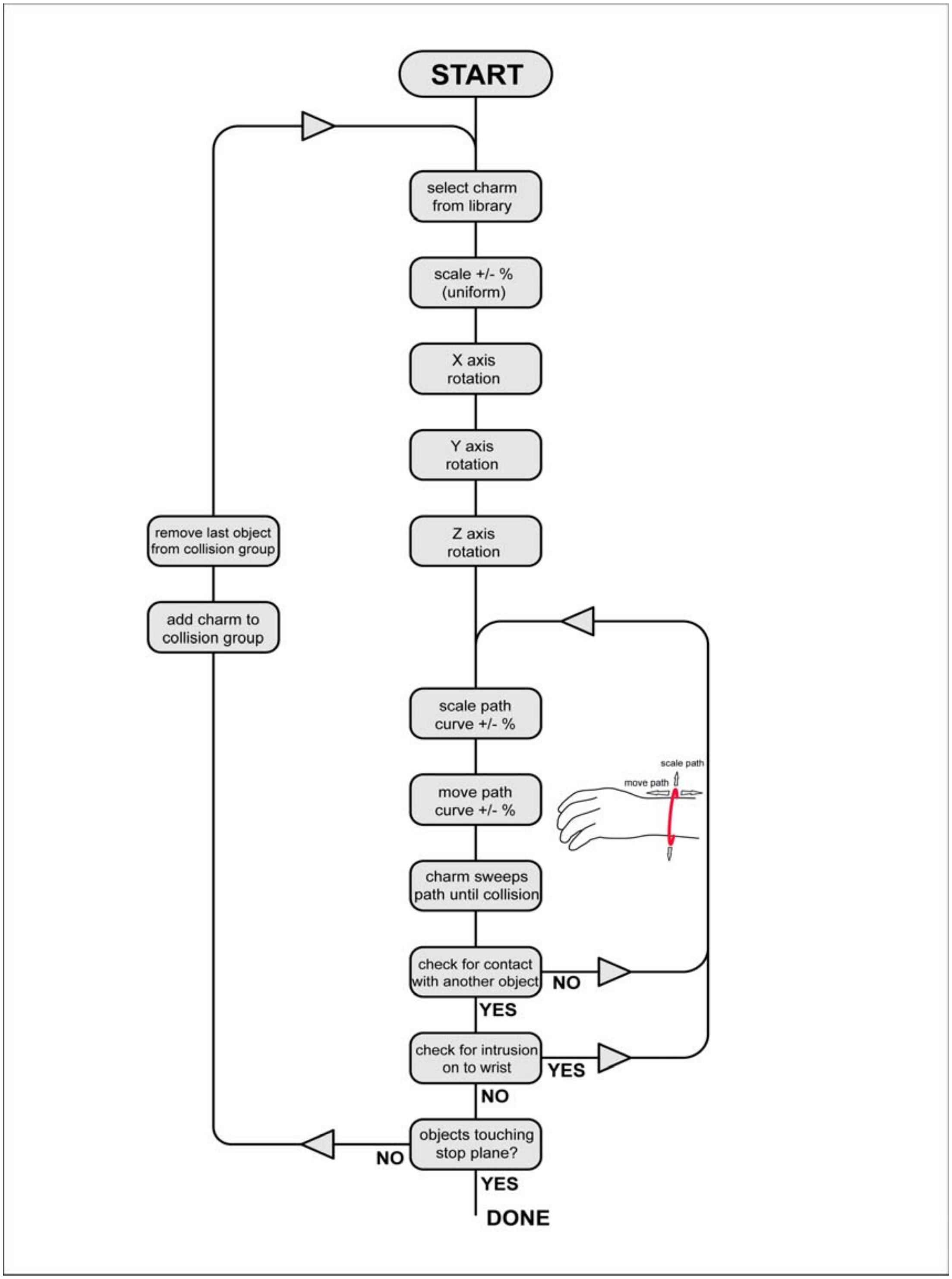


Figure 71
SuperKitsch Script Schematic

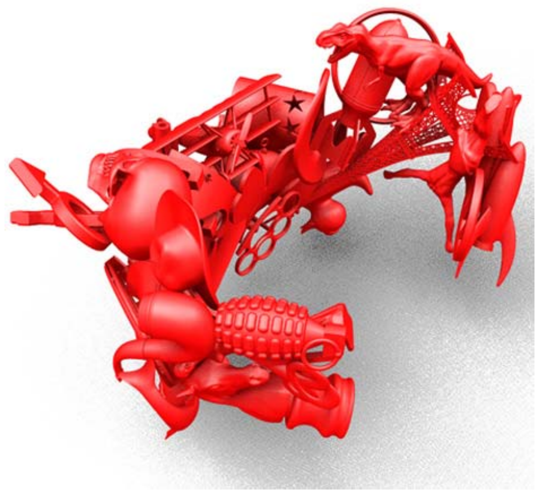


Figure 72
SuperKitsch Iteration

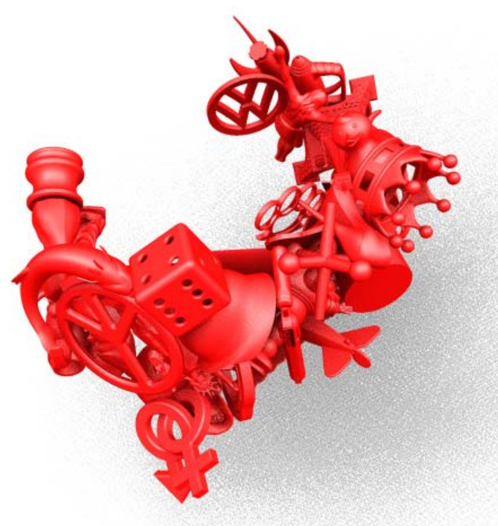


Figure 73
SuperKitsch Iteration

Figure 74
SuperKitsch SLS Prototype

4.5 Section Summary

In common with conventional industrial design practice there is a need to balance conflicting demands and criteria within acceptable budgets. Complexity in the design needs to be balanced against stability and control. A simple form with limited freedom to change over time should be easy to predict; keeping intricate geometry true to the designer's intent is a more difficult proposition. Yet complexity is almost a requirement in order to exploit the free form potential of additive manufacture and thereby justify the premium costs of the technology. In addition, dissemination of the work highlighted a consumer desire for significant step changes over and above the subtle morphing of Tuber.

The building block approach first adopted with DNA offers the potential of significant step changes to the geometry with a high degree of stability since its constituent elements are pre-proven. The aesthetic is limited however, to repeated elements which cannot adapt in form and perhaps give too much of a random air. The approach adopted in Holy Ghost of combining the building block approach with morphing proved successful. The controlled spread of the button forms provides the look of a 'designed' form whilst the building block placement of these elements provides dramatic change.

Also highlighted in this section is the need to justify computational investment against the manual preparation of production data. In all commercial practice, design investment, in common with plant and tooling, has to be balance against sales volumes and amortised over a period of time. It will sometimes make commercial sense in a scripted design to leave aspects of the computer modelling out of the programming and to add these manually on each CAD model prepared for production. This simplification of the script can also increase its speed and stability.

5.0 Summary of Design Work and Exhibitions 2003-2006

An essential proof of the individualisation concept is that it responds to commercial and cultural pressures to create desirable artefacts. Producing random, computer generated shapes, regardless of their aesthetics, would be straight forward and has been done in computer art since the early days of the microprocessor. It is product design criteria surrounding the artefacts' appearance and function that presents the challenge. Assessing functionality is relatively easy in the laboratory and can usually be measured in an absolute sense. Subjective aesthetics, however, can only be judged by public reaction to the actual artefacts created. Aesthetics and desirability are the driving factors for the work; with the aim that consumer interest will support relatively expensive production methods. There is no technical benefit to the morphing. It is not an attempt to breed an optimal solution, via the use of evolutionary and genetic algorithms, and random variance inevitably brings a level of technical compromise (4.3). The physical production of artefacts and dissemination of works are central to the thesis in order to justify the concepts' premises.

It is important to distinguish FutureFactories from digital art and virtual sculpture. There is a huge practical, developmental gulf between 3D visualisation models that exist only in the virtual world and technically resolved CAD models that can be exported for manufacture. In the virtual world simple polygons can be disguised with shaders and textures to resemble all manner of complex form: flowing hair for example, when in reality, little is defined. A decision was made not to publish designs unless they had been physically built, at least as a prototype. Functionality places a huge burden on product designs over artworks and physical factors can only be readily appreciated in the real world. This section will examine the 3D output of the 'First Collection' produced for the residency exhibitions October 2003 – April 2004. The aim in producing this body of work was to achieve recognisable differences between iterations of a coherent identifiable design. These were to be 3D designs that could be modified and controlled by scripting. The target was to generate unique five iterations of each design; these are identified by the numbering #1 - #5.

The First Collection focuses on lighting objects, in part because of prior commercial experience in the field. Allied to this, there are important physical factors that make lighting objects a good proposition for Direct Digital Manufacture and explain why lighting design has proved popular with digital practitioners worldwide: Materialise and Freedom of Creation, for example.

In its basic form, lighting design can be simply an optical barrier hiding the naked bulb from direct line-of–sight; such as a lampshade that is placed over the light-source. In a pendant format there is very little restriction on geometry, almost any shape can be hung. Then there is the material. RP offers only a limited palette of materials and their finishes are generally inferior to the consumer product norm. When they are backlit, however, they are arguably more attractive than moulded plastics and in a light fitting are unlikely to suffer unduly from handling.

5.0.1 Lighting Objects

Lighting (object) design is a field that straddles design disciplines giving a wide ranging of promotional and marketing opportunities. Lighting designs can be technical and performance driven or primarily decorative. It is a product genre well catered for in the international design press being extensively covered in product, furniture, interior design and architecture, events and publications. It is a market with avant-guard buyers; consumers who value scientific novelty and who are often prepared to be patient with the shortcomings of an immature technology, a market in which the designer item, is prized and bought at a premium.

5.0.2 Materials and Processes

There is a hierarchy of RP technologies; from the high-end laser based systems, to budget '3D printing' systems that employ inkjet printing technology (1.4.2). Three dimensional printing machines cost around a tenth that of their laser based technology counterparts, but have significant performance drawbacks. They are usually aimed at visualisation rather than testing function. Selective Laser Sintering, SLS, can deliver an acceptable if not decorative surface finish and a mechanical performance similar, in lamp fittings at least, to that of moulded plastics. Selective Laser Sintering as a powder based system that requires no temporary support structure and places little or no restrictions on the designer: this has made SLS the tool of choice for commercial direct manufacturing.

Understandably, given the difference in capital cost, inkjet based processes tend to be inferior in both finish and mechanical performance. The resolution is typically cruder, giving a rougher surface, and the materials weaker, requiring thicker walls than would be expected of a conventional moulded plastic part.

Budgetary constraints restricted early FutureFactories 3D outputs to the economy 3D printing technologies. This imposed limitations on form, function and surface finish. Designs had to accommodate heavy wall thicknesses whilst retaining the look of industrial production with precision details. In many instances the additive fabrication process was combined with significant amounts of hand-finishing in order to achieve presentable surfaces. As the scope and profile of the project developed, industrial support for the work grew and enabled access to some of the more exotic technologies. The First Collection however, was limited to two 3D printing processes, 3DSystems Thermojet, which prints in wax and the ZCorp process, which prints in plaster or starch based powder.

5.0.3 The Driving Computation

As discussed in a scripting context, in Section 4.0, the need to exhibit credible 3D output so early in the project necessitated a separation and parallel development of scripting and 3D design development. Through the residency period various approaches to driving computer based models via scripting were explored, working initially with relatively basic forms. Alongside the scripting, 3D designs were created which were based on animations. These designs, driven by fixed length animation ‘clips’, illustrated the potential of the scripting rather than resulting from programming running in real-time. The scope of these concepts was limited by the number of frames in the clip. They could not offer the potentially infinite stream of unique solutions demanded by the concept. The intention was for these early pieces to prove the merits of the concept, garner public interest and encourage debate at a time when the actual scripts created, while technically promising, were still in their infancy. As the project progressed beyond the initial residency period scripted outputs of increasing sophistication began to appear.

5.1 The 'First Collection'

A series of local exhibitions was planned from the inception of the design residency. This program was scheduled to begin in the autumn of 2004, at the end of the one year residency period, as the culmination of the project. The FutureFactories 'First Collection', comprising of five designs, was created for these exhibitions. There were three lighting pieces, Lampdina Mutanta, Nautilus and Tuber and two pieces of tableware, Twist and Let's Twist Again candlesticks. The lighting designs were presented from the outset as a series of fully functional pieces. The tableware generally remained as non-functional appearance models, built in a Z-Corp impregnated plaster. One functional example of each design was investment cast and presented in the later exhibitions.

Each of the five designs in the 'First Collection' is detailed below, in terms of:

(i) The Design;
(ii) The Morphing Features;
(iii) The Production; and
(iv) Design Issues Highlighted

5.1.1 Lampadina Mutanta

(i) Design

The early months of the residency were spent exploring and communicating the overall concept without looking toward the production of particular artefacts. When it came to creating design examples, as demanded for the exhibition program, the task proved far from simple. The researcher's training and experience, along with product design culture itself, all tended towards the singular outcome and an iterative honing toward the 'ideal' solution. A different approach was needed and, in search of this, the researcher looked to film where content changes over time and is choreographed. Lampadina Mutanta, Figure 75, or mutant light bulb (the Italian 'lampadina' had been used previously by the researcher) was the first design created. It was based on an imaginary screenplay. The subject of this animation was the iconic GLS Edison Screw light bulb. The light bulb was pictured, forgotten, in an abandoned warehouse. Over time, like a potato in a darkened cupboard, the light bulb begins to sprout tentacles, each with its own light source 'head'. Adopting this fantasy approach, it became possible to visualise the physical manner in which the design might evolve and mutate, mimicking organic growth of nature. This 'growth' would have algorithmic rules to drive it, providing a level of control necessary to appear 'natural' and convincing.

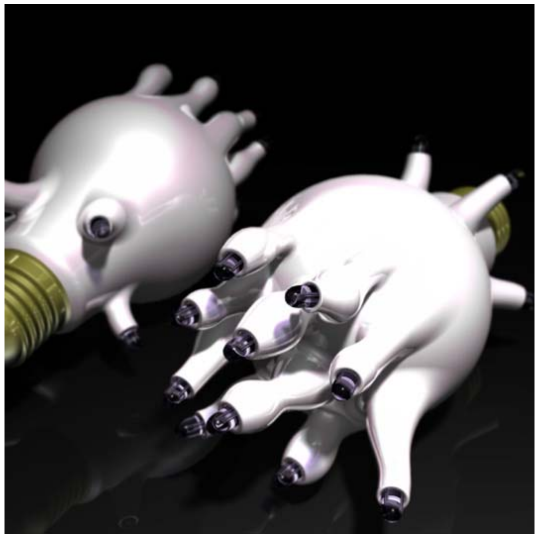


Figure 75
Lampadina Mutanta

In Lampadina Mutanta the light source is a series of high intensity white Light Emitting Diodes, LEDs. The LEDs are mounted in the ends of ‘tentacles’ which appear to grow at random from the bulb form. Lampadina Mutanta is the size and form of a standard GLS light bulb. An irregular growth of tentacles sprouts from the top and bottom of the bulb, with each tentacle bearing a white LED. These tentacles are animated, swelling and writhing to mutate the overall form.

Design rules dictate that there are fifteen tentacles, ten facing downwards and five up. This number and ratio is both an aesthetic decision and a practical one, providing a reasonable light output balanced between up-light and down-light. There should also be a reasonable spread of light. If too many LEDs point in the same direction a particular solution is rejected. In the examples produced this was a manual visual assessment to determine if light would be seen from each angle around the hanging bulb. In an automated system virtual cones of light from each LED would be intersected with a horizontal plane and the area covered assessed against a minimum value. Overlapping beams would reduce this area of coverage and increase the possibility of rejection.

The end of each ‘tentacle’ is dimensionally constrained to accept an LED and the direction of the LED beam is restricted to certain angles from the vertical to avoid glare. The form makes full use of the flexibility inherent in RP processes. The curling, closely grouped mass of hollow tentacles is full of re-entrant forms (undercuts) that would be almost impossible to manufacture conventionally, Figure 76.

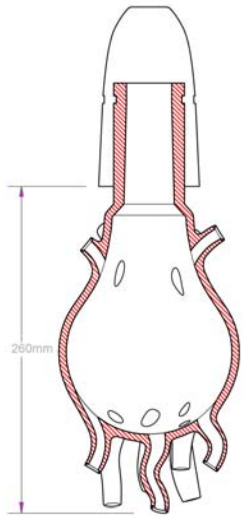


Figure 76
Lampadina Mutanta cross-section

Three distinct characters of 'tentacle' have been created:

- 'Drops' form like stalactites on the lower half of the bulb, tapering as they 'grow' downwards, as if acting under the combined effects of gravity and a surface tension on the bulb, Figure 77;

- 'Tentacles' form from the Drops. These have grown beyond the effects of the surface tension and have developed sufficient strength to resist gravity to some degree, they have a tendency to curl and coil, Figure 78; and

- 'Risers' form like stalagmites rising from the upper half of the bulb. As they rise they lean out from the bulb body and begin to curl down under gravity, Figure 79.

These tentacle types appear in varying proportion and at random positions over the bulb, each developing according to its type.

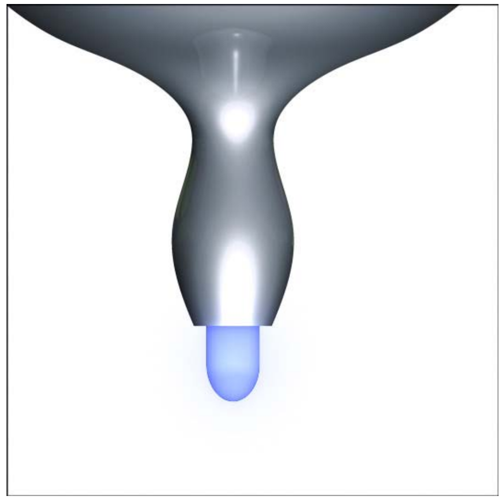


Figure 77
Lampadina Mutanta ‘Drops’

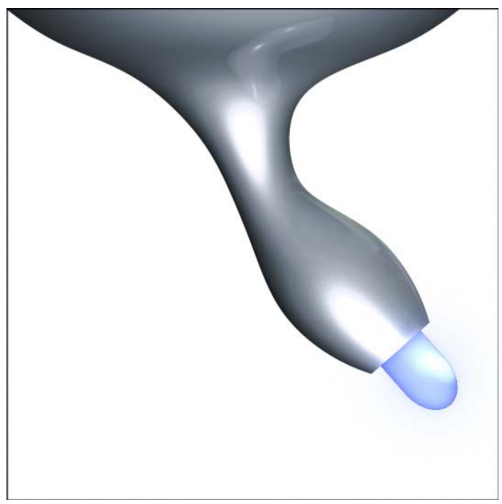


Figure 78
Lampadina Mutanta ‘Tentacles’

Figure 79
Lampadina Mutanta ‘Risers’

(ii) Morphing Features

The morphing features of Lampadina Mutanta can be seen in Figure 80, with the construction of one tentacle highlighted. The GLS light bulb profile body (green) is fixed while the fifteen tubular tentacles that emerge from it (pink) are free to mutate. The tentacles are skin or loft surfaces controlled by circular control curves. Theses circles are manipulated using translate, rotate and scale operations.

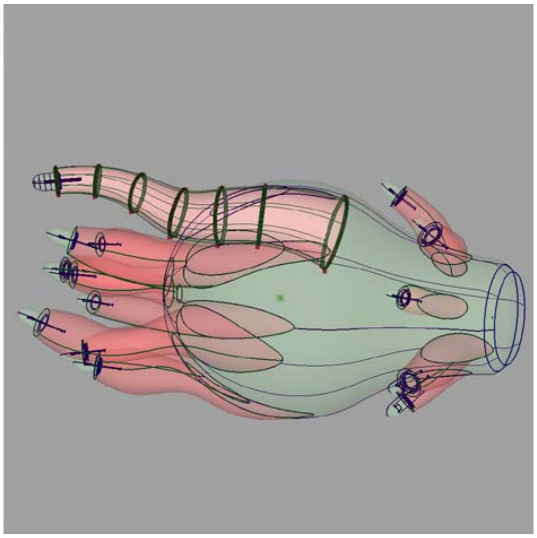


Figure 80
Lampadina Mutanta Morphing Features

(iii) Production

Laser sintering in stainless steel was already commercially available when the project was conceived and it was the possibility of building in such a durable and, potentially, decorative material that was one of the drivers for the concept. The plastics and resins commonly associated with RP at the time did not appear to offer either sufficient physical strength or surface finish for use in high-end consumer products.

The use of Direct Manufacture in metals early in the project proved impossible: additive fabrication in metals was expensive, was not widely available and even if it could be afforded, the surface finishes achieved were crude. These problems were seen as short term issues that did not diminish the overall viability of the concept. As a short term solution, the decision was made to produce designs in stainless steel using an indirect form of digital manufacturing whereby single use wax patterns would be 'printed' and artefacts would then be investment cast conventionally from these masters. The main implication of this was an increase in material thickness required to ensure an adequate flow of molten metal though the investment casting mould. Without this restriction, additive fabrication would only build material as and where required to achieve the desired physical strength. The intended thickness was 2-3mm depending on the particular RP process employed. For conventionally casting a component of this size, and complexity, a minimum thickness 3mm was recommended with 6mm preferred. The design's section thicknesses were increased to accommodate the casting process, tapering from the mid-section where the sprue would be added, to 3mm at the tentacles, Figure 76. At the tentacle tips, the design features a thin-walled 'cup' in which the LED is bonded. As this wall surrounds the fixed diameter LED, thickening the section at this point would be difficult. Given that the wall only extends for approximately 2mm, the decision was made to leave this thickness at the 1mm planned. The early attempts at casting, iteration #1, highlighted this wall as a problem area and its thickness was gradually increased from the technically possible to that which can be reliably cast. Figure 81, demonstrates problems with thickness at the base of the tentacles and incomplete forming of the LED mounting cup.

Figure 81
Casting Problems at the Tentacle Tips

The need to thicken the outer skin left little room for internal wiring and components. The Lampadina Mutanta concept was for a stand alone device that simply screwed into a standard bulb holder, with an electronic LED driver housed within the bulb body. The substantial material sections required for the casting process meant that the idea of an internal driver had to be abandoned. The device would be 'wired-up' through the narrow neck of the bulb rather than have any visible split-lines in the form.

The technology used for printing the investment casting waxes was the 3D Systems' Thermojet process. This system requires support structure for any overhanging geometry. The removal of this material can be difficult, time consuming and marks the surface. Removing support material from the inside of a closed volume would be virtually impossible. The wax pattern was therefore built in two halves, split on the centre-line of the bulb, to keep the support material to a minimum and to ensure accessibility, Figure 82. The intention was to assemble the wax halves and to cast a single, closed volume. Figure 83, illustrates two early prototypes cast in one piece. The tendency for the investment material to get caught in the confined spaces between the tentacles can be noted.

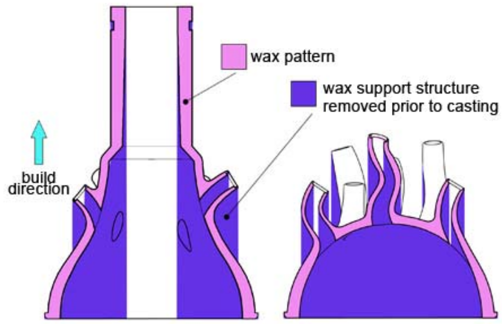


Figure 82
Wax halves for casting

Figure 83
The first, single piece, castings, March 2003

In practice casting the artefact in one piece proved difficult. ‘Setting up’ for investment casting is imprecise: the size and positions of sprues and risers is critical and reliant on the intuitive experience of foundry technicians. In the early casting attempts the lower tentacles, the mould extremities, failed to fully form. Rather than waste costly waxes, a decision was made to cast the halves separately and weld them together afterwards. The chamfered bead around the ‘base’,

Figure 82, is to provide material for the welded joint which is subsequently ground off. Casting the pieces in two halves generally worked well and, in total, five iterations of the design were produced. A set of four was produced for the local exhibitions and a fifth added for the Milan International Furniture Fair, in April 2004. It should be noted from the following production photographs, Figures 84 to 87, that considerable hand-finishing was required to achieve the desired, polished surface, particularly bearing in mind the joining weld. Stainless steel is a difficult material to finish. Marks left from the support in the close confines of the intertwined tentacles proved extremely difficult to work.

Figure 84
Thermojet Wax Patterns

Figure 85
Stainless Steel Cast Halves

Figure 86
Halves welded and the weld dressed

Figure 87
Lampadina Mutanta #3, Barnsley Design Centre October 2003

Five stainless steel Lampadina Mutanta iterations were produced in stainless steel. The pieces were fitted with LEDs and were fully functional. For exhibition, they were suspended from matt black bulb holders on period style, braided twin-core cable. In addition to the stainless steel pieces, a sample was tried in brass. The brass proved attractive, but the halves had to be joined by brazing. Whilst the welded joint in the stainless steel pieces had been invisible when polished out, the brazed brass joint remained visible.

An impression of what could be achieved using laser sintering was indicated by a sample built for the project by The Institute of Technology Tallaght, Dublin, Figure 88. This part was built as a single component and with the intended fine material thicknesses. No support structure is required in the laser sintering of plastics and consequently there was no marking to clean up post-production.

Figure 88
SLS Lampadina Mutanta

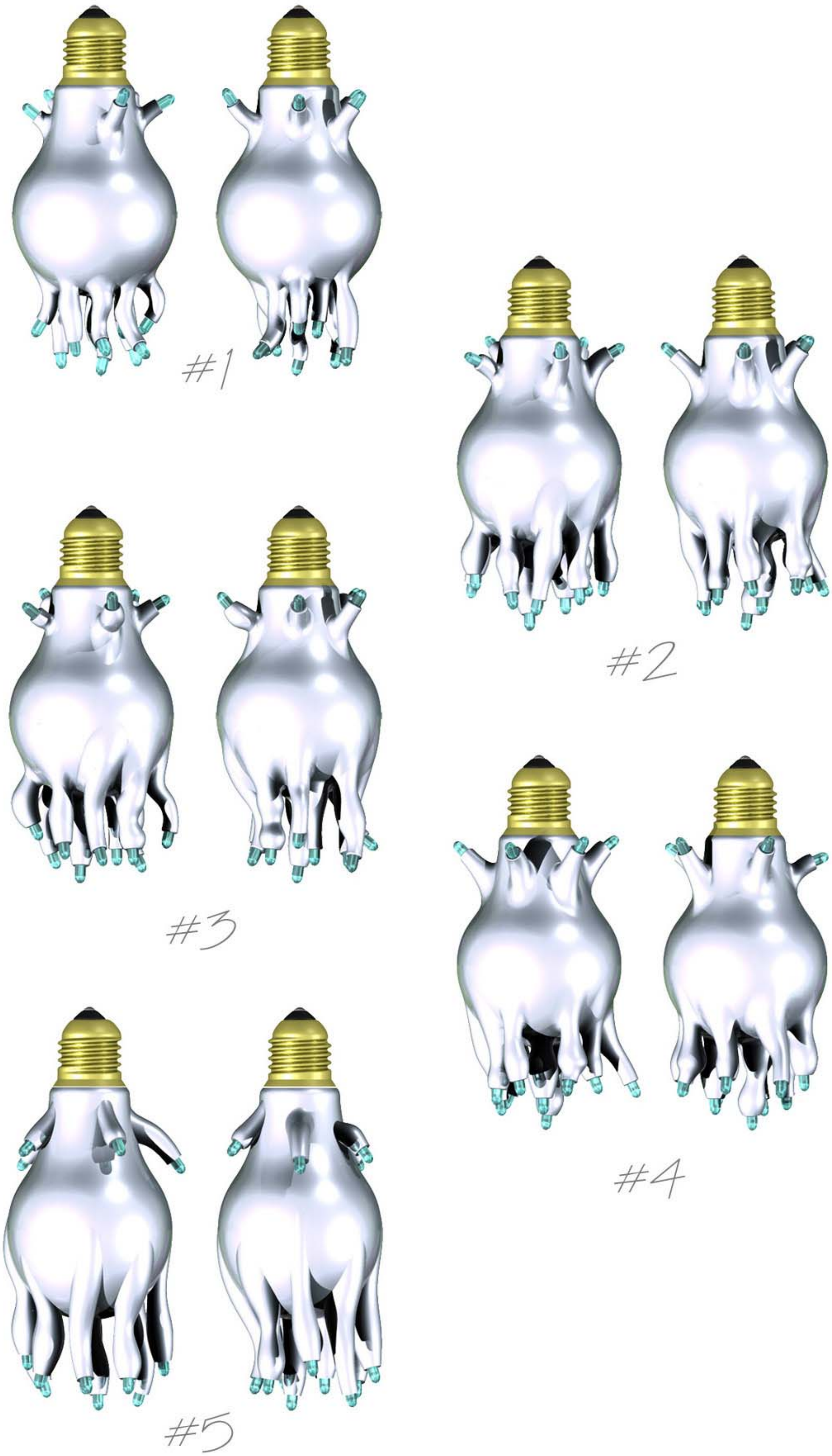


Figure 89
Lampadina Mutanta iterations #1 -#5

Five Lampadina Mutanta iterations were generated, Figure 89. In common with most of the 3D output, the set of Lampadina Mutanta iterations were not generated and produced at the same time. The production was expensive and experimental. It had to be tested and the design developed to suit. This is perhaps symptomatic of the technology. Freedom from fixed tooling allows continuous development; by manufacturing in this way, a design can rarely be said to be definitive and fixed.

The first Lampadina Mutanta iteration produced was very much a test piece. Reflecting upon it, the design was adjusted technically to improve the production results but also from an aesthetic standpoint. Design iterations #2 to #4 were produced as a batch, prior to the three-venue local exhibition. There was then a gap which enabled a further period of reflection and adjustment before the fifth Lampadina was produced for the first international showing in Milan 2004.

On reflection the tentacles of the first iteration appear as an addition, imposed on the form. In the second set of designs produced, #2 - #4, there is an increased confidence in the visual language. The tentacles are still a growth applied to the conventional bulb form, but in these pieces the tentacles appear to grow from the form rather than being superimposed. The distorting affect of the tentacle is carried further up into the body of the bulb giving a more natural appearance. This development came from both improving digital skills and a clearer FutureFactories aesthetic 'vision'. Two significant factors affected in the integration of the tentacles are their size in relation to the bulb body and the size of fillet given to their join. Smaller tentacles with little or no fillet give superimposed bodies with little relation between them, Figure 93. A larger fillet allows a degree of tangency between the fillet surface and the two bodies allowing a more flowing form. As the tentacle becomes larger in relation to the bulb there is greater possibility that the curvature of the tentacle will match that of the bulb surfaces giving rise to a flowing integrated form.

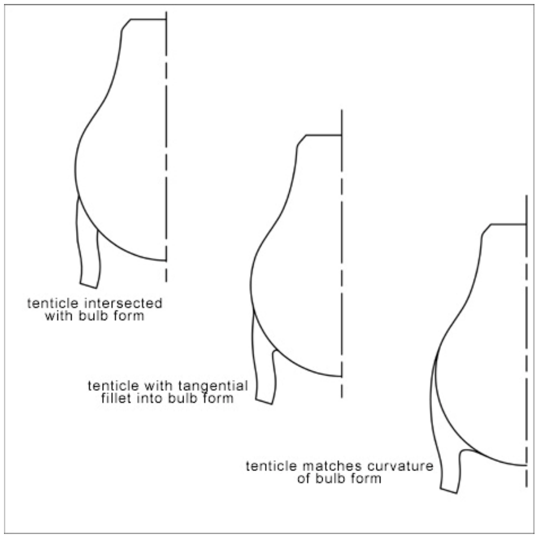


Figure 90
Lampadina Mutanta tentacle integration

There was a significant opportunity for the researcher to develop the fifth Lampadina Mutanta variant based on public feedback and personal reflection from the regional exhibitions. The length of the bulb body form was increased in #5 stretching the form vertically and reinforcing the impression of growth and distortion. The body appears to stretch under the weight of the developing tentacles. The tentacles themselves flow further still into the body of the bulb. A significant practical development in iteration #5 was to orientate the upper set of LEDs downwards, Figure 91. As uplighters these LEDs had been somewhat wasted as they lacked the intensity to reflect light off the ceiling. Aesthetically however, and in hindsight, this does not appear to have been a good decision. The increased length of #5 is an undoubted success but the upper LED should have perhaps remained upward facing. The first four Lampadina Mutanta finished variants, #1 - #4, can be seen in Figure 92. This is a photograph taken by Arkima, the exhibition publication producer, in September 2003. The variants are identified on the image.

Figure 91
Lamadina Mutanta #5 pictured in Milan 2004

Figure 92
Lampadina Mutanta variants, September 2003

(iv) Design Issues Highlighted

The physical manufacturing issues and consequent developments have been discussed. In terms of its success as a script-driven design, Lampadina Mutanta highlighted important issues. The three characters of tentacle envisaged for the piece were each intended to develop in their own characteristic fashion. This meant developing separate scripting approaches for all three. A better solution would be to have a single computer script generate three different types of output. In later work a common scripting approach was adopted for all features within a design.

As discussed in the comparison of variants, the filleting between tentacle and bulb body is a key factor determining the character of the design. The aim through the development of the iterations was a flowing, natural form. From a scripting point of view, the fillet should be a constant radius allowing an automated generation of the feature:

1. Select surface 1, the bulb body

2. Select surface 2, the tentacle

3. Specify the constant radius to build between them.

The geometric regularity of a constant radius fillet however does not appear 'natural' in this design. An appropriate radius in one area of the join is too large or small in another, Figure 93. Larger fillets can also be unstable and a radius that is successful in one position may not be in another depending on the surrounding geometry. A variable radius was built manually in the examples produced. For a design better suited to scripting, the aesthetic influence of the fillet should be reduced allowing the automatic generation of a small, stable constant radius fillet feature.

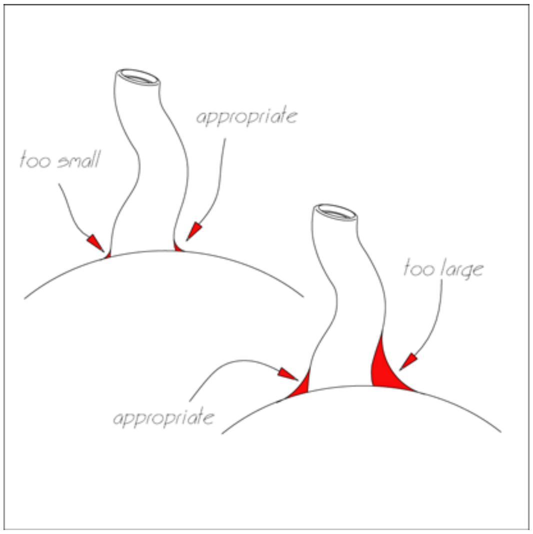


Figure 93
Constant Fillet Radius Problems

5.1.2 Nautilus

(i) Design

Nautilus is a development of the Lampadina Mutanta concept and uses the same tentacle geometry, Figure 94. In Lampadina Mutanta the form was constrained by the need to preserve the iconic light bulb form. As the design progressed from the initial concept, the tentacles become increasingly integrated into the bulb body from which they protruded distorting the original volume. This distortion of the original bulb had to be limited in order to preserve the bulb identity.

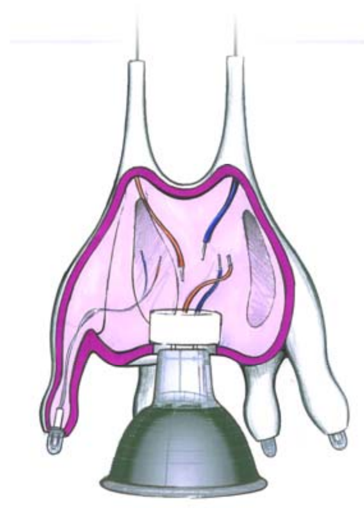


Figure 94
Nautilus Cut-Away

A further limitation was the Edison Screw mounting and associated bulbholder. In Nautilus eight tentacles develop from an abstract volume that may be dominated entirely by the tentacle 'growth'. A minimal, dual cable suspension system was adopted that imposed little restraint on the form (provision for two holes at a fixed separation) and allowed the artefact to be visible from all angles. These cables would carry power to the lamp, one positive, and one negative. Lampadina Mutanta and Nautilus both use 5mm, indicator lamp style, LEDs; rather than rely on these as the primary light source, Nautilus features a low voltage halogen spotlight at its centre (refer to cut-away, Figure 94). As the LEDs are not the primary light source a decorative blue coloured LED could be used. The eight tentacles are arranged around the central spotlight accenting it with decorative light. The effect of this can be seen in Figure 95.

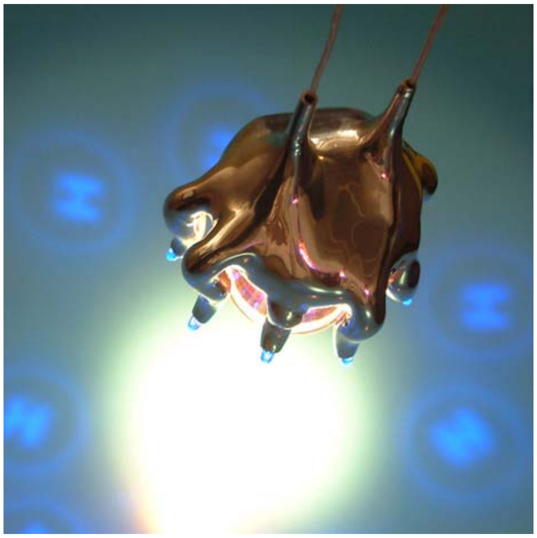


Figure 95
Nautilus Lighting Effect

(ii) Morphing Features

The morphing features of Nautilus can be seen in Figure 96; with the construction of one tentacle highlighted. Eight tentacles connect to a suspended volume. This suspended volume, illustrated in green, remains fixed. The eight tubular tentacles (pink) are free to mutate. The tentacles are skin or loft surfaces controlled by circular control curves. These circles are manipulated using translate, rotate and scale operations.

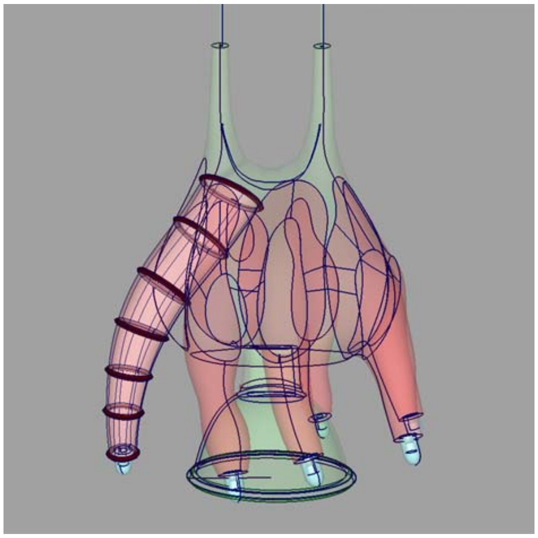


Figure 96
Nautilus Morphing Features

(iii) Production

Nautilus was created after the first Lampadina Mutanta prototype had been produced. It was designed specifically for investment casting, from digitally manufactured waxes, and was created with the benefit of previous production experience. Few problems were experienced therefore in the production of the first piece which was again cast in stainless steel, Figure 97. This first piece, as with Lampadina Mutanta, was produced by the Leicester based foundry, Lestercast. Lestercast's experience was with technical engineering industry components, rather than creative pieces. To explore a more experimental approach to casting, an artisan foundry was approached to produce Nautilus in bronze, Figure 98. These were less successful and were replaced with stainless steel versions in time for the third exhibition at the Media Centre, Huddersfield. A fifth iteration was added to complete the set for the Milan exhibition in April 2004.

Figure 97
Nautilus #1, September 2003

Figure 98,
Nautilus #4 in bronze

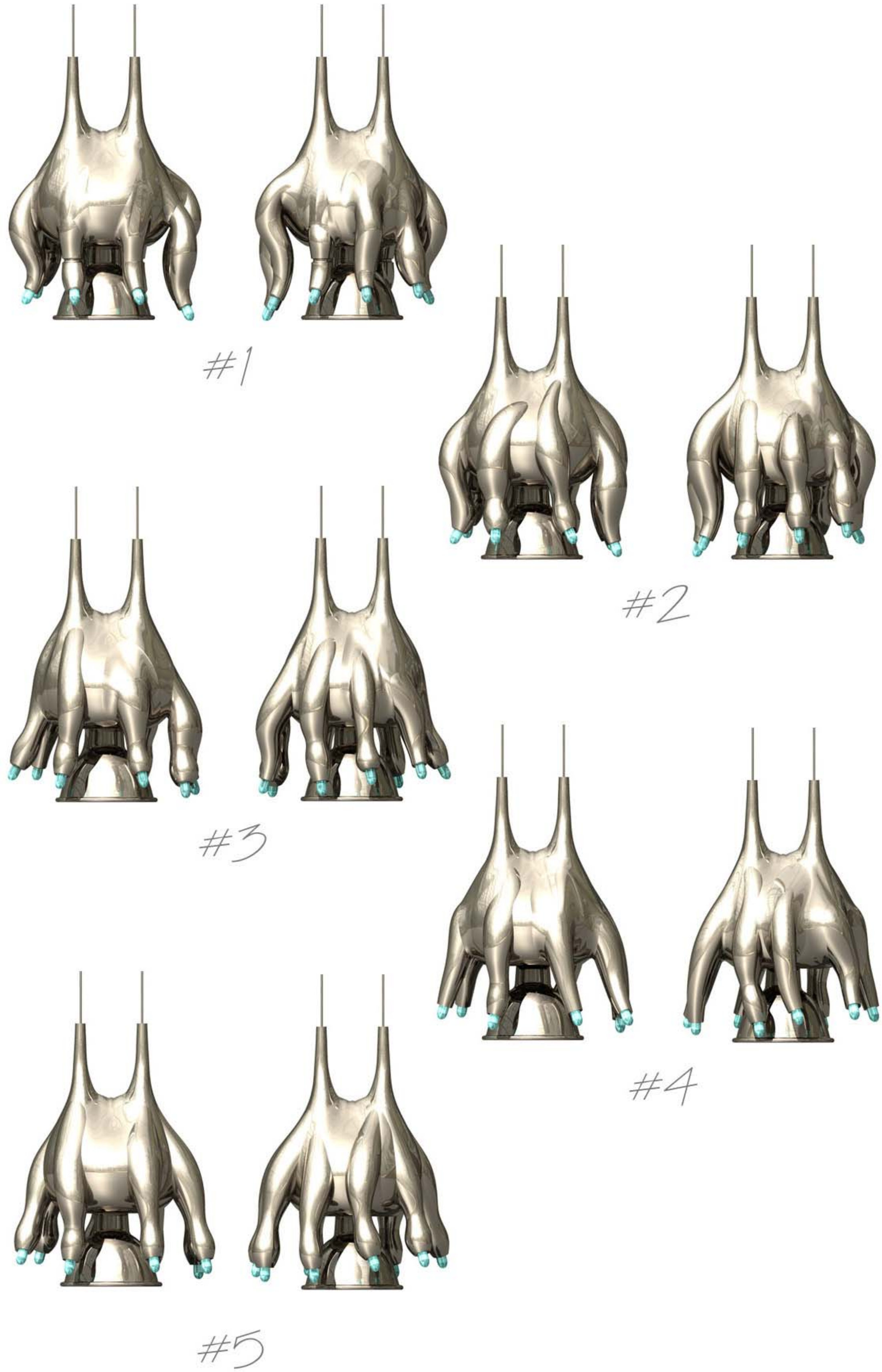


Figure 99
Nautilus Iterations

Five Nautilus iterations were generated, Figure 99. As with Lampadina Mutanta, there were developments in the design between the iterations. There is a marked difference in the integration of the tentacles into the body between the first two iterations and the ones that came later. In the first two iterations and in particular #1, the treatment is similar to Lampadina Mutanta; there is a body to which tentacles have been applied. They emerge from the form like the spout of a teapot. In stages, first with #2, the size and influence of the tentacles was increased to the point where the separation between tentacles and body is no longer as apparent, Figure 100. From the design of Lampadina Mutanta, through the iterations of Nautilus, the tentacle geometry has grown in significance relative to the body it is attached to. In Nautilus's iterations #3 - #5, the tentacles almost engulf the body. The form appears as a mass of tentacles with the connections for the suspension cables appearing as two further limbs. The evolved form gives the impression of resulting from organic growth and natural forces. The design development was fixed for iterations #3 to #5 and these give an indication of how variants can differ whilst maintaining a coherent design.

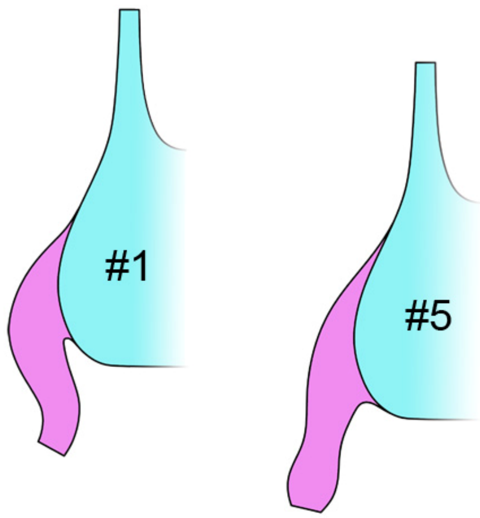


Figure 100
Nautilus Tentacle Development

The first iteration featured grooves around two of the tentacles to allow for a locking wire that would retain the 50mm spotlight. Once a prototype had been built, testing proved the retention device to be unnecessary. As the groove, with a specific location in 3D space restricted the form of two out of eight tentacles the feature was abandoned. The grooves remain in #1, but they have been polished out as far as possible. Figure 101 shows Nautilus exhibited at the Barnsley Design Centre, October 2003.

Figure 101
Nautilus iterations, Barnsley Design Centre, October 2003

(iv) Design Issues Highlighted

The outer skin of CAD surface models has to be broken down into surface patches similar to the panels of a tailored garment. A level of surface tangency between the assembled patches is needed for the overall surface to read as one. This continuity is difficult to maintain in a morphing model. The most effective solution has proved to be the use of as fewer surfaces as possible. A natural hanging appearance is achieved in the body of Nautilus by using a single, tubular surface, running in a loop from one suspension cable to the other, Figure 102.

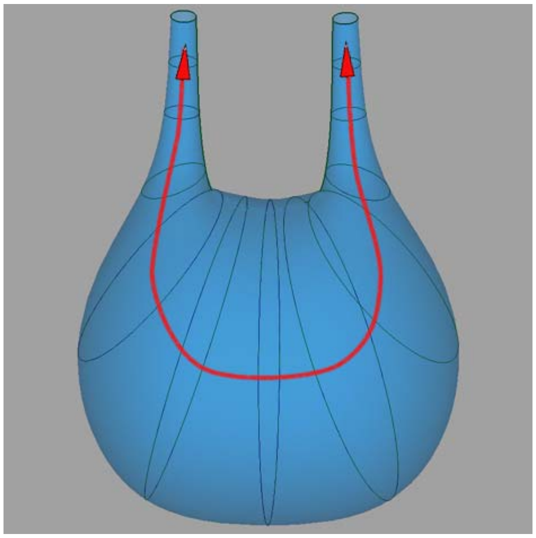


Figure 102
Nautilus Body Geometry

5.1.3 Tuber

(i) Design

In the design of Lampadina Mutanta and Nautilus, the tentacle geometry to which morphing would be applied had developed in significance, from mere appendages in the early iterations of Lampadina, to almost engulfing the host body in Nautilus. A logical progression from this was to do away with the host body entirely. In Tuber, limbs similar to the tentacle geometry are linked together to form a pendant structure, Figure 103.

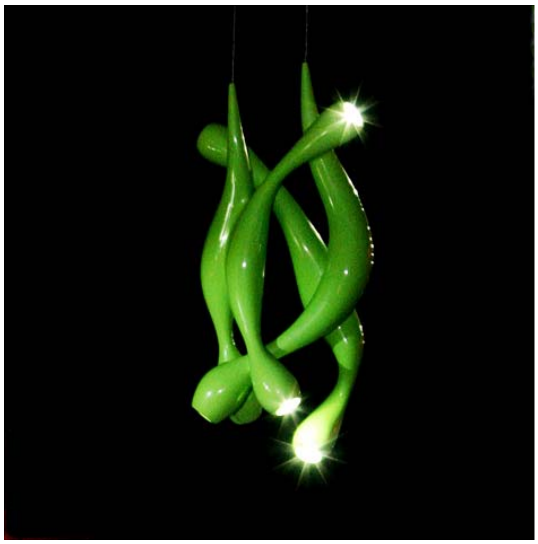


Figure 103
Tuber#5

Two limbs hang from positive and negative power cable respectively, one made higher than the other to distinguish polarity. At the opposite end of the limb to the cable entry is a 1 watt, high power LED. Two further limbs intersect with the suspended pair linking them and forming a united structure. The two linking limbs have an LED at either end making six in total, four facing down and two up. High power LEDs are typically powered at hundreds of mA (vs. tens of mA for general purpose LEDs) and can deliver large amounts of light comparable to incadencent bulbs. They also generate destructive heat which, if not dissipated, will quickly destroy the LED. For this reason they are mounted on a heat sink. One watt Luxeon LEDs driven at 350mA were selected for the design. These were mounted on a disc shaped heat sink that would be bonded into the mouths of the tubular volumes as shown in Figure 104. The links between the limbs are not only structural, but also provide passageways for wiring. The intersection must be sufficient therefore to allow the internal voids of each volume to combine.

As the artefact is suspended from cables, its centre of gravity is a potential issue and needs to remain as far as possible mid-way between the two cables for the piece to hang straight. At this stage of the project the morphing was driven by key frame animation of fixed length. Key frames were set manually which allowed a visual assessment to ensure that the volume appeared 'balanced' at regular points in the animation. This approach which proved adequate for the numbers produced. In a real-time scripted solution, iterations would be rejected if their centre of gravity fell outside specific limits. This would be checked automatically.

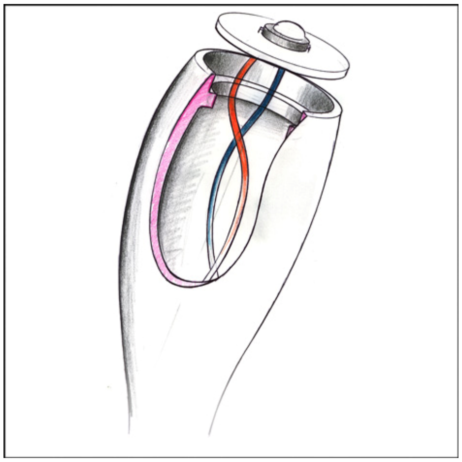


Figure 104
Tuber HP LED mounting

(ii) Morphing features

The morphing features of Tuber can be seen in Figure 105, in which the construction of one tubular 'limb' volume is highlighted. Each of the four limbs that make up the form is free to morph and there are no fixed areas. Each of the four tuboid volumes is a 'skin' or 'loft' surface created by forming a surface between a series of curves, in this case circles. The form of each volume is manipulated via the control curves or circles that define its surface. Translation, rotation and scale operations modify the position, orientation and size of each circle and thereby the cross-section of the form at those respective points.

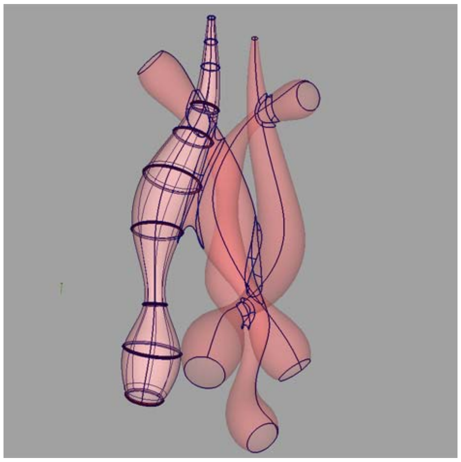


Figure 105
Tuber Morphing Features

(iii) **Production**

Given that a significant amount of hand finishing was being used for the indirect digital manufacture of the cast forms, an option to be considered was using a similar level post-finishing on the RP piece itself. During design development of the piece, it had been digitally rendered using a high gloss green shade. In an attempt to replicate this effect, and to obtain a finish close to that of high gloss moulded plastics, the decision was made to combine budget 3D printing with an automotive paint finish.

The Tuber pendant luminaires were designed for the Z-Corp 3D printing process (Dean 2004 Appendix 4). In this process layers are built by applying a binder to plaster-based powder. The resulting porous model is impregnated with either cyanoacrylate (superglue) or wax in a post-production process: Tuber uses cyanoacrylate for strength. Absolute dimensional accuracy was not important in this design, only the character of the form. In addition surface finish was not a significant issue as the surface would require hand finishing in preparation for paint whatever the process. Removing the loose powder from the somewhat inaccessible internal passageways, which serve as wire runs, proved a challenge; as did handling the delicate model prior to impregnation. The first four Tuber iterations produced can be seen in Figure 106.

Figure 106
ZCorp process Tuber iterations

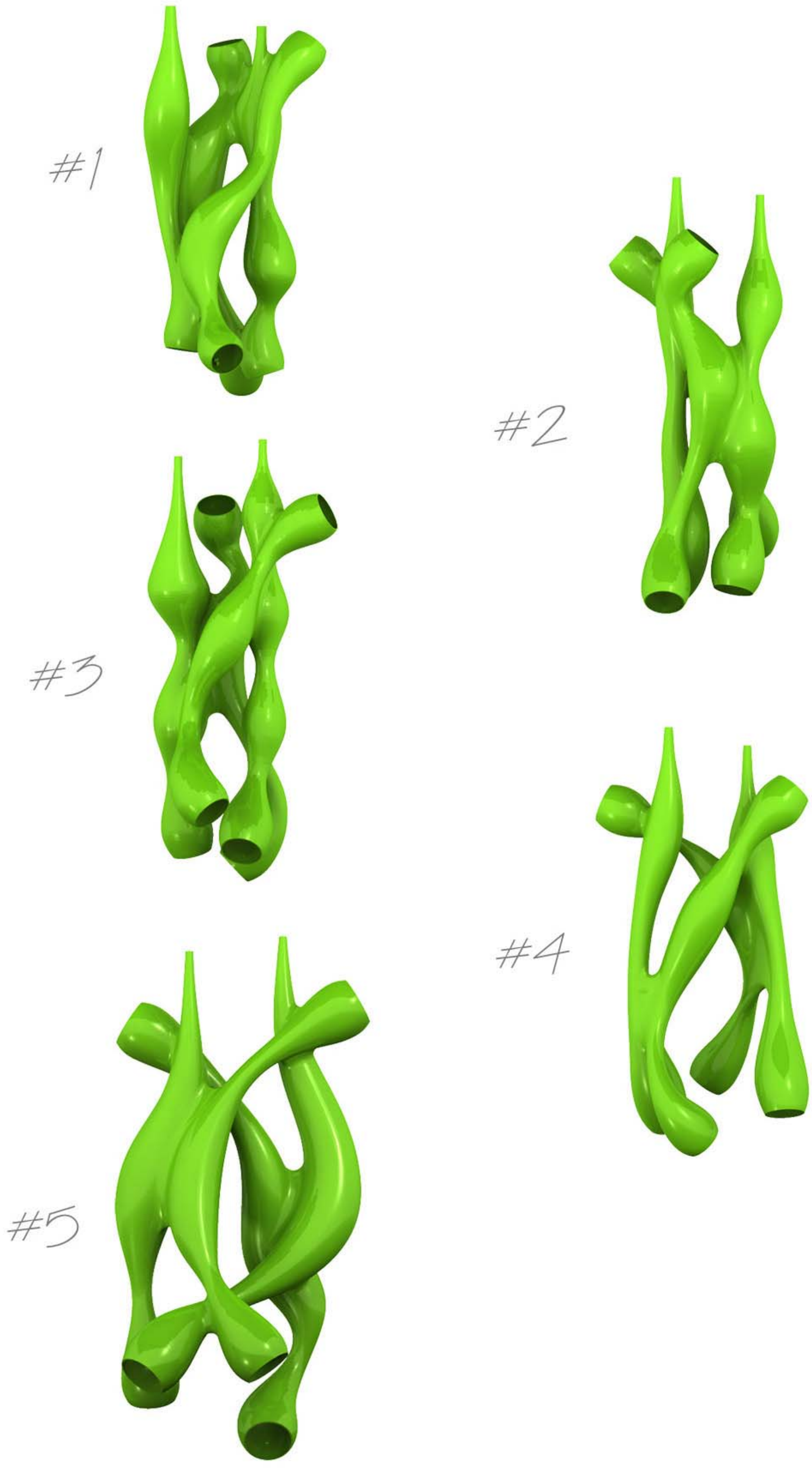


Figure 107
Tuber Iterations

The five Tuber iterations generated can be seen in Figure 106. A significant development across the set of five pieces is the scale: the first iteration is significantly smaller than subsequent variants. Initially the model was orientated upright when considering the build volume. As the process became familiar, the dimensions were ‘pushed’, orientating the part on a diagonal across the chamber so that it would just fit in. The dimensions of #5 were increased further still, but this meant building the part in two halves. The design principle does not change significantly across the variants. There was an increasing level of confidence in the material. In the later iterations limbs were allowed to separate further and the tubular form to ‘neck’ more. This went perhaps too far in #5 which suffered several breakages as a result of the fragile build material.

(iv) Design Issues Highlighted

Installation issues were identified at the various venues. Hanging the lights required precise adjustment of the twin cables to ensure that both cables shared the weight. If they were not balanced correctly the lamp would twist about the one cable carrying the weight. As the lamps themselves are comparatively light achieving sufficient balance proved difficult; a situation that worsens with repeated installations as the cable became distorted and less inclined to hang straight. The current carrying cables were designed to be minimal and un-insulated. In view of the amount of twisting occurring a length of clear insulation was added to one of the cables to prevent shorting.

The Z-Corp plaster based composite is a material intended for short term visualisation. This material has distorted slightly over time. By the second venue in the regional tour the Tubers were showing signs of cracking. There were subsequently re-painted for the Milan exhibition and have been re-finished again for every exhibition showing since.

The LEDs fitted to Tuber are bright but very directional. In the original composite Tubers effectiveness of the design is diminished by the opacity of the build material. In a reasonably lit space it proved impossible to ascertain whether LEDs facing away from the viewer were on or off. This was remedied by the change to translucent Polyamide in Tuber9.

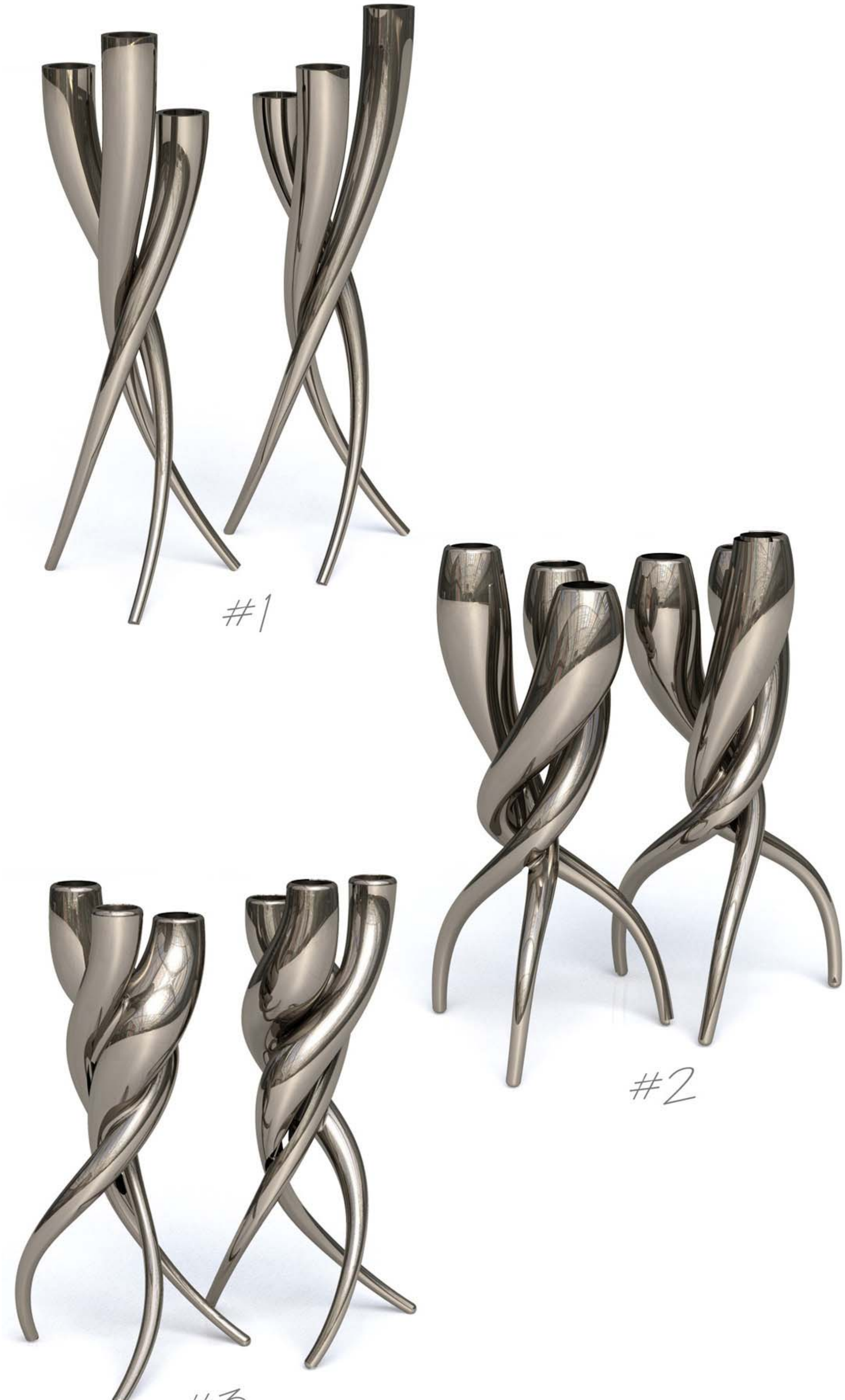


Figure 108
Let’s Twist Again iterations

5.1.4 'Let's Twist Again' Candle Holder

Chronologically and counter intuitively, Let's Twist Again came before Twist. Let's Twist Again was a name suggested by Curator Paul Atkinson at the time of the First Collection exhibition. The visuals for the exhibition featured computer generated time lapse imagery of the morphing and iterations of the tripod form assembled in groups. These images were suggestive of dancing and the original candlestick project names, Twist and Twist II, did not seem to do the flamboyant forms justice. The dancing theme suited the elegant tapering legs of the first candlestick design more than the solid geometric second version and so the original 'Twist' was remained 'Let's Twist Again' and 'Twist II' became 'Twist'. The renamed Let's Twist Again iterations are illustrated in Figure 108 and iteration #1, cast in bronze, is pictured in Figure 109.

Figure 109
Let's Twist Again #1, cast in bronze

(i) Design

Let's Twist Again was conceived early in the project and was initially developed in parallel with Lampadina Mutanta. Difficulties in realising the design, in that the fine tapering legs did not suit 3D printing, resulted in a delay in the production. It was produced after the lighting pieces. The geometry is simple, with three of the familiar tubular volumes connected to form a tripod structure. One end of each volume tapers to a foot; at the other there is a mouth to accept a candle. All three of the legs must have an intersection. This intersection should not be too great. The aim is for surfaces to just 'kiss' rather than run into each other.

(ii) Morphing Features

The morphing features of Tuber can be seen in Figure 110; in which the construction of one tubular 'leg' volume is highlighted. Each leg has four control curves to which morphing operations can be applied:

(a) Scale: The uppermost circle is constrained to accept the candle and to preserve an acceptable proportion of leg diameter to candle. The bottom circle sets the diameter of the foot which is a ball radius on the tubular volume; the foot diameter is fixed at 5mm. The two mid-circles are free to scale.

(b) Translate: The position of all control curves is free as long as the 120 degree separation between the feet is maintained. Added to this, the upper circles must remain within the triangular plan footprint that the feet create. These measures are designed to ensure stability. The height of each leg i.e. the candle mounting may vary, separately, between a maximum and a minimum value.

(c) Rotation: With the exception of the uppermost circle, which is constrained to the horizontal plane, all circles are free to rotate.

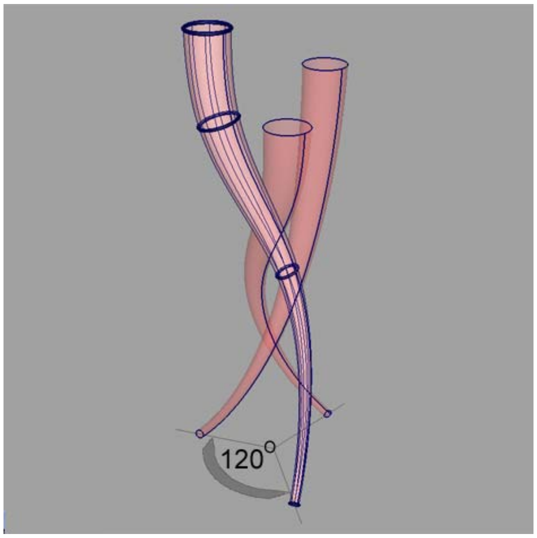


Figure 110
Let's Twist Again Morphing Features

(iii) Production

As with Lampadina Mutanta and Nautilus, the production material was to be cast metal. The candle sticks however are two to three times the size of the lighting pieces and it would be costly to print waxes this size. With budgets already stretched, it was impossible to print waxes for the piece. The first iteration was prototyped using a desktop CNC machine and chemical wood. The CAD model was divided into sections which could be produced by this 3-axis milling process and bonded together. For the exhibition program, two further iterations, #2 and #3 were added. These were 'printed' using the ZCorp powder method. Whilst in Tuber the ZCorp process could be considered to offer a functional part, the physical demands of the legged structure meant that in this application, it remained very much an appearance model process. A silicone mould was taken from the chemical wood model #1. This mould was used to produce a wax for investment casting allowing #1 to be cast in bronze. It is possible to cast direct from the ZCorp process, provided the appropriate starch-based rather than plaster-based powder is used: although not all foundries are prepared to work with this unfamiliar material and a fresh ZCorp model would be needed for every casting attempt. Creating a mould seemed the better option.

(iv) Design Limitations

Out of the five designs created for the first collection Let's Twist again proved the least successful a fact that owes much to the level of finish achieved in the iterations produced. The design is nevertheless flawed in terms of individualisation and function. The overall form is too governed by the need to spread the feet and to a lesser extent the candles. The form can be more of less twisted and the coming together of the volumes can be higher or lower. This however does not give much scope for significant differences beyond the three iterations produced. From a practical point of view the tapering form, while elegant, is volumetrically top heavy which inevitably presents stability issues. This would not be an issue in direct manufacture the wall thicknesses can be kept to a minimum; the pieces produced were solid however. In direct manufacture the artefact would be formed as a hollow volume and the lower reaches of each leg could be filled to ensure a low centre of gravity and stability. The more twisted the form became, the worse the resultant stability issues were. As an appearance model in the fragile ZCorp composite, the problem was exacerbated, as in the more twisted forms the legs would bear side-loading forces. The inability to present effective models led to only three iterations of the design being produced.

5.1.5 Twist

(i) Design

As with Let's Twist Again, Twist is a three legged, tripod candlestick, Figure 111. This design however, accommodates a single large diameter candle. The geometry consists of three independent CAD model volumes which are treated separately. There are no blending surfaces between the surfaces that would require differing geometry depending on the leg configuration. This makes the control and adjustment of the model a much simpler proposition than in any of the previous designs. As the upper portion of each leg is coincident and fixed, the join between the legs is controlled and the only issue is stability, which is governed by the leg separation. There need be no post production of the CAD model and the information can be taken straight from the three animated legs. In practice, the three legs were joined together in a Boolean operation and the candle hole formed in the united block. The legs exhibit, once again, the tuboid tentacle geometry seen in the previous pieces. In this instance, however, the cross-section curves that define the form, are allowed through the manipulation of CVs, to morph between circles and squares. Each leg begins and ends with a square cross section, creating a geometric form.

Figure 111
#1Twist candlestick in cast aluminium

(ii) Morphing Features

The morphing features of Twist can be seen in Figure 112, in which the construction of one tubular 'leg' volume is highlighted. Each leg has four control curves, the top two of which are fixed, anchoring the leg at a common start point at the base of the candle. The three control curves below this section are free to morph, provided that the foot of each leg remains horizontal and maintains a minimum separation from the other two feet. In addition to the scale, rotation and translation operations; the degree to which the cross section is square is also adjusted, Figure 113.

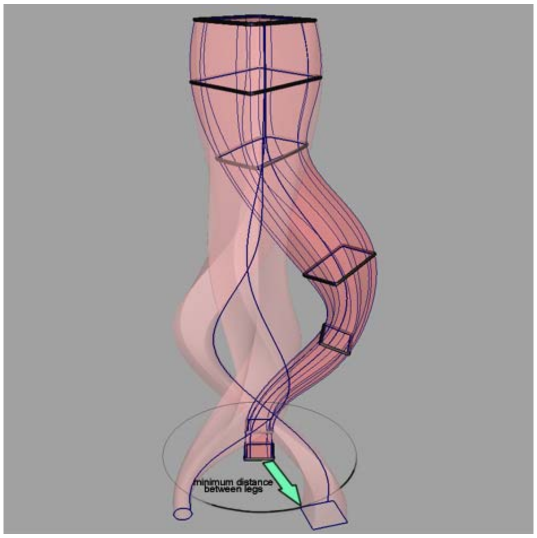


Figure 112
Twist Morphing Features

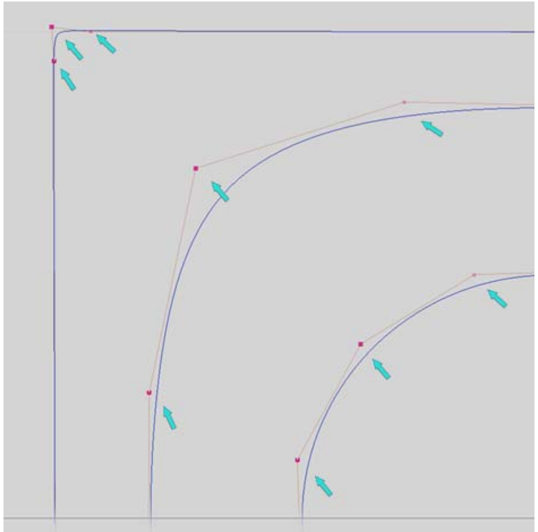


Figure 113
Twist Cross-Section Morphing, Square to Circular

(iii) Production

As with Let's Twist Again, the first model, #1, was made from chemical wood and subsequent iterations #2 - #5 manufactured as appearance models using the ZCorp process. A silicone mould was made from #1 to enable waxes to be produced for investment casting. Using these waxes, #1 models were cast in bronze and aluminium. The bronze was not of very high quality and contained too many imperfections to allow a highly polished finish. This piece was available for all of the exhibitions. The aluminium piece was much more successful and polished well, in spite of some degree of porosity. Unfortunately it was not cast in an aluminium grade that could be anodised. This piece was produced in time for the Milan exhibition, April 2004. Figure 114, shows the Twist iterations as displayed in Milan

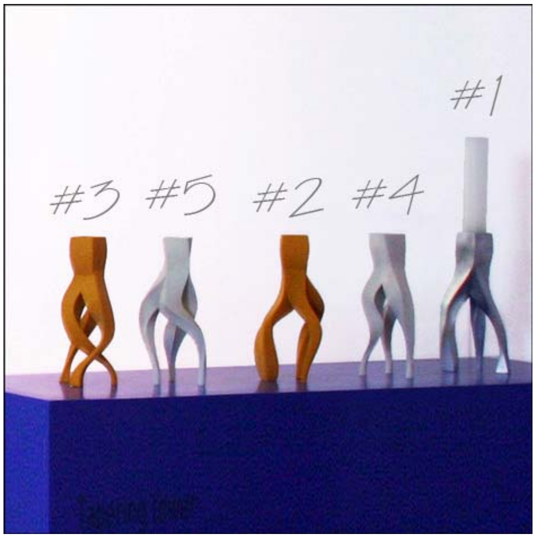


Figure 114
Twist Iterations, Photographed in Milan, April 2004

The five Twist iterations generated are shown in Figure 115. Unlike previous designs there was comparatively little adjustment to the design between the iterations. The first iteration is somewhat conservative, reflecting the need to fabricate the model; the later iterations are more flamboyant by comparison. Once the animation had been created, frames were selected from it for building. Due to the cost implications of build failures, it was the more conservative forms that were initially selected. Confidence grew with each build, allowing the building of more marginal geometry. Iterations #1 and #2 are visibly more robust than the later pieces.

Attempting to maintain stability, via the feet positions alone, is somewhat ineffective as it takes no account of the mass above and the physical balance of the form. Assessing the balance computationally, however, would be complex. A visual assessment would be possible in volume production. Small corrections would be relatively simple to apply and aesthetic judgement would not be required.

Figure 115
Twist Iterations

(iv) Design Factors Highlighted

Unlike Let's Twist Again, the geometry of Twist offers the potential for substantial feet. While stability remains an issue it does not threaten the viability of the design.

The scope for change and difference which was somewhat limited in Let's Twist Again is dramatically increased by the changes in cross section from round to geometric. This combines soft natural forms with hard edged 'manufactured' surfaces which are still curvaceous and flowing. This generates an interesting aesthetic that is not seen elsewhere in the work.

5.2 The Local Exhibitions

Three exhibitions venues in the Yorkshire region, The Barnsley Design Centre, Dean Clough, Halifax and The Media Centre, Huddersfield were booked to disseminate the residency work locally.

The five designs of the first collection, Lampadina Mutanta, Nautilus, Tuber, Twist and Let's Twist Again, were displayed at each venue; alongside video projections of the virtual designs in metamorphosis. The exhibition space for all three venues was approximately 30 square metres. An exhibition system was designed that featured a series of long plinths, one for each design type. The plinths were colour coded with a high quality automotive paint finish. A 37 page A6 colour booklet was produced to accompany the exhibition and the plinth colours were matched with the digital render backgrounds from this publication. The design iterations were presented sequentially, on or above these plinths.

Coming from the Design Industry, it was perhaps easy to underestimate the depth to which the technical issues surrounding the work required communication. The majority of visitors had not come across Rapid Prototyping. Before the individualisation concept could be explained, the visitor had to first understand what additive digital manufacture was and that it was available. Secondly, they had to understand that these prototyping technologies could be turned to volume manufacturing, which they were not at the time; that they would become cheaper and commonplace. Only when the technology was understood, could consideration be made of creative uses for it. A series of graphic panels were designed to communicate the project ideas, in conjunction with the exhibition booklet.

The Tuber and Twist animations were projected on large screens and ran in loops. On separate PCs there were animations which demonstrated the ordering process. These animations were driven by scripts written in the Delphi Programming Language (Technical Glossary). The software enabled users to stop, select, replay, and store selected iterations; but rather than placing an order, selected design iterations would be printed as an image on a sheet of paper. As designs were selected the software captured design data and created a database. This database enabled a search for any correlations between chosen iterations. It was envisaged that in the future, this facility could provide data on the preferences of different genders and age groups or other criteria (Unver et al 2004, Appendix 5).

5.2.1 Barnsley Design Centre 27/10/03 – 21/11/03

The Barnsley Design Centre was a surprisingly large, glass fronted, venue, in the market town of Barnsley. In a modernist concrete run of shop fronts, it provided an open, uncluttered dedicated exhibition space with full time supervision. Sadly the Centre no longer exists.

The FutureFactories exhibition shared the space taking the central floor area of the venue, while separate exhibitions were arranged around the walls, Figure 116. The work was first partnered by a photographic exhibition consisting of wall mounted flat work and then by a collection of the 2002 Peugeot Design Award winners. The Design centre provided a large open space and it was the 3D work of the Peugeot winners that made the best accompaniment; filling the vast floor space effectively with complimentary pieces of contemporary design.

The 2D printing of iterations proved disappointing. Only with invigilators present were significant numbers encouraged to participate. This was only possible on the opening day. There was interest in the projections from the majority of visitors, but the idea of selecting and printing a particular form attracted few. In hindsight, this is probably due to the fact that no purchase was being made, there was interest in where the animation was going but which frame got printed seemed to be of little consequence.

Figure 116
Exhibition Layout, Barnsley Design Centre, 2003

5.2.2 Dean Clough, Halifax 01/12/03 – 16/01/04

Dean Clough is a large, ex-carpet mill, arts venue, offering some beautiful contemporary exhibition spaces. The comparatively modest size of the FutureFactories exhibition, however, coupled with a lack of supervision and consequent need for security, led to the provision of a board-room adjacent to an administrative office for the show, Figure 117. Unlike the previous venue, which was a dedicated exhibition space with a suspended ceiling littered with abandoned cup hooks, what was permissible in terms of fitments was limited. The arrangement of the plinths was governed by a suspended lighting track which had to be employed as the only ceiling mounting point. The exhibition at Dean Clough lacked the professional appearance of the other two venues. Generally, perhaps due to a time slot straddling the seasonal holiday, it did not seem to attract comparable attention.

Figure 117
The Dean Clough Board Room, December 2003

5.2.3 The Media Centre, Huddersfield 23/01/04 – 13/02/04

The Media Centre, Huddersfield, offers business spaces to the creative industries, holds regular creative events and has a thriving café. Audio visual works rather than artefacts are the usual focus of the Centre. The digital start-up business located there, and the café scene, provides a ready audience for the digitally aware. The exhibition at the Media Centre, Huddersfield, proved by far the most successful of the three local exhibitions. Three months further on from the opening in Barnsley, there had been time and opportunity to refine the exhibits and to replace some of them, with improved pieces, the bronze Nautili, for example.

The Media Centre actively promoted the event by including it in their printed publication and attracting local press. The press included a magazine article in the Leeds' Review entitled, 'The light at the end of the tunnel is a mutant potato.'

The smaller size of the venue assisted with the exhibits comfortably filling the space, Figure 118. Added to this was the advantage that the space had been professionally blacked-out for a previous exhibition. The exhibition space had been partitioned off from the 'shop front' windowed area with stud walling, the walls painted black and all extraneous light sources curtained off. There was a separate projection booth and quality projection screen. Of the three venues the audience at the Media Centre seemed the most receptive to the concept. This was unexpected since out of all the venues considered, this was the one least familiar with 3D work. Immersed in digital music and graphics culture, however, the audience were possibly more used to the consideration of digital futures and alive to the creative possibilities of digital manufacturing. Photographs from the opening night private view can be seen in Figures 119 – 121.

Figure 118
The Media Centre exhibition set-up, Huddersfield, Spring 2004

Figure 119
The Media Centre, Huddersfield on the opening night (i)

Figure 120
The Media Centre, Huddersfield on the opening night (ii)

Figure 121
The Media Centre, Huddersfield on the opening night (iii)

5.3 Designersblock, Milan, 14/04/04 – 19/04/04

Designersblock, which was launched in 1998, curates and produces international design shows. Typically, these are satellite events to the major corporate design fairs and are held outside of the fairgrounds in 'transitional' architectural spaces. The Milan Furniture Fair is one of the biggest events in the international design calendar. It has a long standing tradition of satellite events, or 'Fouri Salone', championed over the years by the design magazine, Interni, who publish an annual guide to these events.

FutureFactories was invited to take part in the 2004 Designersblock Exhibition, Milan, to be held to coincide with the Milan Furniture Fair 13th-19th April 2004. The exhibition was held at Studio Zeta, a centrally located retail fashion space that is let out for the period of the design fair, Figure 122. The two storey building is spacious and open with a gated court yard. The 2004 Milan show was a significant one for Designersblock. Alongside their regular selected show they put on a well funded, touring 'Scottish Show'. This made for a very full exhibition and helped attract crowds, in spite of a number of competing festival events in the city.

Figure 122
Studio Zeta, Milan 2004

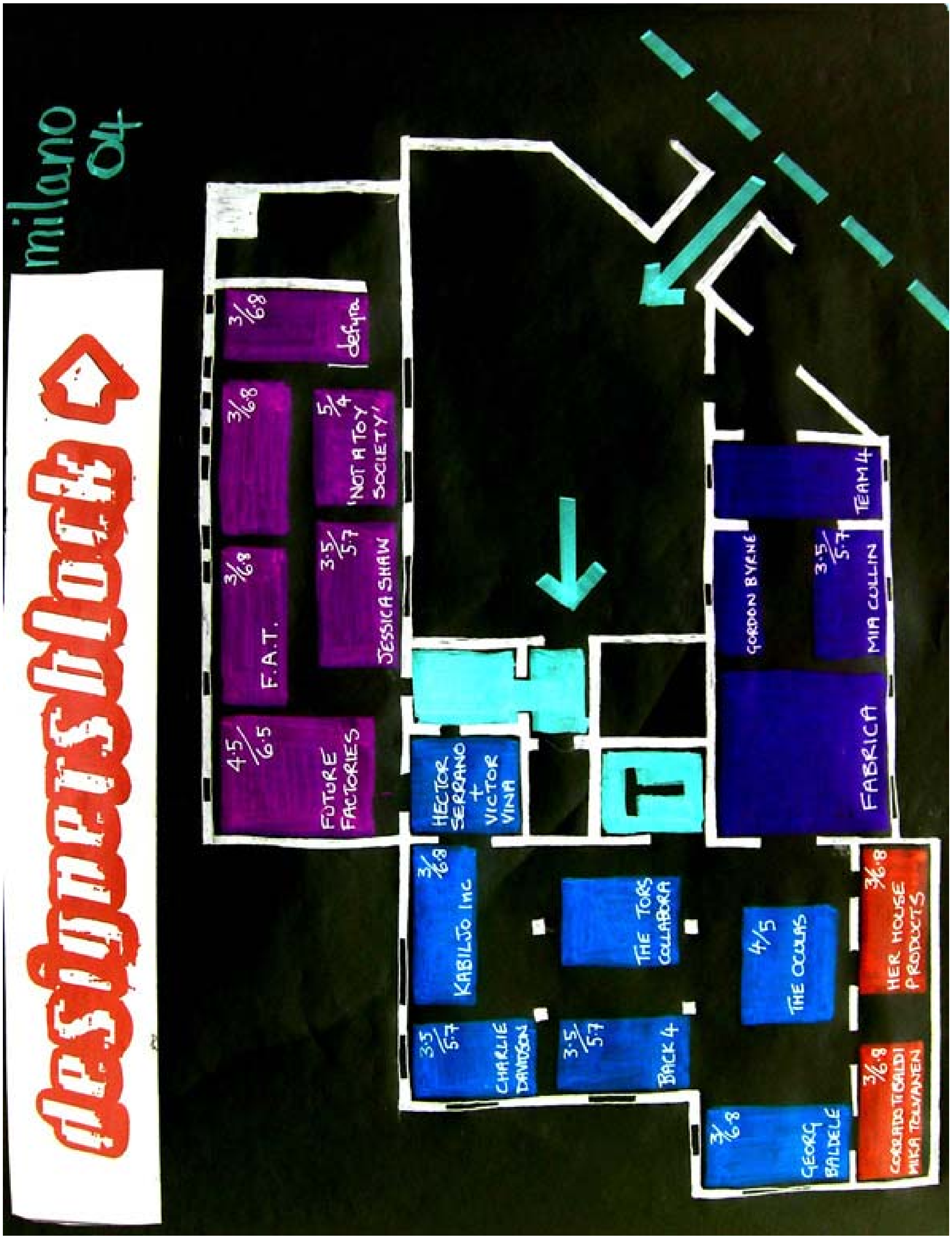


Figure 123
Designersblock, Milan 2004, Ground Floor Plan
The Scottish Show Occupied the First Floor

In the Designersblock exhibition the work was seen for the first time alongside other experimental design projects. In all there were 35 international exhibitors and a huge diversity of practice. The exhibition floor plan can be seen in Figure 123.

The Milan FutureFactories show was the same installation that had been used for the three local exhibitions. The entire exhibition, including the unwieldy 2.4m plinths, was shipped to Italy by truck. The exhibition space surveyed in a pre-exhibition visit in March 2004 was airy, but with high ceilings and a limited number of power points, Figures 124 and 125.

Figure 124
Studio Zeta on the March survey visit, 2004

Figure 125
Studio Zeta on the March survey visit, 2004

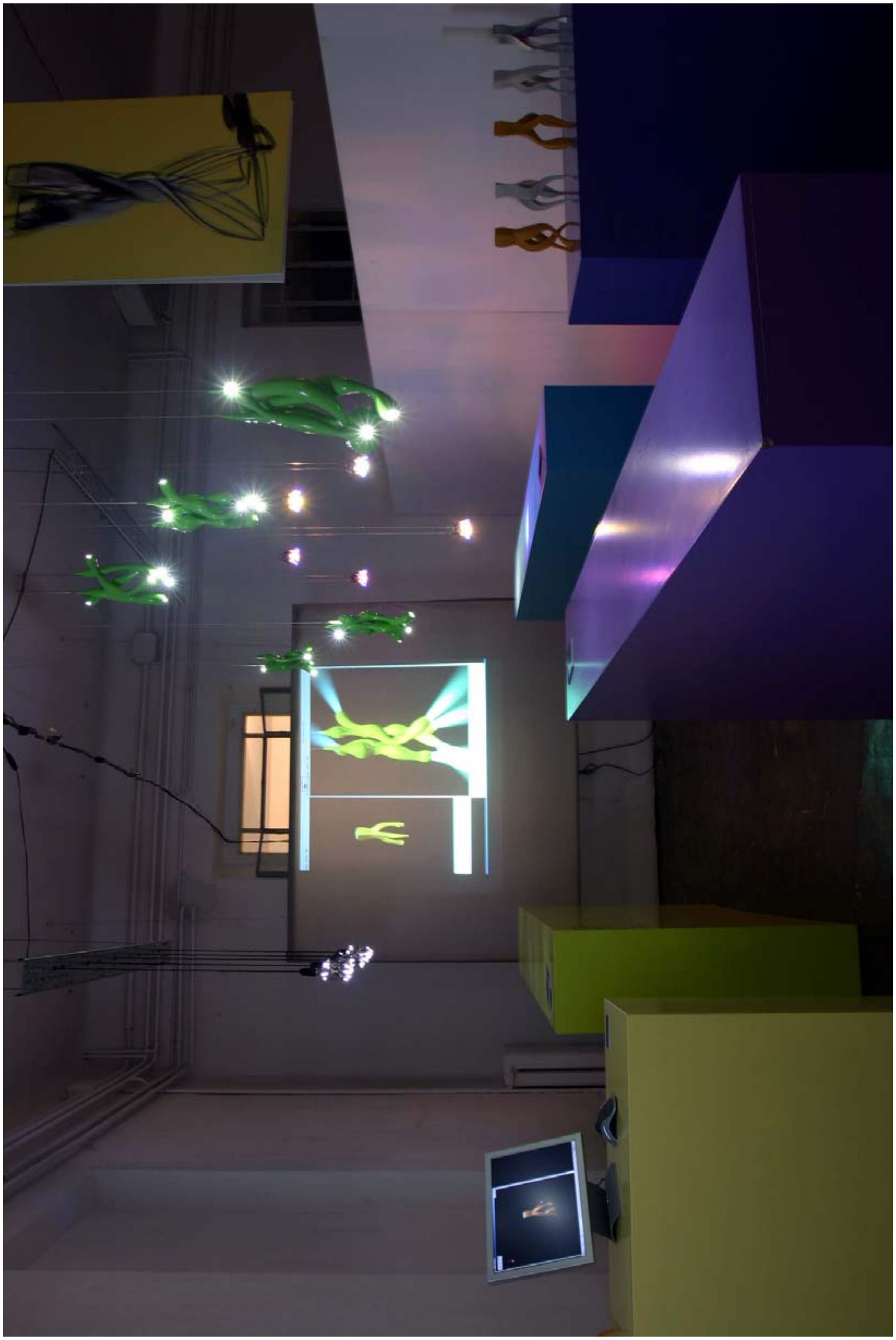


Figure 126
Studio Zeta installation, Milan, April 2004

Unlike the previous regional exhibitions, which were held in dedicated exhibition spaces with assistance from the venue, Studio Zeta provided the space only. Previous venues had each provided a projection screen for example, whereas a screen had to be constructed for the Studio Zeta installation. The use of a back projection screen in Barnsley and the separate projection booth in Huddersfield had proved professional and effective; keeping the exhibition space free of projection equipment. Studio Zeta were persuaded to allow the use of a closed adjoining office as a 'projection booth' allowing animations to be back projected through a communicating window onto a large format fabricated screen. This screen, effectively filling the back wall, formed a back-drop to the exhibition showing the Tuber and Twist animations alongside each other, Figure 126. The 3.5m metre ceiling proved a challenge for installation and required a tower system to be shipped along with the work.

The exhibits presented were principally those shown at the final local exhibition at the Media Centre, Huddersfield. The intervening time however allowed a substantial rework of the pieces with repainting, rewiring and polishing. The visitor numbers were significantly greater than anything seen at the local venues and, unlike the previous events, the audience were, by virtue of the time and place, predominantly interested in design and design technology. There was a steady flow of visitors throughout the first four days of the show, with only the final Monday slightly quiet. The preview night was filled to capacity for the duration, Figure 127.

Figure 127
Designersblock, Milan 2004, Preview Night

Reaction to the work was strong with the work featuring on several websites including Core77. The images published by Core77 can be seen in Figures 128 to 130.

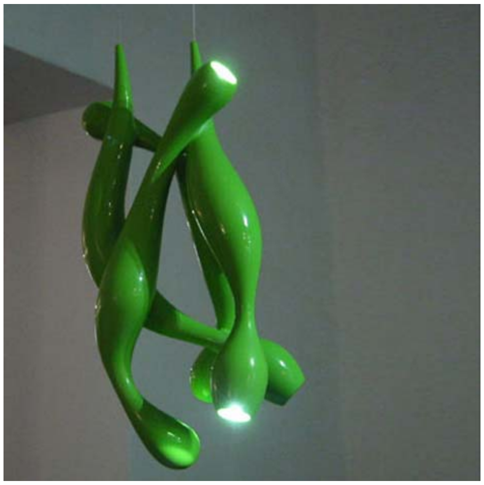


Figure 128
FutureFactories at Designersblock, Milan 2004 - Photograph Core77 (i)

Figure 129
FutureFactories at Designersblock, Milan 2004 - Photograph Core77 (ii)

Figure 130
FutureFactories at Designersblock, Milan 2004 - Photograph Core77 (iii)

5.4 Evolution of the First Collection

By Spring 2004, the project was benefiting from a growing media profile. There had been the distribution of the exhibition publication, conference papers, internet press reports on the Milan exhibition and editorials in Icon and NewDesign Magazine, Figure 131. At the same time, the rise of Materialise-mgx, as a manufacturer, was stimulating great interest in all aspects of digital manufacturing. As a result of growing awareness of the project, contacts were made with a number of industrial bodies including EOS, Germany, a manufacturer of laser sintering equipment.

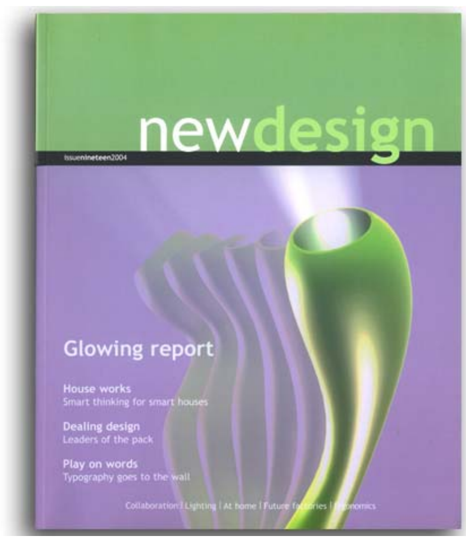


Figure 131
Newdesign Issue Nineteen Front Cover, 2004

EOS offered to produce a piece using Laser Sintering to demonstrate what the technology could offer. Rather than reproducing one of the existing designs, there was an opportunity to produce something more complex that could not be realistically achieved with the 3D printing methods employed to that point. Tuber was by far the most successful design at the time, and the decision was made to develop a more intricate SLS version of the form, Tuber9, Figure 132.

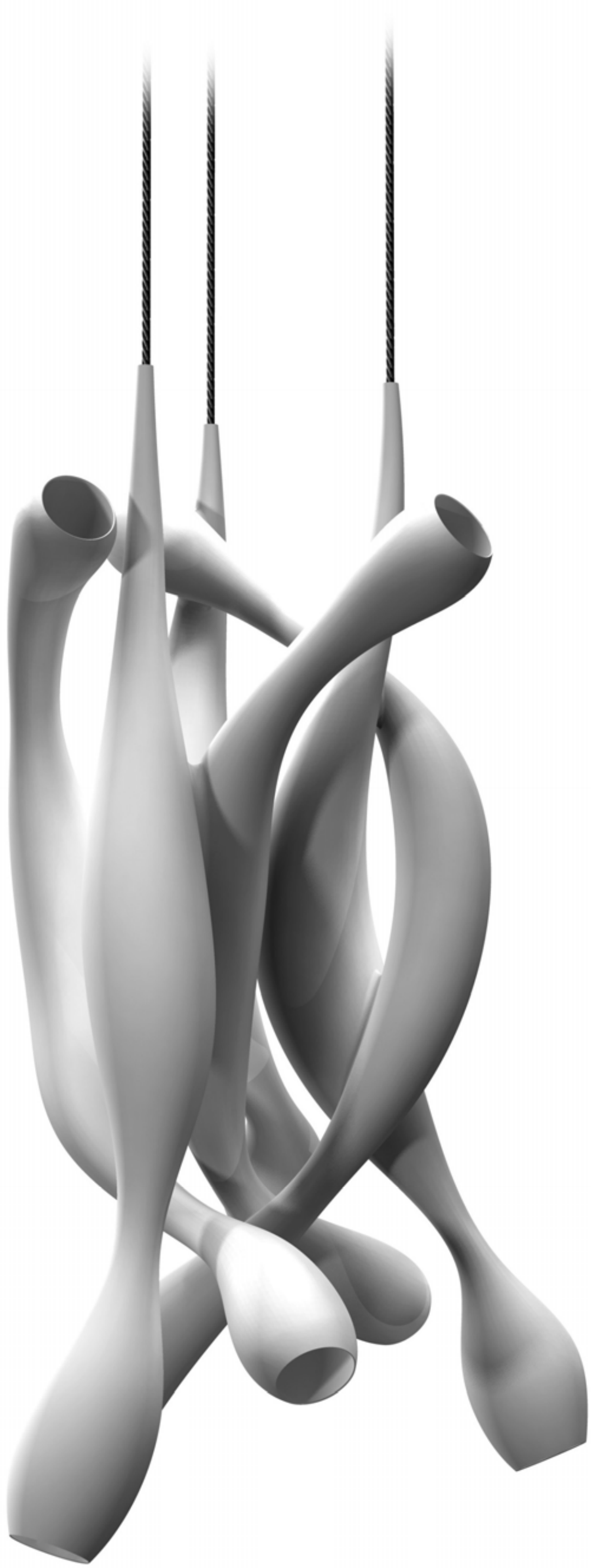


Figure 132
Tuber9

5.4.1 Tuber9

(i) Design

The original Tuber hangs from two separate power cables, one positive and one negative. The cable lengths are critical in order that the piece hangs correctly (with the design Z axis vertical). The two cables must share the weight of the relatively light weight luminaire and this makes installation difficult. In a larger piece, the balance issue would become more acute and the design moved therefore to 3 suspension cables, one positive, one negative and one for support only. The cable lengths still need to be adjusted but with more leeway as there is less of a tendency for the piece to twist.

Moving to SLS manufacture the wall thickness could be reduced, this would give more room for wiring in the internal voids allowing the use of more LEDs. There would be three tubular volumes one from each of the cables, each with an LED at the bottom. Added to these would be similar linking volumes with an LED at either end, Figure 133.

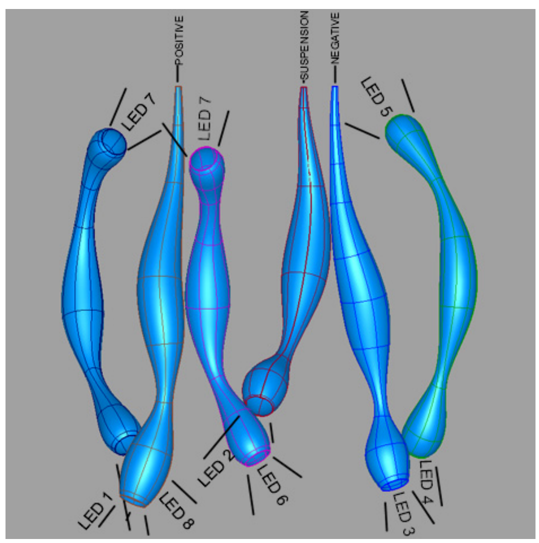


Figure 133
Tuber9 configuration

The possible configurations for Tuber9 were as follows:-

3 suspended members + 1 linking member = 4 downlight LEDs + 1 uplight LEDs

3 suspended members + 2 linking member = 5 downlight LEDs + 2 uplight LEDs

3 suspended members + 3 linking member = 6 downlight LEDs + 3 uplight LEDs

3 suspended members + 4 linking member = 7 downlight LEDs + 4 uplight LEDs

A configuration of three linking members, giving nine LEDs, was selected. Compact electronic constant current drivers were available for up to nine LEDs and this seemed to offer an appropriate light output for a stand-alone luminaire (the original Tuber were designed for use in groups).

The majority of issues to this point had been in the digital manufacturing processes themselves. Moving from limitations of 3D printing to more complex geometries highlighted assembly issues. Consumer products usually consist of a number of parts, some manufactured specifically for the product and some ‘standard’ stock components. The product requires assembly either as an automated process or by hand. The need to pass wires from one Tuber volume to the next was highlighted in the original design; this issue became more acute in Tuber9. It is possible to check that the volumes intersect on the virtual model. The degree to which volumes connect can be assessed by checking if surfaces offset from the originals would still intersect. These assessments can be automated. It would be extremely difficult however to access the degree of difficulty in threading a wire through the assembly. It is not easy to do this ‘manually’ looking around the virtual design on screen. Blind corners and forking paths coupled with a textured surface that ‘grips’ the minimal wire can make the task more difficult than it would appear on the computer. An additional problem is the removal of loose powder, that although un-fused, can remain in place were the geometry tends to retain it; this material can block the passageways.

The strength and integrity of the build brought design benefits beyond complexity. The material around the LED could be made fine enough to become translucent. This allows the whole structure to glow rather than merely emit beams of light. The stair step striations of the process, at this fine resolution of the SLS system, become an attractive decorative feature back-lit, Figure 134.

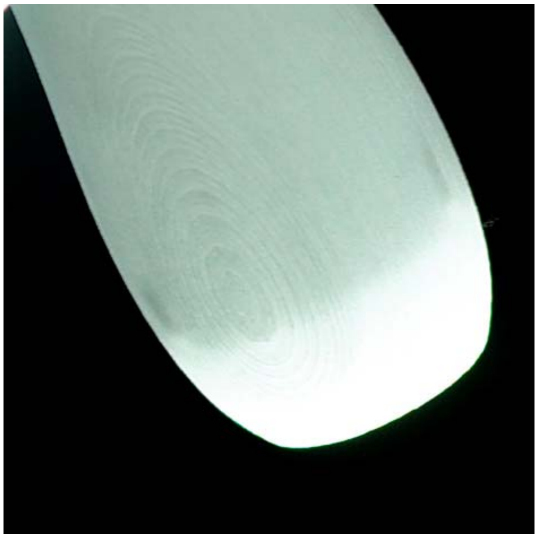


Figure 134
SLS Translucency in Tuber9

The strength and elasticity of the polyamide allowed spring-clip features to be designed into the form. Rather than bond the LEDs into place, spring-clip mountings were incorporated into the structure, Figure 135. This solution was more minimal than the flange required for bonding, allowing greater translucency.

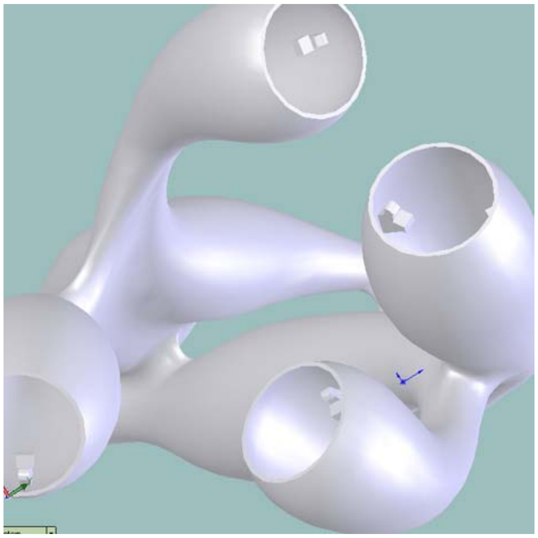


Figure 135
Tuber9 LED Clip Fittings

(ii) Morphing Features

In terms of the morphing, Tuber9 has the same geometry as the original, Figure 136; only this time there are six tubular volumes rather than four. Each of the six limbs is free to morph and there are no fixed areas of the form. The limbs are skin or loft surfaces controlled by circular control curves. These circles are manipulated using translate, rotate and scale operations.

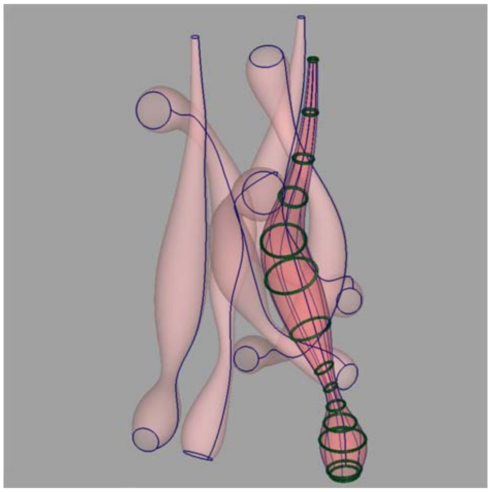


Figure 136
Tuber9 Morphing Features

(iii) Production

Significantly Tuber9, Figure 137, required no production work beyond the automatic SLS build and electrical assembly. There was no post-finishing or the significantly skilled operations to perform (although wiring issues have already been documented). This could therefore have been an industrial production process independent of the designer's input.

Figure 137
Tuber9 in Laser Sintered Nylon

5.4.2 Lightbikes

The Lightbikes were created for the London Design Festival in 2005. The idea was to create an independent satellite event outside the main exhibition venues. A set of three bicycle trailers were produced; each trailer carried a series of laser sintered lighting designs, Figure 138. The geometry of these lamps was taken from Tuber. The morphing features are illustrated in Figure 139 and the five iterations generated in Figure 140. The Lightbikes were presented as part of the London Design Festival 2005 and in various Italian cities through 2006 in collaboration with Italian cultural group Esterni, Figures 141- 143.

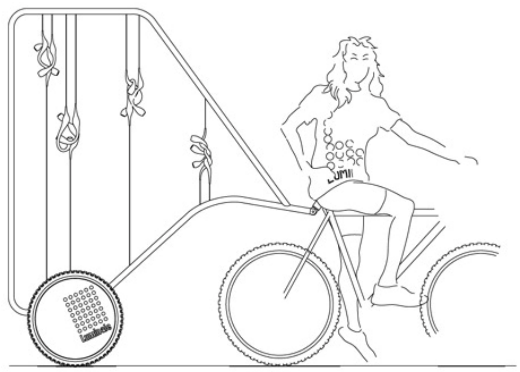


Figure 138
Lightbikes Bicycle Concept

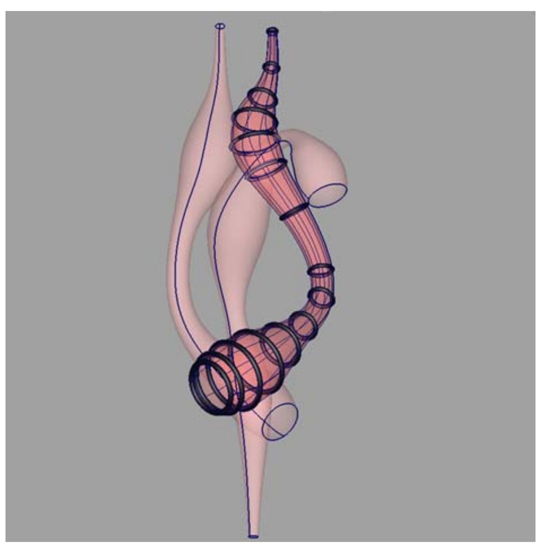


Figure 139
Lightbikes Tuber, Morphing Features

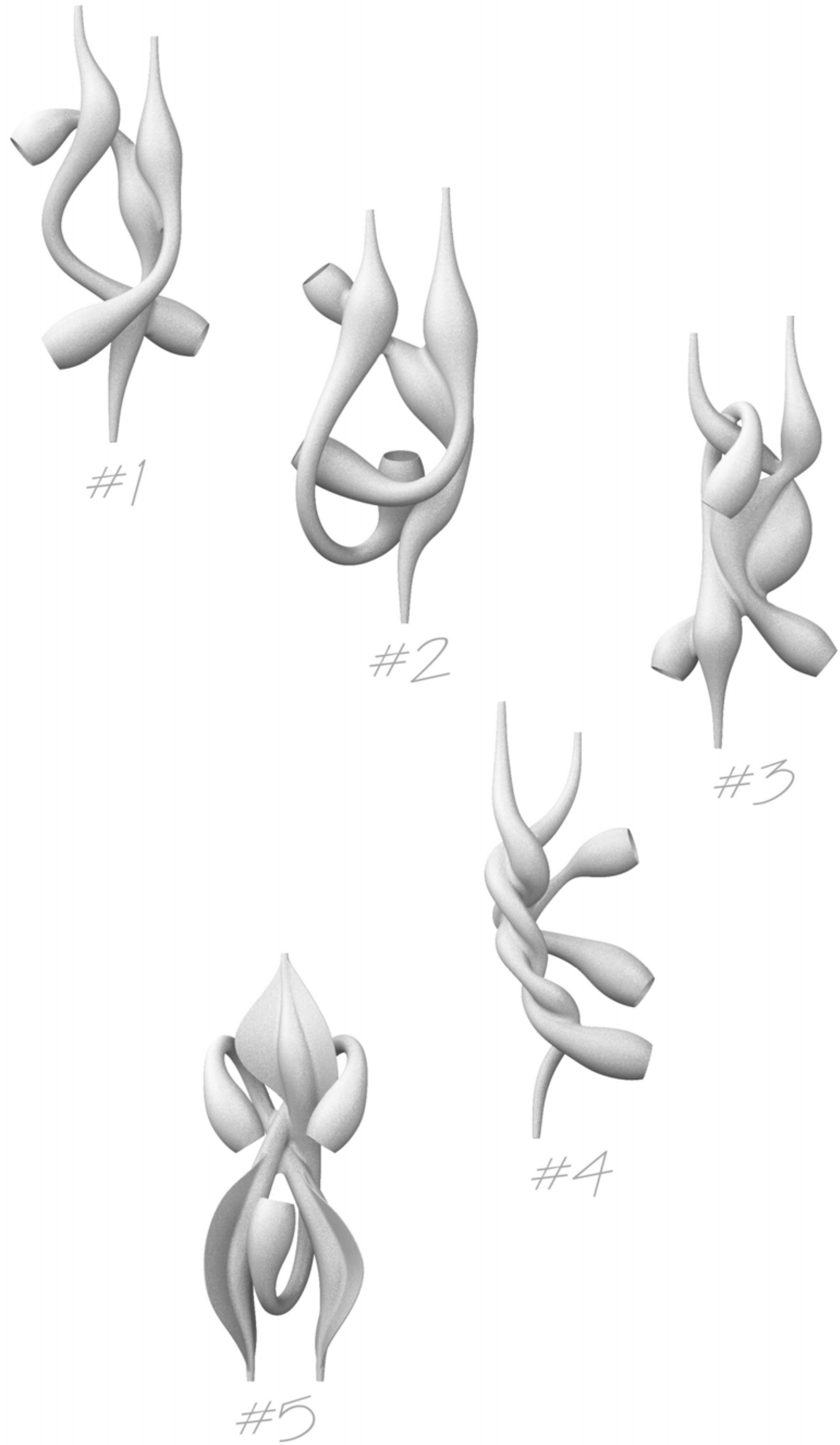


Figure 140
Lightbikes Tuber Iterations

Figure 141
Lightbikes, Milan 2006

Figure 142
Lightbikes, Rome (i) 2006

Figure 143
Lightbikes, Rome (ii) 2006

5.5 Section Summary and Audience Feedback

By April 2004 and the Milan exhibition, FutureFactories' output had built into a sizable exhibition with some 23 artefacts. There were five design families and a range of materials and finishes. The designs presented were functional, highly finished and worthy of exhibition in their own right.

Before the regional exhibition program began there had been little external feedback to the work. There had been several presentations of the project to Huddersfield staff and undergraduates, but these were audiences familiar with the concept and they were not seeing finished artefacts.

The exhibitions gave the opportunities to gauge reactions of those new to the concept. The Milan exhibition was particularly useful in this respect as it had a high footfall and the researcher was present throughout the event. The researcher was also exhibiting alongside fellow practitioners and through the event itself, the preparation for it and the break down afterward, there were many valuable opportunities to discuss the work on show.

The main comment arising was a demand for more dramatic change in the forms. The researcher had felt that the morphing was dramatic, given the geometric constraint of the CAD models. The audience did not have these preconceptions and wanted to see new elements evolve, features to be subsumed or to wither away. It needs to be remembered that the audience could ignore physical practicalities and that unlike a manufacturer they have little concern with building a brand or identity. Nevertheless this pressure for increased drama had to be recognised and future research adapted accordingly.

Out of the five designs presented, Tuber drew by far the most attention. Feedback from visitors indicated that they felt this was both the most dramatic design and the most effective consumer product delivering a powerful lighting effect. Tuber also benefited from the looped animation presented alongside it with Twist the only other animation shown. The tableware drew the least attention, these however were the least well finished of the pieces with some of the iterations presented in the raw Z-Corp finish. In addition to this all of the installations were dimly lit to suit the lighting exhibits, in spite of spot lighting this did not suit the remainder of the work. Lampadina Mutanta was the second most popular piece but the public perception of it was more of an art installation than a collection of functional consumer products.

6.0 Commercial Retail Products

By late 2003, Materialise, Belgium, had established themselves as pioneers of RM (Section 1.6.2). The researcher met Materialise.mgx Art Director, Naomi Kaemfer, in May 2004, and began discussing designs concepts. While the concept of individualisation did not fit the company's marketing plans the aesthetics of FutureFactories were of interest. Two approaches were considered, adapting an existing FutureFactories design and that of creating a new design specifically for Materialise.

6.1 RGB.mgx

The Tuber family of lights had received a good public reaction at the Milan Fair in 2004 and Materialise were keen to see a less complex, more commercial adaptation of this design. The high intensity white LEDs used in Tuber were also available in red, green and blue for colour change applications. Using these LEDs with a colour change electronic driver, which varies the power delivered to three coloured channels individually, a spectrum of colours can be created. Incorporating colour change in a pendant Tuber would have been difficult, as separate circuits are required for each of the three colour channels. Tuber pendant lamps are wired in a 'daisy chain' with wires passed through often tortuous internal passageways; a single circuit is fed through the two live suspension cables. Moving to three colour channels would mean three times the wiring and would be impractical. A simpler wall lamp adaptation was proposed, with short, accessible wiring runs feeding into a spacious central void. This design would have three LED 'heads' as opposed to the original Tuber's 6. Each of three 'heads' would have a different colour LED, red green and blue respectively. The LEDs would shine back onto the supporting wall creating a wall wash of the mixed colour, Figure 144.

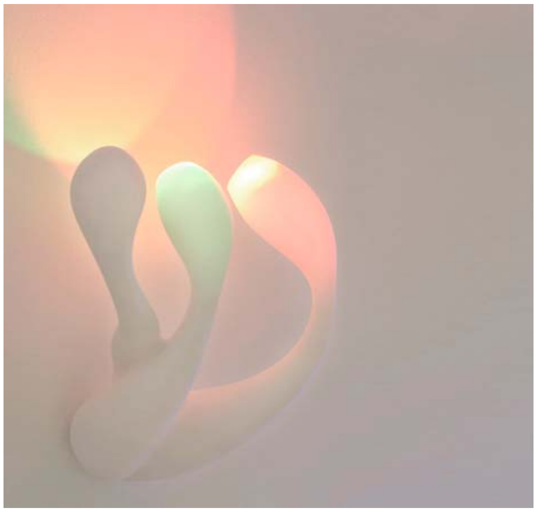
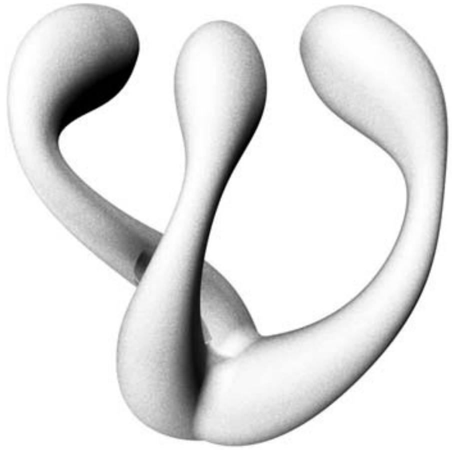
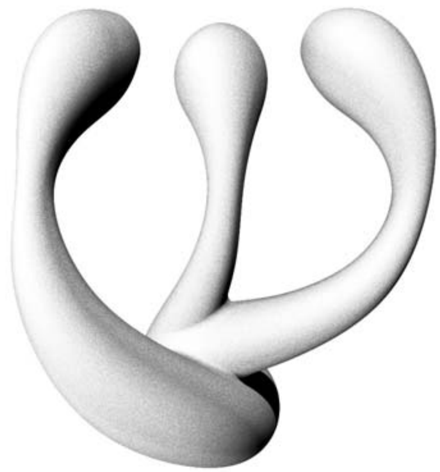


Figure 144
RGB detail showing the colour mix



#1



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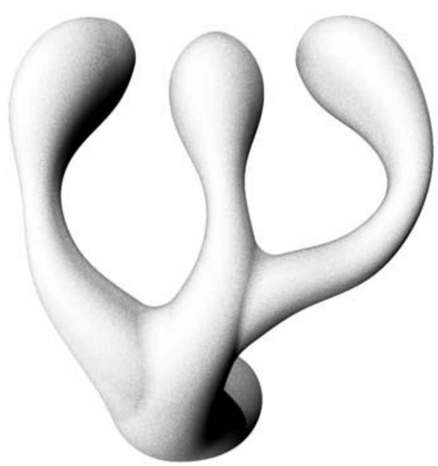

#3

Figure 145
RGB iterations

Materialise wanted to serially produce designs, rather than pursue any form of individualisation. However, the researcher was keen to promote the project ideas, in addition to aesthetics, and created the design with the same morphing strategies seen in the earlier work.

(i) What Morphs?

RGB combines the ideas of Tuber and Twist. There are three of the familiar Tuber tuboid volumes, each with a common fixed base. The geometry of RGB can be seen in Figure 146, in which the construction of one tubular 'leg' volume is highlighted. The position and angle of each head is fixed, relative to the base. The 4 circular control curves between the head and base sections are free to morph.

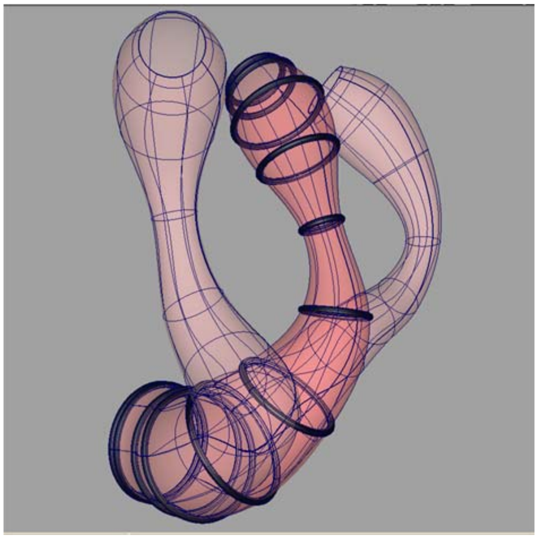

Figure 146
RGB morphing features

(ii) Production

A set of three RGB variants were commercially produced, Figure 145. RGB was initially designed to be installed as a set of at least four, powered by a remote electronic driver that can be programmed to give a set of preset colours or a sequence of colour change. Materialise later introduced a stand alone option with three identical fixed colour LEDs, Figure 147.

Figure 147
Stand Alone Fixed Colour RGBs

An experimental element introduced on RGB was a delicate ‘eyelash’ feature on the LED apertures, Figure 148. Fine tendrils would extend from the edge of the aperture into the LED beam catching intense light to form a decorative feature. The eyelashes blocked the insertion of the LED to a degree but were flexible enough to be pushed aside. The main design issue at the time seemed to be balancing a delicate appearance with reliable production. This was achieved with a diameter of only 0.8mm.

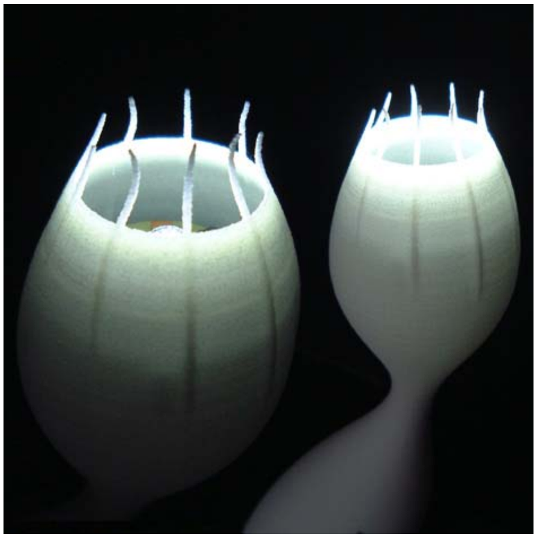

Figure 148
RGB ‘Eyelash’ Feature

In practice the issues proved to be packaging and handling. The feature is effectively a series of fine hooks in a textured material that grips fabric. It was easy to accidentally catch the eyelash on clothing and break it off. In spite of production success and dramatic aesthetics, Figure 149, the feature was abandoned for fear of excessive number of returns. This experience highlighted the fact that there are production limitations beyond the performance of the production systems themselves.

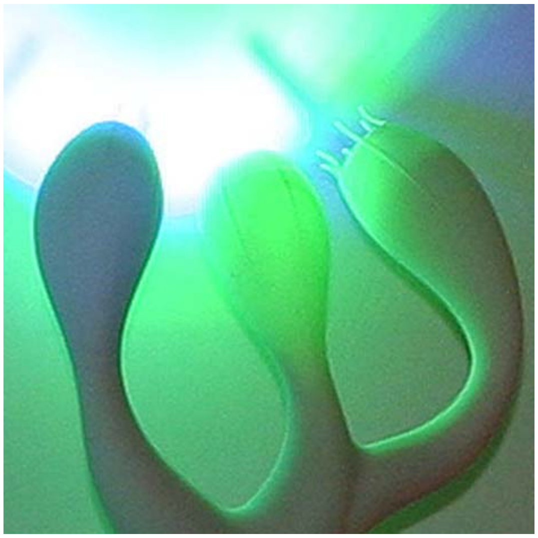

Figure 149
RGB 'Eyelash' Feature Lighting Effect

RGB was selected for the International Conference and Exhibition 'Colour Days' Warsaw, Poland 16th October – 16th November 2007. Curated by Anna Siedlecka and Radek Achramowicz, the exhibition explored the innovative use of colour in architecture and design. A set of six RGBs were exhibited running a sequenced colour change, Figure 150.

Figure 150
Colour Days Installation, Warsaw 2007

Figure 151
Creepers Iterations

6.2 Creepers.mgx

RGB was an immediate response to the opportunity of working with Materialise and built on existing work. Alongside this development, a second proposal was considered; this would be a new piece designed specifically to exploit the capabilities of RM in SLS nylon. The design would be a lighting piece designed for LEDs: it would not be the high power LEDs used in the Tuber designs, but low power 5mm LEDs commonly used as equipment indicator lamps. There is a 'trade-off' in these LEDs between light output and beam angle, the brighter LEDs have a comparatively narrow beam. For an ambient light application, it was essential that the beam illuminated a reflector or diffuser to make the narrow beam visible from a variety of viewing angles.

The aim was to create a new form of lighting; a modular concept that uses decorative light to divide interior space. A Creepers installation would be made up of stems that clip between vertical low voltage suspension cables: ideally, floor to ceiling, so that there is almost no supporting structure. These stems would be small enough to be digitally manufactured economically whilst cumulatively creating a light much larger than anything previously seen in RM. Clusters of reflectors would appear to float, 'cloud like', supported only by the minimal cables. Stems would be attached, in a seemingly random disorder, clustered in groups, and reaching out in 'spore-like' trails. The first Creepers concept is shown in Figure 152.

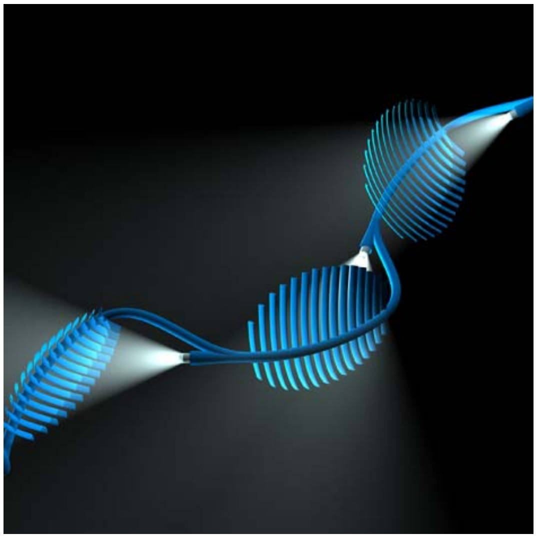

Figure 152
Early Creepers Concept

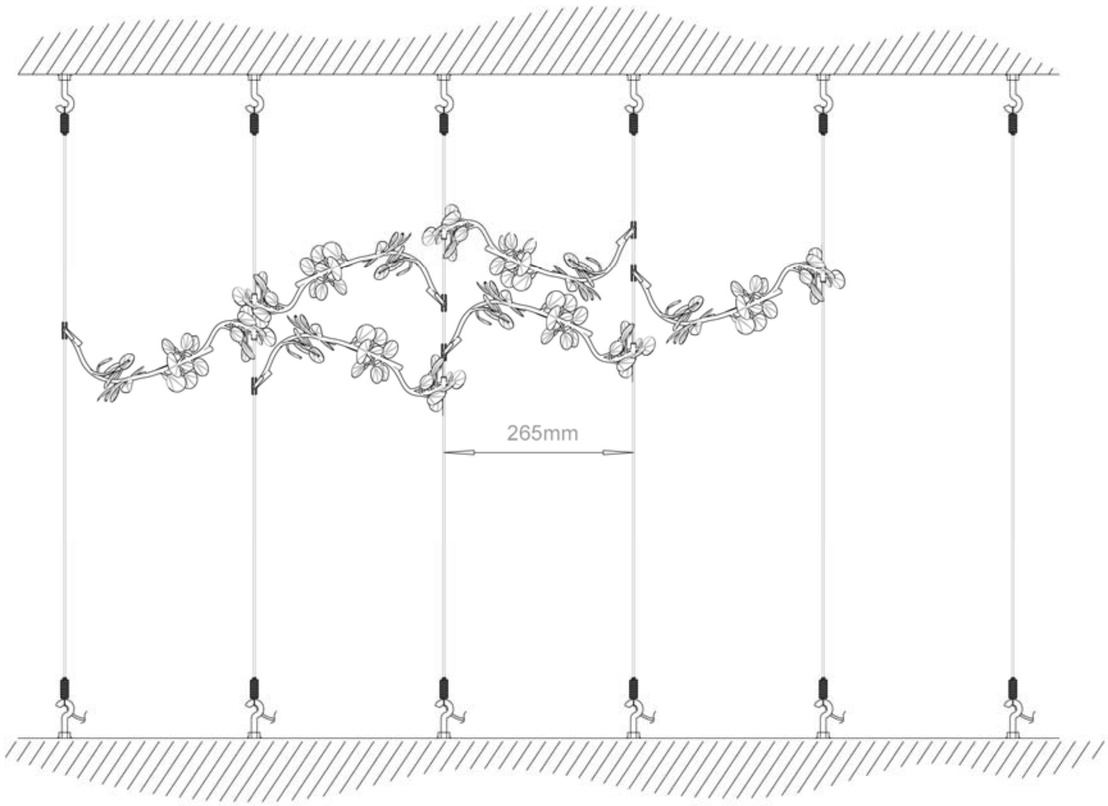

Figure 153
Creepers Installation

The suspension wires are spaced 265mm apart and are alternately connected to the positive and negative of a 12v dc supply. Some tensioning provision for the suspension wires is recommended to prevent sagging in the cable. The stems are fitted to span between positive and negative support cables, Figure 153. The 5mm LEDs typically give a voltage drop of approximately 3 - 4 volts, allowing three LEDs per stem, with a 12v supply.

(i) **What Morphs?**

As with RGB, Materialise were looking for a serially produce design rather than to pursue individualisation. Nevertheless, the design is based on a morphing strategy. The beam of light from each LED is caught on ‘leaf’ or ‘petal-like’ reflector/diffusers. The arrangement of these petals gives the impression of random chaos. They are, however, grouped and orientated, 9 or 10 to an LED, to catch the entire cone of light from the LED. The size and position of each reflector can change. The aim is to fill as much of the light beam as possible, with as little overlap as possible, as detailed in the pink area, in Figure 154.

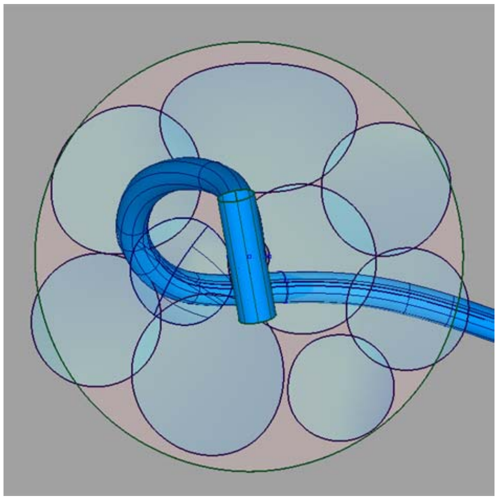

Figure 154
Creepers' reflector group

The reflectors are positioned in three dimensional space. As well as a plan view, positioning the distance of the reflectors from the LED can also change within pre-set boundaries, Figure 155. The reflectors are wafer thin and therefore semi-translucent. They act both as reflectors and diffusers. The SLS nylon from which they are made is white: the colour comes from the LED lighting and Creepers is pure white when switched off. Red LEDs were selected for the design as they provided the greatest light output.

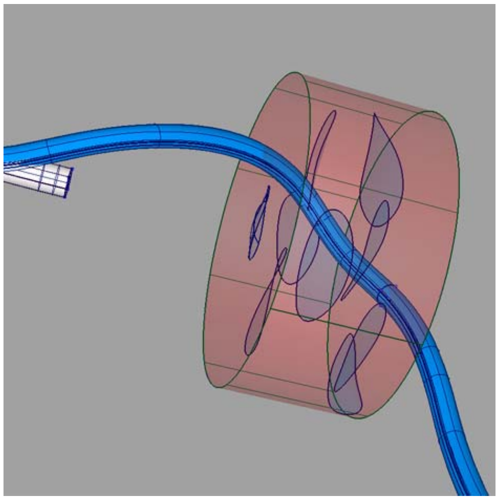

Figure 155
3D Envelope of a Reflector Group

(ii) Production

Creepers exploits the flexibility of digital design and RM with built-in functionality. The stems themselves act as flexible conduits into which the pre-wired LED string is sprung, via a slot running the length of the stem. Spring clips at either end of the stem attach it to the suspension wires, while two further integral springs push home conductor pins through the support cable insulation, Figure 156.

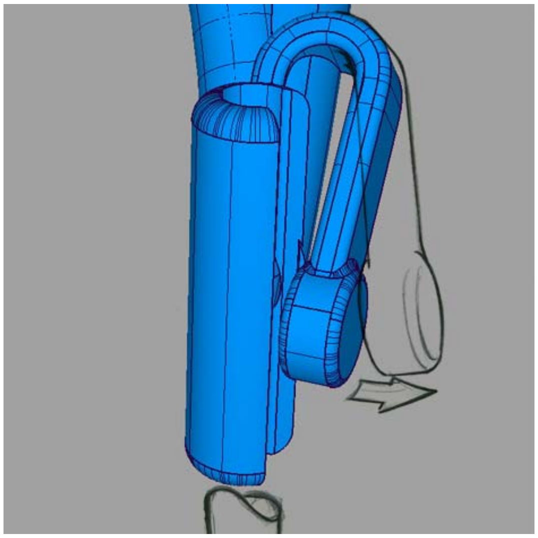

Figure 156
Integral Spring Clips

In service, users felt uncomfortable with the degree of bending required to fit the conductor and the spring was later replaced by a separate clip component. In the revised system, the stem would be clipped into place via the integral spring clips at either end, Figure 157. When the Creepers composition has been arranged as required, the separate conductor clips, which hang loose at either ends of the LED wiring string, are clipped into place making the electrical connection, Figure 158. These clips carry positive and negative markings to ensure correct connection.

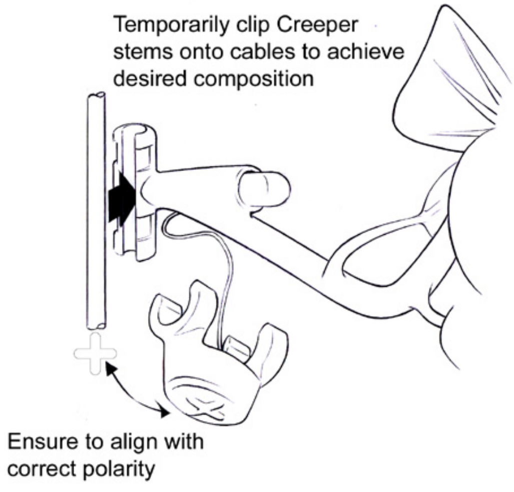

Figure 157
Revised Clip Detail

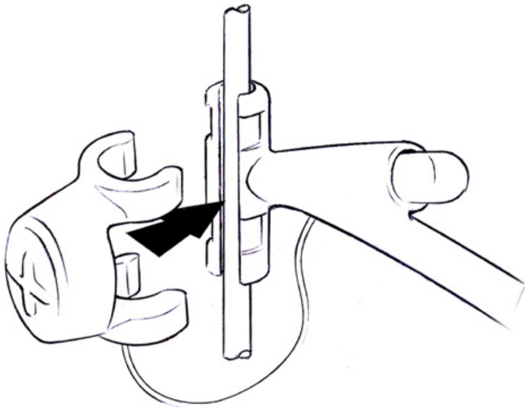

Figure 158
New Conductor Button

Details of a Creepers' installation can be seen in Figures 159 and 160.

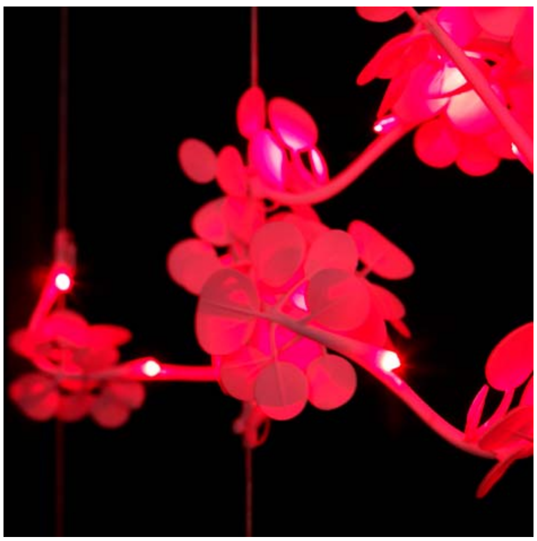

Figure 159
Creepers Installation Detail (i)

Figure 160
Creepers' installation detail (ii)

Creepers was launched at the Milan Furniture Fair in 2005, Figure 161. In 2007, Creepers was short-listed for the SWELL - Future Friendly Design Awards, Vancouver, Canada, and featured in the accompanying exhibition. In 2008, the design was included in a curated exhibition and publication, "all light-all right", at the Hangaram Design Museum, Seoul, Korea.

Figure 161
Creepers' Installation, Milan 2005

6.2.1 Tangle

Creepers is an architectural product. The power floor-to-ceiling cables are site-specific, requiring skilled specification and installation. A simpler, complimentary design to Creepers was considered that would be stand-alone and require no installation. The result was ‘Tangle’, a simple lamp shade, of a similar format to the early Materialise designs (Section 1.6.2). Materialise, however, felt that Tangle might compromise the commercial positioning of Creepers and the design was shelved. The Tangle prototype was shown alongside Creepers at Funky, an exhibition at the Norsu Gallery, Helsinki, Finland, Figure 162.

Figure 162
Tangle Photographed at ‘Funky’, Norsu Gallery, Finland, 2007

Funky, curated by Stephanie Seege, featured the work of six practitioners, whose works were considered to be, *“Finding a balance between the strangely shaped borderline of design and craft”* (Norsu Gallery 2007).

Lin Cheung, (ENG) jewellery
Lionel T Dean, (ENG) FutureFactories
Elina Rebers, (FIN) textile: fabrics
Hans Sandgren Jakobsen, (DEN) furniture
David Taylor, (SWE) silver/metal design
Maria Zitting, (FIN) textile: wall hanging

The FutureFactories work exhibited, comprised Creepers, Tangle, Tuber, and Icon. Creepers was used for the event publicity, Figure 163.

Figure 163
'Funky' Event Invitation, Norsu Gallery. Finland 2007

6.4 Entropia

Entropia was launched at Light and Building, Frankfurt, April 2006, by Italian lighting and furniture manufacturer Kundalini. Kundalini celebrated its tenth year, in 2006, and has a reputation for blending tradition and technology, mixing hand blown glass with 5-axis waterjet cutting, for example. At the time, Kundalini had no previous experience of Rapid Manufacture or even Rapid Prototyping. This design was believed to be the first Rapid Manufactured retail product by a recognised manufacturer i.e. other than an RP service provider (Dean 2006). The significance is that Kundalini's primary function is retail manufacturing. Rapid Manufacture could be considered as a logical step for companies possessing Rapid Prototyping capital equipment. Unused machine capacity can be turned to in-house production and the artefacts manufactured serve as marketing tools, thus promoting the capacity, technology and expertise of the company. The products effectively become larger scale versions of the samples produced by machine vendors, only in this instance saleable. Materialise, for example, were one the first RP service bureaus in Europe and one of the biggest by the time they began their own production.

The principle component in Entropia is a 120mm diameter spherical diffuser, produced in laser sintered nylon, Figure 164. The design is available in table, suspension, and wall variants, Figure 165. It retails at between 400 and 500 Euro, depending on the model; a price comparable with traditionally manufactured artefacts, from design-led manufacturers in materials such as hand blown glass and ceramic.

Kundalini's founder, Gregorio Spini, wanted to use the geometric freedom of RM to the full in a product that would baffle; whose conventional production would be inconceivable. A geometry without pattern or order, without any hint of logic that would suggest how the form had been created. At the same time, this was to be a commercial retail product with its production price determined by the market.

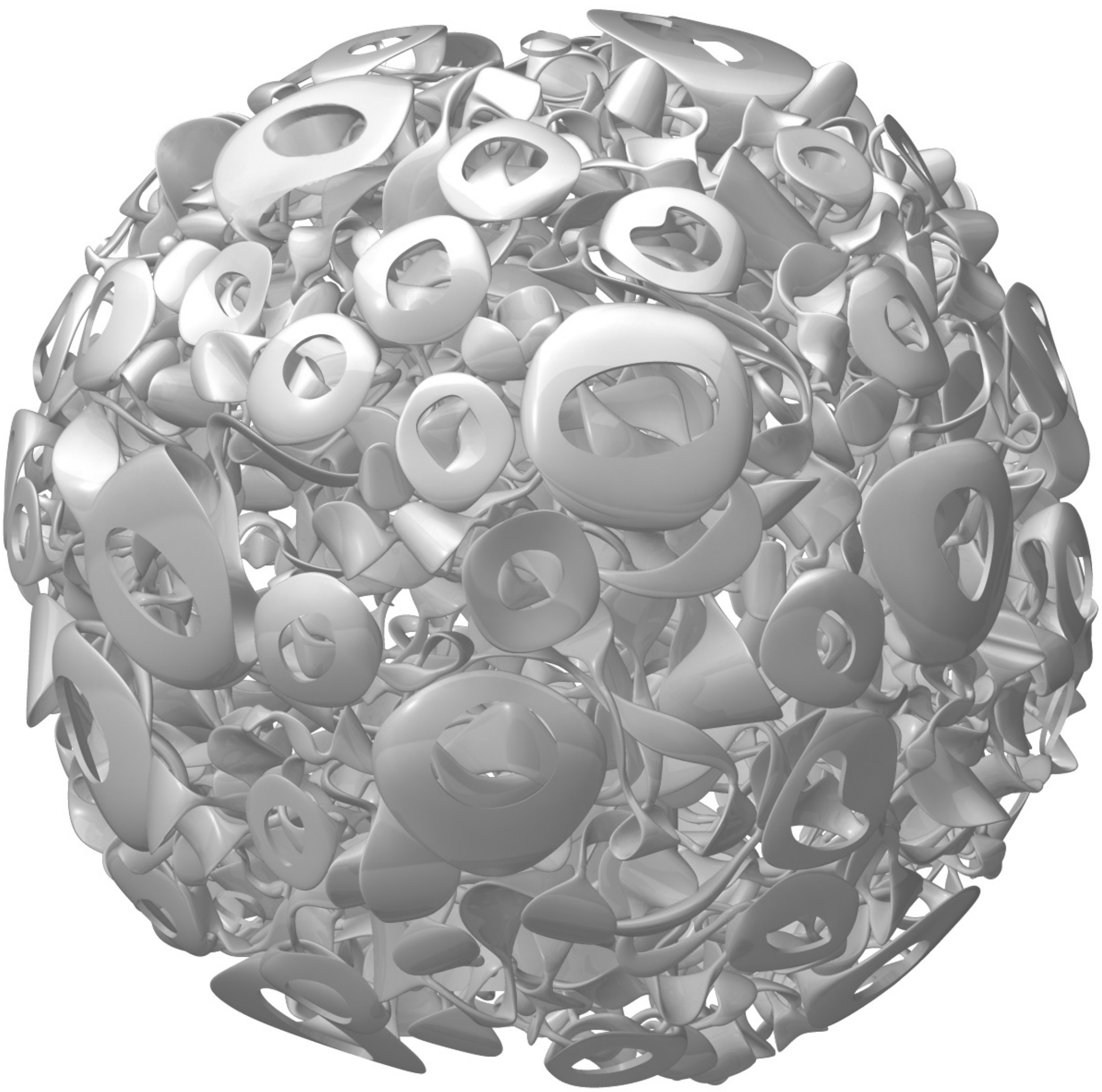

Figure 164
Entropia

Figure 165
Table, Wall and Pendant Entropia Variants

The cost of Rapid Manufacture is to a large degree predictable at the concept stage. It is generally independent of the geometry and is governed by the number of layers built. It was clear that the best chance of commercial viability lay in packing the build chamber efficiently with multiples of a compact form (Dean 2006, Appendix 6). The cost of a full chamber build would be divided between the number of pieces it contained. Accommodating one or two extra units would have a significant impact on production price per unit and may prove to be the difference between viability or otherwise. Early in the concept design stage, a spherical form emerged as the most likely solution. Externally the design needed to be as compact as possible, internally appropriate clearance would be required around the hot light source. Working back from a market derived target production price, gave a maximum diameter of 110mm. After prototyping, however, this diameter was felt to be a little small and that an increase of diameter to 120mm would have a marked impact on the products' received value, outweighing increased production cost. A diameter of 120mm was fixed upon therefore as offering the best balance of perceived value and manufacturing cost. Despite its compact nature, the design would use G9 halogen fittings; these run at line voltage, eliminating the cost of a transformer. Early pieces were built at Protosystems, Parma, Italy, who advised on the project along with EOS, Italy. Figure 166, shows a batch of parts being unpacked from an EOS sintering machine at Protosystems.

Figure 166

Entropia Parts at the Break-Out Station, Protosytems, Palma

It was important to the client that the design was taken as far from conventional industrial manufacture as possible. Complexity was 'a given' as any regular form could be produced more economically by conventional means. The idea was, however, to go beyond awkward geometry. Although certain forms may be impossible to produce conventionally, undercuts, re-entrant shapes, and the like, this fact will not necessarily be appreciated by the lay-customer. To the consumer it makes little difference if a product is produced in one piece via some exotic means or is made as a well disguised assembly of cheaper components.

It was necessary to convince the buying public that this plastic product was as precious as, for example, hand blown Murano glass that would sit beside it in the Kundalini Collection. The idea was to achieve a crafted object that was as far from 'design-for-manufacture' as possible. The idea was to remove all regular pattern and logic from the form; there could be no repeats or symmetry. At the same time and perhaps in contradiction, there needed to be evidence of human craft.

The solution was to adopt a rule based approach of previous work; but to apply this to elements within the design rather than to individualising the artefact as a whole. Parametric design templates were created for a series of features that would appear in varying numbers throughout the form. These templates dictate the underlying style of a specific feature, but allow considerable flexibility in its particular embodiment. The Entropia design is made up of approximately 200 features, consisting of ‘flower’ forms and various ‘leaf forms’, Figure 167.

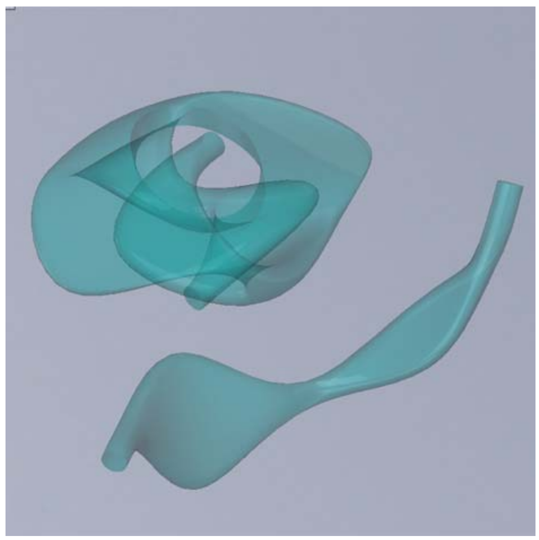

Figure 167
Flower (top left) and Leaf (bottom right) features

These features are assembled into strings, which are interwoven to create the overall spherical form. Each time a flower or leaf feature is repeated in the assembly, the parametric template is modified to give a slightly different outcome, Figure 168.

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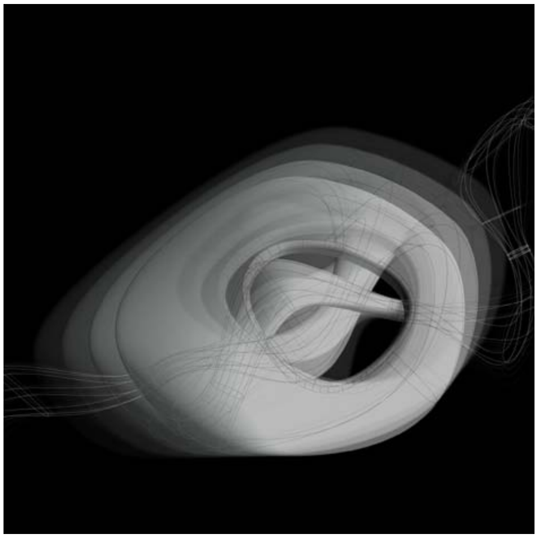


Figure 168
Time Lapse Morphing of the Flower Feature

The result is the impression of a natural phenomenon, such as coral. There are clear patterns to the ‘growth’; the form appears to have evolved rather than to have been constructed, Figures 169 and 170.

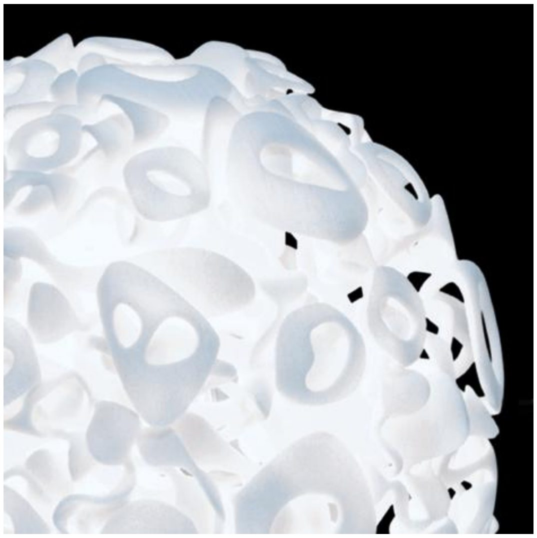


Figure 169
Entropia detail (i)

Figure 170
Entropia detail (ii)

Although this was not a primary consideration, Rapid Manufacture enabled an extremely short product development cycle. The concept was agreed, in early January 2006, and the product launched in April 2006. While the design task was long and onerous, digital design and manufacture allowed prototypes to be built, based on sections of the design that were complete. The design was manufactured in a series of increasingly complete releases, with activities such as catalogue photography and testing taking place in parallel to an ongoing design development.

Entropia has been in production since 2006 and went on to be featured in the 2008 Publication Process, edited by Jennifer Hudson and published by Laurence King publishing, Figure 171. A morphing Entropia wireframe image featured on the publication cover.

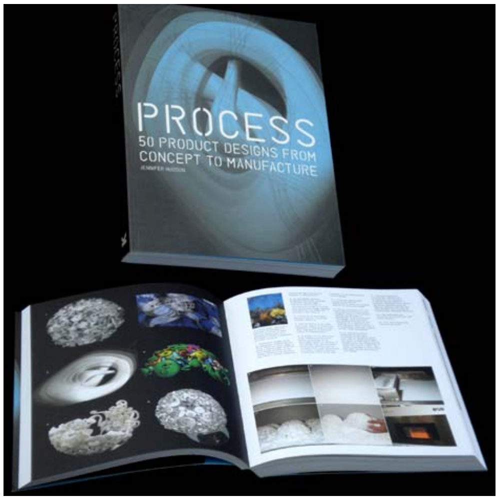


Figure 171
The 2008 Publication “Process”

6.4 Section Summary

The commercial production of Creepers, RGB and Entropia prove the commercial viability of the concept. Their commissioning and subsequent sales also indicate a desirability in the project aesthetics.

Although these designs are serially produced they were created with individualisation in mind and their forms reflect this. Three variants of RGB were produced and the potential is there to create hundreds more. Entropia and Creeper perhaps suggest that there is not always a need to individualise. Their designs are chaotic and irregular making it difficult to identify similarity or difference. The experience of these projects shows that there are issues such as marketing, packaging and distribution to deal with beyond the economics of design and production.

7.0 Later works

7.1 Artenoma

Artenoma is both the name of a design and the name of the commissioning, producing company. A group of Italian design enthusiasts formed a company called Art Change in 2001. Their idea was to market Artenoma; collectable sculptures by named artists, designers and architects produced in a range of styles and materials. The sculptures, no bigger than a “bar of soap”, would be sold individually and as box-set collections. The first set, ‘The 2003 Collection’, was launched at the Milan Furniture Fair in 2003. It comprised four pieces by Alejandro Ruiz, Antonia Campi, Stefano Giovannoni and Ettore Sottsass in bronze, porcelain, aluminium and glass respectively, Figure 172. Each piece was numbered and produced in a limited edition, for example the Campi piece was an edition of 500, the Sottsass an edition of 1500.

Figure 172
Artenoma 2003 Collection

The researcher was invited to submit a design for a second, 2004 Collection, alongside designs from James Irvine, Ritsue Mishima and Ross Lovegrove, Figure 173. Unlike previous Artenoma, the FutureFactories pieces would be an individualised set, with the production run set at 500 pieces.

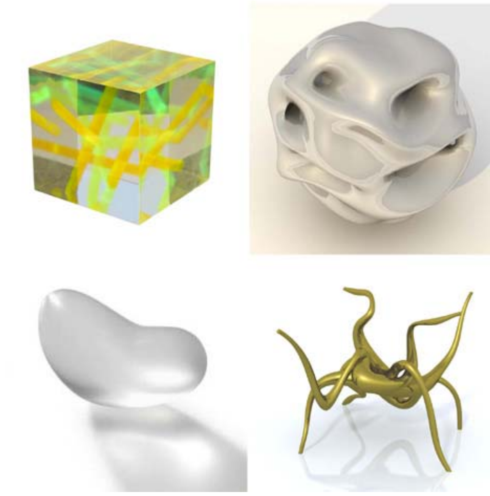


Figure 173
Proposed Artenoma 2005 Collection

Unfortunately the company ceased trading before production began, but the design remains significant to this project. The only physical limitation in the brief was that the artefact should fit within a 10cm cube presentation box, which was standard across the Artenoma collection. Prior to the FutureFactories commission, Artenoma artefacts or, Artenome - the Italian plural, had been limited edition, serially produced, pieces. The FutureFactories Artenoma was to be an individualised run, released in stages. As the production run was fixed a key frame animation approach similar to that used in the Tuber design was employed. An Artenoma would be produced from every tenth frame of a 5000 frame, approximately 3 minute animation. The design would consist of four intersecting volumes. These would each run corner to corner, between the eight nodes of the presentation box. In the initial pieces these volumes would be gently curved. As the production run progressed the design would become increasingly complex and interwoven. The design was to be introduced in stages, with an animation to accompany each realise. This was a practical device to reduce the amount of design investment and development time required, ahead of the launch. In Artenoma, the animation would proceed outside of the consumer's control and would be common to all users. Examples of Artenoma iterations can be seen in Figure 174 and an SLS prototype, in Figure 175.

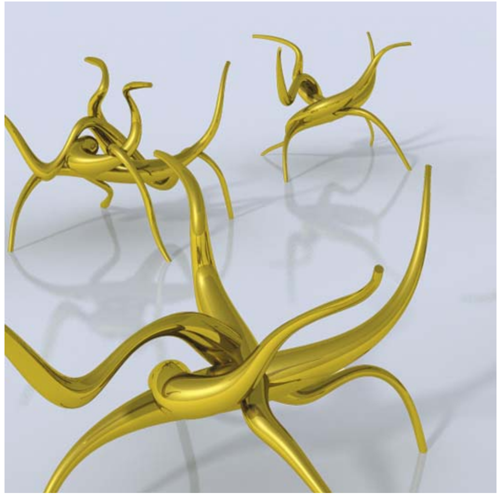


Figure 174
Artenoma iterations

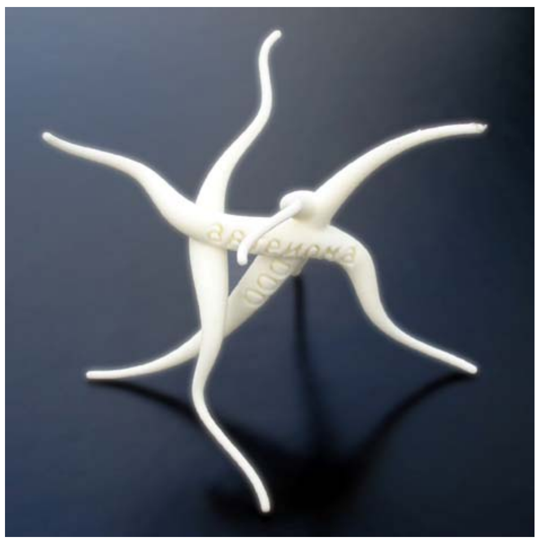


Figure 175
Artenoma SLS prototype

Frames from the Artenoma animation can be seen in Figures 176 and 177.

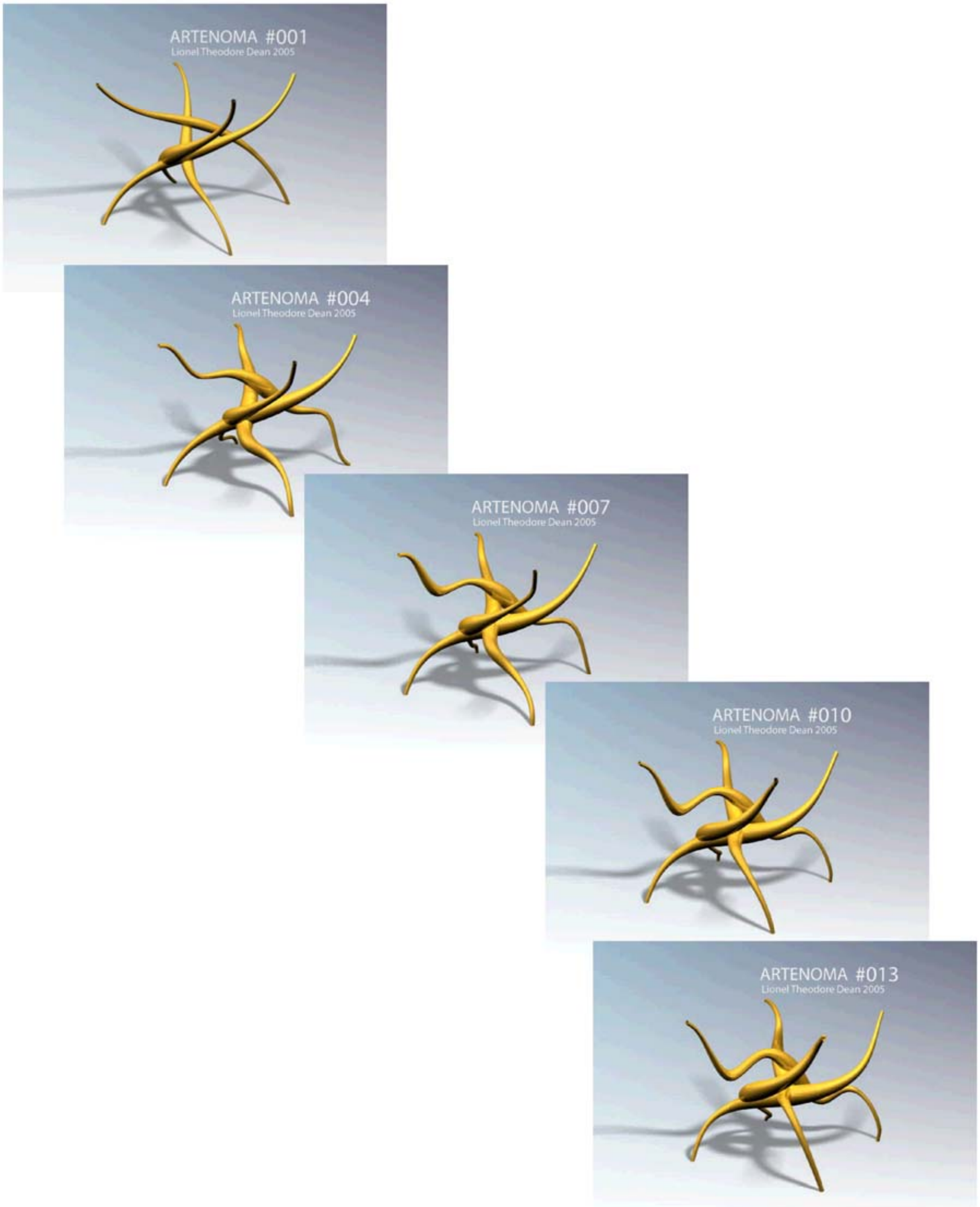


Figure 176
Artenoma Animation (i)

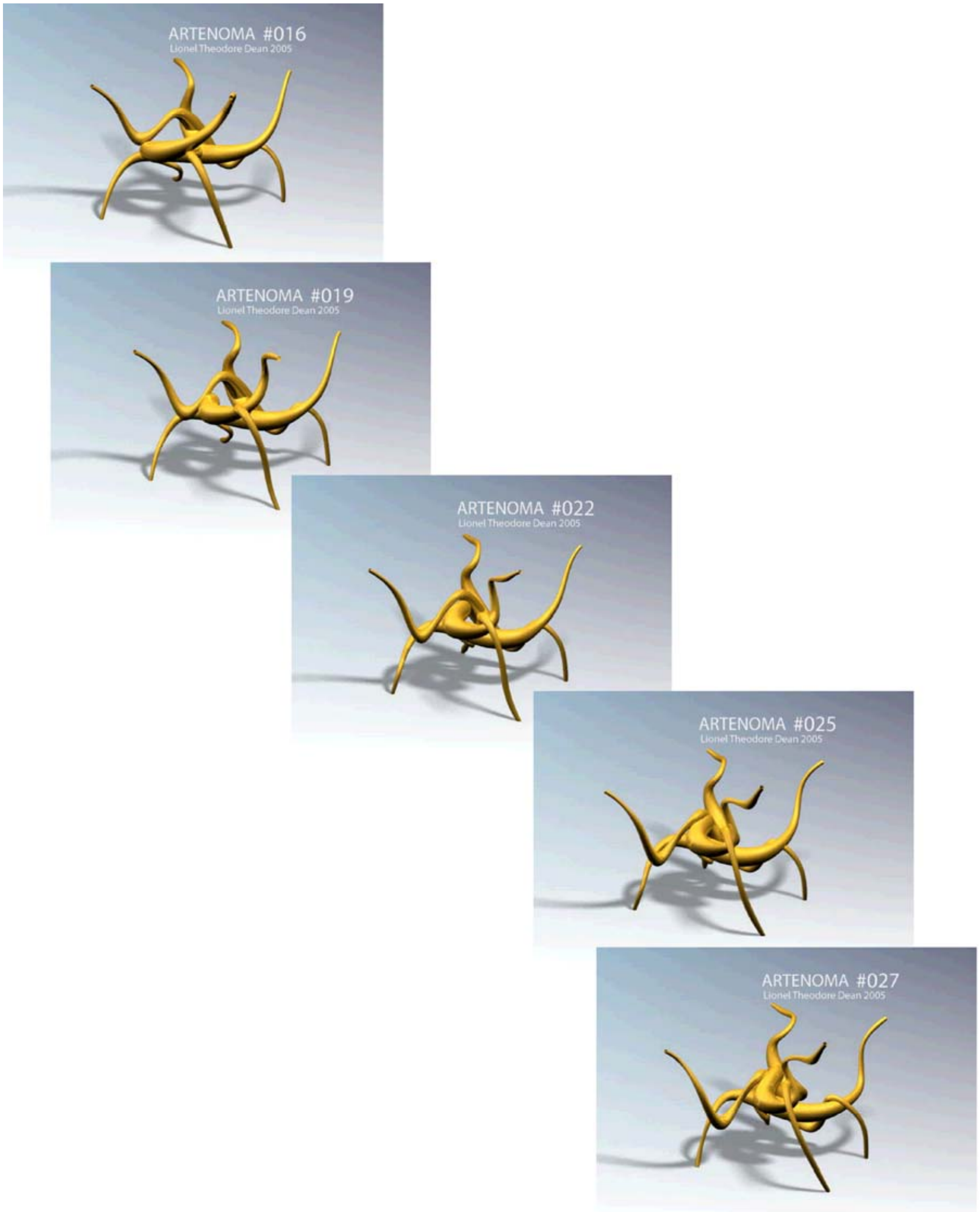


Figure 177
Artenoma Animation (ii)

Figure 178
Cornuta Iterations

7.2 Cornuta

In 2005, the author began a collaboration with software developer Genometri, Singapore (Section 1.8.1). The researcher became a beta-tester of the Genovate software plug-in for Solidworks: a package that randomly reassigns dimension variables within a Solidworks model. Genovate is somewhat crude, taking random leaps in solution space, added to this Solidworks, as a solid rather than a surface modelling package, lacks suitability for the complex 3D forms seen in the previous, surface modeller derived pieces. Genovate was never-the-less interesting; as working within a robust parametric CAD package, post generation mapping operations, such as the Tuber fillets (Section 4.4.3) could take place automatically. Added to this the geometric viability of the model would be automatically tested. A case study design, Cornuta, was created for the Solidworks' World Conference and Exhibition, Las Vegas, 2006. The Cornuta form is simple, compared to earlier FutureFactories pieces: it was significant, however, in that it was the first meta-design to yield one-off iterations on demand. A series of Cornuta iterations can be seen in Figure 178.

The design is similar in concept to RGB (Section 6.1), with separate volumes meeting at a common mounting point. There are three tubular volumes all of which start from the same hemisphere. This hemisphere houses a high-intensity LED, which illuminates the internal surfaces of the volumes, Figure 179.

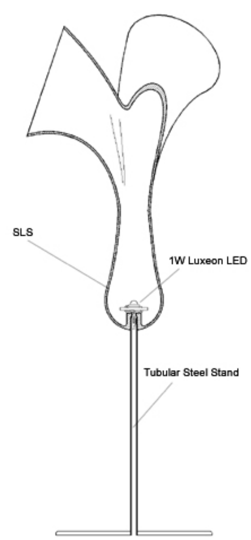


Figure 179
Cornuta Cross-Section

(i) What Morphs?

As with previous work the form is defined by a series of circular control curves, the positions and scales of which are free to morph within pre-defined bounds. In order to link the morphing effects, and to create a flowing form, the position of the control curves is not controlled directly. Instead, CVs on a three dimensional spline curve are moved. The control curves are positioned on this curve and their positions update accordingly. They remain normal to the smoothed curve ensuring a flowing form. Rather than use full circles, each volume is modelled in two halves, Figure 173. This is a device to prevent axial twists in the form. Each of the three 'horns' is modelled in the same orientation and then two rotated to give equal spacing. In fact, the spacing is not equal, but subject to random morphing 120^{o} +/- X.

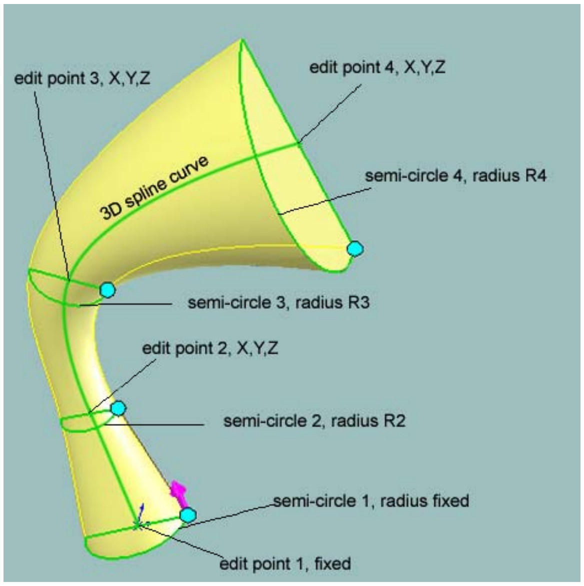


Figure 180
Cornuta Geometry

7.3 Holy Ghost

In 2006, the author was invited to submit a proposal for one of four commissions for an exhibition, Perimeters, Boundaries and Borders, to be held in Lancaster, UK, October-November 2006. The exhibition was organised jointly by Folly and Fast-UK. Folly is a non-profit digital arts organisation based in the North West of the UK. Fast-UK (Fine Art Science and Technology in the UK) is an organisation that supports and encourages practitioners using digital and/or electronics technologies in their work. The author's successful proposal for the commission was to be an adaptation of a well known, pre-existing, design; the Louis Ghost chair.

The Louis Ghost chair was designed by Philippe Stark, for Italian furniture manufacturer Kartell in 2002, Figure 181. The one-piece clear polycarbonate (solid colours were introduced later) chair is an ironic take on 18th-century Louis XVI salon chairs. It has proved a highly popular piece and is widely recognised as a symbol of modern design. Stark's press release rated this piece of furniture as his, "*Most successful, technologically and culturally*" and, "*A true object of modernity which represents a dematerialisation of design*" (Stark, Network, 2008). In 2006, design commentator Stephen Bayley, took a chainsaw to a number of the chairs to promote an article bemoaning the descent of design, "*From ennobling industrial art to the silly designer chair*" (Bayley, 2006). Frivolous or masterful, the chair is ubiquitous and instantly recognisable by even the most mildly design-aware. It is both an everyday object and an object of desire. It was for this iconic status, that it was selected for adaptation.

Figure 181
Louis Ghost Chair, Philippe Stark, Kartell, 2002

Of the four works commissioned for the exhibition, Holy Ghost caused the most controversy between the commissioning partners (Marshall 2007). One reason for this was that the author had a reputation for lighting objects, but was charting new territory with a furniture piece. The biggest issue, however, and the most significant in terms of this thesis, was in the communication of the concept. The norm in design industry practice is that projects are initially outlined by concept sketch-work. A multi-million automotive design project, for instance will typically begin with a quick loosely defined sketch-work that, whilst short on detail, identifies key lines, proportion and character. A work that is computer generated via scripts and formula cannot be easily summed up in this fashion before the rules are created. Computer programming is used to create complexity that, almost by definition, cannot be readily mentally pictured and committed to paper. The early sketch of Holy Ghost produced for the exhibition panel, Figure 182, was only intended to specify the areas of the chair that would be replaced and to hint at a level of intricacy and ornamentation. This drawing raised issues amongst the panel as inappropriate aesthetic judgements were made on it. Fortunately Fast-UK were fully behind the project and Holy Ghost was, *"The one work in the exhibition that Fast-UK was completely committed to having"* (Marshall, 2007), despite reservations from Folly.

Figure 182
Holy Ghost Concept Sketch

In Holy Ghost, the back and arms of the original Louis Ghost chair would be replaced entirely. These sections would be cut from the one piece polycarbonate injection moulding and a Laser Sintered component attached in their place, Figure 183. The idea behind adapting an existing, recognised, design was to highlight the creative possibilities for personalisation and subversion that digital technologies enable. 'Sampling' in which portion, or sample, of one sound recording is used as an 'instrument' in a second piece, has been part of the music industry since the switch from anoloque to digital production in the eighties. Collages, found footage and video montage are commonplace in film and graphics. Until recently however, 3D artefacts have been more difficult to access and manipulate. Digital technologies employed in reverse engineering, along with additive fabrication RM, make it increasingly possible to access, manipulate and reproduce 3D artefacts.

Figure 183
Portions of Louis Ghost Chair Replaced

A well as being a vehicle for stimulating creative debate, the hybrid structure of conventional and RP technologies offered some practical advantages. One aim was to build the SLS component in one-piece, minimising assembly and moving as close as possible to the 'straight from the machine' aspirations of the thesis. A whole chair could not be accommodated in anything other than SLA equipment (as demonstrated by Patrick Jouin Section 1.6.4). SLA technology, however, would not give sufficient strength for the chair to be used and would require significant hand finishing. SLS was the only practical option that would produce a functional artefact. Limiting the RP structure to the back and arms meant that the part could be accommodated in one piece in the EOS P700 laser sintering machine. An additional advantage was the use of the standard chair's injection moulded legs; this removed the areas of highest mechanical stress from the structure, thus limiting the physical demands on the RM component.

The commission budget was not sufficient to cover the commercial production costs of such a large component. Sponsorship in kind was provided by RP service providers, 3T RPD of Newbury. However, 3T requested that the two arms were built separate to the back, Figure 184. Although the back and arms could technically be built as one, the savings associated with filling the build volume efficiently were too significant to ignore. In practice the attachment of the arms caused some difficulty. From a visual point of view the joint was easily hidden below the SLS nylon surface. Mechanically, however, the SLS with its textured finish, proved very difficult to bond. The first two chairs had a hole and peg locations built into the part, the bonding of which proved prone to failure. In #3 the joint was dowelled with aluminium rod and the dowel pinned at either end.

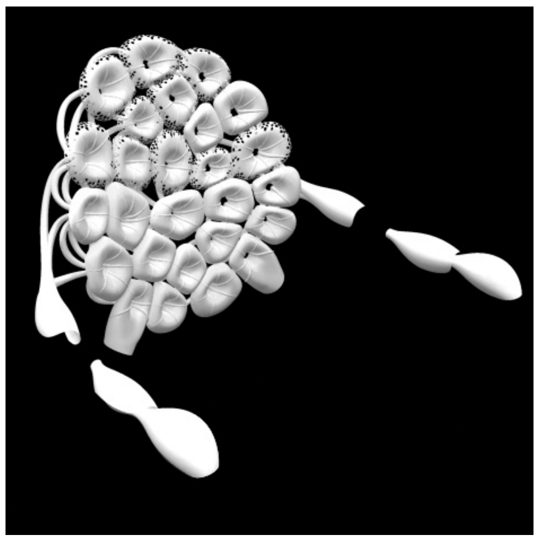


Figure 184
Holy Ghost Arm Separation

Three iterations of Holy Ghost have been produced to-date, out of a planned edition of 10. Iterations 1 and 2 were produced for the Perimeters, Boundaries and Borders' commission in Autumn 2006. Iteration 3 was commissioned in 2008 by a private Milanese architect. As the script is quick and easy to run and only a few are being produced there has been an ability to select preferred outcomes. The biggest factor aesthetically is the number of buttons allocated by the script from a range of 23-27 (4.4.3). The first two chairs were selected with the aim of achieving a contrast. Iteration 1 has 26 buttons making it the back visually 'cramped' and 'busy'. Iteration 2 has 24 buttons and is by contrast, a little sparse with several gaps. For the third iteration a compromise was sought and an outcome with 25 buttons selected.

The Perimeters, Boundaries and Borders Exhibition was held 29th September - 21st October 2006, at the CityLab, Lancaster, UK. The exhibition comprised of four new commissions (including Holy Ghost) and 16 selected works. Alongside the exhibition there was a complimentary symposium with presentations by the artists. The aim of exhibition was to, "*Present the very latest examples of work that blur the conventional boundaries of art and design practice through the use of technology"* (Brown, 2008). Iterations #1 and #2 of Holy Ghost were exhibited on a low plinth alongside a projected animation, Figure 185. The animation was back projected onto a frosted screen which was suspended alongside the chairs themselves. The Virtools' script (4.4.3) was projected running in real-time, constantly rebuilding itself, with a build cycle lasting approximately 6 minutes. Feedback from the curators suggested that the real-time animation was too slow and not as exciting as the pieces themselves. For later exhibitions, the real-time animation was replaced by a show-reel made up of edited Virtools clips. The show reel is visually more dramatic but less significant from a technical standpoint.

Figure 185
Perimeters, Boundaries and Borders, Lancaster 2006

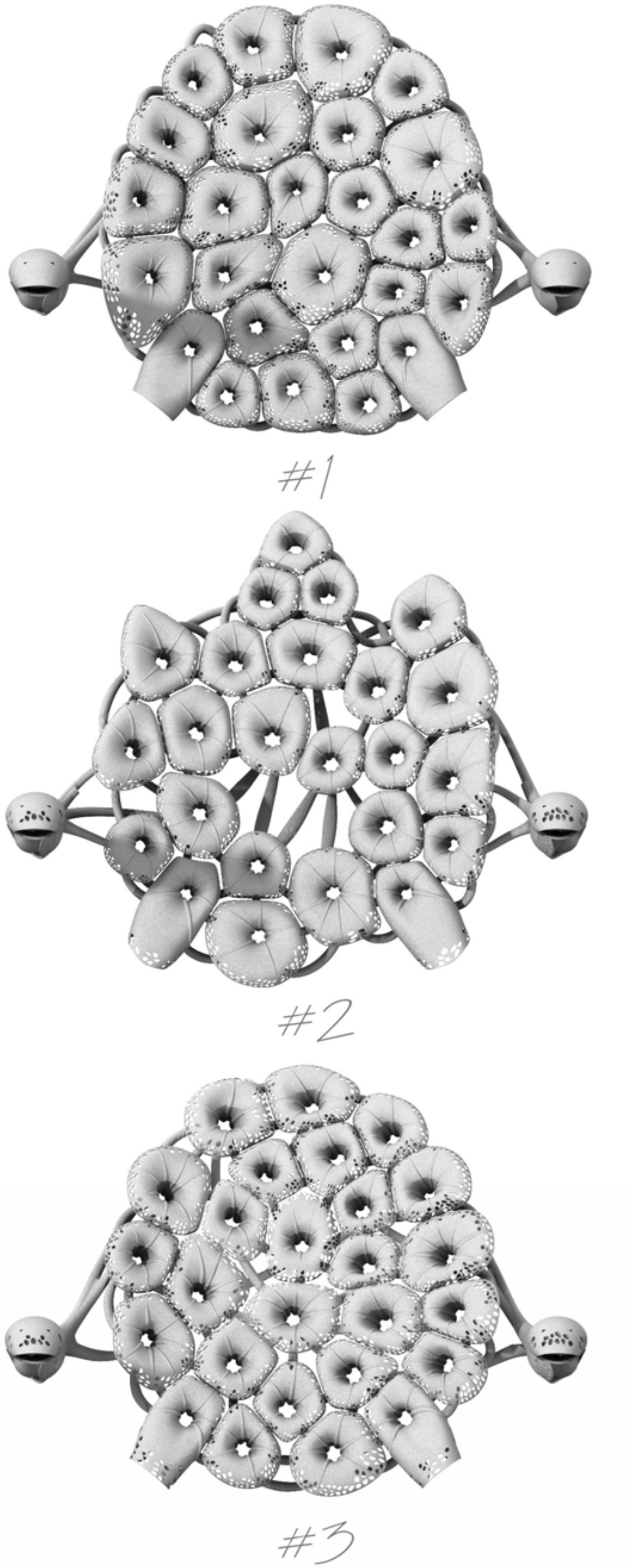


Figure 186
Holy Ghost iterations

Three iterations of the design have been physically produced, Figure 186. These have been included in curated exhibitions, Digitability, Berlin and Trans-Form, Paris.

Digitability held as part of the DesignMai Festival, May 2007, and was curated by Atilano González, Figure 187. The exhibition aimed to take *a, "Close look at the relationship between digital technology and design, paying special attention to digital crafts (digital technologies such as laser sintering now being applied to products as well as customization and a revival in ornamentation)"* (DesignMai 2007). Holy Ghost iterations, #1 and #2, were exhibited along with a new design, Pallavi (Section 7.4).

Figure 187
Digitability DesignMai, Berlin 2007

Trans-Form was curated by Elizabeth Leriche. It was held 25-29th January 2008, to coincide with the Paris furniture and furnishings fair, Maison et Objet. The exhibition examined transformation and distortion in design; the application of, *"Tools primarily reserved for the digital processing of the image are applied to the materialised object"* (Leriche 2007). The exhibition featured physical iterations, #1 and #2, along with two widescreen show reels of the build animation, Figures 188 – 184.

Figure 188
Trans-Form, Paris 2008 (i)

Figure 189
Trans-Form, Paris 2008 (ii)

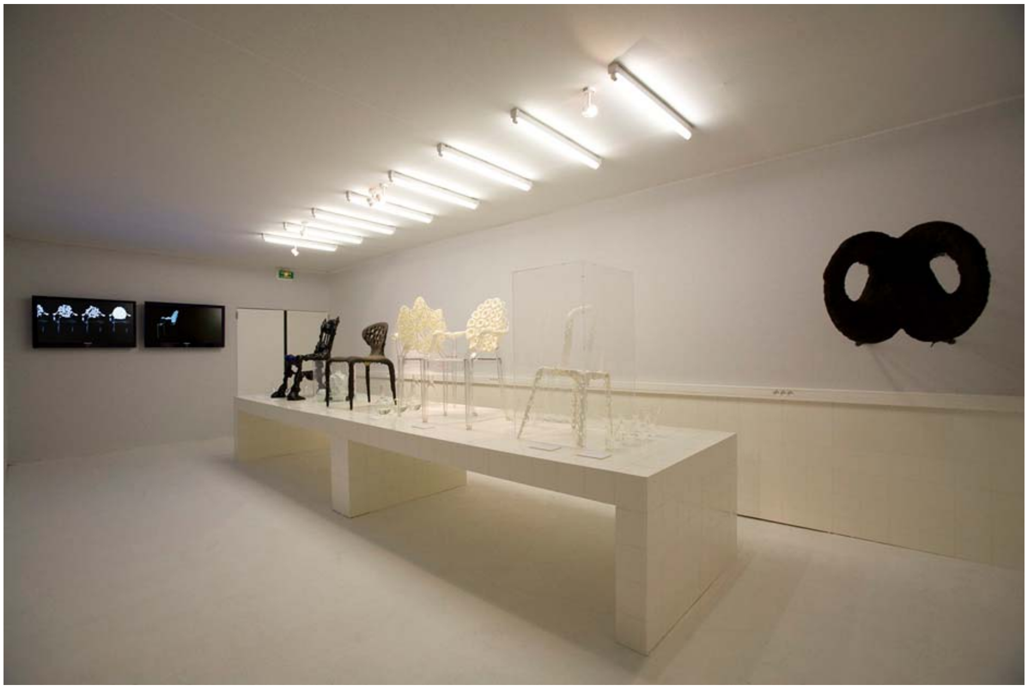


Figure 190
Trans-Form, Paris 2008 (iii)

Figure 191
Trans-Form, Paris 2008 (iv)

7.3.1 **Metal Plated Holy Ghost**

The white texture finish of the SLS marks easily and is difficult to clean. In an attempt to achieve a more durable product, Holy Ghost #2 was metal plated, Figures 192 and 193. In this process the SLS is sealed and sprayed with a conductive paint. It is the plated with first copper then nickel. As well as providing a more durable decorative finish, the metal skin (approximately 300 microns) provides considerable additional strength. The plated chair was exhibited at the Art and Design Gallery of SIGGRAPH 2009, New Orleans, curated by Makai Smith and the Cheongju International Craft Biennale, Korea.

Figure 192
Nickel plated Holy Ghost #2, Front

Figure 193
Nickel plated Holy Ghost #2, Rear

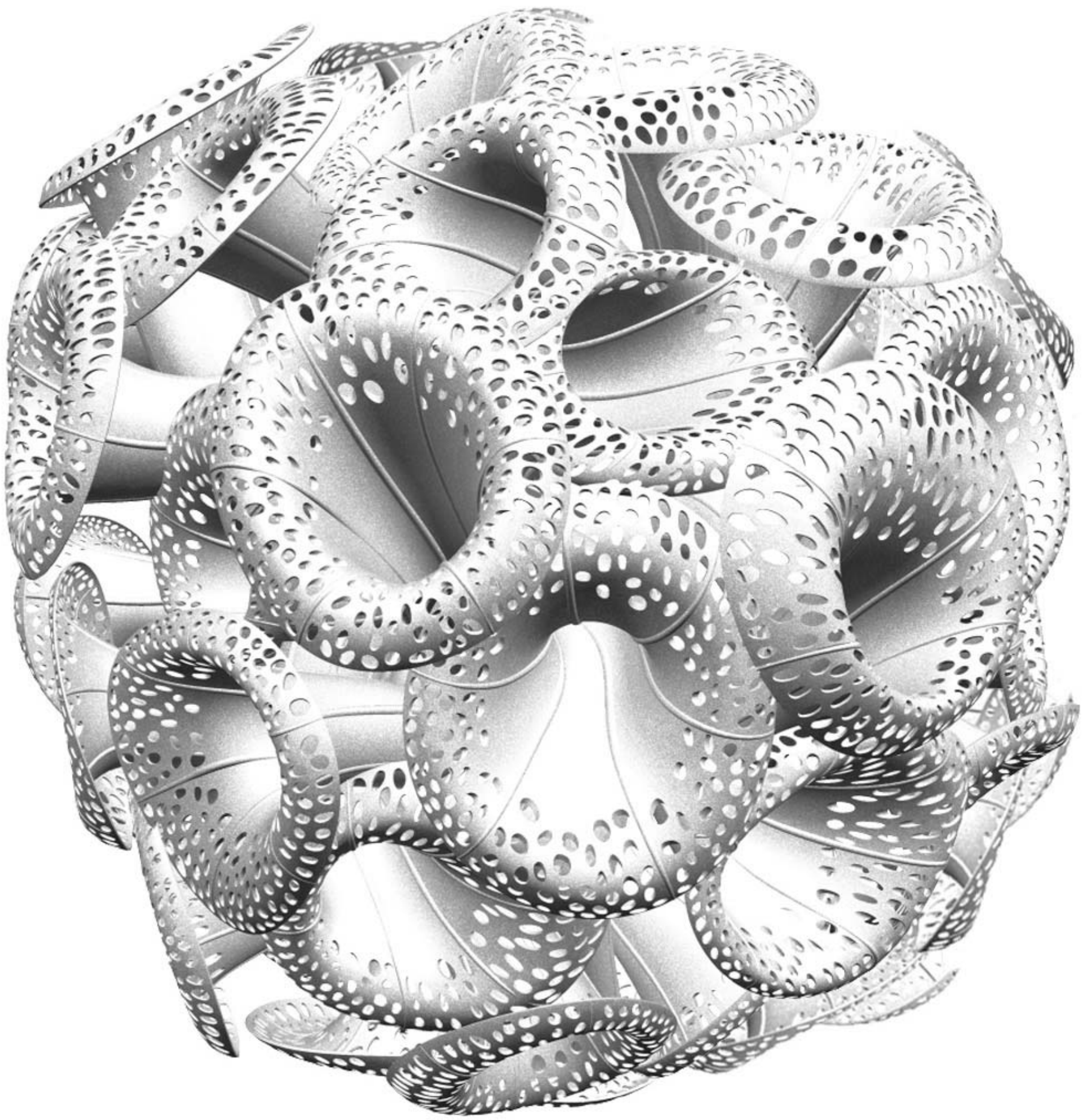


Figure 194
Pallavi

7.4 Pallavi

Pallavi is a 400mm diameter spherical chandelier, Figure 194, created for Designmai Berlin 2007. It was produced using an adaptation of the Holy Ghost button geometry: sixty of the trumpet-like forms are clustered into a sphere. Each trumpet is lit by a colour change LED at its base, shining up the funnel form. Rather that being positioned at random, the base of each trumpet is deliberately placed and orientated on a dodecahedral matrix; five to a pentagonal face, Figure 195.

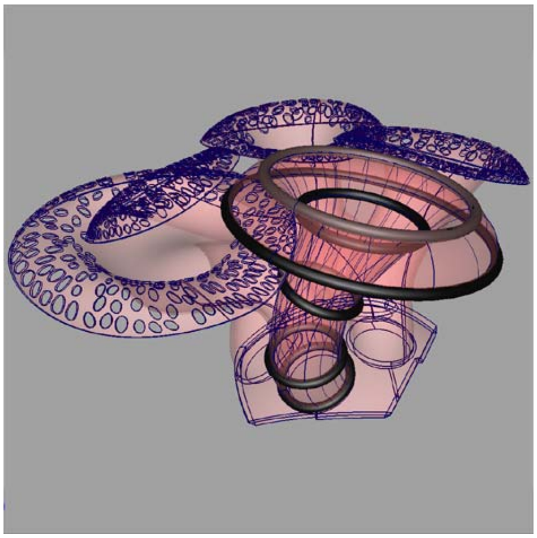


Figure 195
Pallavi geometry

The outer edges of the trumpets are allowed to move and distort within a spherical volume, while their bases remain fixed. The aim is to have sufficient curvature in the funnel-like internal passageway of each trumpet, to prevent direct line-of-sight with the LED at its base, Figure 196.

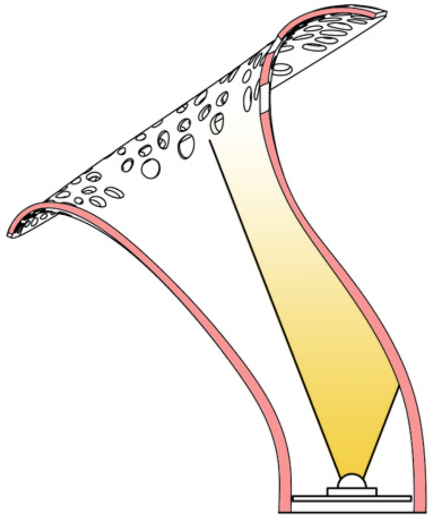


Figure 196
Pallavi LED position out of direct view

The Pallavi trumpets are manipulated independently and each one is different. They are built in laser sintered nylon in groups of five on a pentagonal mounting, Figure 197. The finished design can be seen in Figures 198 and 199.

Figure 197
Pallavi Trumpet Cluster

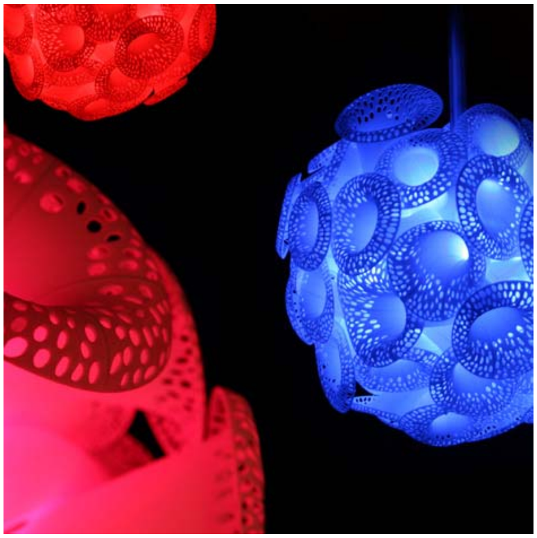


Figure 198
Pallavi Lighting Effects

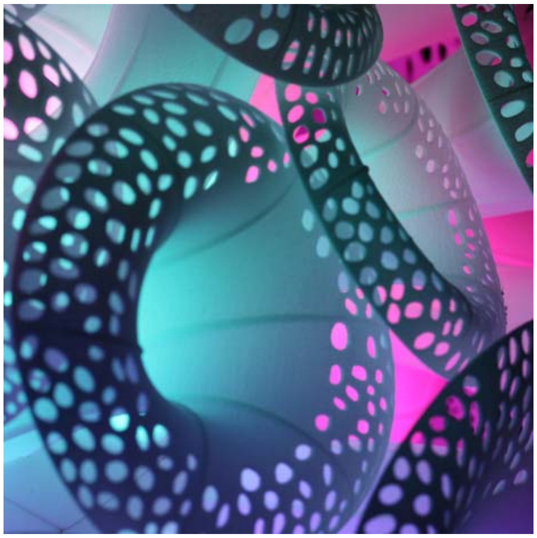


Figure 199
Pallavi Close-Up

7.5 Jewellery

To this point, commercial interest had been in either serially produced identical retail products, for example, Creepers and Entropia; or in selling high value one-off gallery pieces, such as Tuber9 and Holy Ghost. The quest remained to achieve a significant run of individualised pieces, beyond the collections produced for exhibition. An exploration of jewellery seemed a logical step (Dean 2008, Appendix 7). Jewellery is a market in which intricacy and complexity are valued and where premiums may be paid for exquisite form. It is also a market in which the boundaries between industrial production and craftsmanship are blurred and where the value of a bespoke piece is readily appreciated. The jewellery market is, however, generally conservative; particularly in terms of material. Precious metals associated with jewellery have intrinsic value, are durable, inert and long lasting. The polymers of RP, beautiful as they can be, would not win over all but the most avant-guard consumer in this field. A metal, if not a precious metal, seemed essential to ‘compete’ in this market.

Experimentation with jewellery came about through a connection with the Jewellery Industry Innovation Centre (JIIC), in Birmingham, during the organisations tenth anniversary celebrations in 2007. The JIIC is part of the School of Jewellery, within Birmingham City University (formally UCE Birmingham). Based in Birmingham’s jewellery quarter, the centre encourages innovation within jewellery and high value goods industry SMEs (small and medium enterprise), through design, research and technology. As a case study for a two-day industry event, the centre prototyped a series of FutureFactories design proposals. These designs were produced indirectly in silver. A wax pattern was built by additive manufacture and the piece investment cast from this master. Three designs were produced, Aorta, Puja and Icon.

7.5.1 Aorta

The starting point for Aorta was the traditional heart necklace and the notion of substituting the caricature heart with something closer in form to the organ it represents. Aorta uses similar geometry to the Tuber family of lights: in this case with two tuboid volumes that wrap around each other, Figure 200. A closed loop of chain passes through both volumes end to end. Each volume is punctured around its middle revealing the chain and a red enamel inner surface.

Figure 200
Digital Rendering of Aorta 2007

7.5.2 Puja

Puja continued the exploration of a more literal heart organ form. In this case four limbs emerge from a volume. A single closed length of chain loops twice through the volume, passing one though each limb, Figure 201.

Figure 201
Digital Rendering of Puja, 2007

7.5.3 **Icon**

In Icon the geometric techniques and leaf forms first explored in Entropia (6.3) were developed further. Whereas in the interwoven leaf-forms of Entropia were used to create a hollow sphere, the geometry of Icon is allowed to fill an ellipsoid volume to create a pendant form. A continuous string of leaf-forms passes to and fro across the bounding envelope with the form of the leaves conforming to its contours, Figure 202.

Figure 202
Digital Rendering of Icon 2007

Production of the three jewellery pieces was far from straight forward. The designs were first digitally printed in wax, then coated with refractory material to form a mould for the investment casting process. It was essential that the coating filled the fine internal passageways of the wax pattern and that this material could be cleared away after casting. Aorta and Puja both presented problems with keeping the internal passageways clear enough to allow the chain to pass through. This places design limitations on the length and internal diameter of such internal voids. In Icon it was the fine strands of the design that gave rise to problems. Molten metal was required to flow through and fill an irregular assortment of fine passageways and voids, which again placed limitations on what could be produced.

The results from all three pieces were beautiful: but in production terms, heavily reliant on the skills of the JIIC to cast and polish the intricate forms (Dean 2008, Appendix 9). Complexity can be expected in Rapid Manufacture in order to exploit the process's freedoms and to justify the expense relative to conventional methodologies. FutureFactories designs intentionally push the boundaries of what the RP industry can produce. Whilst these forms can be ‘printed’ in wax, or substitute polymer honeycomb, it is clear that coupling this digital fabrication with a secondary conventional casting process would impose significant limitations. Even if the forms could ultimately be cast, setting up the casting with appropriate sprues and risers requires considerable experience: once worked out, the process is reasonably robust but it is seldom right first time. In an extended run this is not a problem with set-up costs amortised over the run, with individualisation, however, it would be. A small change in form might require a complete reassessment of how the piece would be cast.

It became clear that the only way to exploit the full potential of additive manufacture was to build directly in metal. Metal sintering whist technically feasible early in the project had been, prohibitively expensive, hard to access and crude in terms of finish. During the course of the project the technology had improved and become more widely available. Working with EOS and 3T-RPD the possibility of using Direct Metal Laser Sintering in the EOS M270 machine was explored. Of the three designs produced, Icon received by far the strongest reaction and the decision was made to start with this piece.

(i) The Direct Metal laser Sintering, DMLS, Production of Icon

In spite of their free form potential, RP technologies each have their own technical limitations to accommodate. Powder-based methods of rapid prototyping are generally self-supporting for features such as overhangs and undercuts. In production these features are supported by loose un-fused powder thus avoiding the need to fabricate a support structure along with the part. If support structure is required, it must be removed in potentially difficult and costly secondary operations. The lack of support structure in the laser sintering of plastics, coupled with the materials’ mechanical performance, accounts for the dominance of this methodology in Rapid Manufacture.

In spite of the fact that it is powder based, the Direct Metal laser Sintering process with the associated forces of contracting metal, does require support, at least to anchor the part to the machine platform. Each element of the form begins with its underside surfaces linked directly to the bed. In addition to the support underneath, any surface that develops beyond a given angle to the vertical, typically around 40 degrees requires supplementary support from below, Figure 203.

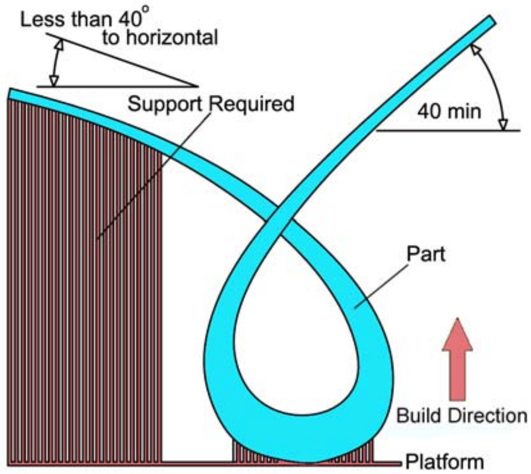


Figure 203
DMLS Support Requirements

Support material is designed for easy removal. In practice this removal is time consuming and leaves surface marking. The problem of support structure removal becomes more acute if the free form potential of RM is to be exploited. In the Icon design, support material within the form, attached to inaccessible inner surfaces would be virtually impossible to remove completely. In addition to the issues of access, the support structure, being of the same material in this process, only breaks away easily when the removable support is finer and weaker that the geometry it supports. The treads of Icon are as fine as will build reliably: this makes the safe removal of support structure difficult. To use DMLS as an effective industrial production tool, support structure, whilst it could not be avoided entirely, had to be limited to easily accessible areas. Working with EOS and 3T technical staff, the original Icon concept was adapted for DMLS production, Figure 204.

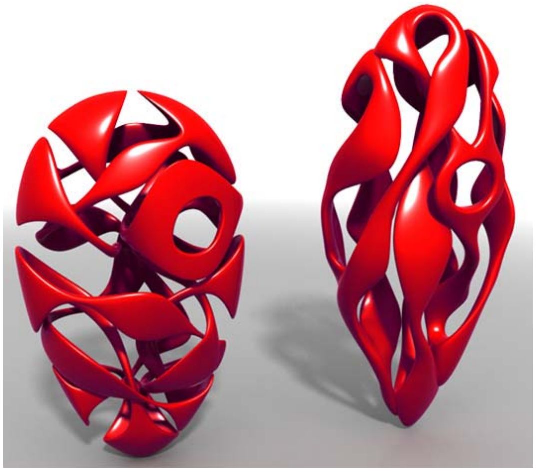


Figure 204
The Original Icon Design on the Left Alongside its DMLS Adaptation

The first decision was to orientate the parts in the build chamber upright, building from top to bottom. Building upside down meant that more area for support was available at the base of the tampering form as built. For cost effectiveness, parts should be orientated with the minimum height in the build chamber. This would have meant building the part on its side and had to be discounted, owing to the internal support structure this orientation would have required.

The original Icon is one chaotic intertwined loop. This was replaced by a four, simpler, separate loops generally running top to bottom in order to restrict the angle to the vertical. Each of the loops starts at the same point touching, and running parallel to, the supporting platform. The loops form a filled-in convex surface where they are overlaid at the base regardless of the morphing. The support structure could be limited to this convex surface at the top of the design (the base as built) where it can be easily removed and the inevitable witness marks polished off, Figure 205.

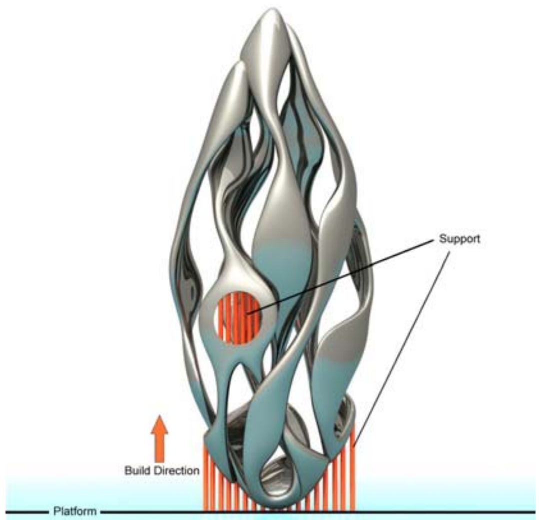


Figure 205
Icon DMLS Build Orientation

The only other area of support required was to form the round ‘eye’ feature, a key element in the character of the design that, it was felt, had to be retained. The supports for the eye feature, across its centre, could be removed with a punch with relative ease.

Stainless steel, cobalt chrome and titanium are commonly used in DMLS. Gold is technically possible. Swede Lena Thorsson has developed a gold alloy for DMLS and together, with designer, Towe Norlén, created gold chain designs using the process, Figure 206. In practice however, gold as a build material is currently inaccessible, amongst other reasons the build chamber must be filled with powdered metal to the build height, requiring substantial investment. Smaller sub-chambers have been developed for gold research and dentistry but the availability as a bureau service is not great.

Figure 206
18K DMLS Gold Chain, Towe Norlén, Lena Thorsson

Titanium, whilst not a precious metal; is recognised and valued as a contemporary jewellery material. For this reason, it was selected as the best option for Icon. Titanium cannot be soldered, which limits the forms that can be created conventionally. Laser welding is possible but it is an expensive, skilled and time consuming process. The use of titanium in intricate pieces is consequently rare. Trial pieces of #1 were successfully built by EOS, Germany, in titanium and stainless steel in January 2008. As a cost saving measure, the design was scaled to 85% of its original height, Z, with X and Y dimensions unchanged. Following this success, a series of 25 pieces were produced as an initial batch of what is ultimately intended to be an edition of 100 individualised pieces, Figure 207. Out of the batch of 25, 24 built successfully with one failure. All 25 were built together alongside each other on the platform, minimising production cost.

Figure 207
First batch of titanium Icons

Icon iterations #1 to #24 can be seen in Figures 208 and 209.

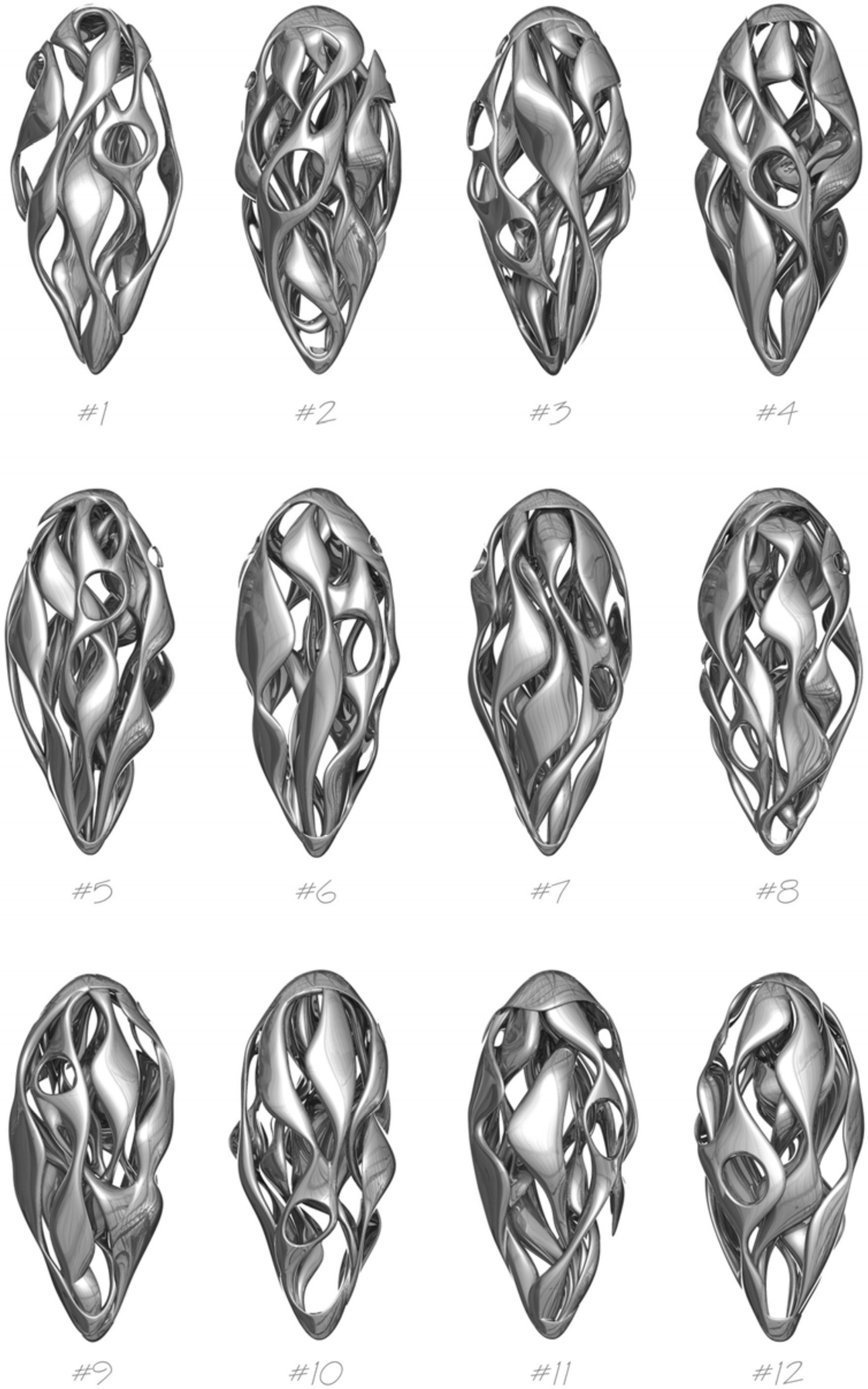


Figure 208
Icon Iterations 1 -12

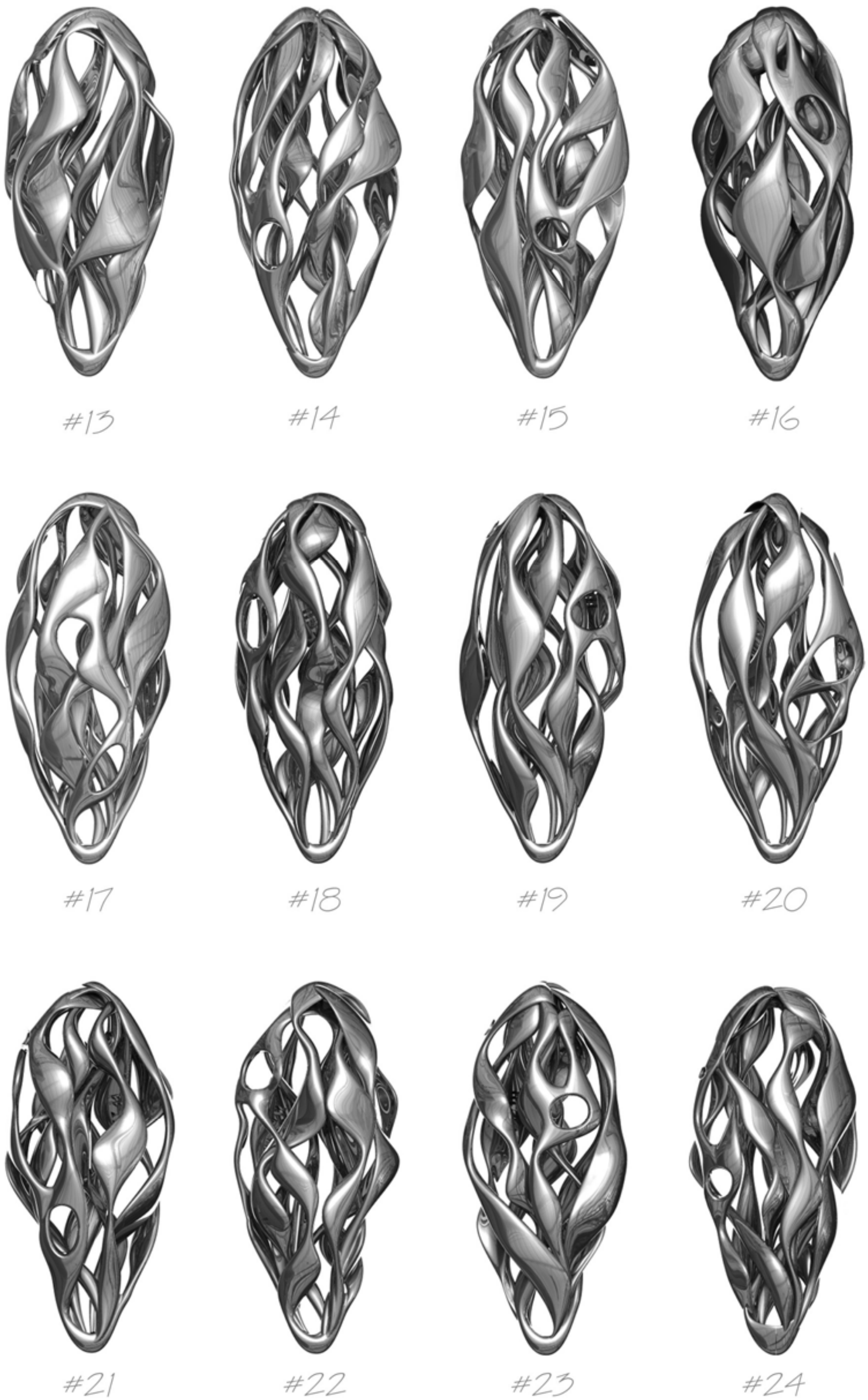


Figure 209
Icon Iterations 13 - 24

Added to the challenges of the casting process, the intricate forms produced require skilled hand finishing. The need to access the form for polishing can again limit the design possibilities. Tailoring the form to the DMLS process had solved the production issue, but the problem of surface finish remained. After building and shot peening, the surface is regular but textured, Figure 210. This finish is not unattractive and would have a market. It does not, however, show off the flowing curves of the form, nor does it fit with the highly finished surfaces of the jewellery market.

Figure 210
Icon Surface Finish After Building and Shot Peening

A level of hand finishing is common in jewellery, but for industrial production this work should not be too lengthy and should ideally be undertaken with the aid of power tools. Inner faces, inaccessible with a polishing mop, and different issues occurring with each piece would not be tenable. To meet the industrial production aspirations of the project a methodology was needed that could be automated and would cope with a variety of geometries.

A study was made of conventional polishing procedures, with the help of the JIIC, Birmingham, Figures 211 - 213. Tumbling with steel shot and a water blast with glass beads had virtually no effect. A centrifugal barrel polisher, with ceramic cones as the medium, had some effect but only on the external surface and this after 25 hours. There are two reasons for the ineffectiveness of these processes: the grade of titanium, which is particularly hard, and the size of the polishing media relative to the forms being processed. Tests are ongoing at the JIIC using smaller media. Historically, the surface of titanium would be treated with perchloric acid. This approach was discounted due to the dangers of using this chemical; the use of which is restricted by Heath and Safety legislation.

Figure 211
Conventional Polishing – Steel Shot

Figure 212
Conventional Polishing – Wet Blast

Figure 213
Conventional Polishing – Ceramic Cones

Polishing the external surfaces only using the barrel polisher, followed by the use of a polishing mop whilst leaving the internal surfaces untouched, was considered as a possible option and the approach adopted for the first batch. A longer term solution came with the use of the Micro-Machining Process, MMP of Best in Class, Switzerland. Working with 3T, Newbury, pieces were prototyped in stainless steel and cobalt chrome. Figure 214 shows a Cobalt Chrome part with the support structure still in place. Some damage can be seen at the top left of the part, as built. Such flaws in the building of delicate parts, such as Icon, necessitated a modification to the standard DMLS machine. The re-coater arm that spreads the layers of powder was changed from a rigid blade to a carbon fibre brush, to avoid the wiper fouling and breaking delicate sections. The revised re-coater is now standard.

Figure 214
A Full Z height Icon in cobalt chrome

Two of the stainless steel parts were finished by the Best in Class Company's process, which employs a mechanical-chemical reaction to produce an automated equivalent of traditional polishing. The process requires a relatively substantial mounting boss to be built onto the part by which it is fastened for the operation. This is not a huge problem in the case of Icon, as the boss was built in place of the support structure at the build base. This feature needed to be more substantial than the fine support structure it replaced, but on a convex external surface it could be ground off and polished with relative ease. The automated polishing proved most successful on the external surfaces, but there was also a marked improvement on the internal surfaces, Figure 215.

Figure 215
MMP Polished Stainless Steel Icon

The results could be improved further with development, principally by increasing the level of energy used; the security of the mounting now being proven. The individualisation of Icon would present no problem for this process and would simply require the addition of a standard boss to each part.

The efficacy of the Best in Class Company's process coupled with DMLS, was proved further with the production of a trophy for the 3rd International Conference on Rapid Manufacturing, Loughborough. A design was created, by the author, which was produced by three methodologies, DMLS, SLS and SLA, to signify 1st, 2nd and 3rd. The DMLS piece made was approximately 220mm high and was polished using the Best in Class MMP process, Figure 216.

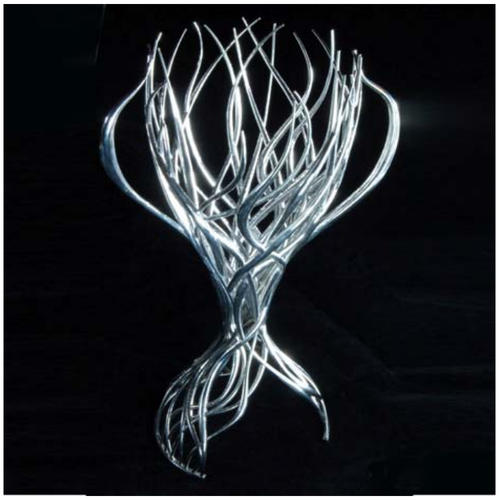


Figure 216
DMLS Trophy 2008

Titanium can be anodised and this option was explored, once again with the aid of the JIIC, Birmingham. Test pieces were produced with blue, gold and purple finishes, Figure 217. As a spectrum of colours is produced according to the time that the current is applied, this could also become a randomly generated variable.

Figure 217
Anodised Icons

7.6 Puja Table Lamp

The Puja jewellery design was revisited in the Puja table lamp, Figure 218. The design was cast first in aluminium and then later in stainless steel. The stainless steel lamp is 600mm tall and weighs 12kg. The pattern was manufactured by printing cross-sections on paper and cutting these shapes from thin board. The board sections were then assembled on dowel pegs and the resulting, stepped form, smoothed. This is a laborious method, but an effective way to achieve strong, inexpensive, large scale pieces. The system could be automated further by CNC laser cutting, or routing, the sections direct from CAD data.

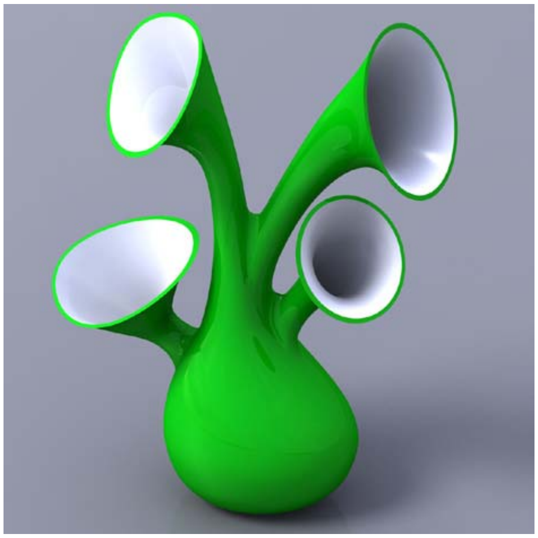


Figure 218
Puja Table Lamp Design

The lamp is lit by four high intensity LEDs, one per trumpet. This design was initially intended for individualisation using the Genemetri software (Section 1.6.1). In the event, the character of the form seemed too attached to single configuration and no further variants were produced. Even the vagaries of casting the form proved a problem. The design was sand cast in sections and welded together before polishing. The first attempts were inaccurate and, while the discrepancies were relatively minor, the character of the design seemed lacking, Figures 219.

Figure 219
Aluminium (right) and First Stainless Steel Prototypes

The first finished Puja can be seen in Figure 220.

Figure 220
Puja Table Lamp, Stainless Steel, 2008

7.7 Section Summary

The First Collection (Section 5) effectively demonstrated the concept. The retail design projects resulting from this work (Section 6) then proved the commercial viability and desirability of the design ideas. The practice documented in this section proves the objectives set out at the start of the thesis. The case studies presented begin with and are driven by computer programming. The programs for Cornuta, Holy Ghost, DNA (I and II) and Superkitch all generate unique solutions each time they are run. Differing approaches are demonstrated, the morphing form seen in the first collection and a building block approach developed to allow for more fundamental change. The artefacts produced come far closer to the project ideal of retail products direct from the machine and there is little of the post-finishing seen in the first collection. In the Icon pendant design, a collection of 25 iterations, is the most extensive individualised production run to-date. Each is visibly unique yet, at the same time, recognisably an ‘Icon’.

8.0 Summary and Conclusions

This thesis develops the ideas set out by Soddu (Soddu 1997). Whereas Soddu's focuses on the generative computation and the artefacts remains for the most part a graphic exercise; this thesis has placed emphasis on the viability of the designs produced. It was a project objective that the artefacts generated be both desirable and functional. Functionality has been demonstrated through lighting that has operated throughout an extensive program of exhibitions. In consumer product terms pendant lighting has limited functional requirement which was to a large extent why it was selected, nevertheless the need to house fixed dimension components and maintain internal clearances for wiring requires technical consideration that is not seen in previous work. The desirability of the artefacts has been demonstrated through the extensive publication and exhibition of the work, perhaps most notably the acquisition of Tuber9 by MoMA the Museum of Modern Art in New York, 2005.

Ron Arad's bouncing vases (Arad 2000) demonstrate the potential for extensive editions of unique artefacts by combining parametric CAD with animation and direct digital manufacturing. In this work iterations are derived from fixed length animations and the animations created from a relatively simple predictable mechanism. Whilst in principle each animations can yield hundreds of frames (Arad 2000) the potential variation in the models presented is limited. They are based on a simple mechanical (in the virtual realm) coil spring action with predictable outcomes. Whilst there will stark contrast between the 'compressed' and 'extended' extremes there will be little discernable difference between individual frames. An aim of this thesis is to achieve obvious visible difference between iterations while maintaining a coherent design identity. This is successfully demonstrated in the Icon pendant jewellery. The 25 pieces produced are all identifiable as the Icon design, while each remains distinctly unique.

This thesis has successfully combined parametric CAD, computer scripts and digital manufacturing. The Virtools scripts created for Holy Ghost, DNA and Superkitsch can be run on virtually any pc with the freely available Virtools player. In a matter of minutes they will generate a unique iteration of the respective design each and every time they are run.

8.1 Technology

8.1.1 Additive Fabrication

When the project began, Direct or Rapid Manufacturing, the production of end–use artefacts direct from CAD data, was only a theoretical possibility. There were examples of functional parts being built by additive fabrication for engineering applications in the automotive and aerospace sectors. There were also examples of customisation via RM in medical applications, hearing aids, for example. There were however no examples of commercial retail products. High capital equipment costs, slow cycle times, inferior high cost materials and poor surface finishes, seemed to limit Direct Digital Manufacturing to technical niches for the short to medium term.

Less than a year after the project began the first RM retail products appeared. Arguably this was initially as much a PR opportunity from a major RP service provider as a commercial venture; never the less the euphoric media and public reaction that the products generated established RM as a mainstream manufacturing process. Two years later Kundalini, Italy, became the first established manufacturer, other that an RP bureau, to mass market an RM product with Entropia from this project.

Counter intuitively, current examples of RM have tended to be high end domestic interior products, a market in which surface finish is of high importance. It is however also a market that embraces new technologies. Rather than being seen as a coarse equivalent of moulded plastics, RP materials have been accepted in their own right. The stair-step striations of the layer build processes are accepted provided the resolution is fine enough. The finish may even be celebrated, especially in lighting objects, as discussed in Section 6.3.1.

Today there seems little need to justify Direct Digital Manufacturing, at least at low volumes. It is however, and will remain for the foreseeable future, a premium process over conventional mass market methodologies, injection moulding and die casting for example. The use of RM has to be justified by exploiting the freedoms of additive manufacture and exploring new modes of both design and consumption. This project represents one of these alternative approaches to production and consumerism. It seems clear that computer-based design and fabrication tools have the potential to affect the wider cultural landscape in profound ways (Rahim 2005, cited in Marshall 2007). Wilson suggests that, *"Rapid Prototyping is culturally significant because it moves into territory that is under explored, namely, the linkage of the virtual and the physical"* (Wilson 2002).

The excitement of digital manufacturing is not in its gradual adoption by mainstream manufacturing, this is already underway; but in the increasingly blurred boundaries between industry and the creative arts.

Exploiting the freedoms of Digital Manufacturing will require new approaches across the corporate landscape and not merely in production. The lack of physical production tooling eliminates a key stage from the design process; the point at which production drawings would be passed to a toolmaker. After this point, the design would become fixed with further modifications costly. In Direct Manufacture design development can continue up to the eve of product launch and even beyond. In the design of Entropia (Section 6.3), design development continued after the first saleable batch had been produced. A situation can be envisaged, similar to computer software releases, in which a product improves by degrees through its lifetime, versions 1.0, 1.1, 1.2 etc. In view of the potentially large design investment required in complex designs, products could evolve in stages. The early design could be sold in modest quantities to avant-garde buyers in order to fund ongoing development; a 3D equivalent of computer software beta testing. Over time, the product could gradually become sophisticated and 'mainstream' appealing to a widening market.

Marketing practices, such as an annual printed catalogue mitigate against flexibility. The 2006 Kundalini catalogue ran to 166 pages and featured Entropia on the cover, Figure 221. Over time, new marketing practices will emerge; consumers' behaviour will also need to adapt.

Figure 221

Kundalini Brochure, 2006

8.1.2 **Bureau Culture**

Rapid Manufacture is something of a misnomer in the industry generally. Product development speed was not a primary consideration in this project. Speed is more applicable to the prototyping side of additive fabrication rather than industrial production. The emphasis placed on rapid turn around by service bureaus, which is such an asset in product development, is often a barrier to Rapid Manufacture. The prototyping bureau industry is characterised by feast/famine workloads and large amounts of overtime. This model does not lend itself to manufacturing where efficiency is paramount and profits are made over a longer term. If Direct Manufacture is to develop, the approach of service providers will need to change. The marketing approach of the machine manufacturers has already changed in recognition of the sales opportunities RM offers. EOS, the largest provider of sintering equipment now refers to themselves as EOS e-manufacturing solutions (http://www.eos.info/en/home).

In current industry practice the set-up and optimisation of the additive fabrication build is the province of the RP bureau. Outside of the automotive and aerospace industries, it is rare for a manufacturer to possess in-house equipment. The placement and arrangement of models within the build volume is undertaken by RP bureau staff, who are presented with the model when it is complete or in the final stages of development. As has been demonstrated in the case studies, the efficient use of the build volume is the most important factor in determining the viability or otherwise of Digital Manufacturing projects. It is vital that the design is tailored, from the concept stage, to use the chamber efficiently and to allow the accommodation of a commercially viable number of units. Ideally, software for this function would be brought within high-end CAD packages so that it can be referred to by designers, throughout the design process, rather than existing as a stand-alone package aimed at RP service providers.

8.1.3 **Materials**

Early RP materials and equipment were split between the roles of visualisation and testing. This divide is familiar from the aesthetic models and test rigs of traditional design development. Models for visualisation would be non functional solid blocks; test rigs would prove function but convey little of the design’s finesse. The early technological limitations and the inability of RP equipment to couple surface finish with engineering performance tended to recreate this divide. Processes such as Selective Laser Sintering (SLS) and Fused Deposition Modelling, FDM, could provide structure and demonstrate ‘moulded-in’ features such as live hinges and springs clips, the surface finish however would be coarse. Stereolythography, SLA, with a little hand finishing, could achieve an excellent surface finish but would be too brittle for practical use and would be dimensionally unstable over time, as the material absorbs water from the atmosphere.

Recent developments in materials and processes have narrowed the gap between visualisation and testing roles considerably. Increased resolution has given sintered and FDM components if not a smooth, then a much finer finish. SLA epoxies have brought increased stability and improved functionality. SLA resin supplier, DSM Somas, have registered the trademark *proto-functional* to describe their products. True prototypes are now possible, that both allows aesthetic assessment and proves function.

In Rapid Manufacture, for the decorative design market, public perceptions of material value are a significant issue. Plastics, however exotic from a material's science perspective, do not have the same cache as, for example, glass or ceramic. Whilst RP plastics have been well received amongst avant-guard buyers, this may not last and a wider customer acceptance must be achieved for the market to grow.

Material strength and build resolution can improve perceptions of quality; fine detailing and a delicacy of proportion communicate craftsmanship. This is exaggerated in lighting applications, where translucency accentuates fine section thicknesses. He researcher has used thicknesses as low as 0.5mm and these have built reliably. This is well below that which would be recommended for the process. Many bureaus give a standard warning if model section thicknesses drops below 2mm. Many FutureFactories designs do not have any sections above 2mm. Robust sections are encouraged in the RP industry because of the cost of the process and the risk of scrap. This caution however means that the full potential of the processes may not be realised.

As seen in the RGB 'eyelashes' (6.1), the nature of the material can limit the design as much as the production technology. Material strength must develop to match what can be built. Designs also should accommodate potential build shortcomings. Ultra-fine sections can be used in areas that are purely decorative and where the overall structure would not suffer unduly, should fine edges not build completely. Redundancy could mitigate against the risk of failure in minor decorative elements. Where there are massed numbers of features, following no discernible pattern, the absence of one or two may pass unnoticed should they fail. Creepers (6.2) features groups of leaf like reflectors on delicate stems, Figure 222. One or two of these reflectors have periodically been damaged, during transport or assembly. In these cases the remainder of the stem has been removed and the product distributed as normal.

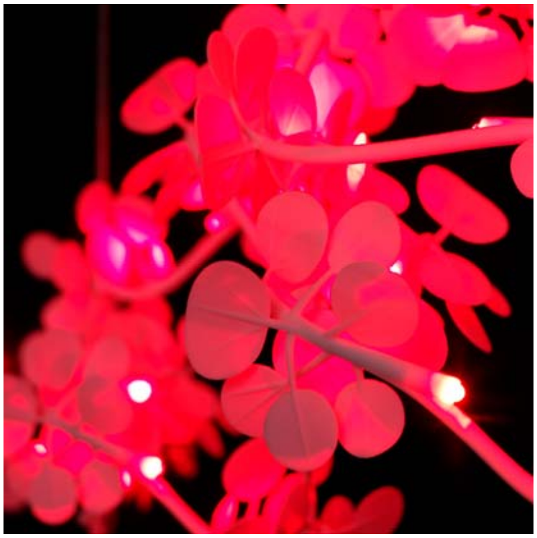


Figure 222
'Redundant' Creepers' reflectors

8.1.4 Sustainability

In consumer product development, the sustainability or otherwise of prototyping equipment is of little significance compared to the volume production it will influence. More effective prototyping should, through more considered designs, lead to more sustainable production. Consequently, little or no emphasis has been placed by manufacturers on RP equipment and processes. As the industry turns its attention to manufacturing, this issue needs to be addressed.

Additive manufacture is in principle a more sustainable practice than anything subtractive. In theory no more material is used in additive manufacture than is employed in the artefact itself. In many technologies however considerable additional material is indirectly consumed. In the laser sintering of plastics, artefacts are built within a block of un-fused powder. This unused material is degraded by the heat of the process forming longer polymer chains. Only a proportion of recycled material can be used in the process (up to 20% is recommended) if surface finish is not to suffer. Other processes such as SLA require a physical support structure to be built along with the artefact requiring both energy and material. There are however less energy intensive processes such as those of Z-Corp, USA, whose materials are lower tech; being based on the likes of plaster and corn starch. In this process the powder is 100% recyclable.

Aside from the equipment and processes, the flexibility inherent in digital manufacturing offers significantly more sustainable models of a consumer society than the one we take for granted today. In particular:

- Products can be produced on demand and not stocked;
- Ideas can be transferred electronically rather than freight being shipped;
- Products can be manufactured locally for local needs; and
- If consumers are engaged with the creative process, there is a greater likelihood that there will be an emotional attachment to the product, which will consequently become less disposable.

8.2 The Consumer Interface

A key component in any customisation or individualisation system is the consumer interface. Rather than there being a static product outcome there are potentially infinite solutions. To appreciate this capacity for change the consumer needs to see more than a single solution. In the context of this research a capacity for change over time needs to be demonstrated. Screen based Internet shopping offers the possibility of digital animation: however, a single video clip played on demand would be insufficient as there should be no cycle to the mutations. Ideally the consumer should witness the script driven model itself 'morphing' in real time.

Systems are envisaged where the consumer is presented with the virtual meta-design via a website. The consumer may access the website directly on their own computer equipment or via a sales outlet, a pop-up shop in a gallery or in a department store for example. The web site would offer a series of current designs. Having selected a product the user would be presented with a real-time animation of that design in metamorphosis. At any given point, the consumer may 'freeze' the animation, effectively creating a one-off design on screen. Should they wish, they might then proceed with an order, in which case the relevant digital production files, for example Standard Triangulation Language (stl), would be generated automatically and sent to one of a group of participating bureaus for manufacture using appropriate rapid prototyping techniques. The animation is changing in real time and is thus outside the users control; this should be the allure of the process. A unique solution is generated which can be accepted or replaced by an alternative as the animation continues. The interface therefore is aimed solely at ensuring effective communication of the form rather than being any form of design tool in itself.

8.2.1 Virtual Reality, VR

Visualisation is a significant issue in internet shopping generally where there can be no physical sample to examine. Web based marketing can be used to access global niche markets, the difficulty lies in convincing would-be consumers of the suitability of products they are unable to physically handle. Visitors to an individualisation website must be able to appreciate the potentially complex forms with which they are presented, a difficulty exasperated by designs in a constant state of flux. Some form of web-based Virtual Reality, VR, experience might help overcome this difficulty, enabling the consumer to 'move around' the design in their own time and at will.

'Virtual Reality' refers to a computer-based activity that mimics real experience. The primary characteristics of such an experience are that it is three-dimensional and that it is interactive. At its simplest VR may be a 3D image that the user can rotate to view from various angles. At an intermediate level, it can be an entire scene or virtual world that the user enters and interacts with. Advanced systems require the user to wear special equipment, goggles and gloves for instance, that make the illusion of reality more complete. High-end VR is expensive and complex: it is the province of games or specialised applications like military training and is not usually web-based. The less sophisticated forms of VR however, offer significant potential for consumers to interact with a virtual design. This can be web based and need not require any specific equipment.

Conventional marketing usually centres on still studio photography. VR content enables websites to bring the products 'to life' with interactive animation allowing the product to be seen from all angles. Potential customers are able to examine the virtual 3D model moving, rotating, and zooming in and out at will. This ‘hands-on’ interaction allows something of a “try before you buy” experience. Internet shoppers may spend 50% more time in the part of the site that offers interactive 3D images (Hurwicz 2000). Historic barriers to uptake of VR, the power of PCs (Personal Computers), the speed of internet connections and availability of authoring tools and expertise, are now greatly reduced; although there is likely to always be a trade off between advances in audio visual technology and the computational power to supply them. A level of audiovisual interactivity should therefore be considered.

Discounting expensive gloves, VR remains an audiovisual experience and consumers will always prefer to handle the merchandise. A middle ground solution may be to provide a VR interface within high street retail outlets, where physical samples and a tactile experience of material are also available.

8.2.2 The User-Script Interface

In the FutureFactories consumption model the consumer needs to interact with the scripted meta-design in real time. This can be achieved in one of two ways; the script can be run on either the host server or the customer’s PC, Figure 223. Each approach has both merits and drawbacks.

(i) Host Server Approach

The script can be run on the vendor’s equipment, giving the developer complete control over its operation. Only video content, and no 3D data, is transmitted to the consumer or client PC. This is a security benefit and there is no requirement for specific content playing software. Video streaming is extremely common: there are several suitable players available and the vast majority of PCs will already have appropriate software installed.

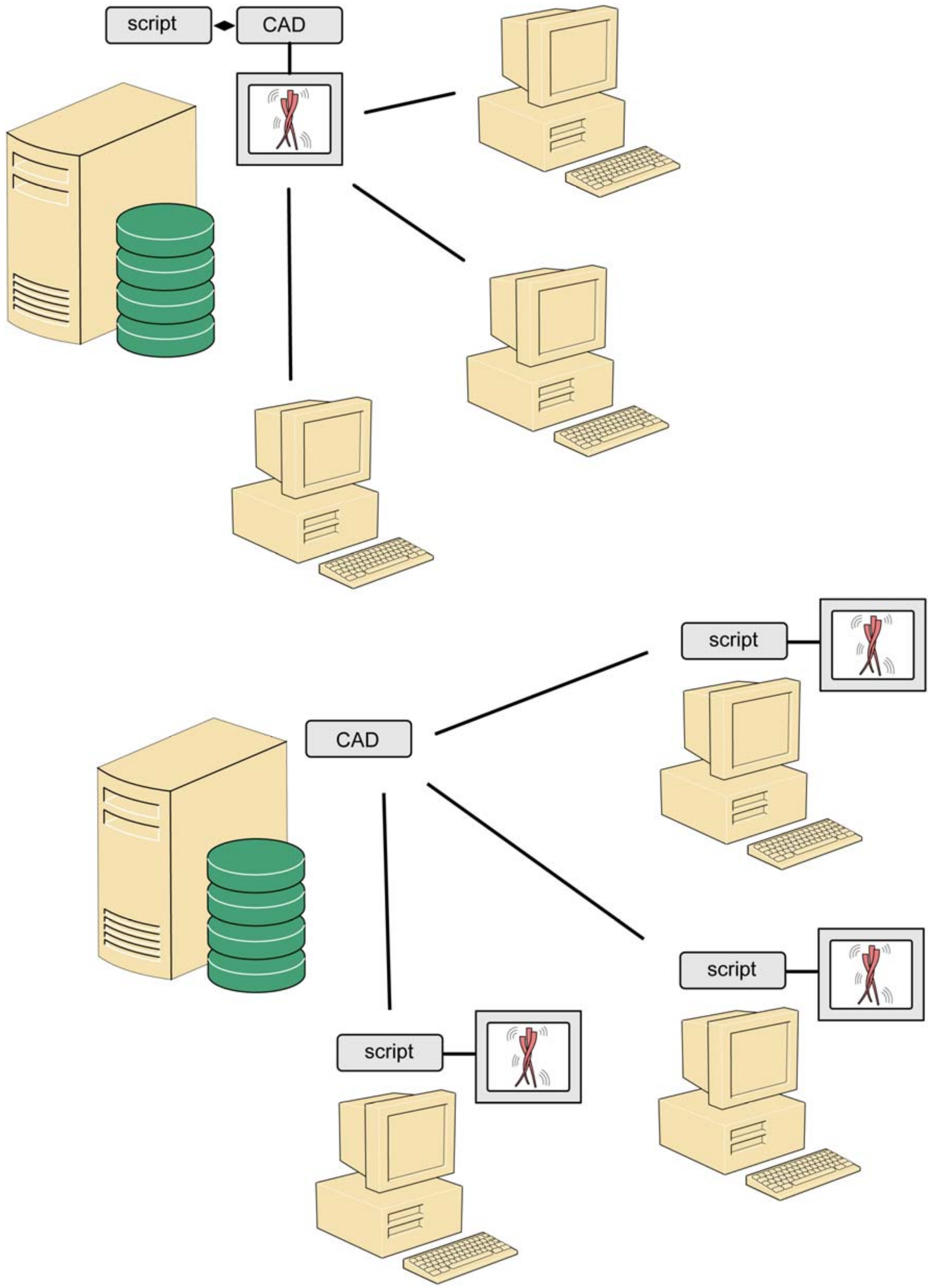


Figure 223
Host Server and Client PC Approaches

A drawback is the need for the server to handle unknown numbers of users simultaneously. This capacity may be redundant for the vast majority of time. Then there is the issue of pausing the animation. The animation could not be truly halted (as it would stop for everyone) and some form of 'live-pause' of the kind seen in digital broadcasting would be required. As a positive, the consumer's lack of direct control might encourage the air of the on-line auction with the imperative to act before it is too late.

The host server approach has advantages from a digital manufacturing perspective as no design data is required from the customer's computer. The only information required from the client PC is the precise moment or frame that the animation is stopped. This frame identifies a particular configuration of the meta-design scripted on the host server and any amount of CAD data can be extracted from it regardless of the technology at the user end. This form of interface would suit procedural animation based designs (Section 4.2) such as Tuber where there is no particular beginning and end to the metamorphosis.

(ii) Client PC Approach

In this approach the computer script controlling the virtual model is downloaded and run on the client's PC using web browser plug-in software. 3D software applications are available that offer both developer and plug-in player levels. The developer version is typically commercial and allows the creation of sophisticated 3D content for the web. Content created may then be distributed via the internet and 'played' on web browsers using free 'plug-in' software.

Running the script on the client's PC means that each customer is seeing their own metamorphosis, which can be stopped and started again from the same point as they see fit. If appropriate, the design can build from scratch each time it is loaded allowing the user to see much more dramatic change than might be evident in the mature mutations.

The most obvious drawback with this methodology is that the script has to be tailored to the likely power of the client's PC and to a file size which can be acceptably transferred. Added to this a specific plug-in is required which will need to be installed on first use. There is also an issue with information transfer. If and when a design is ordered, sufficient information must be transferred from the client's PC to either build the part directly or replicate the virtual design on the host server. A further potential problem is that of security: 3D data, albeit not necessarily sophisticated CAD data, is generated on the client's PC. These issues mitigate against complex surface models that required heavy scripts and large data sets. There is however great potential for more simple designs, specifically designed to run on plug-in applications such as the Virtools 3D Life Player (Section 4.4). An example of this is the SuperKitsch bangle created as a case study using Virtools' software as the scripting tool.

8.3 The Role of the Designer

The development techniques developed though this thesis have in aspects matched the researcher's regular practice and elsewhere been diametrically opposed to it. Defining forms technically through parameters, relationships and cross sections has come very naturally. The need to begin by setting up rules and relationships rather than through inspirational sketchwork has been more of a shift. In the early work there was a tendency for form to come before the script and to drive its development, in part perhaps due to the timing of the exhibition programme. In the later work however the script came to lead the design process. Script driven geometry would be conceived and then consideration given to forms that might be derived from it.

The lack of exciting visuals in the early stage of design development may present problems in an industry with commissioning processes geared around the artist impression, rendering or concept sketch. This issue was highlighted in the commissioning of Holy Ghost (Section 7.3).

8.3.1 Design for Manufacture

As product design moves into a post-industrial era creative industries and design education will need to adapt. Design for industrial manufacture is central to, if not the definition of product and/or industrial design. This has previously meant design for mass-production and the tailoring of components to specific manufacturing technologies. Design for manufacture has been the central tenet of design education. There are of course manufacturing considerations in design for additive fabrication, as is evident in the case studies and the notion of 'free-form' fabrication is something of a myth. Such restrictions as there are, however, do not carry the same weight as those in conventional manufacturing. The injection moulding of plastics is conceptually similar to the pressure die casting of metals. Not withstanding their similarity, switching production between these two methodologies would be an onerous task requiring new tooling and a huge investment. In additive fabrication a part can be changed from metal to plastic simply by sending the 'stl' file to a different machine.

Consumer products are often complex assemblies. There is often a need to work around fixed, conventionally produced components. This restriction is likely to diminish however, as it becomes possible to build in a greater variety of materials and material combinations. Absolute dimensions no longer have the relevance they once had. Materialise-MGX offer to produce their designs to order in any reasonable size (http://materialise-mgx.com). Manual drafting has been replaced by 2D CAD drafting packages, such as AutoCad, both in industry and in design education. As 3D CAD becomes the common methodology and with it the provision to output technical drawings automatically, the need for any training in 2D drafting can be questioned. Is there even a need to dimensions a drawing if dimensions can be taken directly off a 3D virtual model? Arguments such as these are set to develop as digital technologies shift the emphasis onto abstract formula underpinning a design rather than absolute solutions. There is a gradual shift in emphasis from the physical datum, printed drawings,models and the like, to virtual computer-based master data.

8.3.2 Communication

Traditionally, product design development models begin with loose concept ideas that are gradually refined as the project develops. Practicalities are fed in gradually, so as not to 'suffocate' the style of the raw concept. Early sketches communicate the character of the design before detailed technical work has begun. This allows the design to be assessed before significant investment is made.

Computer generated forms are hard to envisage and complexity, by its very nature, cannot be easily reduced or predicted. In computational design the initial priority is in setting up relationships, parameters, and formula, rather that looking ahead to what they will ultimately produce. Creating such rule-based systems takes time and requires something of a leap of faith on the part of those commissioning the process (as was required in the commissioning of Holy Ghost 7.3). It is not usually possible to generate outcomes before the system is established. Once the rules are in place, however, any number of design iterations can be generated with relative ease.

8.3.3 Authorship

Interactive selection by the consumer and computer generated form, raise philosophical questions around definitions of terms such as 'design' and 'designer', challenging accepted notions of authorship. There is debate as to whether the end results are 'art', 'design', 'craft', or 'computer generated'. FutureFactories is among a wave of emergent digital practices which are forming a new position for practitioners, with alternative routes to manufacture and modes of consumption. The potential impact of FutureFactories has been noted and described since the first stage of this work (Atkinson and Dean 2003, Appendix 3) and are still considered significant. As the project has developed, additional elements have been recognised with respect to the system's impact on issues of authorship and accepted notions or definitions of design practice (Atkinson and Hales 2004).

Where a consumer is interacting directly with generative software, the original 'designer' may not even be aware of products selected and produced in his or her name. Computer control and autonomous production potentially act to isolate the author of the work from the outcome, and raise questions of responsibility and ownership. The potential for remote manufacture brings isolation in itself. Digital sculptor, Keith Brown, commented that he had contributed work to exhibitions in other continents without having seen the work in the flesh. Digital files had been sent to remote exhibitions, where the pieces were digitally manufactured and exhibited, without the creator seeing them. Freedom of Creation founder, Janne Kyttänen, spoke of designing a trophy for an organisation in the USA. The award was manufactured and presented without the designer seeing it. In these examples the practitioner had at least seen the virtual design, in an automated production system this might not be the case. A careful setting of constraints and considerable faith would be required for designs to be allowed to evolve and mutate unseen by their creator.

The individualization concept of this project requires inputs from designer, software and consumer. If the user, the consumer ordering a piece, makes an aesthetic judgment on a form, the precise configuration of which has been generated by a piece of software; then who has 'designed' it? The author has deliberately limited the consumers' input to the selection of one variant over another. This is in contrast with the slider bar approaches of some systems (e.g. Fluidforms, Section 1.5.3). Nevertheless; the consumer is able to express an aesthetic preference. Is the selection of one variant over another a significant creative decision? Similar issues were identified by Todd and Latham, with respect to virtual sculptures created via the 'Mutator' code: "*Who owns the copyright? What is copyright? The generative system? The genetic code for a final form? The computer form? The computer image? The artwork on a gallery wall?"* (Todd and Latham 1992). Limiting the 'customer' to a simple start, stop, and order commands has proved untenable. In the trial computer interfaces created for the First Collection exhibitions, 2003, the user was allowed to temporally save a series of selections rather than choosing between ordering a single selection or restarting the animation. A on-screen folder would display up to three selected iterations. The user could then choose which of the selected iterations to ultimately print. Whilst this does not represent significant creative control, aesthetic judgement is being exercised which cumulatively, over a population of users, could potentially steer the design direction.

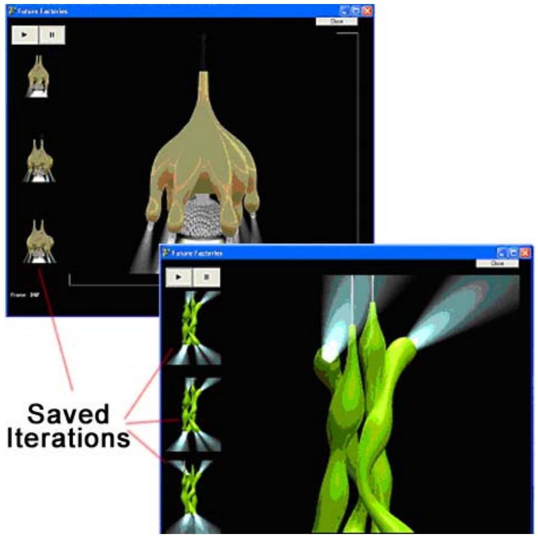


Figure 224
The Experimental User Interface

The potential effects on the practice of design are considerable. Whatever the future holds, there are certain to be serious changes occurring. Obviously, the future role of the designer and where he or she fits into the design process is one that will need to be examined closely and perhaps readdressed.

8.3.4 The Geometry Comes Free 'Myth'

Additive fabrication can do more than replicate the intricate moulded components of contemporary consumer products. If Direct Manufacture is to be viable, it must take advantage of inherent flexibility and freedoms to justify elevated costs. Digital manufacturing can go far beyond the bounds of moulded plastics producing components that would be far too expensive to tool for conventional manufacture. Multi-piece assemblies can be replaced by single components not by merely 'stitching together' conventional parts, but by building the function of one component into another. Components become multi-layered simultaneously addressing aesthetic, structural and functional requirements. The integration of features is common in design and engineering practice; it is the extent to which this becomes possible that presents both the challenge and the opportunity of digital manufacturing. Traditional product development roles become blurred as individual components address a range of criteria and require input from a range of disciplines. In the Rapid Prototyping industry, geometry is often said to 'come free' with parts of similar dimensions costing the same regardless of complexity. This is true in terms of manufacture; exploiting this freedom however requires considerable investment in design. Instead of being centred on tooling; production investment moves to the development of ever more complex virtual models. Engineers and designers need new skills and understanding to manage complex multi-layered projects, in order to fully exploit the potential of digital manufacture.

When a complex design is being created, visualisation in the virtual world becomes an issue. It is difficult to orientate ones self in a complex on-screen model. It becomes hard to identify issues that would be readily apparent when handling an actual prototype. A greater range of more flexible visualisation tools are required; ideally built into the CAD software systems themselves. For the trans-disciplinary potential of digital design and manufacturing technologies to be realised; interface improvements must, however, go further than providing increased functionality for the formally trained. Currently, *“Digital tools and media change almost as rapidly as anyone can master them”*, and *“New features keep appearing, interaction methods evolve, and underlying contexts such as operating systems change”* (McCullough 1996). Much software development centres on increased functionality, which only benefits full time operators, while constant updates confuse the casual user. One software package or suite rarely offers all the potential required. In this project regular use has been made of the following packages:

- Alias StudioTools
- SolidWorks
- Rhino
- 3D StudioMax
- AutoCad
- Virtools

Each software package has a different interface, different terminology and different sequences of commands for broadly similar operations.

8.3.5 Art, Craft and Design

The use of software processes and real-time networks as generative tools, questions existing, transient, boundaries of practice, and exposes the irrelevance of conventional definitions of role. It is clear that the outcomes of such a new model of creative production cannot be thought of as traditionally conceived pieces. Existing definitions convey little of the reality of their production and they lie in some new, as yet unspecified, arena of production.

Despite the highly complex issue of defining ‘design’ per se (Micklethwaite 2000), and without wishing to enter an extended debate about the distinctions between craft and design; a simplistic approach can be adopted. If the outcome is dependant on a particular individual making skills it can be considered a craft. If the artefact could be equally well manufactured by a number of appropriately skilled companies, then it is surely a piece of design. The FutureFactories production model is intended to be a design process in that sense. The designer creates a system capable of generating endless design iterations. A specification is created thereafter outputs are mechanistically generated. The practitioner is only required to create the initial meta-design rather than for day to day production

Pye differentiates the processes of making things into either “the workmanship of risk” or the workmanship of certainty” (Pye 1968) and describes a spectrum of operations from “free-“ to “regulated-“ (Pye cited by Gordon, Woodwork 1996). The economics of conventional mass manufacture depend upon standardisation and uniformity; the highly regulated workmanship of certainty with no room for risk. FutureFactories introduces or reintroduces in the industrial era, risk in mass produced goods and in doing so blurs the boundaries between traditional notions of craft and design. The ethos remains clearly within design however and the ambiguity indicative of a need to separate design from traditional notions of mass manufacture.

The consumers input must also be considered. The fact that customers can make an aesthetic decision to buy one variant over another does not seem significant when considered in isolation. One can imagine that volumes of consumers making particular selections would steer the design in the longer term, but sales pressure is also a factor in conventional design and manufacture. The FutureFactories’ concept attempts to remain solidly within design, dismissing the creative input of a user offered given little control. There is again some blurring of boundaries and distinctions; the preferences of consumers will be more readily felt than in conventional models of consumption. Added to this there is the possibility, and therefore pressure, to react to demand now that product life cycles are no longer fixed.

8.3.6 Design Skills and Education

As far as the impact on design education is concerned, every aspect of the curriculum may need to be addressed. Design for manufacture will be less concerned with specific production processes and the generation of a specification; and more concerned with the creation of producible entities by a digital manufacturing process and creative systems. The teaching of materials and processes for manufacture premised on mass-production would, of course, also have to be reduced or replaced with a higher level of emphasis given to digital manufacturing techniques and computational design techniques.

The emphasis on achieving mass market production volumes will need to be re-balanced. Target markets can become more focused and respond to immediate opportunities. Market research will become more concerned with discovering untapped niches, rather than common denominators. There will be a need, perhaps, to consider in far more depth the user needs of individuals: more attention paid to personal preference and the celebration of diversity over convergence. If the notion of brand ethos is to continue in this scenario, surely it will have to move further into the realm of individual interpretation; rather than some manufactured and marketed ‘lifestyle’ or ‘brand value’ heterogeneity. Certainly there would at least be a requirement for learning more about ‘people’ and less about ‘markets’: more about the choices people make about objects and the emotional relationships people have with them.

8.4 Achieving Balance Between Order and Chaos

There has been a constant tension in the project between a desire to deliver unexpected drama and a need for coherent identifiable designs. The need to balance the degree of random form generation has been acutely felt. Completely random form could not develop ‘brand recognition’ and would be of dubious artistic merit. At the same time there has to be some relinquishing of control practically, to achieve the stated aim of variance, and creatively, for the drama of the unexpected. As Colson states in respect of generative art: *“Computers offer access to data that does not have to be sequential. It too can be random. Digital artists need to negotiate with delicacy the boundary between logical methodologies that are part of the way they have to work and the undefined artistic intentions, which sometimes require withdrawal of conscious control in order to be really compelling. Their work is often tipped more one way than the other but when evenly balanced, these two elements can result in work that is tense and exciting”* (Colson 2007).

In the jewellery design Icon (8.3.3), it has been demonstrated that a coherent design identity can be achieved over an extended run of 25 pieces; this has been the greatest number of iterations produced from a FutureFactories design to-date. These 25 pieces remain distinctly unique and it would seem likely that the full target edition of 100 pieces could be achieved without identity clashes. The scope for this design is limited however. The form is made up of only a few elements with restricted movement and there is one key feature that to a large extent defines the character of the piece. If the production were extended, to 500 units, and beyond for instance, a greater perception of similarity would be expected. As the individualisation is randomly generated, there is the potential for similarities even in a small batch. The concern, however, is not a single instance of deja-vu, but in repeated similarity which would undermine the concept and value of the system. Similar pairs from the first batch have been identified in Figure 225. Iteration #4 has been mirrored to increase the similarity. Whist there is little similarity in the overall forms the dominance of the ‘eye’ feature makes even slight similarity noticeable.

Figure 225
Similar Pairs in Icon Production

It is clear from the works created that some geometries carry more scope for individualisation than others. The SuperKitch bangle is made up of approximately 30 distinct pieces taken from a library of 50 pieces, arranged in a random string.

For an identical set of pieces to be selected in the same build order, the probability of selecting the first piece would be 1 in 50, the second 1 in 49 and so on for the 30 pieces.

In a niche product, where a significant marketing emphasis is placed on individuality, the production run should be limited according to the geometries' potential for difference. Contour changes in surfaces can be used to create difference, but in extended runs the distinction between iterations may not always be obvious. In Tuber, for example (5.1.3), the individualisation was driven by key-frame animation. Five iterations were produced from an animation clip of 3600 frames. The virtual model changes with each frame of the animation and this clip could therefore have yielded 3600 discreet artefacts. Iterations generated from neighbouring frames, however, would be perceived as identical without careful measurement and iterations even 10 -20 frames apart would be hard to distinguish, Figure 226.

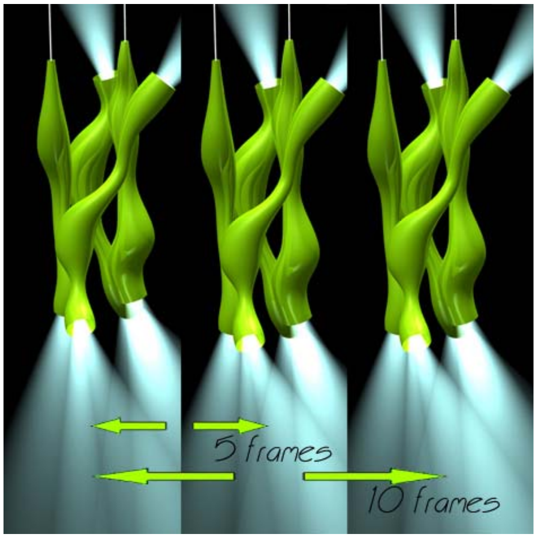


Figure 226
Tuber Animation Frames

The more elements that are subject to change, the more scope there is for generating difference. This favours more detailed, chaotic forms over minimalist simplicity. Models that can be reconfigured rather than merely adjusted offer significantly more potential. A change in configuration is immediately apparent, whereas adjustments to a form only become noticeable over certain amplitude, Figure 227.

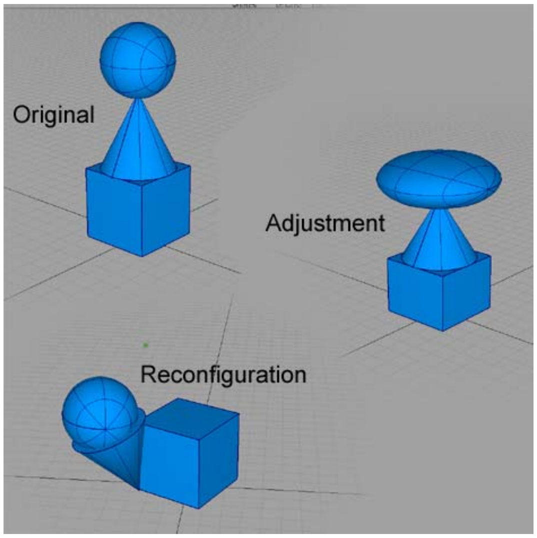


Figure 227
Adjustment vs. Reconfiguration

Individualisation lends itself to forms in which there are arbitrary design decisions, for instance the number of ‘buttons’ in the back of the Holy Ghost chair (3.5).

Increased complexity reduces the visual impact of details. In Tuber the interfaces between the four volumes require careful filleting in a post production process. This involves trimming back surfaces and adding a fillet of varying radius. In Tuber9 the increased visual complexity means that less emphasis is placed on these intersections allowing them to be treated with a single command constant radius fillet.

The Puja is a table lamp design (Section 7.6) intended as a follow-up to Cornuta (Section 7.2) and was to be the second design created using Solidworks and driven by Genovate. Whilst the design proved successful and has been widely exhibited, it did not prove possible to create design variants to the researcher’s satisfaction. The design is sand-cast in sections which are subsequently welded together and the joints polished out. The first prototypes of the design were produced in India and even the variance introduced by the production process (as opposed to deliberate individualisation), proved problematic. The combination of an arbitrary dressing of edges and the positioning of parts by eye, prior to welding, introduced detrimental changes to the design’s character. It is clear, therefore, that not all designs are suitable for individualisation and that in some designs the aesthetic is too heavily bound up with a discreet set of proportions.

The SuperKitch jewellery design demonstrates that computer script can be combined with CAD to generate a potentially infinite stream of discreet 3D outcomes. Superkitch typically generates a new form in 4 -5 minutes depending on the processors speed. The script configures pre-existing CAD models in a Constructive Solid Geometry approach. There is no post-generation CAD modelling, other than to mirror the virtual model configuration from a library of CAD components, a process that could easily be automated.

8.5 Recommendations for Further Research

From the early residency period of this study, opportunities to expand its' scope have constantly arisen. Inevitably the thesis had a specific focus and this leaves future research opportunities that are worth highlighting.

8.5.1 CAD and Programming

As the project progressed the geometries created became increasing driven by programming. The researchers' prior experience however, has had a significant bearing. The influence of various approaches, programming techniques and software platforms would be worthy of further study, for example:

- NURBS geometry vs. Polygon mesh;
- Writing code versus script writing packages such as Virtools; and
- Dedicated generative design packages vs. custom written scripts.

Different approaches to computer programming have been experimented with in this study. Successful 3D output was only achieved when the researcher was involved directly in the programming. This was perhaps necessary with a novel concept and where there was little pre-existing output to reference. With the example of this thesis and with a growing number of creatives experimenting with generative techniques, future researchers can perhaps have greater clarity regarding scripting requirements enabling a separation of roles. The involvement of specialist programmers would allow the designer to focus on their creative aims rather that the limitations of particular software.

8.5.2 The Designs

Throughout the study the researcher has placed emphasis on the need for control and for keeping the output true to the 'designer's intent'. The value of this should be explored and a computer programmers raw interpretation of a design brief compared and contrasted with programmer/designer collaboration.

In this thesis interactivity with the consumer has been deliberately restricted and individualisation favoured over customisation. This distinction is worthy of in-depth exploration and the introduction of random input (as in this study) compared with co-design.

8.5.3 The Artefacts

The premise of this thesis was based on the availability of additive manufacturing. The high cost of these technologies has tended towards expensive gallery outputs which inevitably influence perceptions. To increase the relevance to commercial production, simple, low cost, high volume outputs should be explored. This could be achieved through the use of emergent lower cost additive technologies or through the use of lower cost digital manufacturing techniques e.g. laser cutting.

The thesis has proved the possibility of generating significant numbers of variants from a meta-design template. It would be interesting to explore preference though such a collect of pieces with the public offered samples to select from;

for example:

- Would there be significant preferences for individual pieces?
- Would there be significant preferences for recognisable types (8.4)?
- Are there disliked ‘failures’?

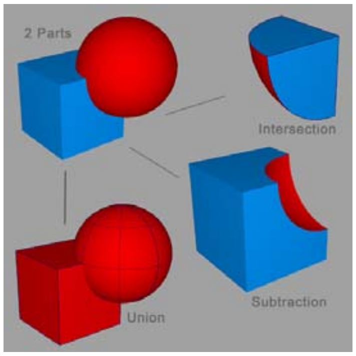
Technical Glossary

3D printing, 3DP

Three Dimensional Printing (3DP): is at the budget end of the Rapid Prototyping spectrum. The processes use inkjet printing technology and the equipment costs are around a tenth of those for STL/SLS. Each layer is formed by a jet of material or binder from a multi-nozzle print head. 3DP tends to be used for concept rather than functional models. The term 3DP has considerable appeal; aptly summing up the technology and its context, the use of the term however has been limited by its becoming a trade mark.

Boolean Operations

Boolean Operations in the CAD (Computer Aided Design) context are a set of logical (Boolean logic) operations that can be applied to 3D closed volumes. Intersecting entities can:-



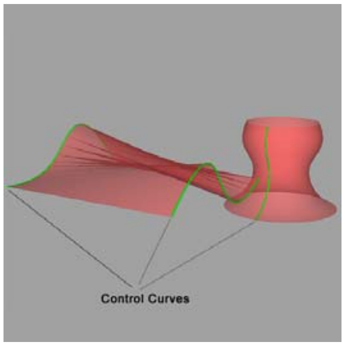
- i) Be united into a single part with a Union operation;
- ii) Have the intersecting portion of one entity removed from the other, in a subtraction or difference operation;
- iii) Have everything removed apart from the intersecting portions in an intersection operation.

C++

C++ is a general purpose computer programming language that is widely used throughout software development. It is generally regarded as a middle level language combining basic functionality with some advanced features.

Control Curve

Control Curves are a feature of CAD geometry in which surfaces are defined by 2D or 3D profiles.



Construction History: Please refer to parametric design.

Constructive Solid Geometry, CSG

Constructive solid geometry is a technique used in **Solid Modelling**. It allows the creation of complex models from a simple primative. The primatives are either assembled or used to cut away 'material' from each other using Boolean Operations.

One of the advantages of CSG is that is easy to ensure that a water-tight, closed, volume is achieved; an important factor in Digital manufacturing.

Computational Design

Computational Design is the combination of Computer Aided Design with computer programming. Computer scripts can be embedded in CAD software, such that aspects of the geometry are computer generated.

Computer Aided Design, CAD
CAD is the generic term for computer-based geometry authoring tools that are used throughout design and engineering industries. CAD initially stood for 'Computer Aided Drafting' and was seen as a direct replacement for the manual drawing board. Software packages soon developed capabilities beyond traditional drafting; hence the switch in terminology to Computer Aided Design. There are different levels of CAD software: 2D drafting systems (e.g. AutoCAD, MicroStation); mid-range 3D modellers (e.g. SolidWorks, Rhino); and high-end 3D hybrid systems (e.g., Alias, Pro/ENGINEER, CATIA). The boundaries between these categories is fluid; with the 2D packages including some basic 3D capability and the mid-range packages increasing their functionality. Within the mid and high end packages there are **Parametric** and non-parametric packages, **Solid Modellers** and **Surface Modellers**.

Computer Generated Design, CGD
Computer Generated Design is geometry that has been created or modified by computer algorithms.

CV, Control Vertex
See **NURBS Geometry**

Cybersculpture
This represents computer-based 3D geometry, or virtual 'structures', that may be impossible to realise with the physical constraints of the real world.

Delphi Programming Language
Delphi is a programming language, first released in the mid-nineties, that runs under Microsoft Windows. It uses visual programming tools that make programming for Windows easier.

Direct Metal Laser Sintering (DMLS)
Selective Laser Sintering applied to metals; please refer to SLS.

Edit Point (curve)
Edit Point is a computational geometry curve defined by points on that curve.

Genotype
A biological term used to refer to the coded representation of a possible structure. In biology the genotype is composed of DNA and contains information that will determine the development of an organism (the phenotype).

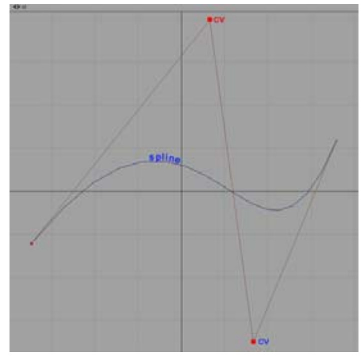
Java3D
This is an application programming interface, API, for drawing 3D graphics using the Java language.

Key-frame Animation
In key-frame animation an entity is created along with a series of developmental states for that entity over time. Software then extrapolates between these stages to create a seamless animation. A key-frame animation is of fixed length and yields only as many solutions as there are key frames.

Lofting
Lofting is a 3D CAD modelling operation that creates of a 3D transitional surface (or solid volume) between usually 2D profiles and is a common feature in high end CAD programs. Also known as a Skin command (Alias Studio Tools).

NURBS Geometry

NURBS (Non Uniform Rational Basis Spline) geometry is controlled by 'weighting' Control Vertices (CVs) that lie off the curve or surface. NURBS geometry was developed to enable engineers to reproduce accurately curvature for naval and aerospace application. NURBS geometry allows representation of controlled geometrical shapes in a mathematically compact form that can be scaled indefinitely. NURBS' curves and surfaces are highly intuitive and predictable. CVs are connected directly to the curve/surface, or act as if they were connected by an elastic link. Manipulating them changes the character of the curve or surface.



A NURBS Curve

Phenotype

A biological term for the physical solution, in biological systems: an organism that is derived from a particular genotype.

Parametric Design

Convectional CAD defines objects with fixed dimensions. Typically, artefacts' geometry will be defined in Cartesian space via a series of vectors. Parametric CAD defines the nature of the design via relationships between degrees of freedom rather than attributing absolute dimensional values to the degrees of freedom themselves. For example, if a feature is positioned two thirds of the way along a face; it is not important how long that face is, this can be modified at will: the importance is that the two thirds proportion is maintained. If a particular attribute of a design is modified, the whole model will update to maintain a set of relationships which are pre-defined within the CAD file.

In parametric CAD, the sequences of geometric operations underlying a design are recorded in what is often referred to as a **Construction History**. The user is able to go back through this history of parent/child features and to adjusted elements on which later (in the history) operations depend.

Polygon Based or Mesh CAD Geometry

A polygon mesh or unstructured grid is a collection of vertices, edges and faces that defines the shape of a polyhedral object in 3D computer graphics and CAD modeling applications. Polygon based models are used in web, animation and visualization applications where ease of manipulation outweighs mathematical purity. Unlike NURBS geometry, which can be scaled indefinitely, mesh surface have a fixed resolution.

Procedural Animation

In a procedural animation entities are modified by a procedure or algorithm. A set of developmental rules and relationships are set out along with an initial condition. Solutions are then generated automatically. A procedural animation by contrast can yield a potentially infinite series of solutions.

Generative Design

Generative design can be defined as the approach of developing applications, or systems which can develop, evolve, or design structures, objects, or spaces more or less autonomously depending on the circumstance (Krause 2003).

Rapid Manufacturing (RM) (Direct Manufacture, Digital Manufacturing)

"The use of a CAD based automated additive manufacturing process to construct parts that are used directly as finished products or components" (Hopkinson 2006). Rapid prototyping is now

well established; the new frontier is direct manufacture. Direct or Rapid Manufacture is essentially the adaptation of RP technologies to the manufacture of end-use products. There are several niche markets emerging: the mass customization of medical products, low volume-high unit cost applications, such as aerospace and F1.

Rapid Prototyping, RP
Rapid Prototyping (RP) is a catch-all term that applies to the automated manufacture of prototypes directly from digital CAD data. Simplistically speaking, RP allows the designer to 'print out' on-screen models in 3D. Most of the recently developed processes are layer additive. Software 'slices' the CAD model into thin layers (down to 0.05mm). The model then 'grows' one thin layer at a time, as each data 'slice' is replicated in 3D from the bottom up. The layers are built on a moving platform, each built on its predecessor as the platform steps down in layer thicknesses. There is no tooling or cutting away of material. This allows unlimited geometry. Forms may be produced that would be almost impossible to mould or machine. RP processes can be additive or subtractive (subtractive where material is cut away from a solid blank). However, the term is more commonly applied to additive processes.

Robosculpture (1988-Christian Lavigne)
Computer aided sculpture, manufactured automatically, via rapid-prototyping technologies.

Selective Laser Sintering, SLS
Laser Sintering is powder based. Here the layers are 'drawn' on fusible powder which is sintered by laser, the powder being ordinarily maintained just below its melting point. The finished part is formed within a cake of un-fused powder, which supports the features: the final step is to remove this loose powder. SLS components are much more than appearance models, they have sufficient durability to be considered functional. A wide range of powder based materials are available to the process including nylon, stainless steel, synthetic rubber and ceramics.

Skin Surface
A Skin Surface is a 3D modelling operation within Alias CAD software that creates of a transitional surface between curve profiles. It is a common feature in high-end CAD programs and is alternatively known as a Lofting operation.

Solid Modelling (CAD)
Solid Modelling is a CAD technique for representing and manipulating solid objects. In general terms, features are defined rather than surfaces: for example, block with a hole in it is defined by a block plus a hole. Due to fact that forms are defined by operations performed on them, solid modellers are best at 'regular' forms produced by commands that mirror the physical world, for example, lathe and extrude.

SLM
SLM is a metal RP process similar to SLS/DMLS developed by MCP. As the name suggests, the material is melted rather than sintered with claimed structural benefits.

Spline Curve
A tool commonly used in computational geometry for generating smooth curves that can be scaled indefinitely: please refer to NURBS geometry.

Stereo Lithography, SLA (Stereo Lithography Apparatus)
Stereolithography was the first of the modern layer build systems. It was developed by 3D Systems in the eighties. It accounts for 45% of new machine installations (Wohler's Report 2003). In this process each layer is 'drawn' by laser in a photosensitive liquid polymer; the laser light solidifies the liquid. The advantage of this process is the surface finish, which is good; the disadvantage is that delicate features and overhangs require thin supports that must be removed post-production.

STL , Standard Triangulation Language, file format
An STL file is a triangular representation of a 3D surface geometry native to additive fabrication, that was created by 3D Systems. An STL file describes a raw unstructured triangulated surface by defining the vertices of each triangular face. STL files describe only the surface geometry of a three dimensional object without any representation of colour, texture or material attributes.

Surface Modelling (CAD)
Surface modelling is a CAD technique, in which a form is constructed from a number of discrete surfaces. Usually the NURB's surfaces are constructed from curves.

Telesculpture (Christian Lavigne, Alexandre Vitkine1994)
The remote production of digitally created sculpture, using RP technologies, via the electronic transfer of data (Networks, Internet, ISDN).

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‘FUTURE FACTORIES’: DEVELOPING INDIVIDUALISED PRODUCTION METHODS

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KEYWORDS
Mass Customisation, Mass Individualization, Rapid Prototyping, Virtual Reality, Virtual Merchandising, Animation, Organic design, Interactive, Computer Generated, 3D modelling, 3D Printing.

ABSTRACT
'Future Factories' is an exploration of the possibilities for flexibility in the manufacture of artefacts inherent in digitally driven production techniques. The concept considers individualised production – in which a random element of variance over parameters such as the relative positioning of features, scale, proportion, surface texture, and the like is introduced by the computer within a parameter envelope defined by the designer. This paper is the feasibility study of, and design of, a production system for the 'Future Factories' concept.

In 'Future Factories', a production system is envisaged in which the consumer is presented with a 3D digital model of the design. The design is presented as an animation showing the design morphing within a parameter envelope specified by the designer. At any given point the consumer may freeze the design, place an order, and generate the relevant digital production files (.stl etc.). A unique, individual artefact will then be manufactured using Rapid Prototyping techniques. This may be achieved directly, via Stereo Laser Sintering in a suitable material for example, or indirectly via the production of a single use tool or pattern.

This paper presents results from research conducted as part of the Designer in Residence project at the School of Design Technology, University of Huddersfield. Firstly a selection of design concepts with associated parameter envelopes are created using relevant 3D design software. Animations are then created showing the design moving within its parameter envelope. A new computer program is being developed to enable the generation of digital production files direct from a selected animation frame. There will be a study of existing rapid prototyping techniques with regard to their suitability for direct manufacture of this type and speculation on future potential.

INTRODUCTION
The School of Design Technology at the University of Huddersfield recently decided to allocate an amount of research funding to provide an ‘Artist-in-Residence’ to work alongside Fine Art students, and a ‘Designer-in-Residence’ to work alongside Product and Transport design students for a period of one year. The work currently being undertaken by the Designer in Residence along with contributions made by other academic staff are the subject of this paper. The title of the project ‘Future Factories’ describes an exploration of the creative potential inherent in digital design and manufacture to offer more than a single discrete 3D outcome. The outputs from this practice-based research project are expected to consist of a number of inspirational products which will be exhibited in a traditional gallery environment and later digitally – either on-line or by CD-ROM dissemination. Alongside the practice-based research outputs there will be a number of different academic papers (such as this one) addressing the different technical, theoretical and contextual issues raised by the content of the ‘Future Factories’ project.

THE 'FUTURE FACTORIES' CONCEPT
Rapid Prototyping technologies, developed to compress product development cycles, offer the potential for much more. Layer-build production processes allow for the direct transfer of virtual CAD models to real objects. As in reprographics, model files can be emailed to an agency for production or desktop printed on machines using inkjet technology. Through direct digital production a revolution is underway in 3D Product Design that is likely to be as radical as that already seen in Graphic Design.

In essence the project proposes an inversion of the mass production paradigm to one of individualised production – in which a computer generated random element of variance is introduced. Each artefact physically produced is a one-off variant of an organic design. The design is defined by parametric relationships and is maintained in a constant state of metamorphosis by the computer software.

The variance introduced may be over factors such as the relative positioning of features, scale, proportion, surface texture, pattern, and the like. These variable factors may be multiple and interrelated. The intention is to achieve subtly different aesthetics around a central theme rather than mere differentiation that might be achieved by, say, scale or colour change alone. We do not claim here that the notion of computer generated random form is in itself an original one. Perhaps some of the best-known computer generated forms are those resulting from the collaboration between the artist William Latham and the mathematician and computer graphics expert Stephen Todd. Although the resulting ‘sculptures’ were only ever intended to be seen as 2D representations of complex 3D models presented as art in a gallery context, the principle behind it can just as easily be used to create variations on ‘usable’ forms to produce designs for ‘anything from buildings to shampoo bottles’ (Computer Artworks 2003). The potential of this proposition has not yet been fully realised. The ‘Future Factories’ concept explores an aspect of this potential.

MASS CUSTOMIZATION

It is perhaps pertinent here to specify what 'Future Factories' is not - and it is not 'Mass Customization'. The term 'Mass Customization’ was coined by Stan Davies in his book Future Perfect (Davies 1987). The term is deliberately paradoxical. There are many different models for mass customization suiting different products and market sectors. They are all however, consumer driven. Products are "decomposed" into modular components or subsystems that can be recombined to more nearly satisfy consumer needs.' (Crayton 2001: 78). In contrast to mass customization, the 'Future Factories' model derives no input from the consumer. Where mass customization consists of consumer selection and specification, 'Future Factories' allows the consumer only to select the moment at which the process of form generation is arrested.

DESIGN FORMULA

In the 'Future Factories' model, rather than specify a discrete design solution, the designer sets up a series of rules and relationships that achieve a desired aesthetic over a potentially infinite range of outcomes. This is achieved using parametric CAD software. The aim is a degree of random mutation. This does not mean a series of staccato jumps as one random value is replaced by another. The model should appear to ‘grow’ with one mutation flowing seamlessly into the next. Each solution is intended to be unique and not repeated in a cycle, however long. The desired result can be achieved by setting variables to cycle through specified ranges. Different variables are set to cycle at different rates, with the differential providing the random element. In addition, the rates of change can themselves vary, increasing or decreasing at random (though with smooth implementation) over time.

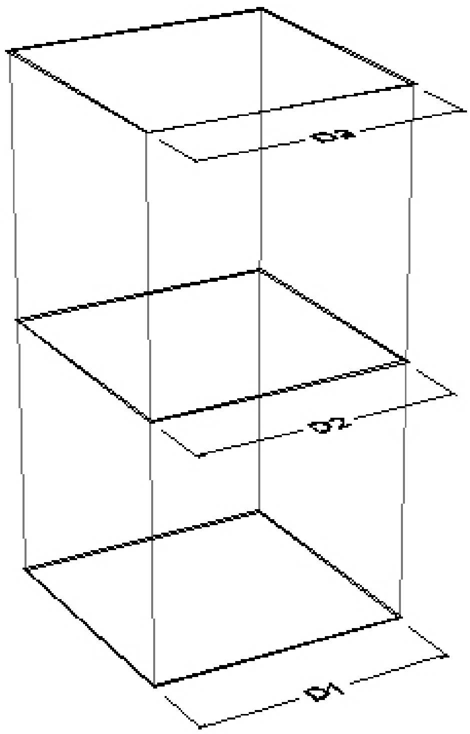

Fig 1: A solid formed by lofted square profiles

EXAMPLE OF THE RANDOM ELEMENT GENERATION PRINCIPLE

To understand the principles proposed we can start with a simple box, as illustrated in figure 1, this will become a product structural leg. A simple solid model is created by ‘lofting’ three square sections. ‘Lofting’ is the creation of a 3D transitional form between usually 2D profiles and is a common feature in high end CAD. The dimension value of each the squares (D1, D2, D3) is allowed to cycle 100% - 70%. Figure 2 shows the effect of this applied to D3.

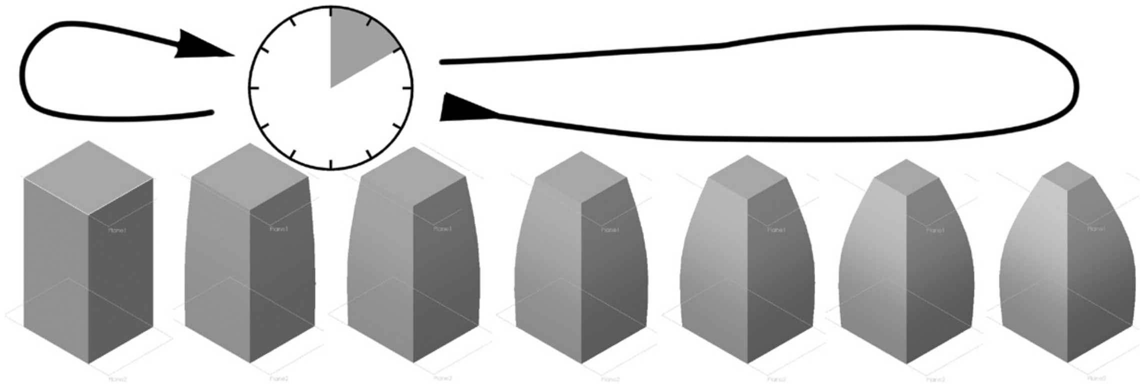

Fig 2: The effect of scale variance on one lofted profile

The cycling of the variable D3 is set at a given rate. The other two variables, D1 and D2 are set to cycle though the same value range but at different rates. The effect of this is illustrated in figure 3.

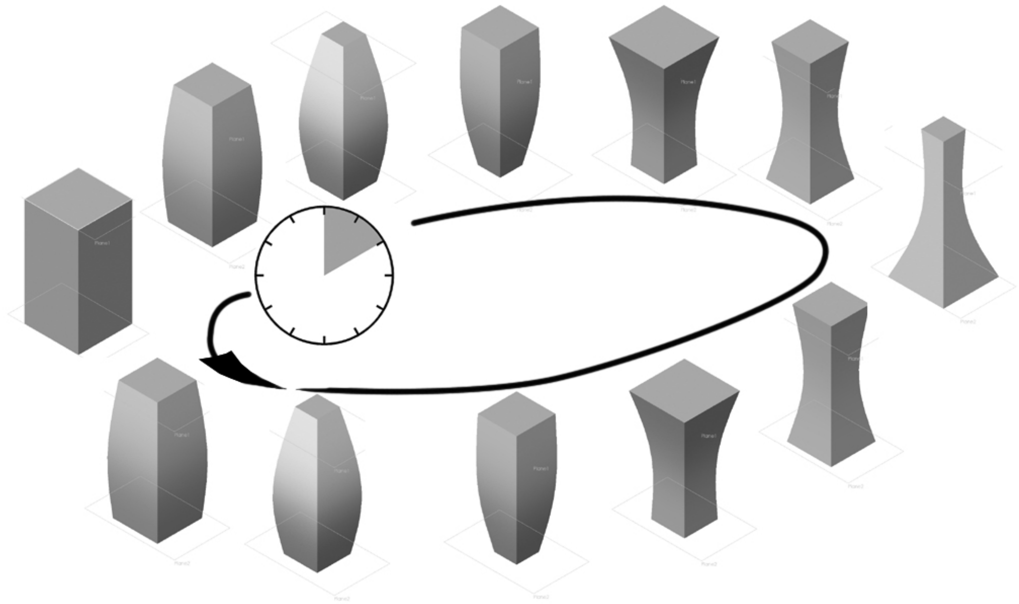

Fig 3: The effect of differing scale variance on all three lofted profiles

Another element of variance that could be considered is the addition of a twist about a vertical axis formed by rotating the horizontal profiles relative to each other as illustrated in fig 4.

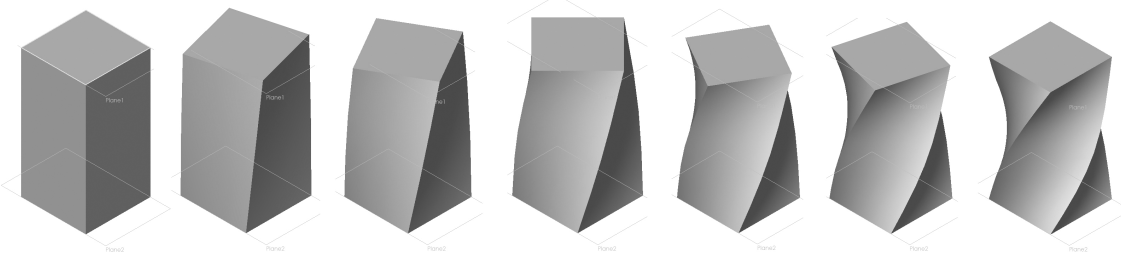

Fig 4: The effect of rotating lofted profiles to produce twist

So far the mid-profile of the loft construction has always been located mid-way up the form, but this profile can be allowed to rise or fall (figure 5).

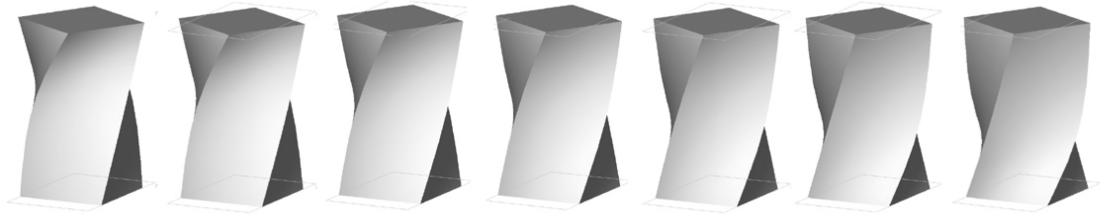

Fig 5: The effect of altering the height of the central lofted profile

The rotation about the vertical axis and the asymmetric placement of the mid profile are assigned ranges and independent rates of change. These transformations are overlaid on the earlier figure 3 model, and the resulting forms illustrated in figure 6.

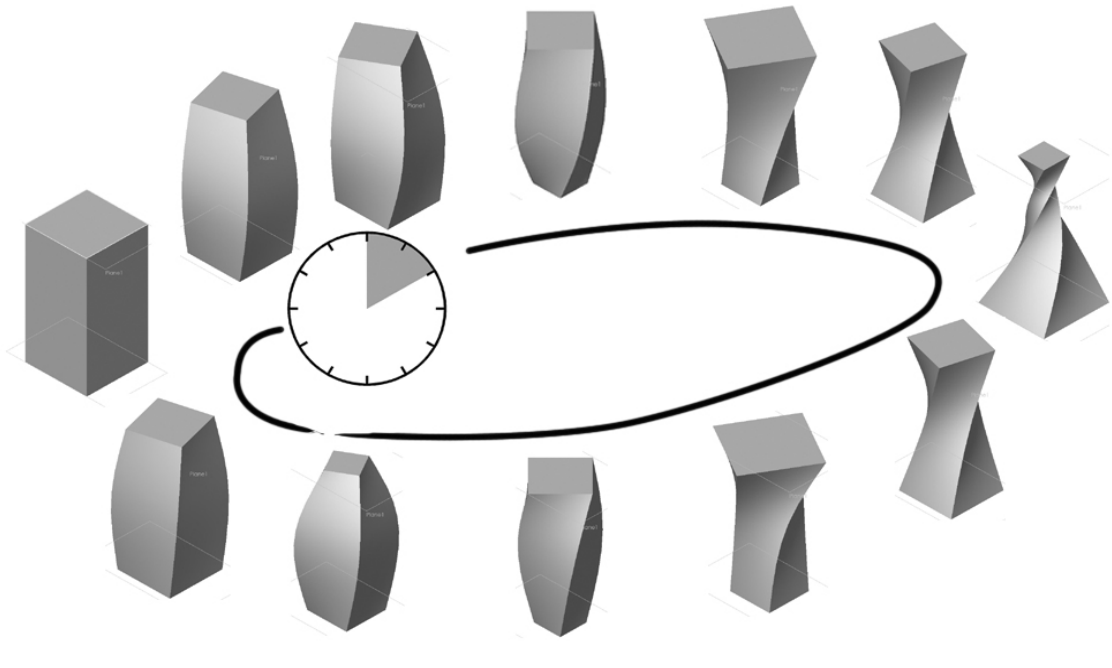

Fig 6: Combined effects of transformations

The Twist II candlestick (figure 7) was developed using these principles. The design has three legs which meet at the top. Each of the legs has elements of variance similar to those used in the box example (figures 1-6). The three legs morph independently but with a constraint to ensure the tops match. The legs are equally spaced at a separation specified for stability. The footprint of the legs is allowed to both twist about a vertical axis and move in a horizontal plane relative to the top to create further distortions. It can be seen that the scope for variance is vast. It is important to highlight, however, that the changes in form are not arbitrary. Each of the variables has been applied so that through their combination a desired aesthetic is achieved in an organic form.

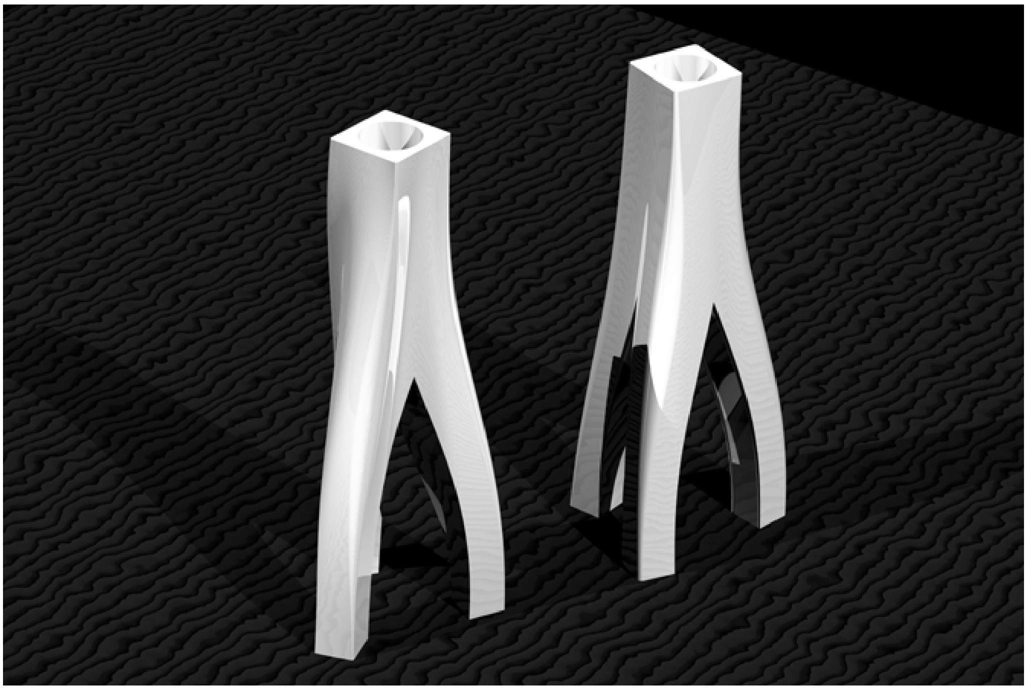

Fig 7: The 'Twist II' Candlestick

Other models developed for the project include the Twist I candlestick (figures 8 and 9) and Lampadina Mutanta (figures 10 and 11). Lampadina Mutanta is a luminaire with a light source of high intensity white Light Emitting Diodes (LED's). The LED's are mounted in the ends of 'tentacles' which appear to grow at random from the bulb form. The end of each 'tentacle' is dimensionally constrained to accept an LED and the direction in which the LED points restricted to certain angles from the vertical (to avoid glare).

Fig 8: The 'Twist II' Candlestick

Fig 9: The 'Twist II' Candlestick

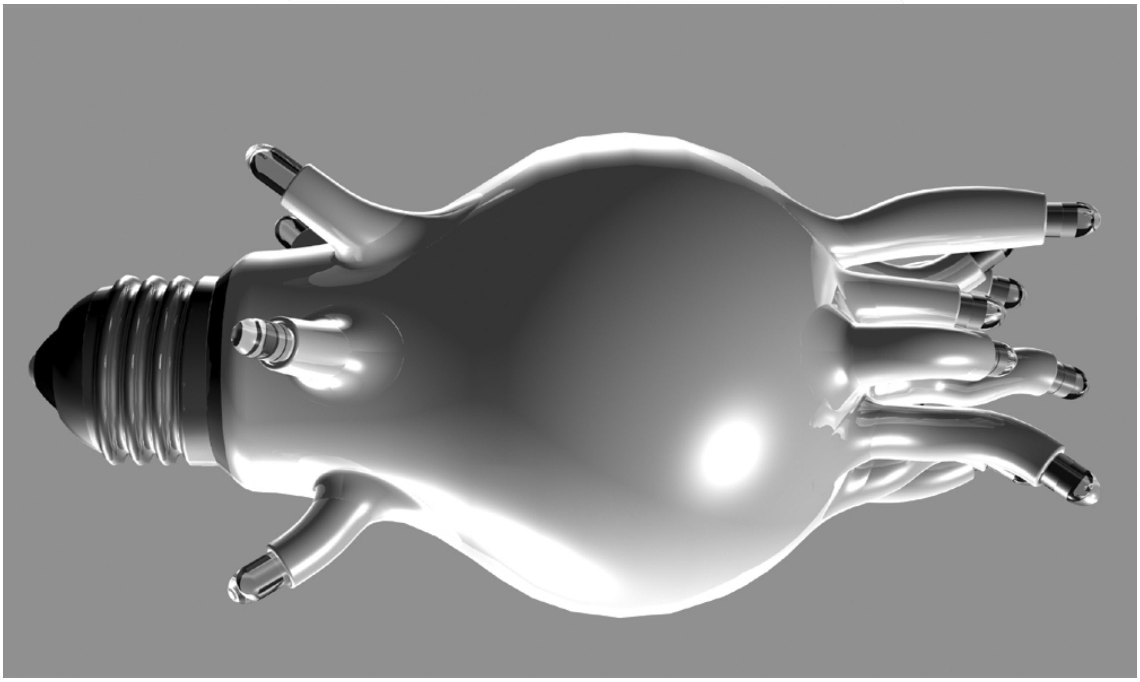

Fig 10: 'Lampadina Mutanta' lumiere

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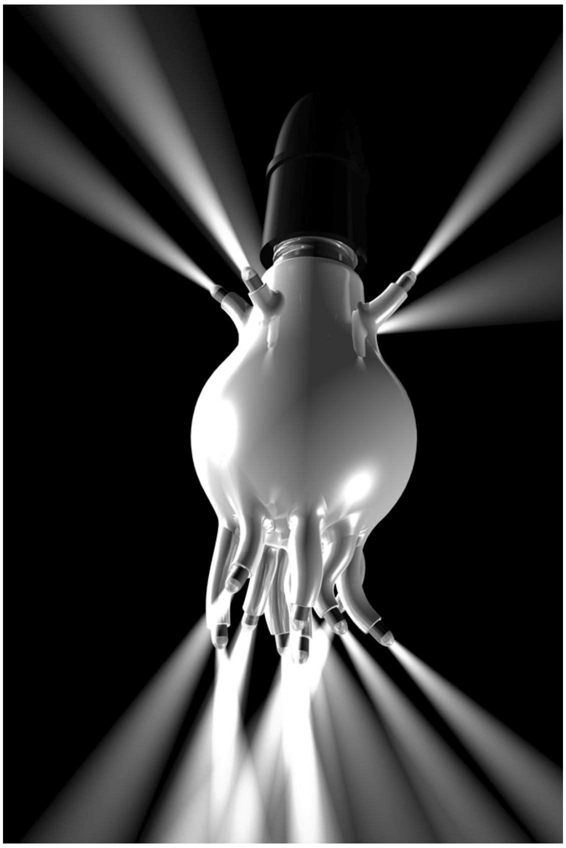

Fig 11: 'Lampadina Mutanta' lumiere

PRESENTATION

Each organic design is defined by a production formula which can yield an infinite range of equally valid outcomes – How should such a design be presented to both clients and consumers? To appreciate their organic nature the designs must be seen continuously 'morphing' in real time - this requires animation. A video clip played on demand would not be sufficient as there is no cycle to the mutations. The consumer must be offered a 'webcam' window onto a design which is changing whether they are watching or not. Clearly the project lends itself to some form of 'virtual' web-based merchandising. A system is envisaged in which the consumer is presented with a 3D animated model of the artefact via a website. The consumer may access the website directly or via a sales outlet, at a gallery or in a department store for example. The web site, the 'Future Factory' itself, would have a series of 'production lines' corresponding to different products. When a particular production line is selected the user is presented with a computer animation showing that particular product in metamorphosis. At any given point the consumer may freeze the animation, effectively creating a one-off design on screen. Should the consumer wish, they might then proceed with an order, in which case the relevant digital production files (stl etc.) would be generated automatically and sent to the appropriate RP production facility. The unique, one-off would then be manufactured using layer additive manufacturing (Rapid Prototyping) techniques. This may be achieved directly, via laser sintering in a suitable material for example, or indirectly via the production of a single use tool or pattern. It should be pointed out that the intention is not for the consumer to use the animation to adjust design features to their liking. The animation is changing in real time and is outside their control (this is part of the allure of the process). A variant can be 'designed' for them and they can choose to order it or not. Visitors to the website must therefore be able to 'read' the designs, to appreciate the form of the artefact with which they are being presented. This is made difficult by the fact that the object is changing. A Virtual Reality experience would help overcome this difficulty, enabling the consumer to 'move around' the design in their own time and at will.

WEB-BASED VIRTUAL REALITY (VR)

"Virtual Reality" refers to technology used to provide computer-based experience that mimics real experience. The two primary characteristics of such an experience are that it is three-dimensional and that it is interactive. At its simplest, it is a 3D image of a single object that the user can rotate to see from various angles. At a middle level, it can be an entire scene or virtual world that the user enters and interacts with. High-end VR requires the user to wear special goggles and gloves that make the illusion of reality more complete, this is the province of games or specialised applications like military training, which are not typically Web-based. VR applications on the Web include entertainment, education, medicine, marketing, training and, as in this application, merchandising.

VIRTUAL MERCHANDISING

Conventional marketing usually centres around a glossy photograph of the product shown from its best angle. VR content enables websites to bring the products 'to life' with 3D models, user interactivity, animation, sound, and detailed views. An interactive image allows the product to be seen from all angles. Potential customers are able to examine the design in the form of a 3D model moving, rotating, and zooming in and out at will. This 'hands-on' interaction allows something of a "try before you buy" experience. Internet shoppers have been reported to spend 50% more time in the part of the site that offers interactive 3D images (Mike Hurwicz, 2000), yet VR on the Web is not yet mainstream or widespread. Why has this exciting technology made such slow progress? This may be due to the fact that VR content is costly to develop, mostly because the expertise to create it is still rare, and a direct link to sales revenue is as yet unproven. In addition, content creators typically make a substantial investment in computers, software, and digital equipment. Technical difficulties have discouraged the take up of website based VR marketing. The technology is most convincing and pleasing when it uses realistic textures, lighting and sounds. The use of these elements requires large files which leads to slow performance, and web designers fight a constant battle between high graphical appeal and slow download times. High-resolution graphics and elaborate animations are notoriously slow to download, especially through a dial-up connection. Add to that bandwidth limitations and the possibly unreliable connections of the Web, and you have the potential for a deeply dissatisfying experience.

INHERENT LIMITATIONS OF VR

We can assume that consumers will always prefer hands-on experience with a product before purchase. Barring cumbersome and expensive gloves and goggles, VR is still strictly an audiovisual experience. Even gloves have serious limitations in that they cannot provide a tactile experience of texture. This might be solved if the website access was via a retail outlet and samples were available. It would also avoid 'user end' technical issues. VR content cannot be viewed with a standard browser - a special-purpose browser or a plug-in is required. In addition there is no single viewer that can handle all VR content. The requirement to download additional software merely to, in effect, browse a shopping catalogue is a severe disincentive. The user may not even have administrator rights to the computer or the desire to involve themselves in IT issues. The lack of an industry standard also affects content creators (and their cost), as each viewer typically has its own authoring tool. There is no single tool that a programmer can learn with any expectation of addressing more than a fraction of Web users. The limitations of computers and the technological demands of VR should not be exaggerated however. VR files are not necessarily huge. Files consisting mostly of vector graphics are relatively small. Problems of speed and resolution will be solved over time as standard-issue desktop computers gain speed and are optimized for 3D graphics. Higher-bandwidth and more reliable connections to the Internet will also become more common. Proprietary viewer and content creation software offer increasingly high-quality images within compact, efficient files.

HTML, SGML, VRML, XML and X3D

Conceived when the Internet was still in its infancy, SGML (Standard Generic Mark-up Language), defined by ISO 8879, was created to describe the 'look' of a document. SGML is very complicated and is best suited to solving large, complex problems that justify its use. Viewing structured documents sent over the web rarely carries such justification. HTML (Hypertext Mark-up Language) was developed in the early 1990's, essentially from a stripped-down version of SGML. HTML has become widely used in spite of never becoming standardized, with vendors such as Microsoft and Netscape adapting the language to their needs. Neither SGML nor HTML are particularly well suited to VR applications SGML being overly complex and HTML too rigid and inflexible for development. In the mid-1990's VRML Virtual Reality Modelling Language was developed with the aim of its becoming a standard (supported by the ISO). VRML is a 3D interchange format and is essentially a 3D analogue to HTML. It defines most of the commonly used semantics found in today's 3D applications such as hierarchical transformations, light sources, viewpoints, geometry, animation, fog, material properties and texture mapping. It integrates three dimensions, two dimensions, text and multimedia into a coherent model (Carey and Bell 1997). The uptake of VRML, however, has not been without problems. The language has an extensive set of required features which demand large browsers and plug-ins. The need to integrate with a complex existing feature set also hinders innovation. XML (Extensible Mark-up Language) has emerged as an alternative to, or fix for, VRML. The Core Profile of XML is much lighter than VRML, and additional profiles are implemented as software components to be downloaded as necessary. The user only uses the profiles needed to view the current content, whereas a VRML browser may have many features they don't need. When an innovator comes up with a new profile, they can achieve minimal compatibility by testing only with the Core Profile. The VR community has recognized the growing success of XML, compared to the very limited success of VRML. In response, the Web3D Consortium (http://www.web3d.org), in concert with the W3C (World Wide Web Consortium), has defined an XML-compliant 3D standard for the web: "Extensible 3D" (X3D). X3D extends the capabilities of VRML and provides a means of expressing the geometry and behaviour capabilities of VRML using XML.

3D MODELLING IN THIS STUDY

In this study a series of organic product designs have been created using Alias Wavefront, Solidworks and 3D Studio Max. Domestic interior products, principally lighting and tableware, have been considered for the project thus far. Domestic interior products is a market well used to paying a premium for design and materials technology. Lighting and tableware have been selected to keep the artefacts relatively small. This consideration is based on cost rather than capacity - the largest laser sintering machine commercially available in the UK is 700 x 500 x 350mm for manufacture in one piece, and building in sections could also be considered. The designs selected thus far are for production in cast metal. They make use of layer additive production methods to achieve complex forms almost impossible to achieve with multiple use tooling. This necessitates the use of investment casting, with the wax patterns for use in the process being produced by a layer additive process.

ANIMATION AND PUBLISHING TO THE WEB

There were two options for publishing the designs to the Web. The first was to employ a high end programming language Java3D (an application programming interface, API, for drawing 3D graphics using the Java language) or C++. We evaluated this option in our study using Parasolid Kernel to access the 3D information directly from CAD and then animating/manipulating coordinates using C++ codes. This proved difficult and time consuming. Large file size was also problem as no optimisation procedure was easily available. The adoption of this methodology would require the designer to work via a specialist computer programmer.

The second option was to employ a proprietary 'plug-in'. We have already generated 3D CAD data (using Alias Wavefront format in this instance), which can be exported and animated (we used 3DStudio Max). Several 'plug-ins' are readily available for the publication to the web of 3D content including animations. One such package, Viewpoint, was used in this study. Animation and interactive 3D files were created and exported to Viewpoint for the creation of interactive 3D mtx files using Media Export Utility. These files were then edited using Viewpoint Scene Builder to set the required controls for scene animation in Javascript. The model was then transferred to the web using HTML with embedded Viewpoint XML.

CONCLUSIONS

It is clear that the implications of the widescale adoption of such techniques by industry are potentially serious, and are such that moves to protect the process via patents have been made. The system has the potential to change the perception of design by consumers and manufacturers alike, and to influence considerably the education and training of designers. Despite the philosophical questions the process raises for the definitions of terms such as 'design' and 'designer', (which are potentially misleading in this context), and the scope for confusion as to whether the end results of the process are 'art', 'craft', or 'computer generated' (which are, perhaps, topics for debate in a different arena to this one), there are a number of more pragmatic considerations. The potential for the process to impact on manufacturing and retail industries should not be overlooked. 'Future Factories' allows for the economic large scale production of artefacts while providing important reductions in wastage arising from the over-production of unwanted items, while promoting the move from reductive to additive manufacturing processes. As such, it may point the way to a more sustainable model of a consumer society than the one we take for granted today.

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Dean, L. Atkinson, P and Unver, E.

Evolving individualised consumer products

Abstract

The origins of this project began in 2002 with experimentation into the application of computer generated random form to 3D product design. Advances in the Rapid Prototyping industry were offering the possibility of mss-produced one-off consumer products. Computer based 3D solid models were created that would randomly mutate within parameter envelopes set by the designer. At any given point the mutation could be halted and a real-world product generated via digital manufacture (Rapid Prototyping). This first stage of the work has already been reported on (Atkinson and Dean, 2003).

The next phase of the program has been to introduce evolutionary development so that, via the computer generated random mutation, the model develops generation by generation in a desired direction (though not necessarily to a predictable outcome). This requires an element of selection. There are several examples of computer based evolutionary design experiments that use human by-eye selection methods, notably Richard Dawkins' 'Biomorph' system (Dawkins 1993). The aim of this project is an automated system that selects on some measure of desirability and rejects outright any functional failures.

Each FutureFactories product form is define by a parametric CAD (Computer-Aided-Design) model. When evolution is initiated, a series of mutant designs are generated each with a single parameter, selected at random, adjusted by a small pre-determined step. The step may by be positive or negative, this again is determined at random. The resulting set of mutant progeny is then assessed for their visual 'success' using a quotient. The quotient aims to access the level of visual interest in a form. As the application is 3D products, there are physical parameters to consider, for instance 'hard points' generated by the envelopes of internal components which may not be intruded upon. If any of the offspring do not meet the necessary physical criteria they are rejected. Animation is employed to extrapolate between iteration present the evolution as a smooth metamorphosis. Product forms and associated development criteria have been created capable of evolutionary development over many generations. The resulting designs are both surprising and unpredictable.

Introduction

Future Factories is a digital design and manufacturing concept for the mass-individualisation of products. The project began as a one year Design Residency in School of Art and Design at the University of Huddersfield. The project has now been expanded into a practice-based PhD study. Instead of creating a single discreet design solution (or indeed a finite range of options), the designer creates a template. This template defines not only the functional requirements of the form but also embodies the character of the design. Through the design template, the designer establishes a series of rules and relationships which maintain a desired aesthetic over a potentially infinite range of outcomes. The design becomes a 'living' entity, continuously morphing within its template envelope (Atkinson and Dean, 2003). In a development of the project we have looked at coupling random mutation with selection and the introduction of evolutionary pressure. This application of computer based evolutionary design is the subject of this paper.

Technological context

Computer generated artwork has become commonplace, the creation of three dimensional artifacts from this artwork imposes considerable limitations and is consequently rare. Advances in digital technologies have made the creation of one-off products from computer generated models, a realistic, affordable possibility. There are three principle technologies exploited in the FutureFactories model (fig. 1).

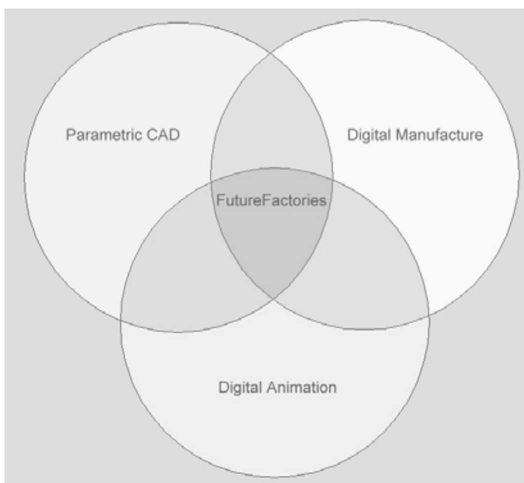

figure 1
Three core digital technologies exploited by FutureFactories

Parametric computer aided design

Parametric computer aided design (CAD) enables the designer to define relationships that form the character of a design rather than a single, discrete, design solution. Parametric design considers the relationships between degrees of freedom rather than the degrees of freedom themselves. When a variable is changed the whole model will up-date to maintain specified proportional relationships. Individual variables in the computer based 3D model can be modified and the whole form will up-date to maintain specified relationships.

Digital Manufacture (Rapid Manufacture, Direct Manufacture)

Now that Rapid Prototyping (RP) is well established – the new frontier for the digital manufacturing industry is Direct Manufacture. Direct or Rapid Manufacture is essentially the adaptation of RP technologies to the manufacture of end-use products. "A number of compelling examples of RM suggest that it will span across many industries in the future. Among these are hearing instruments, dentistry, medicine, aerospace, military, oil exploration, motor-sports, and consumer products" (Wohlers 2003). Rapid Prototyping (RP) is a catch-all term that applies to the digital manufacture of prototypes directly from CAD data. Essentially RP allows on-screen models to 'printed out' in 3D. Most of the recently developed processes are layer additive. Software 'slices' the CAD model into thin layers (down to 0.05mm). The model then 'grows' one thin layer at a time as each data 'slice' is replicated in 3D from the bottom up. The layers are built on a moving platform, each built on its predecessor as the platform steps down in layer thicknesses. There is no tooling or cutting away of material. This allows unlimited geometry. Forms may be produced that would be almost impossible to mould or machine. The relatively slow layer-by-layer building means that digital manufacturing is unlikely to ever match production capacity of die casting and injection moulding. Manufacturing parts without the need for moulds or dies does however makes the volume production of individualised forms an economic possibility.

Graphics

In FutureFactories the product forms are not fixed. The designs exist in a constant state of metamorphosis. To appreciate this, customers should be able to see the designs continuously 'morphing' in real time. The concept lends itself to some form of 'virtual' web-based merchandising (Unver, Dean and Atkinson, 2003). A system is envisaged in which the consumer is presented with a 3D animated model via a website. The consumer may access the website directly or via a sales outlet within, for example, a gallery or a department store. Advances in the graphics capabilities of home PC's and the speed of internet connections allow the display of rendered forms mutating in real time on the customer's home computer. Memory hungry three-dimensional rendering now exploits graphics processors on the video cards instead of consuming valuable CPU resources when drawing 3D images. These advances in video cards and the software that manage them, driven hard by the video game industry, enable the smooth real time display of animated forms complete with realistic scene lighting and material finishes.

The introduction of selection into the FutureFactories model

In the original FutureFactories concept it was necessary to define a complete envelope of parameters. The envelope defined 'solution space' covering every possible mutation of the form. Each individual parameter required specified ranges that considered both the effects of that parameter alone and its effects in combination with others. It is clear to see that if there are more than a handful of parameters and their effects interrelate to any significant degree then the task of specifying such an envelope becomes extremely long and complex. An aim of FutureFactories is to develop generic systems of commercial potential. For commercial viability it should be possible to introduce new designs with reasonable ease. Ideally one would be able to apply mutation rules to a conventional 3D model via an intuitive on-screen process (the system is seen as a plug-in addition to high-end parametric CAD systems). The complexity of specifying a parameter envelope could be reduced by severe restriction of the permissible parameter ranges and by isolating their effects where possible. But this would lead to uninspiring, predictable, movement in the form, repeated oscillations for example. A way of simplifying the rules for mutation had to be found. Evolutionary design principles offered a potential solution. Genetic algorithms permit virtual entities to be created without requiring an understanding of the procedures or parameters used to generate them. Instead of incorporating expert systems of technical knowledge into the programming, evolutionary design systems rely on utilitarian assessments of feasibility and functionality (Sims 1999, Funes and Pollack 1997). Our parameter envelope was designed to perform two functions; to ensure that manufacturability be maintained and that the mutated form retains the 'designers intent'. If these factors can be assessed and scored then mutation, coupled with selection, can be used to drive and control changes in form.

A model for mutation and selection

In the FutureFactories model, mutation takes place in a series of generations. The original model had a single parent producing a single, randomly mutated, child per generation. In this development of the system each generation has a single parent (the starting point) and ten offspring. In each generation, ten randomly mutated iterations are generated from the parent model. Each iteration has a single parameter, chosen at random, modified by a set small amount. The mutant offspring are ranked for 'fitness' and the most successful selected as the parent of the next generation. The scoring for fitness is based on the 'desirability' of the last transformation with reference to the designer's intent. Before becoming the parent of the next generation the selected iteration is tested against functional failure criteria. This ensures that after mutation the design is no less manufacturable. If the parent fails this assessment the next best offspring is selected. Only selected offspring are tested against the failure criteria to reduce computation. Animation is employed to provide a flowing transition between one generation and the next. The generations are a fixed number of animation frames apart with the software extrapolating to fill in the missing frames (fig 2). This is known as key frame animation.

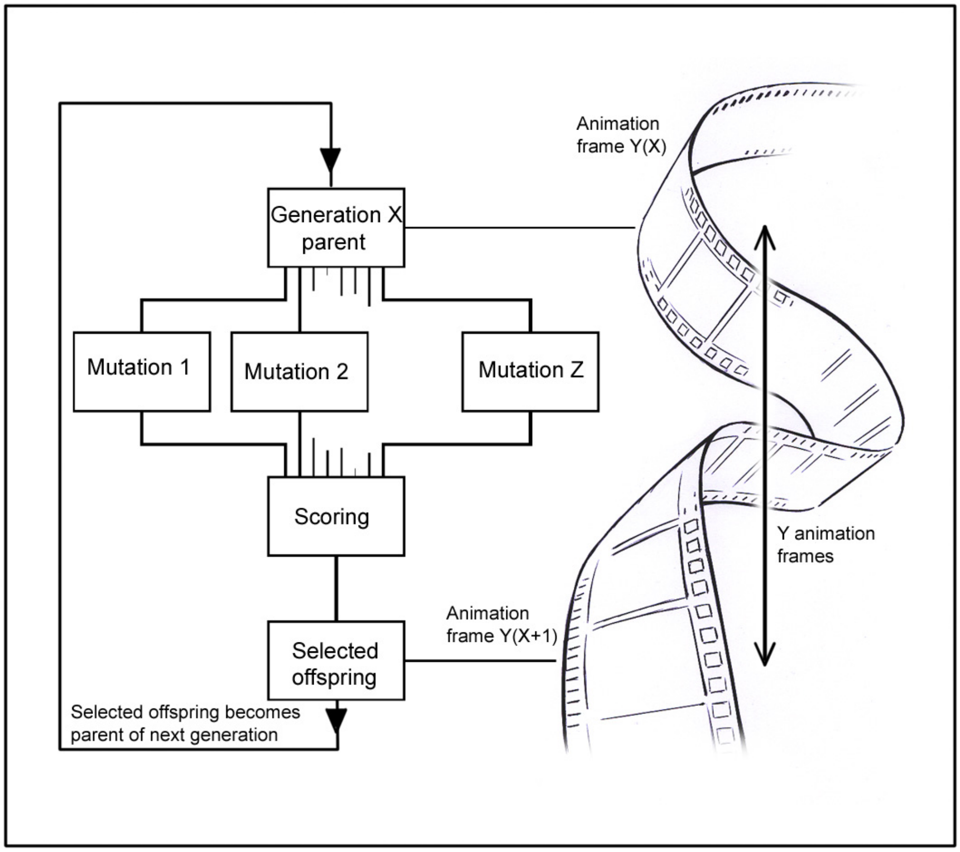

figure 2
The mutation, selection and animation process

The introduction of an evolutionary pressure

Given the use of random mutation and selection, the introduction of an evolutionary pressure was a logical step. Indeed it would be hard to avoid creating such pressure by virtue of the 'fitness' scoring. Public reaction to the early stages of the project also pointed to the inclusion of an evolutionary element.

Public reaction

As part of the Residency program at the University of Huddersfield, a touring exhibition was arranged to communicate the project to a wider public. The exhibition toured three regional venues, before going on to London and Milan. At each venue interactive displays were set up. Visitors were invited to 'try out' the system by selecting their own one-off designs from a computer rendered image of the design as it mutated randomly in real-time. Users received a 2D printed image of their individual design, which mimicked the production proposal, in which a 3D model would be digitally built. This gave the opportunity to assess levels of consumer interest and expectation.

The mutating image proved initially extremely seductive, with visitors drawn to the image and captivated by it. The selection process proved less of an attraction; users were often just as happy for the choice to be made for them. To some extent this is understandable, as no actual purchases were being made and no 3D objects would be generated. But it was nevertheless apparent that as the mutation was completely random there was little intrigue in 'what happens next'. Creating this type of intrigue is obviously important from a marketing point of view. A level of evolutionary development is seen as a way of stimulating this type of interest. The idea is that designs would be available and evolve for a limited period. Different periods of the evolution process may achieve different levels of desirability. The value of an artifact would vary according to its position in the evolution. There may be 'good' and 'bad' generations as there are good and bad vine harvests.

Aesthetic Evolutionary Design

The aim is not the functional optimisation of the designs through evolutionary computation. The suitability and functionality of the design are present in the initial seeded product form. Functionality is then maintained by the selection process, rather than improved upon. The aim is the evolution of aesthetic designs in what is described by Bentley as Aesthetic Evolutionary Design (Bentley 1999), an area that borrows from both Evolutionary Design Optimisation and Evolutionary Art (fig. 4).

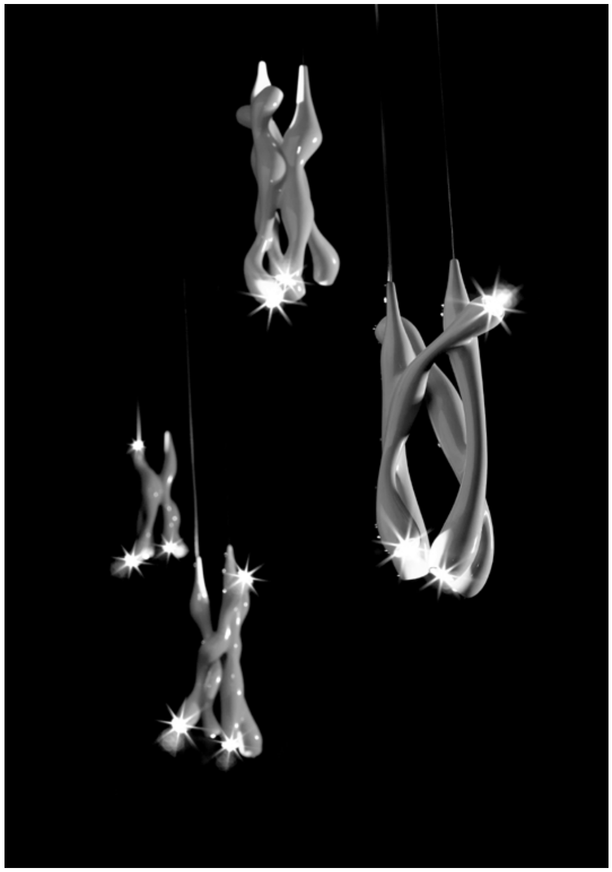

figure 4
‘Tuber’ pendant lamp produced by 3D printing

Failure criteria - feasibility, functionality and manufacturability

Assessing the mutant designs for feasibility, functionality, and manufacturability is relatively straight forward. The validity of the surfaces created can be assessed through the ability to export a suitable digital file for manufacture. Problems, such as overlapping surfaces, either prevent successful export, or are flagged up by error messages. The manufacturing limitations of the intended digital manufacture process can be imposed, minimum material section thickness and the machine build envelope for example. FutureFactories has experienced problems with clearing fine internal passageways of unused build material, this can be mitigated against with a limiting bore diameter/length ratio. Functionality may consider issues such as stability, checked via the position of the center of gravity, and the appropriate housing of internal components. These practical assessments are used to impose absolute limits rather than for relative scoring. The aim of FutureFactories is not technical refinement. It is not the intention to select the quickest to manufacture or the most stable; merely to assure that each generation conforms to a minimum functional standard.

Scoring the aesthetic

Maintaining the designer's intent requires a more relativist approach. Selecting designs based on a scoring of 'fitness' allows the designer to express general ideas for the design rather than absolute limits. For example the notion, "some rotation is fine but not too much," might translate to an exponential decrease in the probability of further rotation being selected as the angle increases. This less rigid form of definition simplifies the set up of the model and also allows the possibility of new unexpected forms (although the possibility of surprising turns has to be balanced against maintaining a coherent, identifiable design). The effects of the rules are 'softened' by the use of probability: a high fitness score can be allocated a higher probability of selection rather than assured selection. This again broadens the possibilities allowing from time to time the success of a less fit parent.

Step size – micro-mutation, macro-mutation and the balance between different transformations

Evolution is the result of accumulated small change. If the geometry of the model were to be re-arranged at random there would be infinitely more ways of creating a failure than a success. As Dawkins points out of the natural world, "Even a small random jump in genetic space is likely to end in death. But the smaller the jump the less likely death is, and the more likely is it that the jump will be in improvement……………The chance of improvement resulting from a transformation tends to zero with increasing step size and to 50% as it decreases" (Dawkins 1986). Also the more transformations that are occurring simultaneously, the lower the probability that they will all be successful. For this reason each offspring 'bred' from the parent form has only one parameter adjusted at random +/- one 'small' step. The step size is an absolute value arrived at through experimentation. A step size is set for rotation, transformation and scaling. The values of these different steps must be balanced so that they each achieve a comparable degree of change to the form. If particular transformations have disproportionate effects, they will inevitably exclude milder transformations from the evolutionary process. A diagnostics screen has been incorporated into the system to guide the setting up process. Amongst other information this screen is shows the percentage breakdown between the three transformation types that have acted on the model up to the current point in the evolution. It is possible to see the balance between the operation types as the evolution progresses.

Evolution – what are the aims?

The designer creates both the initial form of the design and the evolutionary pressure that will govern changes in that form over its evolutionary lifespan. The aim is to evolve increasingly visually interesting designs along the path set by the designer. The use of digital manufacturing favours more complex forms. If the forms are simple or regular, then the options increase for manufacture via faster, cheaper, conventional methods. So whilst simplicity may have elegance, FutureFactories evolutions will necessarily tend toward the more complex.

We have considered surface area divided by volume as a measure of complexity. Dividing by volume prevents simple expansion. When applied repeatedly to a simple model, the resulting forms, after 200 generations, are clearly related, more intricate, and yet still manufacturable (machine build area is used as a failure criteria).

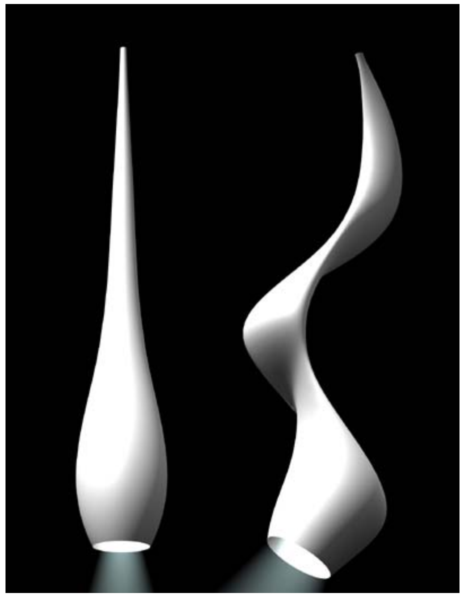

figure 5, the initial form and the form after 200 generations

Detail, grouped, and structural changes

The product forms of the FutureFactories models are made up of surfaces defined by control curves. It is these control curves that are manipulated during the evolutionary process. Each 3D iteration (in evolutionary terminology phenotype), is defined by a list of parameter values (the genotype). Parametric CAD generates the 3D form from this list or genotype. The evolutionary algorithm modifies the list generating mutated genotypes which in turn, via CAD, create mutated 3D objects (fig6).

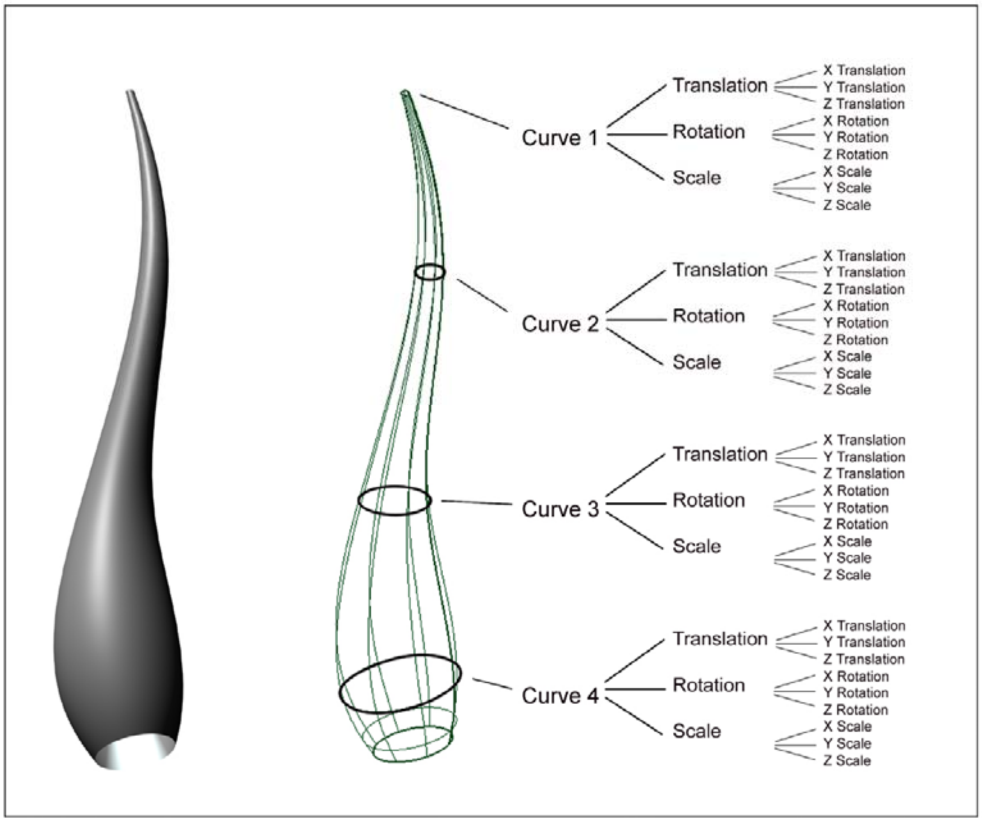

figure 6
The CAD model phenotype and its Parameter genotype

Manipulating individual parameters results in what could be considered as, local, detail changes. As well as detail changes it is often desirable to manipulate larger areas of the form with the same transformation. In a legged structure for example, it may be desirable to apply transformations to legs as a whole rather than specific areas of individual legs. For this reason FutureFactories allows the grouping of parameters at the set up stage, for example, a leg group. The grouped parameters are treated in the same way as the individual ones with a certain probability of random mutation. A transformation may be applied to the grouped parameters, or to individual parameters within the group: the percentage probability of each being dictated by the set-up rules. The particular transformation may be therefore applied to a small area as a detail change or may be spread over a particular feature (fig 7).

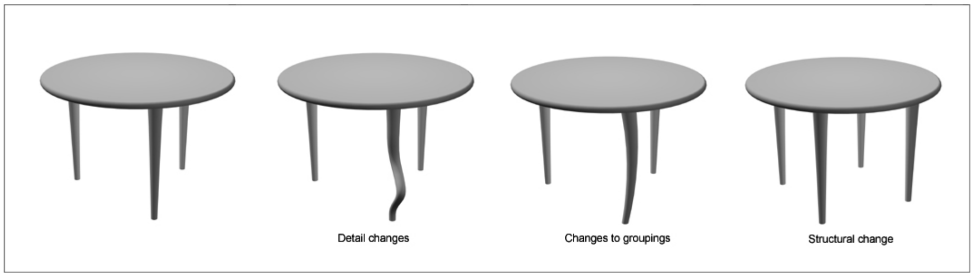

figure 7
Mutation sphere of influence

Structural change involves an alteration of the geometrical make up of the model, rather than adjustment of it. This could be the addition or removal of features, for example, an additional leg on a legged structure. This type of change is very difficult to accommodate in the FutureFactories due to the surface based geometry of the current models and the requirement that each iteration produces a potentially viable product. The system does not allow for the evolution of new features from functionally compromised beginnings. Complex natural systems, such as the human eye, have evolved from much cruder beginnings, like perhaps the light sensitive spots processed by some single celled animals (Dawkins 1986). One can imagine the parallel in the Tuber lamp (fig. 8). A new limb might evolve beginning as a small protuberance on the surface. This would elongate and develop a slight glow to the tip. The glow then intensifies, until it becomes the intense focused beam of the LED. This unfortunately belongs to the virtual world. FutureFactories is able to individualise product forms, but standard, interchangeable functional components are still required. An LED has a fixed size and specification. It is either there, or it is not.

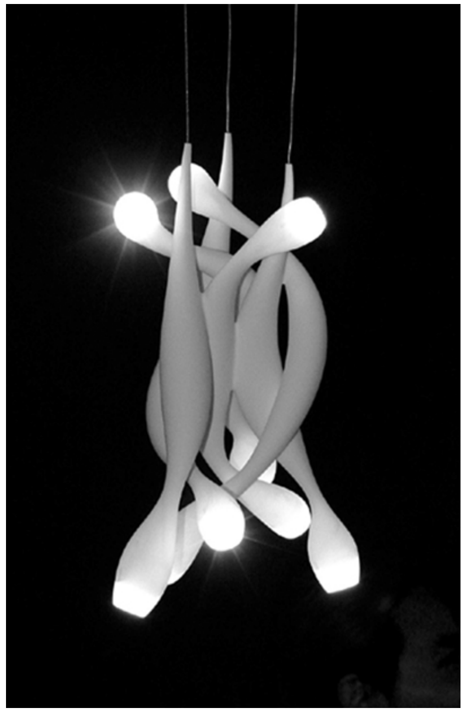

Figure 8
Tuber9 produced in Laser sintered nylon

A degree of structural evolution is desirable, if not essential. FutureFactories achieves this by breaking the design down into an assembly of separate models. Tuber consists of limbs that intersect. These are separate solid models joined by a Boolean operation. The requirement is that all four limbs remain linked by enough material to achieve a structural joint. The format of the assembly can change during the evolution as long as all four limbs remain linked. A link can pass from one limb to another in the manner of a baton being passed in a relay race (fig. 9).

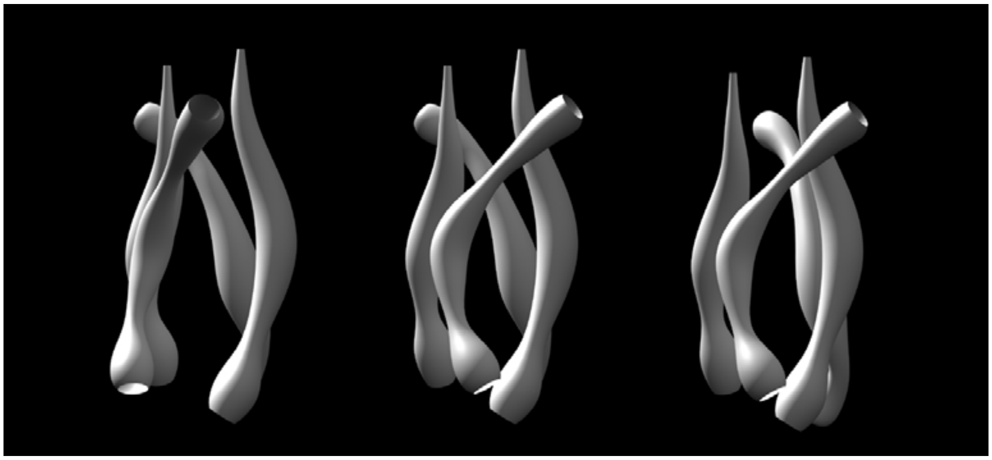

figure 9
changes in model structure

FutureFactories vs. Evolutionary art

FutureFactories employs many of the principles seen in evolutionary art. There are also major differences. Evolutionary art and FutureFactories are similar in that they have no fixed target solution. The design is not homing in on an ideal generation by generation (Although in evolutionary art, with manual selection a user might focus on his/her preference). What is important, is the level of development: this usually means complexity. The number of generations "progress" from the start point. The importance is the distance from the starting point in solution space rather than a particular region of it.

Organic art often starts with simple geometric primitives; effectively a blank canvas. FutureFactories starts with well developed, non random, seeded solutions, a viable design that must be maintained throughout the evolutionary process.

Evolutionary art exists in a virtual world. The constraints of the physical world, gravity for instance, need not exist. In evolutionary art anything is possible and the images are usually scaled as required to fit a convenient screen area. "The scale of forms generated from the same structure can vary by huge amounts as the parameters change: a single family can easily include both whales and insects" (Todd and Latham, 1999). Functional products must adhere to physical rules. In commercial manufacture, certain products would be destined for production in certain machines. The machines have build envelopes, into which parts must fit (although it is possible to subdivide a form into smaller components that are subsequently assembled into a larger structures using built in fastenings). There must be an element of repeatability in the production process if volume production is to be economically viable. Iterations of the same design, in spite of differences in form, should be produced in the same machine and use the same packaging (elements of protective packaging can be incorporated into the build process). Dimensions in FutureFactories are absolute, with limits imposed to ensure manufacturability.

Evolutionary art often allows a user, or 'artist', to guide the evolution. The FutureFactories selection process is automated: there is no human input during the evolutionary process.

One of the 'drawbacks' for Evolutionary art is that the images generated often have very distinct styles. "Often the style of the form generated using a particular representation is more identifiable than the style of the artist used to guide the evolution" (Bentley, 1999). The representations used are often limited to particular types of structure and generate forms with common, readily identifiable elements. In FutureFactories this is an aim - to produce designs that remain identifiable in spite of mutation.

The nature of the FutureFactories designs

From the project's inception, communication of the FutureFactories concept was an important factor. The example designs created had a strong flavour of organic growth in the aesthetic. The name Tuber and Tuber's colour – vivid green, were seen as factors in selling the concept. A frequent question raised is, given that the designs to date have such a strong organic flavor – could the system be applied to other aesthetics, to something more geometric?

Beyond the 'marketing' of the concept, there are other reasons for the preference of organic forms. Firstly, the example products produced to date are the work of one designer; inevitably the work reflects his tastes and ideas. Secondly, the virtual models are literally growing: natural organic forms are the result of growth and so the connection is hardly surprising. Thirdly, one of the transformation types employed is a twisting motion. Twisting a form is almost certain to result in the generation of curves. Where surfaces are formed between control curves, they are geometrically constrained to flow smoothly one curve to the next.

Geometric aesthetics are not being overlooked however. One of the areas for future work is an evolution that favors the creation of flat surfaces, straight edges, and angular relationships between faces. The evolution would start from a simple organic base and evolve into something geometric and faceted.

Conclusions

The use of simple fitness scoring and failure criteria has been used to replace the 'parameter envelope' of the original work. Using this evolutionary algorithm, selection based approach, represents a huge reduction in complexity. Consider the simple limb used in the earlier examples (fig 6). Instead of setting ranges for its 36 parameters, some of which interrelate and cannot be considered in isolation, a scoring system is used. Surface area/volume and machine build envelope limits control the model's evolutionary mutation. Running the evolutionary algorithm for 200 generations results in closely related, but at the same time, distinct solutions. The design progresses along slightly different pathways to the same region in 'solution space'. If we are confident that after a given number of generations the forms, whilst different, will conform to a broad design concept, we can allow the evolution to run repeatedly. On top of the initial design, the designer needs to specify selection criteria that will focus the evolutionary development on a solution space region, as broad or as narrow, as required. This gives the possibility of running the evolution on the customer's home computer, rather than on the host server. Computationally, this is a much more attractive solution than the customer accessing an evolution on a host server: however, conceptually the main benefit is in the flexibility. Running the evolution on the customer's home computer means that the evolution can be started on-demand. The customer can run the evolution at will, stopping, starting and resetting as desired.

FutureFactories focuses on a single mutating solution. Evolutionary algorithms are usually much more sophisticated. They often feature populations of solutions, and two parents, both of whom contribute to the offspring's 'genetic' make up. This 'crossover' contributes to the evolution as well as mutation. So far FutureFactories has been very broad in its aims for evolution. As the complexity of the models, and the degree of evolutionary control required increase, it is likely that the models will become susceptible to 'noise' and 'local optima' (solutions that score high on 'fitness' but are not ultimately the 'target').

The scope of the evolution possible within FutureFactories is restricted. It is limited by the use of standard components, by the geometry of the model, and by the requirement that the iterations remain recognisable designs, true to the designer's intent. Trials have shown us that customer demand is for significant change in the forms. It is also seen as desirable that, whilst conforming to a design idea, the evolved form contains some unexpected twists.

The potential for evolution is restricted by the internal components in the sense that, whist in principle the skin of the design might be allowed to mutate, significant areas of the form will be dictated by standard functional components. Ideally the entire product should be allowed to evolve including any functional components. It is possible that such components could be built digitally along with the body. This already happens with some simple mechanical devices for example, springs, bearings, clips and hinges. There are also machines capable of building in more than one material simultaneously. There are research machines capable of 'growing' circuitry on electronic substrates (de Garis 1999). It is safe to assume that technology will make components ever smaller and easier to package. New materials and possibilities for digital manufacturing are emerging all the time, with ever increasing performance. It will become possible to achieve more and more functionality from digital builds.

Simplicity in the model has been sought to facilitate the creation of generic systems rather than a discrete examples. We have sought to maintain simplicity whilst allowing a degree of structural change through a model made up of multiple bodies. This could be taken further towards the building block approach common amongst evolutionary systems in which geometric primitives are added, subtracted, and modified to achieve a desired form. These methodologies however do not in themselves produce viable products. Further operations are required to translate the primitive blocks into the functional components. The evolution takes place on a simplified model. Each time a real product is required a set of mapping operations are performed, for example, primitive blocks are united into a single volume; this would then be smoothed and hollowed out. The FutureFactories customer sees the evolution occurring in real time. Either the customer is presented with the simplified model or the mapping operations must be computed for each generation. The latter approach is impractical, requiring too much computation. Presenting the customer with a simplified version is open to misinterpretation. If the mapping operation makes significant changes to the model, then too much is left to the imagination. In the FutureFactories multiple body model, the animated evolution shows the separate bodies simply intersecting. Outputting a 3D model gives the intersection between the forms a fillet radius. An integrated form is made from overlaid separate entities. Visually the product becomes more realistic and 'believable' after this 'mapping' (fig 10): however, a reasonable impression can be gained from the simplified animation model. From a computational point of view leaving complex modelling operations to a mapping stage, completed only if a 3D outcome is required is highly desirable. But visually the animation needs to be close to the final outcome. A square block representation of a soft sculptural form, for example, would not be acceptable.

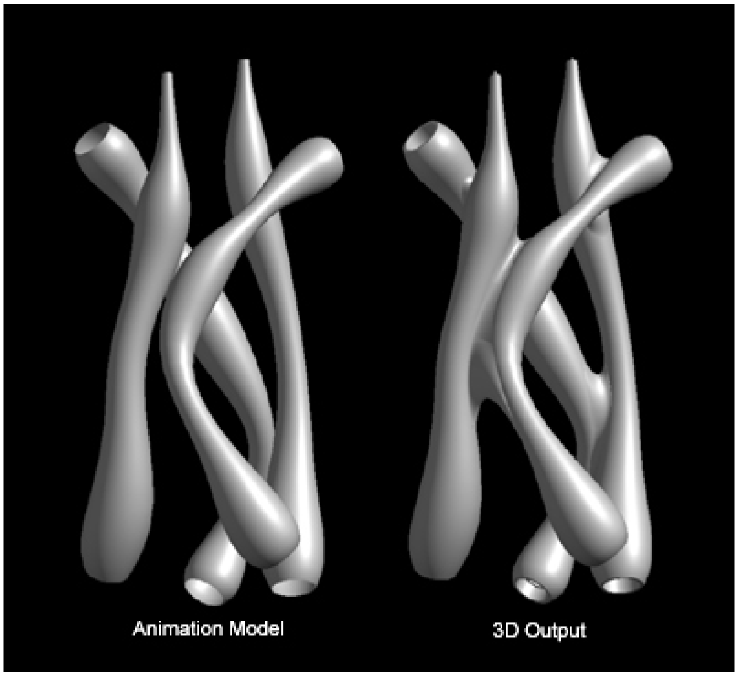

figure 10
Animation model vs. 3D output

Scoring surface area/volume represents a crude beginning. Other assessment methodologies are under consideration. Consideration is also being given to the number of polygons required to idealise a surface, average surface curvature, and the spread of surface-normals as fitness criteria: the results to-date are promising.

The potential impact of 'Future Factories' have been noted and described since the first stage of this work as mentioned (Atkinson & Dean 2003) and are still considered to be significant. As the project has developed, additional elements have been recognised with respect to the system's impact on issues of authorship and accepted notions or definitions of design practice (Atkinson & Hales 2004).

Clearly 'Future Factories' is an example of emerging and converging technologies and new practices which are forming a new position for the maker and author as the creative source of finished pieces. In fact, the designer may not even be aware of products selected and produced in his or her name. The combination of mathematical algorithmic processes and autonomous production potentially act to isolate the author of the work from the outcome, and raises questions of responsibility and ownership.

Finally, the use of software processes and real-time networks as generative tools questions existing, transient boundaries of practice, and also exposes the relevance or irrelevance of conventional definitions and accepted nature of the roles, practices, techniques and processes involved. It is clear that the outcomes of such a new model of creative production cannot be thought of as traditionally conceived pieces. They are, without question, art. Outside of that, existing definitions convey little of the reality of their production, as they lie in some new, as yet unspecified arena of production.

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'Future factories': teaching techné

Paul Atkinson and **Lionel Theodore Dean**

INTRODUCTION: BACKGROUND TO THE PROJECT

‚The phenomenon of the 'Artist-in-Residence' has a long-standing precedent in many areas of social and business activity where the imperative to present a different perspective on a number of aspects of everyday activity and to bring art into otherwise aesthetically impoverished environments has been seen to be of great benefit. Consequently, their appearance in corporations and state institutions is well known. Their place in an art education setting is perhaps less frequent, but by no means unusual, as the educational value of regular exposure to a 'qualified' or 'experienced' practitioner carrying out their own work has long been recognised. However, the use of a 'Designer-in-Residence' in a design for production education setting (as opposed to a designer-maker or craft environment) is perhaps even less well documented.

The School of Design Technology at the University of Huddersfield recently decided to allocate an amount of research funding to provide an 'Artist-in-Residence' to work alongside Fine Art students, and a 'Designer-in-Residence' to work alongside Product and Transport design students for a period of one year.

The detailed description of the role of the Designer-in-Residence in educational terms; the benefits to students in improving project management and time planning; and seeing the pace of professional design work in real time are substantial, but perhaps the subject of a slightly different paper to this one. Here, we wish instead to concentrate not so much on the process of using a Designer-in-Residence, but on the content of the particular project being undertaken, the far-reaching implications the work has for the practice of design and design education both on a theoretical and philosophical as well as a more pragmatic level.

The title of the project 'Future Factories' describes the exploration of the potential for direct digital manufacturing, using the latest CAD 3D modelling and rapid prototyping techniques, in which a random element of variance is introduced by the computer software. The outputs from this practice-based research project are expected to consist of a number of inspirational products produced as a result of the residency itself, which will be exhibited in a traditional gallery environment and later digitally – either on-line or by CD-ROM dissemination.

Alongside the practice-based research outputs, it is hoped there will be a publication describing the parallel Designer-in-Residence and Artist-in-Residence projects at Huddersfield in a pedagogic context, as well as a number of different academic papers (of which this is one) addressing the different theoretical and contextual issues raised by the content of the 'Future Factories' project.

THE 'FUTURE FACTORIES' PROJECT

'Future Factories' is an exploration of the possibilities for flexibility in the manufacture of artefacts inherent in digitally driven production techniques. All such production techniques are considered, the focus however is on the layer additive manufacturing techniques associated with Rapid Prototyping (RP). In essence the project proposes an inversion of the mass production paradigm to one of individualised production – in which a random element of variance is introduced by the computer within a parameter envelope defined by the designer. Each artefact physically produced will be a one-off variant of an organic design that has been defined by the designer and maintained in a constant state of metamorphosis by the computer software. This variance may be over parameters such as the relative positioning of features, scale, proportion, surface texture, pattern, and the like. These variable factors may be multiple and interrelated. The intention is to achieve subtly different aesthetics based on a central theme rather than mere differentiation that might be achieved by say scale or colour change alone. This random variance would simulate the lack of uniformity in one-off craft production where the craftsperson may be guided by a design intent rather than a toleranced production drawing. In this way, 'Future Factories' aims to overcome the split between the technological and the aesthetic, between artistic creativity and machine production – addressing in essence, 'Techné' – the integration of beauty, technical knowledge, and industry.

WHY INDIVIDUAL PRODUCTION?

Mass production itself is a relatively recent concept. Prior to mass production artefacts would be produced by craftsmen whose individual skills would be reflected in the product. The artefacts produced would be individual interpretations of a design formula. Each artefact produced could be more or less faithful to the original 'specification'. The design might be adapted to suit changes in stock material or to work around a fault or blemish. As well as variance introduced by the manufacturer the process itself might have an effect. The process used might not be fully controllable. Many craft processes are a balance between demands made of the process and the control of it, hand-blown glass for example. A craftsperson's mistake, rather than resulting in scrap, might produce an interesting twist on an old theme. The design formula itself might be organic, developing and mutating over time. This lack of uniformity, far from being seen as a negative by the consumer is often valued. Mass production depends on uniformity. Since the worldwide adoption of the mass production model the goal of manufacturing has been accurate repeatability. This has had a number of beneficial effects. Mass production has made desirable objects affordable. The size of the market allows levels of design development and the use of sophisticated processes not possible at lower volumes.

There is however a perception that something has been lost. In today's consumer world we are surrounded by every conceivable product for every possible application, all at affordable prices. This availability and the omnipresence of mass-merchandise fosters within us a desire for something personal and unique, something we can imbue with a soul or character of its own. 'Future Factories' considers the automated production of one-off pieces from organic, ever changing designs, which promotes the notion of the unique and fosters the processes of personalisation.

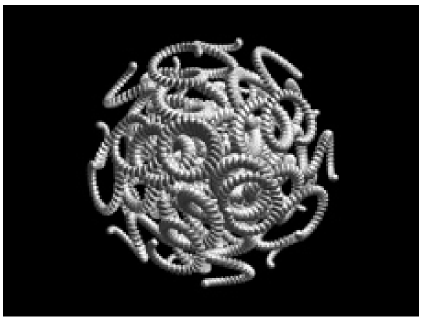
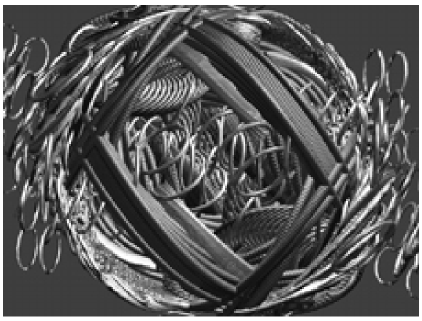
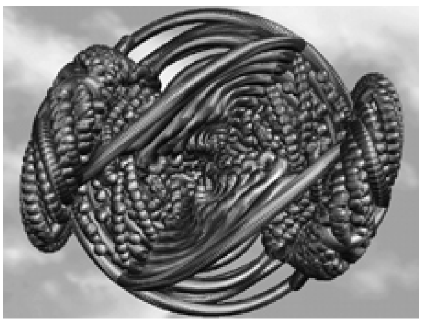
MASS CUSTOMIZATION

It is perhaps pertinent here to specify what 'Future Factories' is not - and it is not 'Mass Customization'. 'Mass Customization' can be defined as 'a delivery process through which mass-market goods and services are individualised to satisfy a very specific customer need at an affordable price. Based on the public's growing desire for product personalisation, it serves as the ultimate combination of "custom made" and "mass produced"' (Fu 2002: 44). The term 'Mass Customization was coined by Stan Davies in his book ***Future Perfect*** (Davies 1987). The term is deliberately paradoxical. There are many different models for mass customization suiting different products and market sectors. They are all however, consumer driven, and the key to mass customization remains 'modularisation and configuration. Products are "decomposed" into modular components or subsytems that can be recombined to more nearly satisfy consumer needs.' (Crayton 2001: 78). This may be through a combination of options as in cosmetic customization, where the consumer selects from an extensive but finite range of colours and finishes. Alternatively the consumers may provide data on personal preferences or accurate measurements of body parts to enable the production of a 'tailor made' product. Consequently, examples of mass customized products range from genuine medical 'needs' such as perfectly fitting hearing aids (Fu 2002) to desired product differentiation in a kitchen stove or better-fitting bespoke jeans (Marsh 1997).

In contrast to mass customization, the 'Future Factories' model derives no input from the consumer. Where mass customization consists of consumer selection and specification, 'Future Factories' allows the consumer only to select the moment at which the process of form generation is arrested. Each artefact produced is therefore a one-off realization of the designer's formula. It is the automated one-off production of an ever changing organic design in a constant state of metamorphosis.

COMPUTER GENERATION OF FORM

We do not claim here that the notion of computer generation of random form is an original one in itself. The capability of computers to add an element of random selection to any mathematical function has been long appreciated. As computers have increased in power and speed, the capacity to randomly generate complex three-dimensional forms can be seen as a logical development of that capability. Perhaps some of the best-known computer generated forms are those resulting from the collaboration between the artist William Latham and the mathematician and computer graphics expert Stephen Todd. Latham had developed a hand-drawn system for generating abstract form called 'form synth' in which geometric forms could be added together, undergo a series of pre-determined deformations and then join with other forms to 'marry' and create 'offspring' consisting of complex forms bearing characteristics of both 'parent' forms. Using the extensive resources of IBM's UK Scientific Centre at Winchester, in the late 1980s Todd developed this method and joined it with elements of Richard Dawkins' 'Biomorph' system (Dawkins 1993) that demonstrated the power of natural selection, in order to create a powerful piece of software called 'Mutator'. The detailed explanation of the workings of this system is best left to those who created it (Todd & Latham 1992), but the end results are staggering. The system has developed a great deal since, most notably in its widely disseminated form as the 'organic art' software package [figures 1-3] (Computer Artworks 1995); yet its potential has not yet been fully realised. Hopefully the 'Future Factories' concept will explore a small part of this potential.

Figures 1 - 3: Organic 3D forms generated (or created?) by Paul Atkinson using the 'Organic Art' software package.
Reproduced with permission of William Latham

Basically 'Mutator' took Latham's 'form synth' principle and expanded it exponentially. Incredibly complex forms would mutate and create eight different offspring. One 'child' could then be selected and a new series of mutations created from that selection. Mutations could then be judged as to how 'good' or 'bad' their forms were considered, and those judgements used to 'steer' the next generation of evolutionary mutation.
The similarities of the process to natural evolution have led to Latham being referred to as a 'Digital Darwin' (Cook 1996: 14-16). The driving force behind 'Mutator' was the creation of art. As the

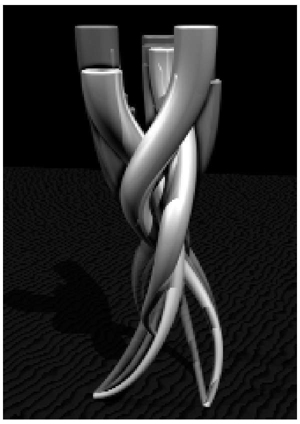
authors stated, 'some artists feel that it provides a genuinely new way of working, and it has certainly led to the creation of forms that would not have been created by other methods' (Todd & Latham 1992: 105). Although the resulting 'sculptures' were only ever intended to be seen as 2D representations of complex 3D models presented as art in a gallery context, the principle behind it can just as easily be used to create variations on 'usable' forms to produce designs for 'anything from buildings to shampoo bottles' (Computer Artworks 2003).

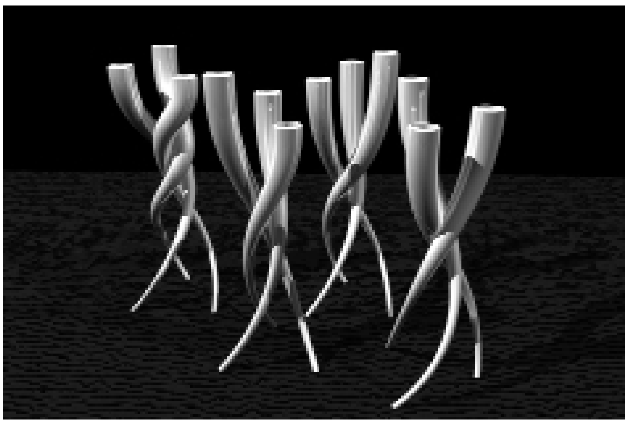
DESIGN FORMULA

The creation of computer generated art has little in the way of physical constraints. The adaptation of these forms into functional products though, obviously requires stricter control. Advances in computer added design have brought a shift to parametric solutions as a methodology for the definition of computer models (3d designs). In parametric design, relationships between the degrees of freedom of a model, instead of the degrees of freedom themselves, are specified. Using parametric design software designs can be quickly manipulated, and alternate solutions considered, simply by changing the variables, or parameters that define the product.

The 'Future Factories' designs are defined by 3d parametric models. In these models, ranges are set for certain parameters within which values are assigned at random by the computer. The range limits, along with further interdependent parametric relationships are imposed by the designer to maintain function and the desired aesthetic. This leaves an organic model free to mutate within a series of interrelated parameter envelopes. Each organic design is defined by a production formula, which can yield an infinite range of equally valid outcomes. We are able to categorise objects in nature by the recognition of certain common patterns and proportional relationships in spite of significant variance. 'Future Factories' aims to achieve this same balance between order and chaos, between manufactured uniformity and individual sensibilities. It aims to develop a system for the automated production of one-off outcomes that are at once distinctly individual and at the same time of a recognizable design.

Two fundamental approaches to the concept of product variance in the 'Future Factories' model have been identified in the work to date; manipulation of the core 3d form and the application to the core 3d form of a variable feature.





Figures 4, 5: 'Twist' candlestick,
Lionel Theodore Dean, 2002
The 'Twist' candlestick is an example of the manipulation of the core 3d form. The candlestick has a simple structure consisting of three legs, each of which carries a candle. The legs are curved in three dimensions and taper from top to bottom. They touch, and are joined, towards the middle of each leg to form a stable three-legged structure.

The 'Twist' candlestick's footprint [Figures 4, 5] is fixed, the legs being evenly spaced and at a fixed separation, for stability. The tops of the legs are also constrained but not fully. Each top is required to remain in the same radial plane as a foot, this is again is for stability. The height of each leg may vary, separately, between a maximum and a minimum value. A relationship is applied to ensure an even spread of heights between the legs. This

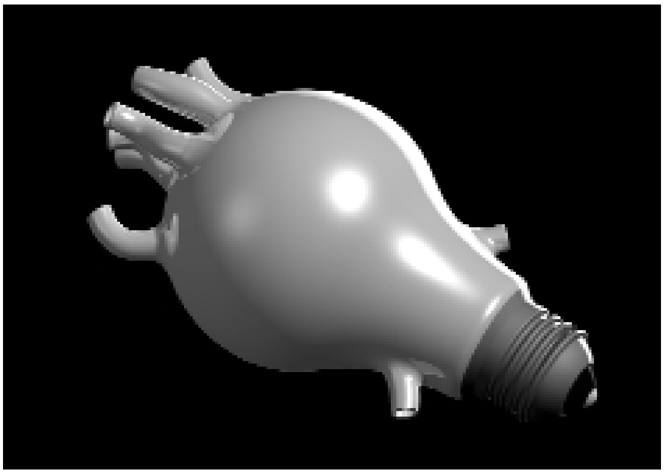


Figure 6, 7: 'Mutant bulb', Lionel Theodore Dean, 2002
This lumiere design is an example of the application of a variable feature to a core 3d form. The core form is that of a bespoke incandescent lightbulb.

relationship prevents an outcome with two legs close to maximum height and one close to the minimum, or the reverse scenario. The only constraints on the form of the legs between top and bottom are the degree of interference required for a joint to be made, and that the legs spiral in the same sense and in a smooth curve.

In the 'Mutant bulb' [Figure 56, 7], the light source is a series of high intensity white Light Emitting Diodes (LED's). The LED's are mounted in the ends of 'tentacles' which appear to grow at random from the bulb form. The end of each 'tentacle' is dimensionally constrained to accept an LED and the direction in which the LED points is restricted to certain angles from the vertical (to avoid glare). Three distinct characters of 'tentacle' have been designed;

- 'Drops' form like stalactites on the lower half of the bulb tapering as they 'grow' downwards as if under gravity.

- 'Tentacles' form like drops from the lower half of the bulb, these however are able to resist gravity to an extent, they have a tendency to curl and coil.

- 'Risers' form like stalagmites rising up from the upper half of the bulb. As they rise they lean out from the bulb body and begin to curl under gravity.

These 'Tentacle' types appear in varying proportion and random positions over the bulb form. Each can then vary in form based on its type.

THE 'FUTURE FACTORIES' SYSTEM

In 'Future Factories', a production system is envisaged in which the consumer is presented with a 3d digital model of the artefact via a website. The consumer may access the website directly or through a sales outlet, at a gallery or in a department store for example. The web site, the 'Future Factory' itself, would have a series of 'production lines' corresponding to different products. When a particular production line is selected the user is presented with a computer animation showing that particular product design metamorphosis within a parameter envelope specified by the designer. At any given point the consumer may freeze the animation effectively creating a one-off design on screen. Should the consumer wish they might then proceed with an order, in which case the relevant digital production files (stl etc.) would be generated automatically and sent to the relevant RP production facility. An artefact, effectively a one-off, will then be manufactured using layer additive manufacturing (rapid prototyping) techniques. This may be achieved directly, via laser sintering in a suitable material for example, or indirectly via the production of a single use tool or pattern. It should be pointed out that the intention is not for the consumer to use the animation to adjust design features to their liking. The animation is changing in real time and is outside their control (this would hopefully be part of the allure). A variant can be 'designed' for them and they can choose to order it or not.

WEPROGRESS SO FAR

A small series of organic product designs have been produced and defined parametrically. Domestic interior products, principally lighting and tableware have been considered for the project thus far. Domestic interior products is a market well used to paying a premium for design and materials technology. Lighting and tableware have been selected to keep the artefacts relatively small (though it should be noted that currently, the largest laser sintering machine commercially available in the UK is 700 Xx 500 x 350mm). The designs selected are for production in cast aluminium. They make use of the layer additive production methods to achieve complex forms almost impossible to achieve with multiple use tooling. This necessitates the use of investment casting with wax patterns for use in the process being produced by a layer additive process.

We are currently developing computer animations that illustrate the designs and the potential variance within them. A new computer program is being developed to enable the generation of digital production files direct from a selected animation frame. These STL files would then be used to directly produce wax patterns for investment casting in aluminium

TECHNÉ

It is clear to see from the detailed description of the 'Future Factories' project that it represents a true convergence of art and science; the aesthetic and the technological; between creativity and production. This integration of the human perception of beauty; the randomly mutated, computer generation of form; and purely neutral cutting-edge industrial production is a far more complex issue than it might at first appear. This is no simple human/machine interface or human/computer binary opposite we are dealing with, but the very nature of 'techné - art and science as one.

The adoption of such a design/production paradigm as the one being put forward by 'Future Factories' raises a whole series of complex issues about the role of the designer. If the user makes an aesthetic judgment on a form, the precise configuration of which has been generated by a piece of software, then who has 'designed' it? Is the designer's role in setting up the algorithms to be employed, the variables and constraints within which the computer generates the form, and the parameter envelopes which limit the amount of variation a major contribution to the finished artefact, or a fairly arbitrary minor consideration? The same problems were encountered by Todd and Latham with respect to the sculptures created via the 'Mutator' code: 'Who owns the copyright? What is copyright? The generative system? The genetic code for a final form? The computer form? The computer image? The artwork on a gallery wall?' (Todd & Latham 1992: 210). The potential effects on the practice of design are considerable. Whatever the future holds for design practice, there is certain to be serious changes occuring. Obviously, the future role of the designer and where he or she fits into the design process is one that will need to be examined closely and perhaps readdressed.

Despite the highly complex issue of defining 'design' per se (Micklethwaite 2000), and without wishing to enter a huge debate about the distinctions between craft and design, consider the following definitions of the two areas to see how the 'Future Factories' concept acts to blur those boundaries and distinctions. If 'craft' is taken to be concerned with the conception of form leading to one-off production; and 'design' is taken to be concerned with the conception of form leading to the production of a specification for later large-scale manufacture by a third party, then the distinction between a craft-person and a designer is clear. Following this distinction, 'Future Factories' aims to allow the use of a designed system to select a form randomly generated by computer software for immediate one-off production by machine. Although such a system has the capacity to make an infinite variety of related forms, it also has the capacity to reproduce exactly the same form, to a massively high level of accuracy, for an unspecified number of repetitions.

The 'Future Factories' system, then, would be seen to fit both the definition of craft, in that it allows one-off variations in form; of design, in allowing repetitive production of the same form; or neither as the form is not generated or conceived by the person who selects it, or even by the designer who specified the parameters within which it was designed. In this context, the previously understood definitions of 'craft' and 'design' as discrete processes become hopelessly blurred, intertwined, inextricable, and as a result, meaningless. Perhaps a completely new terminology will be required to describe such a phenomenon to define its unique nature. The impact on the understanding of design and its practice is potentially huge.

TEACHING TECHNÉ

As far as the impact on design education is concerned, every aspect of the curriculum may need to be addressed. Working backwards from the proposed manufacturing concept, the element of taught CAD would be concerned less with its integration with tool production and the generation of a specification in the form of a solid model geometry or a set of tolerance drawings; and more concerned with its output as a producible entity by a direct digital manufacturing process such as (for example) layer additive rapid prototyping.

The teaching of materials and processes for manufacture premised on mass-production would, of course, also have to be reduced or replaced with a higher level of emphasis given to complex organic forms and correspondingly suitable content to support such new digital technologies.

It is possible that even the visualisation skills taught will be affected if, as is entirely plausible, the final production techniques employed influence the conception of forms in the design process. To what extent are our current designers' forms for products influenced by the ease of manufacture in injection moulded components?

And perhaps, going right back to the starting point of project briefs – how many are based on the premise of a particular product to be produced in quantity for a certain age/gender/lifestyle or so on? There will almost certainly need to be a move from the 'accepted wisdom' of market research in its constant quest for a series of common denominators aiming to produce a product profile to fit the largest possible group of people. There will be a need, perhaps, to consider in far more depth the user needs of individuals – more attention paid to personal preference, the celebration of diversity over convergence. If the notion of the brand ethos were to continue in this scenario, surely it would have to move further into the realm of communicating individual meaning rather than 'lifestyle' or 'brand values' of a group of people, sharing some manufactured and marketed heterogeneity.

Certainly there would at least be a requirement for learning more about 'people' and less about 'markets' – more about the choices people make about objects and the emotional relationships people have with them. In short, less materials, more material culture.

CONCLUSIONS

At the time of writing, the 'Future Factories' project can be seen to have been a resounding success both in terms of a practice-based research project, and as an exercise in design pedagogy. The next stage in the project will be to expand the range of different items produced, and create more examples of products arising from each design formula. These will be exhibited in a number of gallery settings as individual or touring exhibitions. Further dissemination of the work produced will initially be done through the creation of a virtual gallery within the research section of the School website, and the production of a CD-Rom of the work is a distinct possibility.

The project has demonstrated that the potential of computer-generated organic forms to produce viable artefacts for one-off production, hinted at by the creators of the original 'mutator' code is at last a realistic proposition. The outputs from 'Future Factories' will be used as evidence to support bids for external funding to develop the required software further, and to purchase the hardware required to realise and trial the production of finished artefacts in-house.

The 'one design fits all' paradigm of modernist mass production may well have been expanded through the use of interchangeable components to allow for more variation on finishes and textures of standard products. The sheer range of models produced of most consumer products points towards confirmation of the 'myth' of mass production where the number of identical products is minimal. However, in most cases, the differences are superficial, and limited to the surface features of products. The economy of scale in producing similar products still holds sway – for all the variety of any model of mobile phones for example, the internal components remain standardised, and manufacturing technology is such that at least some elements of the political ideologies of modernism remain. The phone may look different, but its capabilities as a functional product are dictated by the manufacturer.

Obviously, 'Future Factories' is not a suitable model for the production of complex technological objects (at least not yet). But the design thinking behind it, and the manufacturing system proposed fits far more comfortably within the tenets of post modernism, and the drive for individuality associated with that philosophy.

As a piece of pedagogic research, the experience of having a designer-in-residence in an educational setting needs to be analysed and reflected upon, and the benefits disseminated through publication in journal articles and conference papers, and possibly in book form. It is clear, however, that the impact on design education of teaching techné is potentially huge.

Even at this stage of the project, graduate designers will leave the University of Huddersfield with a far wider perspective on the nature of their design discipline, and an insight into the possibilities technology holds for the application of craft ideologies to the design process. The project is certainly indicative of future changes that may well be required in design education.

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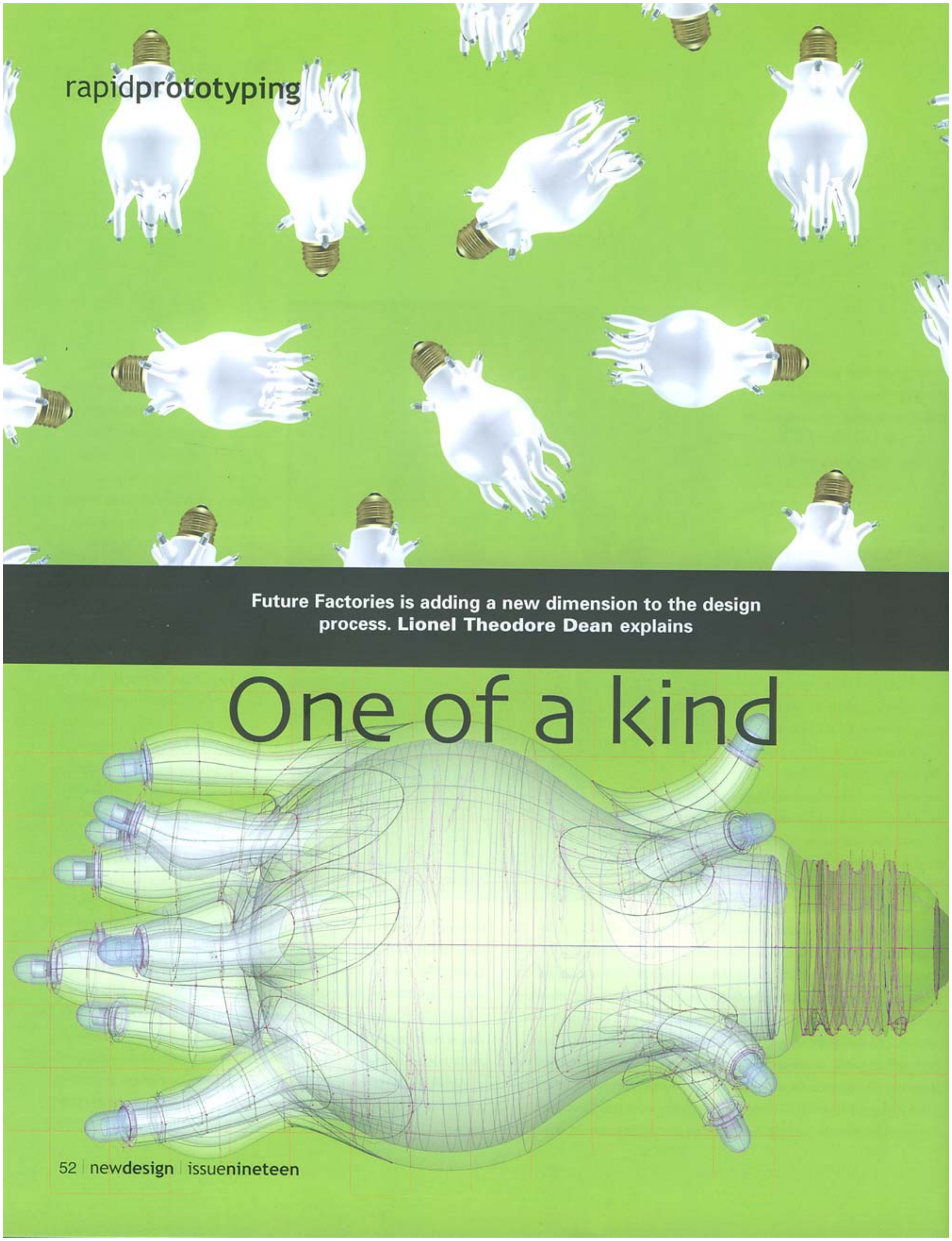

rapid**prototyping**

Future Factories is adding a new dimension to the design process. Lionel Theodore Dean explains

One of a kind

52 | new**design** | issue**nineteen**

rapid**prototyping**

Imagine a future where you could visit a dedicated 'Future Factories' website, a range of products will be on display and once you have selected your product, it will appear in a constant state of metamorphosis - growing, changing and mutating on screen. At any given moment you can pause the animation and view a 3D computer model of the product. A 'snapshot' can be taken at various stages of its growth and, if required, printed onto paper for closer examination. Each one of these 'snapshots' will be a unique form - never to be repeated. If you then decided to purchase one of the designs, you could order it directly from the website, and the product you have selected will be manufactured automatically, exactly as you had seen it on screen, and delivered directly to you. An original. A one-off. A work of art?

Now that rapid prototyping (RP) is well established - the new frontier to explore is direct manufacture. Direct or rapid manufacture is essentially the adaptation of RP technologies to the manufacture of end-use products. There are several niche markets emerging and the coming years are bound to see the technology move to low volume consumer products such as Future Factories.

The costs to produce identical forms are the same as those to produce one-offs - so why not have something unique every time? Since the worldwide adoption of the mass production model, the goal of manufacturing has been accurate repeatability. What if each product 'on the shelf' had its own subtle differences?

Future Factories began life in the Design Department of the School of Design Technology at the University of Huddersfield. The department aimed to introduce practice-based research to the 3D design course as well as demonstrate to students the pace, rigour and structured approach to project work of a professional designer. With this in mind, the university used research monies to fund the post of 'Designer in Residence' whom, it was intended, would carry out their work alongside design students from the product design and transport design courses.

In the summer of 2002, Lionel T Dean, presented his embroyonic Future Factories concept to the university which ultimately led to

rapid**prototyping**

Computer generation | The Future Factories project utilises the technology of direct manufacture to produce: **1. and 2.** The Nautilus and | **3.** Tuber pendant luminaires and | **4.** the 'Let's Twist Again!' candlestick

his appointment as Designer in Residence for the academic year 2002/2003. The project was considered fresh, exciting and potentially stimulating for students to see unfolding.

In today's consumer world we are surrounded by every conceivable product for every possible application, all at affordable prices. This availability and omnipresence of mass-merchandise fosters within us a desire for something personal and unique, something we can imbue with a soul or character of its own. According to Paul Atkinson, the research leader for the School of Design Technology and who is also working on the Future Factories project, says: "Future Factories considers the automated production of one-off pieces from organic, ever changing designs, which promotes the notion of the unique and fosters the processes of personalisation."

The concept allows the consumer only to select the moment at which the process of form generation is arrested. Each artefact produced is therefore a one-off realisation of the designer's formula, as interpreted by computer software.

The project relies on two digital design concepts common to most high-end software packages - parametric design and animation. Parametric design considers the relationships between degrees of freedom rather than the degrees of freedom themselves. If one dimension is changed the whole model will up-date to maintain specified proportional relationships. Animating a digital model means allowing one or more of its attributes to change over time.

The Future Factories design templates are defined using a combination of range limits and parametric relationships. Proportional relationships between characteristics maintain the character and aesthetic of the design while range limits ensure functionality. From a start position a model's key driving dimensions are re-assigned random values from within specified permissible ranges: this creates a revised model. Rather than jump directly to this new form, animation is employed to move gradually to the new position over time. This allows smooth, flowing transitions rather than staccato jumps when the model is viewed in metamorphosis. When the model reaches its new position the random values are re-assigned and the process repeats itself. At any point the animation can be halted and the model exported as an standard triangulation language (.STL) file for digital manufacture.

In the initial stages, Lionel Dean created a collection of domestic lighting and tableware designs using Alias StudioTools and Solidworks CAD software. The relatively low cost of 3D printing (3DP) processes made them ideal for the project as multiple iterations of each design were required.

The Tuber pendant luminaire is built using Z-Corp's 3DP process. In this process layers are built by applying a binder to plaster-based powder. The resulting porous model is then impregnated with either superglue or wax in a post-production process. Absolute dimensional accuracy was not important here only the character of the form. Surface finish was also not an issue as a high quality paint finish was specified; there would be hand finishing whatever the process used. Removing the loose powder from the somewhat inaccessible internal passageways proved to be a challenge as did handling the delicate model prior to impregnation.

The Lampadina Mutanta and Nautilus pendant luminaires were

both designed for direct manufacture in SLS stainless steel. Budgets however dictated a shift to investment casting from 3DP generated wax patterns. The main implication of this was an increase in wall thickness required for casting. Lampadina Mutanta has the size and form of a standard GLS lightbulb. An irregular growth of tentacles sprouts from the top and bottom of the bulb each bearing a white LED. These tentacles move around the bulb swelling and writhing as the design mutates. If too many LED's point in the same direction the solution is rejected and the random variables re-generated. The form makes full use of the flexibility inherent in RP processes. The closely grouped, hollow, curled tentacles are full of re-entrant forms or undercuts that would be almost impossible to manufacture conventionally. Waxes for casting were produced using 3D Systems' Laserjet 3D printing system. This process requires the removal of support structures from the wax prior to investment. Castings have been successfully produced in stainless steel brass and bronze.

The Twist three branch candlestick is also investment cast but this time from a power-based RP pattern. This pattern was produced using the same Z-Corp process as Tuber but with a starch-based powder designed for investment casting. The powder based process offered the advantage of no support structures but not all foundries are prepared to work with this unfamiliar material.

The Future Factories project demonstrates that the use of computer-generated organic forms to produce viable artifacts for one-off production is a realistic proposition. At the same time the project has highlighted the number of checks and balances we, the designers, put on a product form. In designing for this system it becomes necessary to abandon the search for the optimal set of proportions, in favour of capturing the essence of a design. The implications of the wide spread adoption of such techniques by industry are potentially serious, and moves to protect the Future Factories process via patents have been made.

Direct manufacture will change the rules for product design - design for manufacture will lose much of its relevance. High volume production will remain the preserve of high speed moulding processes however, at lower volumes we are likely to see some changes.

INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

Title: ‘Future Factories’: Supportive technologies as creative processes

Keywords: 3D Generative processes, Rapid Prototyping, Direct Digital Manufacture

1. Introduction

Envisage a future where you could visit a dedicated 'Future Factories' website, accessed in a gallery, a department store or directly from your own home. This website would display a range of products, and you could select any one of them. Once you made a choice, you would be presented with an animation, which would show that particular product in a constant state of metamorphosis, as it grows, changes and mutates on the screen. At any given moment you could pause the animation and view a three-dimensional computer model of the product, rotating it to see it from any angle. The animation would continue, and any number of ‘snapshots’ of the product at various stages of its growth could be taken, and if required, printed onto paper for closer examination. Each one of these ‘snapshots’ would be a unique form – never to be repeated. If you then decided to purchase one of the designs, you could order it directly from the website, and the product you had selected would be manufactured automatically, exactly as you had seen it on screen, and delivered directly to your door. An original. A one-off. A work of art?

The School of Design Technology at the University of Huddersfield recently decided to allocate an amount of research funding to provide an ‘Artist-in-Residence’ to work alongside Fine Art students, and a ‘Designer-in-Residence’ to work alongside Product and Transport design students for a period of one year. The work undertaken by the Designer in Residence along with contributions made by other academic staff are the subject of this paper. The title of the project ‘Future Factories’ describes an exploration of the creative potential inherent in digital design and manufacture to offer more than a single discrete 3D outcome. The outputs from this practice-based research project consist of a number of inspirational products which have been exhibited in a number of traditional gallery environments and will be later disseminated digitally – either on-line or by CD-ROM. Alongside the practice-based research outputs there have been a number of different academic papers addressing the different technical, theoretical and contextual issues raised by the content of the ‘Future Factories’ project.

2. Methodology

'Future Factories' is an exploration of the possibilities for flexibility in the manufacture of artefacts inherent in digitally driven production techniques. All such production techniques are considered, the focus however is on the layer additive manufacturing techniques associated with Rapid Prototyping (RP). In essence the project proposes an inversion of the mass production paradigm to one of mass-customisation. However, unlike previous work on mass-customisation, where many design decisions are taken by the consumer or with reference to the particular consumers needs, 'Future Factories' considers individualised production – in which a random element of variance is introduced by the computer within a parameter envelope defined by the designer. Each artefact physically produced will be a one-off variant of an organic design that has been defined by the designer and maintained in a constant state of metamorphosis by the computer software. This variance may be over parameters such as the relative positioning of features, scale, proportion, surface texture, pattern, and the like. These variable factors may be multiple and interrelated. The intention is to achieve subtly different aesthetics based on a central theme rather than mere differentiation that might be achieved by say scale or colour change alone. This random variance would simulate the lack of uniformity in one-off craft production where the craftsperson may be guided by a design intent rather than a toleranced production drawing. In this way, 'Future Factories' aims to overcome the split between the technological and the aesthetic, between artistic creativity and machine production

The creation of computer generated art has little in the way of physical constraints. The adaptation of these forms into functional products though, obviously requires stricter control. Advances in computer added design have brought a shift to parametric solutions as a methodology for the definition of computer models (3d designs). In parametric design, relationships between the degrees of freedom of a model, instead of the degrees of freedom themselves, are specified. Using parametric design software designs can be quickly manipulated, and alternate solutions considered, simply by changing the variables, or parameters that define the product.

The 'Future Factories' designs are defined by 3d parametric models. In these models, ranges are set for certain parameters within which values are assigned at random by the computer. The range limits, along with further interdependent parametric relationships are imposed by the designer to maintain function and the desired aesthetic. This leaves an organic model free to mutate within a series of interrelated parameter envelopes. Each organic design is defined by a production formula, which can yield an infinite range of equally valid outcomes. We are able to categorise objects in nature by the recognition of certain common patterns and proportional relationships in spite of significant variance. 'Future Factories' aims to achieve this same balance between order and chaos, between manufactured uniformity and individual sensibilities. It aims to develop a system for the automated production of one-off outcomes that are at once distinctly individual and at the same time of a recognizable design.

Two fundamental approaches to the concept of product variance in the FF model have been identified in the work to date; manipulation of the core 3D form and the application to the core 3D form of a variable feature.

As an example of the first approach, a three-legged candlestick was designed, having a series of functional requirements – to stand upright and support three candlesticks of a fixed size. The candlestick's footprint is fixed, the legs being evenly spaced and at a fixed separation, for stability. The tops of the legs are also constrained but not fully. Each top is required to remain in the same radial plane as a foot, again for stability. The height of each leg may vary, separately, between a maximum and a minimum value. A relationship is applied to ensure an even spread of heights between the legs. This relationship prevents an outcome with two legs close to maximum height and one close to the minimum, or the reverse scenario. The only constraints on the form of the legs between top and bottom are the degree of interference required for a joint to be made, and that the legs spiral in the same sense and in a smooth curve.

As an example of the second approach, a light fitting was designed which took the existing form of a light bulb, but with a solid metal body. Instead, the light source is a series of high intensity white Light Emitting Diodes (LED's) mounted in the ends of 'tentacles' which appear to grow at random from the bulb form. The end of each 'tentacle' is dimensionally constrained to accept an LED and the direction in which the LED points is restricted to certain angles from the vertical (to avoid glare). Three distinct characters of 'tentacle' have been designed;

‘Drops’ form like stalactites on the lower half of the bulb tapering as they ‘grow’ downwards as if under gravity.

‘Tentacles’ form like drops from the lower half of the bulb, these however are able to resist gravity to an extent, they have a tendency to curl and coil.

‘Risers’ form like stalagmites rising from the upper half of the bulb. As they rise they lean out from the bulb body and begin to curl under gravity.

These ‘Tentacle’ types appear in varying proportion and random positions over the bulb form. Each can then vary in form based on its type.

3. Virtual Merchandising

Conventional marketing usually centres around a glossy photograph of the product shown from its best angle. VR content enables websites to bring the products 'to life' with 3D models, user interactivity, animation, sound, and detailed views. An interactive image allows the product to be seen from all angles. Potential customers are able to examine the design in the form of a 3D model moving, rotating, and zooming in and out at will. This ‘hands-on’ interaction allows something of a “try before you buy” experience. Internet shoppers have been reported to spend 50% more time in the part of the site that offers interactive 3D images, yet VR on the Web is not yet mainstream or widespread. Why has this exciting technology made such slow progress? This may be due to the fact that VR content is costly to develop, mostly because the expertise to create it is still rare, and a direct link to sales revenue is as yet unproven. In addition, content creators typically make a substantial investment in computers, software, and digital equipment. Technical difficulties have discouraged the take up of website based VR marketing. The technology is most convincing and pleasing when it uses realistic textures, lighting and sounds. The use of these elements requires large files which leads to slow performance, and web designers fight a constant battle between high graphical appeal and slow download times. High resolution graphics and elaborate animations are notoriously slow to download, especially through a dial-up connection. Add to that bandwidth limitations and the possibly unreliable connections of the Web, and you have the potential for a deeply dissatisfying experience.

We can assume that consumers will always prefer hands-on experience with a product before purchase. Barring cumbersome and expensive gloves and goggles, VR is still strictly an audiovisual experience. Even gloves have serious limitations in that they cannot provide a tactile experience of texture. This might be solved if the website access was via a retail outlet and samples were available. It would also avoid ‘user end’ technical issues. VR content cannot be viewed with a standard browser - a special-purpose browser or a plug-in is required. In addition there is no single viewer that can handle all VR content. The requirement to download additional software merely to, in effect, browse a shopping catalogue is a severe disincentive. The user may not even have administrator rights to the computer or the desire to involve themselves in IT issues. The lack of an industry standard also affects content creators (and their cost), as each viewer typically has its own authoring tool. There is no single tool that a programmer can learn with any expectation of addressing more than a fraction of Web users. The limitations of computers and the technological demands of VR should not be exaggerated however. VR files are not necessarily huge. Files consisting mostly of vector graphics are relatively small. Problems of speed and resolution will be solved over time as standard-issue desktop computers gain speed and are optimized for 3D graphics. Higher-bandwidth and more reliable connections to the Internet will also become more common. Proprietary viewer and content creation software offer increasingly high-quality images within compact, efficient files.

4. 3D Modelling and Software Development

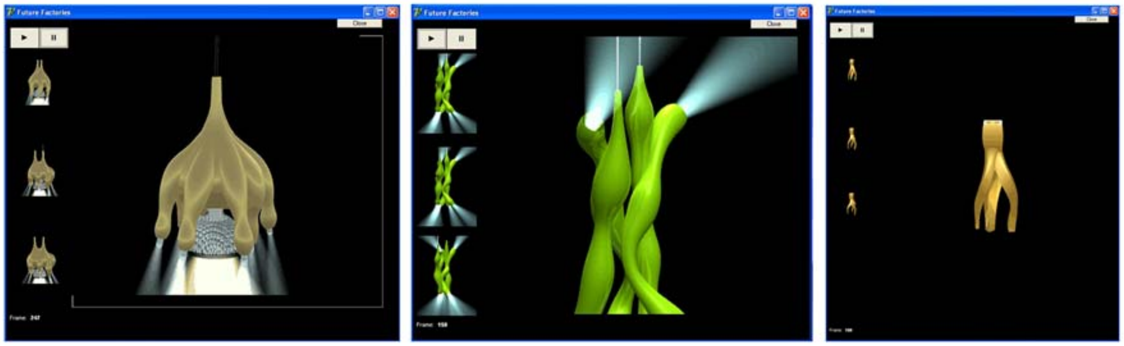

Figure 1. Organic designs created in Future Factories Software

Initially in order to test user interaction and finding out what each individual person choose during the exhibition, a new software FF (Future Factories) is developed. The software written in Delphi Language enabled user to choose, stop, replay, print a 2D picture as well as capturing the selected design parameters and creating a database.

In this study a series of organic product designs shown in Figure 1 were created using this software. Domestic interior products, principally lighting and tableware, have been considered for the project thus far. Domestic interior products is a market well used to paying a premium for design and materials technology. Lighting and tableware have been selected to keep the artefacts relatively small. This consideration is based on cost rather than capacity - the largest laser sintering machine commercially available in the UK is 700 x 500 x 350mm for manufacture in one piece, and building in sections could also be considered. The designs selected thus far are for production in cast metal. They make use of layer additive production methods to achieve complex forms almost impossible to achieve with multiple use tooling. This necessitates the use of investment casting, with the wax patterns for use in the process being produced by a layer additive process.

The software's database enables us to see when each design parameter is selected and if there are any correlations between similar chosen parameters. In future, this facility could provide data on the preferences of different genders and age groups or other criteria.

In 'Future Factories', a production system is envisaged in which the consumer is presented with a 3D digital model of the artefact via a website. The web site, the 'Future Factory' itself, would have a series of 'production lines' corresponding to different products. When a particular production line is selected the user is presented with a computer animation showing that particular product design in metamorphosis within a parameter envelope specified by the designer. At any given point the consumer may freeze the animation effectively creating a one-off design on screen. Should the consumer wish they might then proceed with an order, in which case the relevant digital production files (stl etc.) would be generated automatically and sent to the relevant RP production facility. An artefact, effectively a one-off, will then be manufactured using layer additive manufacturing (rapid prototyping) techniques. This may be achieved directly, via laser sintering in a suitable material for example, or indirectly via the production of a single use tool or pattern. It should be pointed out that the intention is not for the consumer to use the animation to adjust design features to their liking. The animation is changing in real time and is outside their control (this would hopefully be part of the allure). A variant can be 'designed' for them and they can choose to order it or not.

To add to this allure of one-off products, there are a number of ways in which the 'value' of the artefacts produced might be increased. An element of exclusivity can be introduced for customers such as corporate buyers, for whom specific commissions could be undertaken and unique design formulas produced. They could then order as many of the objects (such as light fittings for a particular chain of restaurants) as they required, secure in the knowledge that each product would be unique in itself as well as the design formula being unique to them.

Alternatively, the production of designs can automatically be ‘capped’ to a specified quantity as is the case, for example, with limited edition screen prints, with a numbered system being used to show how many have been produced, and how many opportunities to own a one-off variant of a particular design are left. Another option is not to cap the quantity, but to limit the amount of time for which any particular product will be produced.

Perhaps the most interesting possibility for increasing value is to employ the model of a single line of ‘evolutionary’ development in which a design is created, adapted and finished over a specified time span. Imagine a simple design being created for production for a period of, say, six months. Over that period, the design might become more and more complex, more organic, or more convoluted in form until it reached the end of its ‘growth’ pattern when it would no longer be able to be turned into a real object. At any point during that period, customers could view how the object started out and how it has developed since its inception. They could have the option of purchasing the object at that point (but not be able to purchase any of the forms from a previous time), or anticipate, like gamblers playing a game of chance, how the design might look in a month, when they might return and purchase it. They might plan to purchase a range of objects from a number of different points in its existence, or vectors along the animated production line. It is possible that ‘early’ incarnations of the design could become more valuable than later ones (as with limited edition screenprints having lower imprint numbers). The possible combinations of ways in which the process could be employed are potentially huge and are currently forming the basis of a funded attempt to commercialise the technology developed.

5. Conclusions

The ’Future Factories’ project demonstrates that the potential of computer-generated organic forms to produce viable artefacts for one-off production is at last a realistic proposition. Obviously, ‘Future Factories’ is not a suitable model for the production of complex technological objects (at least not yet). But the design thinking behind it, and the manufacturing system proposed fits comfortably with today’s drive for individuality.

In ’Future Factories’ a direct connection is made between playful desires and the will to take risks through predictive forecasting, as well as connecting with dominant modes of capitalist production via the technologies if not the processes of mass production. ’Future Factories’ is not mass customisation, the mode of production is craft placed momentarily in the hands of the consumer, temporarily liberating them by engaging them in a culture of chance, variability, selection and playfulness. This enables the consumer to engage with a plethora of possibilities through chance decisions that ultimately capture a particular moment, through which a unique object is cast out from a virtual environment into the real world.

It is clear that the implications of the wide scale adoption of such techniques by industry are potentially serious, and are such that moves to protect the process via patents have been made. The system has the potential to change the perception of design by consumers and manufacturers alike, and to influence considerably the education and training of designers. Despite the philosophical questions the process raises for the definitions of terms such as ’design' and 'designer', (which are potentially misleading in this context), and the scope for confusion as to whether the end results of the process are 'art', 'craft', or 'computer generated', there are a number of more pragmatic considerations. The potential for the process to impact on manufacturing and retail industries should not be overlooked. 'Future Factories' allows for the economic large-scale production of artefacts while providing important reductions in wastage arising from the over-production of unwanted items. At the same time the system promotes the move from reductive to additive manufacturing processes, cutting down on waste material from the production of goods. As such, it may point the way to a more sustainable model of a consumer society than the one we take for granted today.

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Abstract

FutureFactories is a design project with the ultimate aim of mass-individualisation: the industrial scale production of one-off artefacts. This is to be achieved by the combination of genetic algorithms, parametric CAD, and Direct Manufacture. Mass individualisation itself remains a blue-skies goal for the project (although it need not be that far away). Rapid Manufacture however, is already with us, and products developed by FutureFactories are currently on retail sale around the world. In April 2006 there was a significant development: Italian lighting and furniture manufacturer Kundalini launched, what they are billing as, the first Rapid Manufactured retail product by a recognised manufacturer (in other words not by an RP bureau). Prophesies such as this are dangerous, given that this is a fast developing field: it is certain however, that Kundalini will be amongst the first.

The significance is that Kundalini's primary function is retail manufacturing. Rapid Manufacture could be considered as a logical step for the larger service bureau, unused machine capacity can be turned to production, and the artefacts produced serve as marketing tools promoting the capacity, technology, and expertise, of the company. The products effectively become larger scale versions of the samples produced by machine vendors, only in this instance saleable. For Rapid Manufacture to become 'mainstream' it must be adopted by those who have no vested interest in promoting the production process itself. The author has long argued that FutureFactories is not about the technologies themselves, but about their application, and the creative opportunities that they facilitate.

From the onset of the Kundalini project, the client was dispassionate about process and entirely focused on form. The brief specified a product that would baffle, whose conventional production would be inconceivable. This departure from the predictable would apply not only in terms of physical manufacture, but in the very nature of the geometry produced. There should be no pattern or order, no hint of logic that would suggest how the form had been created. For Kundalini this could be the only justification for the relative expense of direct manufacture.

This paper will discuss, through the Kundalini case study, the implications of direct manufacture from a design perspective. It will look at the shift in new product investment from physical tooling to the design of increasing complex objects. From a Direct Manufacturing point of view, geometry may 'come free', but this in turn will set up new market demands and expectations. The designer will need new skills, tools, and understanding of the capabilities of Rapid Prototyping, in order to realise the potential of Direct Manufacture in the consumer products market.

Introduction

Entropia was launched at Light and Building, Frankfurt, April 2006 by Italian lighting and furniture manufacturer Kundalini. Kundalini celebrated its tenth year in 2006 and has a reputation for blending tradition and technology, mixing hand blown glass with 5-axis waterjet cutting for example.

Entropia's principle component is a 120mm diameter spherical diffuser produced in laser sintered nylon. The design is available in table, suspension, and wall variants. It retails between 400 and 500 euro depending on the model, a price comparable with traditionally manufactured artefacts from design-led manufacturers in materials such as hand blown glass and ceramic. Kundalini had no previous experience of Rapid Manufacture or even Rapid Prototyping. They were however familiar with the work of FutureFactories. The company had previously expressed interest in FutureFactories' aesthetics, but until recently had considered that the time was not yet right for the technology to be used in a retail context. The plethora of R.P. based concept work seen around the world and the promotion of Direct Manufacture by the R.P. industry began to modify that view point. In autumn 2005 it was decided that the idea needed serious consideration and the author was commissioned to create a series of concepts. At the same time talks began with RP service bureaus and equipment vendors to explore the economic viability.

From the onset the client was extremely passionate about the aesthetics that might be achieved but never at the expense of commercial viability. This was to be a retail product the price of which would be determined by the market. It was clear from early investigations that the best chance of viability lay in a compact form and that the more efficiently the build chamber was filled, the more cost effective the process would become. The cost of a build would be split between the number of components contained within it. Squeezing in one or two extra units would have a significant impact on price and may prove to be the difference between viability or otherwise. Early in the concept design stage a spherical form emerged as the most likely solution as the design needed to be as compact as possible, and leave a certain clearance around the light source for reasons of temperature. A diameter of 120mm was arrived at as offering the best balance of perceived value and manufacturing cost. Despite this compact nature the design would use G9 halogen fittings, these run at line voltage, eliminating the cost of a transformer.

Form

It was important to the client that the design was taken as far from conventional industrial manufacture as possible. Complexity was a given, any regular form could be produced more economically by conventional means. The idea was however, to go beyond awkward geometry. Although certain forms may be impossible to produce conventionally, undercuts, re-entrant shapes, and the like, this fact will not necessarily be appreciated by the lay customer. To the consumer it makes little difference if a product is produced in one piece via some exotic means or is made as a well disguised assembly of cheaper components. The freedom of Rapid Manufacture brings the risk of engaging in party tricks that are only appreciated within the industry itself. The author recently showed a lay audience a sample of SLS manufactured chain link. The audience were unimpressed, plastic chain link could be bought from the local DIY superstore. The aim with this project was to create a form that would intrigue, baffle, and captivate everyone. It would be necessary to convince the buying public that a particular piece of plastic was every bit as valuable, if not more so, than for example, a piece of hand blown Murano glass that would sit beside it in the Kundalini collection. The idea was to remove all traces of pattern and logic from the form, to eliminate any accessibility or key to understanding. The principal of this was easy to grasp, achieving it in practice less so. The language of traditional design-for-manufacture had to be abandoned. There could be no repeats or symmetry. At the same time it needed to be evident that there was process behind the form, a totally random assembly would not be considered particularly valuable. The solution was to adopt the rule based approach used in previous FutureFactories morphing designs. In these designs virtual models were created that allow a design to morph within a parameter envelope set by the designer. Rather than yield a discrete 3D solution these designs were templates from which multiple one-off solutions could be generated, each functional and true to the designers' intent. In the case of Entropia, design templates were created for a series of features that would appear in varying numbers throughout the form. These templates dictate the underlying style of a specific feature but allow considerable flexibility in it's particular embodiment. Each time the feature is repeated within the form there is a slightly different outcome. The result is the impression of a natural phenomenon, such as coral. There are clear patterns to the 'growth' but the form appears to have evolved rather than to have been constructed.

Rapidity

Product development speed was not a primary consideration in this project. Speed is more applicable to the prototyping side of digital manufacture rather than series production. The emphasis placed on rapidity by service bureaus which is such an asset to prototyping, is often a hurdle to Rapid Manufacture. The bureau industry is often characterised by feast/famine workloads and large amounts of overtime. This does not lend itself to rapid manufacture where efficiency is key and profits are made over a longer term.

Whilst not a primary consideration Rapid Manufacture enabled an extremely short product development cycle. The concept was agreed in early January 2006 and the product launched in April 2006. In spite of the designs compact nature, the level of complexity in the form required a lot of 3D modelling. Digital manufacture allowed prototypes to be built based on sections of the design that were complete, incomplete sections were either replaced with simple approximations or simply omitted. This enabled technical development to take place in parallel with the design of the form itself and allowed the compressed timescale.

Conclusions

Complexity

Aesthetics are subjective and the merits of this particular design are not an issue for this paper. A significant factor however is the demand for complexity, a demand coming from the client but driven by the consumer. This demand is sure to increase as the almost free-form potential of Rapid Manufacture becomes more widely appreciated. Greater use of computation in the design process is called for to manage this complexity.

Visualisation

Visualisation is a major issue. It is difficult to orientate ones self in a complex on-screen model. Locating a specific area in a form as complex as Entropia is far from easy. It becomes hard to identify issues that would be readily apparent when handling an actual prototype. A far greater range of more flexible visualisation tools built into CAD software systems would help here.

Visualisation is also an issue for the consumer where there is on sample product to assess. FutureFactories is frequently asked where designs, published on the website, can be seen in the flesh. If only a few artefacts are made to satisfy a market niche it would not be economically viable for stock to be held at retail outlets worldwide, manufacturing to order would be more appropriate. Visualisation beyond the brochure studio photograph is required to convince all but the most avante-guard of buyers, better interfaces are needed to enable consumers to assess products remotely and order them with confidence. Some form of web-based virtual reality, computer-based experience that mimics real experience, may provide a solution. It is perhaps the high-end VR system that come first to mind with the user wearing special goggles and gloves. At its simplest however, VR could be a 3D view of the product that the user can rotate to see from various angles. In this way potential customers would be able to examine the 3D model moving, rotating, and zooming in and out, at will. Such 'hands-on' interaction would allow something of a "try before you buy" experience.

Investment

It is worth noting that although Rapid Manufacture eliminates the need for tooling investment, current marketing practices require investment in printed catalogues and the like. As a designer, it is tempting to believe that manufacturing will become far more flexible and versatile, able to experiment and react quickly to niche markets. In practice it is an attitude that will take time to develop within industry and consumers' behaviour will also need to adapt.

The lack of tooling investment removes a key point from the design process; the point at which production drawings would be passed to a toolmaker. With Rapid Manufacture design development can continue up to the eve of product launch. Need development cease at product launch? A situation can be envisaged similar to software releases with a product improving by degrees during a production run, versions 1.0, 1.1, 1.2 etc.

Process

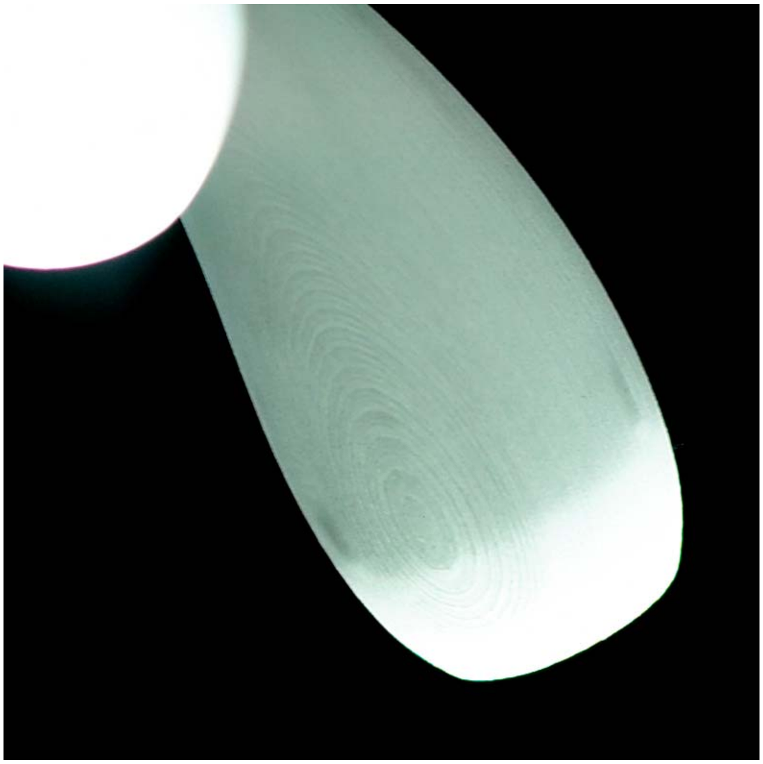
The traditional product design development model begins with loose concept sketches that gradually become more and more refined as the project develops. Practicalities are fed in gradually so as not to kill the style of a concept. When computational design is employed the initial priority is in setting up relationships, parameters, and formula, rather that looking ahead to what they will ultimately produce. Complexity by its very nature cannot be easily reduced or predicted. With Entropia the importance was in defining a language for the elements used. The initial design issue was the definition of developmental rules that would allow diversity yet keep the form true to the designer's intent. Creating such rule-based systems takes time and requires something of a leap of faith on the part of those commissioning the process. It is not possible to generate outcomes before the system is established. Once the rules are in place however, any number of design iterations can be generated with relative ease. It is easy to imagine a step on from the current Entropia in which only the size and developmental rules are pre-defined. A unique form would be 'designed' every time a 3D iteration was generated, this would be the FutureFactories concept of mass-individualisation. The only issues hold back such an idea are the demands of setting up the model and customer acceptance. A virtual model capable of generating endless one-off outcomes must be created, a process that must be automated as, in industrial scale manufacture, a designer cannot modify each and every item produced. Consumers would need to be aware of the concept and celebrate difference, manufacturers considering individualisation fear endless product returns as the product received does not match up to another.

Optimisation

Currently, the placement and arrangement of models within the build volume is undertaken by RP bureau staff who are presented with the model when it is complete or in the final stages of development. The efficient use of the build volume is the most important factor in determining the viability or otherwise of Rapid Manufacturing projects. It is vital that the concept is tailored from the concept stage to use the chamber efficiently and to allow the accommodation of a commercially viable number of units. Ideally, software for this function, would be brought within high end CAD packages so that it can be referred to by designers throughout the design process rather than existing as a stand-alone package aimed at machine operators.

Material

In Rapid Manufacture for the decorative design market, public perceptions of material value becomes an issue. Plastics however exotic do not have the same cache as, for example, glass or ceramic. Hand blown glass artefacts sit beside Entropia in the Kundalini collection and are comparable in price. This perception of inferiority can be combated to some extent via design. Fine detailing and delicacy of proportion communicate quality and craftsmanship. This becomes exaggerated in lighting applications where translucency accentuates fine section thicknesses.



In the laser sintered designs of FutureFactories, thicknesses can be as low as 0.5mm. This is well below that which would be recommended for the process. Many bureaus give a standard warning if model section thicknesses drop below 2mm, Entropia does not have any sections above 2mm. In fairness, robust sections are encouraged because of the cost of the process and the risk of scrapping parts. FutureFactories plays with thickness ensuring that there will always be an appropriate structure. Ultra-fine sections are used in areas that are purely decorative and forms are preferred that will not suffer unduly should fine edges not build completely. Whilst it has not been used as a policy in the output of FutureFactories, redundancy could be considered to mitigate the risk of failure in minor decorative elements. Where there are massed numbers of features following no discernible pattern the absence of one or two may pass unnoticed should they fail.

Early FutureFactories work featured hand finished (paint finish) artefacts built using budget 3D printing processes. It soon became clear however that the budget RP processes were still expensive in relative terms and that hand finishing on top of a costly process was unlikely to prove viable. Hand finishing also went against the principle of automated manufacture. FutureFactories has fastened upon SLS nylon as currently the best option in terms of the balance between cost (process), mechanical performance, and appearance. New materials are appearing all the time many of these have caught FutureFactories eye in terms of their beauty, in particular ceramic-like epoxies with vivid colour. RP materials development however has been focused on providing high mechanical performance rather than cost. This tends to make them unattractive for Rapid Manufacture. We will have to see if embryonic Rapid Manufacturing stimulates a drive for cost effective decorative materials.

One and only

Lionel T Dean describes how FutureFactories is pushing the boundaries of what the rapid prototyping industry can produce

Additive digital manufacture doesn't currently live up to its common name of Rapid Manufacture (RM), being neither rapid, nor producing parts cheap enough to justify volume manufacture. However, in the future, the rate of development of this process will become increasingly rapid and, as such, will be able to offer new opportunities. But this technology should not only be viewed as a niche alternative to mass manufacturing methods, but should be seen as an opportunity to review the consumption patterns and expectations of the consumer.

Since a previous report in newdesign back in 2004 (issue nineteen, page 52), FutureFactories - a digital manufacturing concept for the mass individualisation of products - has developed three designs that have been taken through to production and retail sale by Materialise of Belgium and Kundalini of Italy. Although exploitative of the free-form nature of the RM process, these products do not take advantage of the potential for customisation and individualisation (i.e. all of them are made to a fixed design). However, the latest FutureFactories product, called Icon, aims to break the serial production norm. This piece of pendant jewellery is to be produced by Rapid Manufacture in a limited run of 100 unique design variants.

The move to jewellery was a logical step in the pursuit of individualisation. This is a market that values intricacy and complexity; a market willing to pay a premium for an exquisite form. It is also a market in which the boundaries between industrial production and craftsmanship are blurred and where the value of a bespoke piece is readily appreciated. However, it is simultaneously a conservative market, particularly in terms of materials. The traditional jewellery materials have intrinsic value, are durable, inert and long lasting. The polymers of RP, beautiful as they can be, would not win over all but the most avant-garde consumer in this field. Additive manufacture in more exotic materials, metals and ceramics developed for niche engineering applications would be expensive and, with their focus on technical performance, not necessarily aesthetic.

The combination of finishing requirements and cost seemed to offer no foreseeable way forward to achieve consumer acceptable jewellery pieces using existing RM processes.

rapid**prototyping**

However, this is a fast moving area of technology: after witnessing the latest generation Direct Metal Laser Sintering (DMLS) technology from EOS, it was clear that this process had the potential to offer the quality of finish required in an exciting range of materials - titanium, cobalt-chrome and stainless steel.

FutureFactories' first experimentations with jewellery came about through a connection with the Jewellery Industry Innovation Centre in Birmingham (JIIC). The centre prototyped a series of design proposals indirectly in silver. A wax pattern was built by additive manufacture and the piece investment cast from this master. The results were beautiful, but heavily reliant on the considerable skills of the JIIC to cast and polish these intricate forms.

Complexity can be expected in RM as justification of the high-tech process and FutureFactories designs pushes the boundaries of what the RP industry can produce. So, whilst these forms can be rapid prototyped in wax (or substitute polymer) the casting process itself imposes limitations. Even if the forms can ultimately be cast, setting up the casting with appropriate sprues and risers requires a considerable amount of experience. Once worked out, the process is reasonably robust, but it is seldom right first time. In an extended run this would not be a problem; however, with the proposed individualisation, it would be significant. A small change in form might require a complete reassessment of how the piece would be cast. Added to the challenges of the casting process, the intricate forms produced require skilled hand finishing. The need to access the form for polishing gives rise to further limitations on the form.

It was clear that the only way to exploit the full potential of additive manufacture was to build directly in metal. Working with EOS, a series of prototypes were produced using the company's M270 DMLS machine. In spite of their free form potential, RP technologies have some limitations to design around. In the selective laser sintering (SLS) of plastics, the parts can be built free from the support structure (temporary buttresses that require later removal), as the part is supported automatically in a bed of loose power. In the laser sintering of metals, where there is the energy of semi molten metal, the support of the surrounding power is not always enough. In certain geometries, computer generated temporary structures will be required to support elements of the form during the build process.

In Icon, support material on the inner surfaces had to be avoided at all costs, as clean-

ing up these inaccessible faces would be virtually impossible. In addition to the issues of access, the supports, which are designed to easily break away, only really do so when removed from larger heavy sections. When they are attached to sections nearing their own size their removal becomes more of a problem. Working with industry specialists, FutureFactories aimed to limit this support structure to restricted areas of external convex curvature, where the support could be easily removed and the inevitable witness marks easily polished off.

DMLS solved the manufacture - however, polishing the intricate internal faces remained an issue. As a result, another advanced technology was needed to come into play. Working with 3T RPD in Newbury and its commercial partner BestinClass in Switzerland, the process of micro-machining (MMP) was used to 'superfinish' the designs. MMP employs a mechanical-chemical reaction to produce an automated equivalent of traditional polishing. The process, performed in a bath of liquid, places no restriction on the geometry. The combination of DMLS and MMP allowed the automated production of polished parts direct from the virtual model with the minimum of hand work (the removal of a minimal, strategically placed supports).

The aim of the project is to produce a run of 100 variants of a CAD based 'meta-design'. Starting with a parametric computer model, it is easy to manipulate variables

within a form to produce a string of alternative outcomes/products. If however, the individualisation process were to rely on the skills of an individual to 'tweak' each and every artefact produced, it would become a craft process rather than design and would inevitably be limited in scale. FutureFactories aims for individualised production on an industrial scale. It is possible to instruct CAD software to randomly manipulate the form to produce these alternative outcomes.

As part of an ongoing PhD study at Huddersfield University - conducted under Head of Studies Paul Atkinson - FutureFactories has been developing computer scripts using game-creation software, in order to control the outcomes of the process. These scripts allow the creation of design variants in real-time - that is to say that they are not limited to a fixed length, pre-prepared animation. Such a script was recently developed in order to generate the seat back forms of the Holy Ghost chair design. In this case, the software first selects a number of seat back buttons (reminiscent of button leather) from a given range. These buttons are then arranged at random across a 3D envelope avoiding clashes between them. Once in place the buttons expand - first uniformly until they almost touch and then in a non-uniform manner to fill in the gaps. Every time the script is run a new format is created.

The trick is in the control of the design. The aim is to produce perceptibly differing variants of a recognisable design: coherent design rather than random 'blobjects'. The plethora of subtle design decisions underlying a form soon becomes apparent as it is manipulated. As Richard Dawkins said in regard to evolution: "The number of ways of being dead is so much greater than the number of ways of being alive" (The Blind Watchmaker, 1986).

Checks and balances are required along with an element of 'mapping'. Creating a script to generate a complete design down to the last detail would represent a huge investment. Moreover, it would also be cumbersome to run. A mapping process essentially means generating a reduced version of the design and then working this up manually into the actual variant. The proportion of the design that is resolved automatically and that which is added manually depends on the level of investment.

In the Icon project RM has been coupled with scripting to achieve mass individualisation. In this design we see RM in a material with the permanence expected of high end jewellery. Whilst not a precious metal, the value of titanium is recognised in contemporary jewellery. Titanium cannot be soldered which limits the forms that can be created conventionally. The use of titanium in pendant and necklaces is consequently rare. The forms created in Icon would be virtually impossible to achieve outside of RM, yet it is not the form alone that sets this design apart, it is the fact that each and every piece produced is a unique design variant never to be repeated.

Lionel T Dean is an artist/designer specialising in digital design and Rapid Manufacture. He is the creative director and founder of FutureFactories and speaks widely on digital manufacturing. Much of his success is due to the ongoing support he receives from EOS UK and 3T RPD. For further information visit www.FutureFactories.com