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# Post Industrial Manufacturing Systems:
the undisciplined nature of generative design

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## Abstract

Post Industrial Manufacturing Systems (PIMS) is a research program with the overarching aim to explore the impact of emerging technologies in Rapid Prototyping, Direct Digital Manufacture, Parametric Modelling and Generative Design software on the design process.

The initial research project within PIMS involved an industrial designer working with a CAD programming expert in developing a software system that allowed the user to view various products or designed forms, which were continually randomly mutating in real time. The user could not affect the form itself or the mutation in any way, but could decide at which moment they wanted to 'freeze' the constantly changing form to create a unique, one-off item. The user could then purchase the product, at which point the relevant stl files were created by the computer and exported to a rapid prototyping machine to be manufactured.

As this work progressed, various approaches were tried, including the random placement of a selection of predetermined elements within specified space envelopes. At this point, a second project was started involving a craft practitioner with the express notion of exploring the differences in approach between practitioners of different disciplines. This work has produced a system in which individual building block units are randomly assembled together within three-dimensional mesh forms that can be manipulated in various ways. When the process is complete the resulting object can be digitally manufactured.

This paper will describe these different approaches to random generative design and discuss the implications for the disciplines of design and craft, their interpretation and meaning raised by this research. The experience of using these systems potentially opens the floodgates for amateur design and craft in ways previously unimagined. Developments such as these are clearly harbingers of a new era for design and craft and an example of the reshaping of disciplines.

### Keywords

Rapid Prototyping, Direct Digital Manufacture, Parametric Modelling, Generative Design

Post Industrial Manufacturing Systems (PIMS) is a research program led by Dr. Paul Atkinson, which began life in the School of Art, Architecture and Design at the University of Huddersfield. Lionel T. Dean, a practicing industrial designer, instigated the initial project within this program, titled 'FutureFactories'. The project ran as a Designer-in-Residency program, with Dean developing the work in studio space alongside undergraduate product and transport design students. Dean worked in conjunction with CAD specialist Dr. Ertu Unver in order to develop a software system that could allow a user to view various products or designed forms, which were continually randomly mutating in real time. The user could not affect the form itself or the mutation in any way, but could decide at which moment they wanted to 'freeze' the constantly changing form to create a unique, one-off item. They could then rotate the object in three dimensions on screen before deciding to purchase the product. When bought, the relevant stl files were created by the computer and exported to a rapid prototyping machine to be manufactured.

The FutureFactories project created work that was exhibited internationally (Figure 1), and gave rise to a number of academic conference papers reporting on the development of the designs, (Atkinson, Dean & Unver, 2003; Dean, Atkinson & Unver, 2005) the associated software (Unver, Dean & Atkinson, 2003; Atkinson, Unver & Dean, 2004), and touched on some of the problematic areas and the questions raised by the nature of the work involved (Atkinson, 2004; Atkinson & Hales, 2004).

Figure 1: Exhibited FutureFactories luminaires

It is in the nature Generative Systems that at least some of the control over the end results is relinquished as systems run autonomously. Although the use of generative software in conjunction with rapid prototyping has been employed elsewhere (particularly in the jewellery industry), they have not been used in the same way, or with the level of user interactions employed here. The nature of FutureFactories products is such that they are conceived by a designer who specifies the original form and the parametric modeling rules of the mutation involved but relinquishes the appearance of the final

product to the computer and in fact may never see the final product selected and purchased by the end user. In this scenario, who has designed the product? Where do the boundaries of design start and finish? As the user, in selecting a point in time to freeze the mutation, has made an aesthetic decision over the final form to be manufactured, should their input be considered part of the design process or not? Questions of authenticity, authorship and creative control are all raised here, and they question the nature of design itself.

Another issue raised by FutureFactories has given rise to a second, distinct research project. An item produced in such a system is potentially one of an infinite series of designed pieces, but they are in no way mass produced. The random mutation, in ensuring that no two pieces are identical, is directly in opposition to the aim of mass production and the perfect repetition of a single specified form. They are at least examples of mass individualisation. – unique, bespoke artefacts. Moreover, the forms, being closely related and identifiably a version of a particular product but having obvious, visible differences, have something of the air of craft objects about them.

A logical progression from the utilisation of such a system by a product designer, who by the very nature of his discipline is at least accustomed to a degree of separation from the making process, is to place the same technological capabilities in the hands of a craft practitioner. For a craftsperson, the nature of the outputs of FutureFactories, and in particular the remote nature of their production, might be seen as anathema. After all, Peter Dormer has stated that one of the dominant definitions of craft is that it is "a process over which a person has detailed control" (Dormer, 1997, 7). The impact of these technologies, therefore, is potentially more significant for a craftsperson than a designer. It is also more significant for the status of the artefacts produced from a consumer's perspective, as they too are accustomed to mass produced products not usually being associated with the designer, but might well expect craft products to be associated with a named craftsperson.

This was the starting point for 'Automake' – a research project involving a craft practitioner Dr. Justin Marshall, with no prior knowledge of computer programming, working with the same CAD programming expert to develop systems to enable new craft forms to be created (Marshall, Atkinson & Unver, 2007; Marshall, Unver & Atkinson, 2007). Here, a series of individual building block units having the ability to be connected together in various ways have been created. These units are then assembled together randomly by the computer within a variety of three-dimensional mesh forms. A number of these mesh forms can be selected by the end user and then manipulated, twisted and scaled by the end user to create unique shapes, and the particular building block units to be used to fill the resulting shape envelopes can also be selected. When the process is complete and the mesh envelope has been filled with a unique 3D model, the resulting file can be sent directly to a rapid prototyping machine for building in the same way as FutureFactories products (Figure 2).

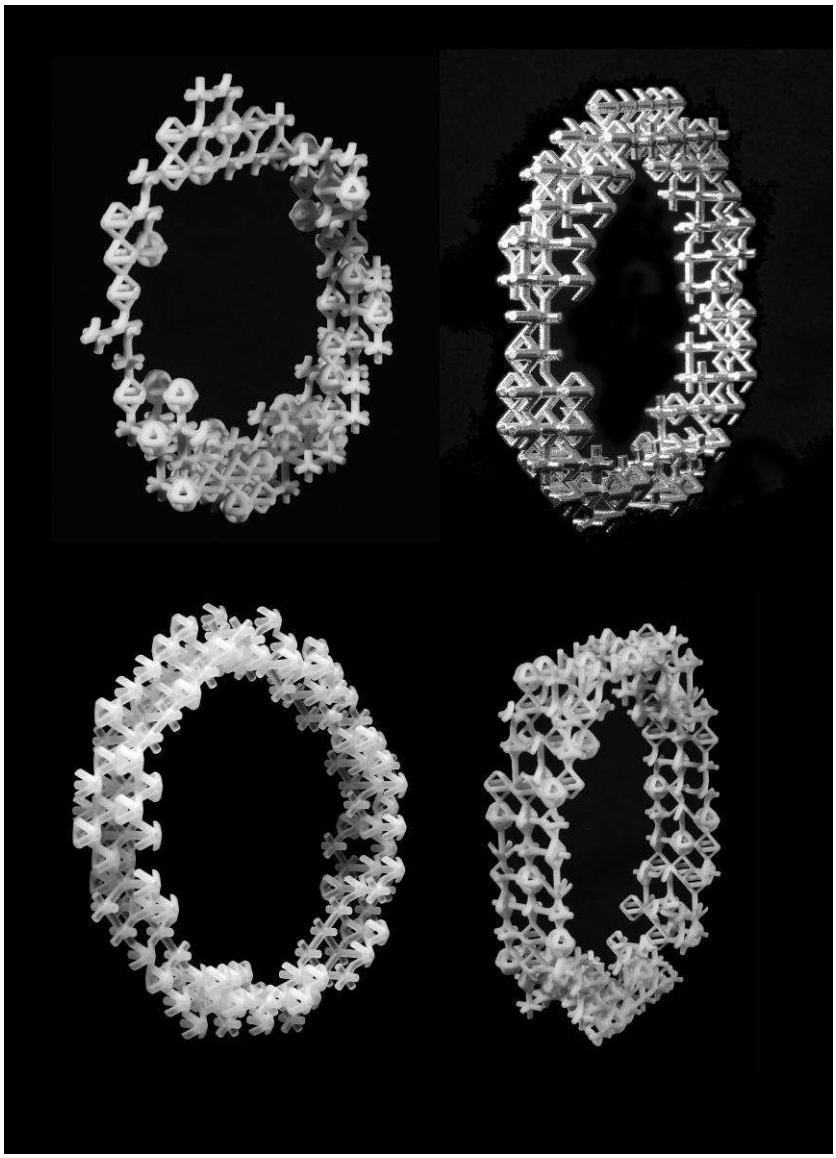

Figure 2: Automake Jewellery

## FutureFactories and Automake: The state of play

### *FutureFactories*

The initial FutureFactories experiments were carried out using 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. Software then extrapolates between these key stages to create a seamless animation. Creating a key-frame animation can be an intuitive process with the development accessed 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). Although there is the potential to create large numbers of iterations, the scope is nevertheless limited and falls short of the project's fully automated production aims.

The second stage of the research was to develop procedural animations. 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 for the entity. Solutions are then generated automatically. In contrast with the 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 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.

National and international exhibitions following the initial residency period yielded valuable feedback on the concept (Atkinson, 2003). Would-be consumers, in this case exhibition attendees, expressed a desire for more dramatic, fundamental changes than the gently writhing designs presented. It also became clear that the number of variables involved in the simplest of designs required a huge about of scripting if a reasonable balance between freedom and control was to be achieved - a design investment that would mitigate against widespread uptake of the system. The FutureFactories key-frame and procedural animation models operate by manipulating the geometry of pre-existing models or entities. The geometry of the models is defined and open to adjustment rather than fundamental change. Rather than seeing a table leg swell from a minimal spike to a fuller volume, for example, visitors to the exhibitions would rather have seen legs added or removed. Achieving such fundamental changes meant a different approach to the geometry and a departure from the initial aim of 'growth' with one mutation flowing seamlessly into the next (Unver, Dean & Atkinson, 2003).

To achieve the goals of more fundamental change and less onerous model creation, a simple building-block design was developed using Virtools - software primarily aimed at video game creation. Virtools was selected for a number of reasons, including the fact that all systems developed using this software run on a web browser using the freely available '3D life' player; software development is based on an intuitive building-block method rather than hard scripting; it allows the creation of highly functional user friendly interfaces relatively easily; and it can import data from a range of CAD software, including 3Dmax. Virtools has been used for creating a range of applications beyond the gaming market, including visualisation for architecture and design, and tools for online learning, and therefore has a strong user community with active forums providing problem/solution sharing.

A simple, modular design was considered comprising a network of multi-coloured lenses arranged around a standard GLS incandescent lightbulb. This design was titled 'DNA'. A series of linked rims rather like spectacle frames build, a step at a time, around the bulb starting from the shade ring. There is a selection of rim modules (Figure 3). There are three different sizes - small, medium and large. In addition, each rim incorporates a link to the previous rim, which may be straight or twisted about one of two axes. The resulting framework of rims would be digitally manufactured in a single piece. Coloured lenses would be clipped into the rims as a postproduction process (Figure 4).

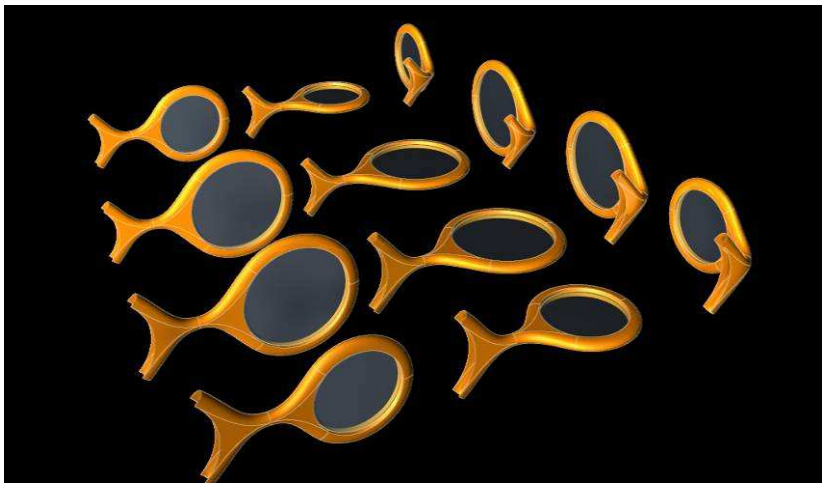

Figure 3: DNA Components

Figure 4: DNA Rendered

In DNA, the geometric rules were simple. There had to be sufficient clearance around the bulb as a thermal constraint and the design had to be restricted to a practical, saleable size. To achieve this, inner and outer boundary spheres were created with the design allowed to grow in the intermediary space. In addition to the boundary envelope constraint, the lenses could not be allowed to clash with each other (although the rims are permitted to do so). The 'success' of each iteration was easy to assess. If the addition did not clash with boundary volumes or established rims, the step was allowed.

Additional rules were then introduced to influence the character of the design. For example, there would be proportionally more of the medium lenses than the extreme sizes and the small lenses would be dead ends to which links could not be made (Figure 5). In this way, the undisciplined nature of the designs is deliberately limited.

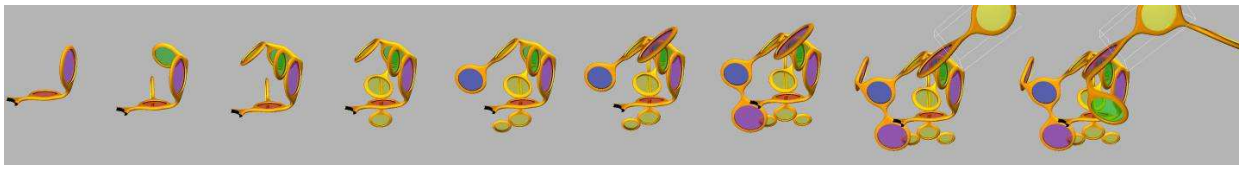

Figure 5: Screens shots of DNA growth

DNA is fairly basic in product design terms. The next step was to apply the building block strategy to a more demanding form. A chair was selected as a product with the appropriate scope for form and demand of function. Given the cost of RP services and the restricted size of available machinery, 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' system was again created in Virtools, only this time the build block approach is combined with the morphing strategy of earlier works. The process begins with a standard build unit termed a button, because arrayed on the chair back they are (deliberately) reminiscent of traditional button leather furniture.

In the first phase of this system, the number of buttons that will make up the back is determined. This set of units is then placed one at a time into a 3D build envelope pre-determined by ergonomics. In the second phase, the placed buttons expand in a uniform manner (whilst maintaining the ergonomic envelope) until they almost touch (Figure 6). 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 7).

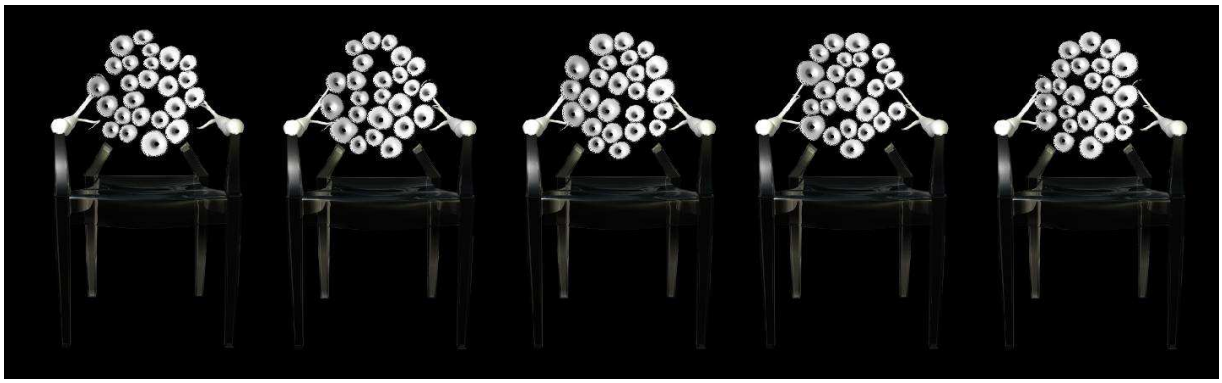

Figure 6: Screenshots of Holy Ghost iterations

The buttons are connected by a matrix of curved links that, built in nylon, act as live springs allowing the whole back to flex like a sprung mattress. The addition of these links is a manual mapping process (Dean, Atkinson & Unver, 2005). The modeling of the links could have been automated in the software with programming investment.

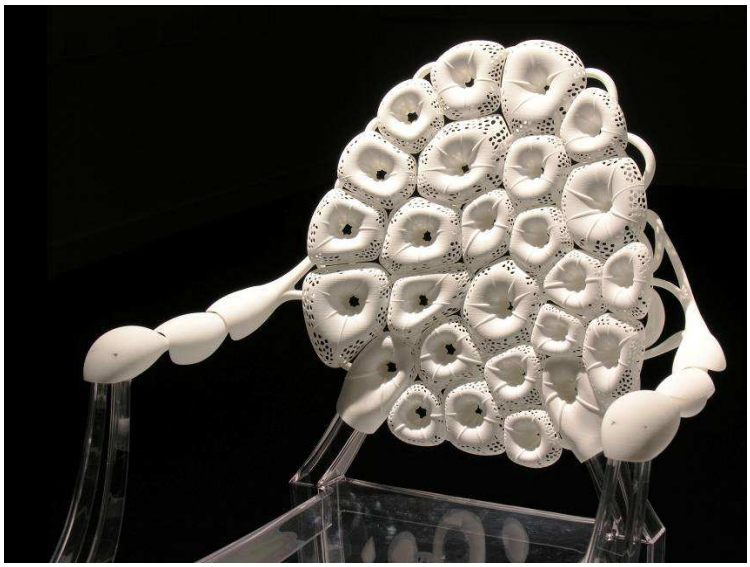

Figure 7: Holy Ghost

Up to this point, FutureFactories individualised design runs had been limited to a handful of prototypes (though several designs had been commercialized for serial production). The most recent project, 'Icon' - a piece of pendant jewellery, represents an attempt to prove the projects concept of individualisation on an industrial scale (Figure 8). Icon is a limited run of one hundred pieces produced directly in titanium using Direct Metal Laser Sintering (DMLS). This set of pieces proves that it is possible to achieve recognizable difference over an extended run whilst maintaining a coherent, identifiable meta-design.

Figure 8: Icon iterations

## *Automake*

The research embodied within the Automake project took a broadly pragmatic and exploratory approach. Many makers and craft practitioners approach the use of technologies, not with a rigid predefined aim to achieve a particular result, but to explore the possibilities the technology affords. The attitude taken by Marshall falls within this approach and the project was

initiated with no fixed aim to solve a particular problem or to produce work of a particular type.

Previous work by Marshall has involved the use of 2D periodic and aperiodic tessellation systems to develop infinitely complex non-repeating patterns and structures. This broad area of interest provided a starting point for the software development. From Marshall's perspective, the Automake project provided an opportunity to extend the use of tessellation into 3D with the potential of creating complex and unique matrix structures.

As with FutureFactories, Virtools game authoring software was employed throughout this project to create the systems. The Automake software described has all been designed with user interaction in mind. In addition to extensive use by Marshall in the creation of new works and test pieces, a recent exhibition included an interactive workstation where members of the public could create pieces and print out 2D versions of the work. Some of these were chosen to take forward into 3D form, produced by the exhibition's industrial sponsors, and were added to the exhibition over its duration (Atkinson (Ed), 2008). Some of the work shown below is the result of a direct translation of the designs generated by the software into physical form, while other works involve a more complex process which involved the employment of other CAD and image manipulation software. Therefore some results of this research are specifically concerned with extending the practice of the maker/researcher, while others focus on users.

## *Development of 'Matrix Build 1 & 2' Software*

As discussed above, using parametric objects provides a mechanism for creating mutable and unique forms. This approach, adopted in the FutureFactories project, relies on the setting of an envelope within which mutations of pre-existing forms can occur. An alternative method for creating unique forms is to use a modular system where the required complexity is created through rules being applied to the repetition of simple units rather than the mutation of a pre-existing object. Marshall was keen to develop a system for building/growing forms, therefore a modular approach was taken with the aim of creating a complex range of 3D matrix structures. Both FutureFactories and Automake provide opportunities for the consumer to interact with a system to create a unique object, but at different levels. FutureFactories allows no interaction other than for the consumer to select the exact moment that the product mutation ceases. In contrast, Automake provides a range of mechanisms for users to interact with the process of creating forms. These opportunities were provided with the aim of engaging the user and so creating some sense of ownership of the forms created.

In order to provide a simple basic structure to the matrixes, a rectilinear format was selected and a series of units designed in such a way that they always joined together when placed next to each other (Figure 4).

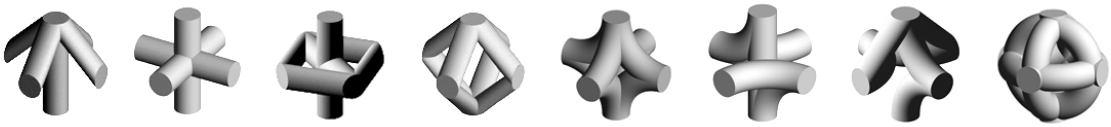

Figure 4: Automake units which connect together at any of six points

The first software developed gave the user the opportunity to select any, or all, of the units. The generative system was then set in motion. This involved one randomly selected unit, (from those chosen by the user), being placed in one of the free spaces next to the initial unit, the system then checked all the spaces around the units and randomly selected one of the free spaces to place another randomly selected unit. This process continued until the system was stopped and a file saved (Figure 5).

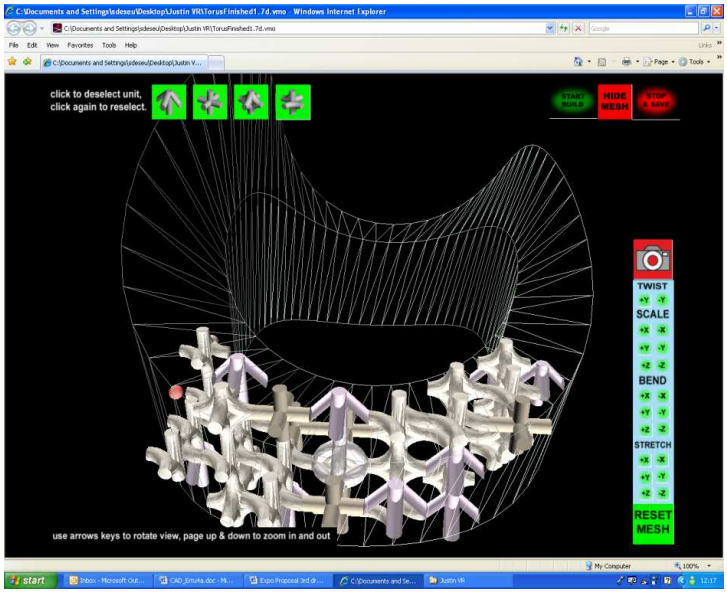


Figure 5: Automake units being randomly connected within a user-manipulated space envelope

This process succeeded in creating random matrix structures, however as the structures grew in size the number of spaces which required checking grew significantly, therefore the system gradually became slower, eventually crashing. In addition, the file saving process was based on writing a 3D file in the .obj format. As there was no optimization or file compression within our system, the exported files were extremely large even when the matrixes were made up of a small number of units. It had always been intended that the matrixes could be made up of many hundreds, or even thousands, of units. Therefore a new approach to placing new units and to exporting files had to be considered.

Adapting the space checking procedure so that only the spaces around the previously placed unit were checked solved these issues. This resulted in a system that did not significantly slow down because the number of spaces checked stays constant as the matrix grows. To solve the file size issue a script was created that allowed a dataset of unit codes and coordinates to be exported from the software. These text files are extremely small, and are therefore easily sent via email. This system has proved very successful, however it did require the creation of a script to be run in 3D Max that recreates the forms generated in the build software. 3D Max can then export the structure in a file format appropriate for digital production (i.e. .stl).

To create a greater level of user control and put some restriction on the generation of potentially infinite matrixes, a series of constraining meshes were

introduced. These meshes function by acting as an obstacle to the growth of the matrixes. In 'Matrix Build 1' three meshes were introduced, any of which could be selected by the user and distorted using a range of tools. In 'Matrix Build 2' a torus mesh was introduced which restricts the growth of matrixes to a shape appropriate for the production of rings, bangles and bracelets (Figure 6).

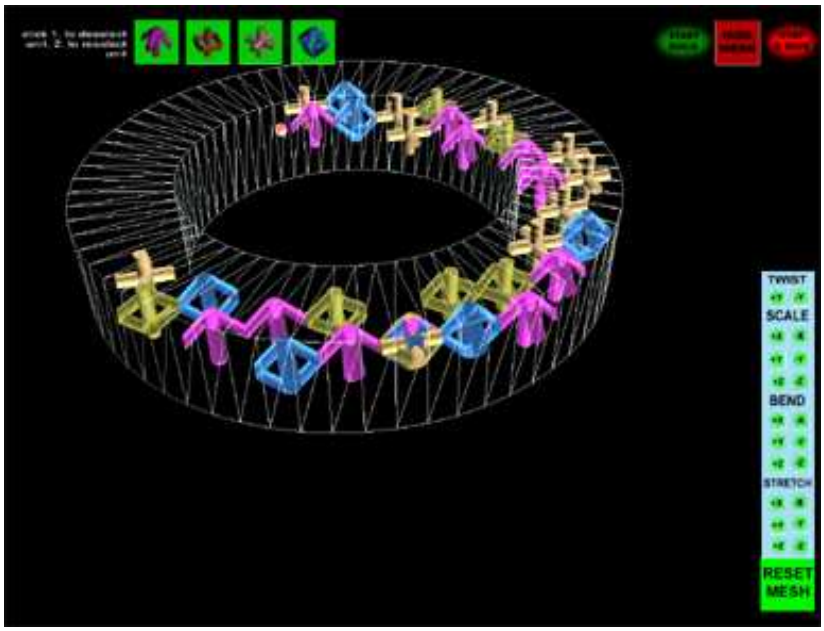


Figure 6: The Torus Mesh in the Matrix build 2 interface

As a restrictive mechanism, the constraining meshes have been reasonably successful, although if the meshes are heavily distorted then units can often 'leak' beyond the mesh and once this has occurred the matrix will grow unrestricted. While this can be frustrating and can lead to a build being abandoned, it also produces 'undisciplined' forms that can exhibit desirable visual characteristics - a balance between the random nature of the underlying generative system and the control the user has attempted to impose (Figure 7).

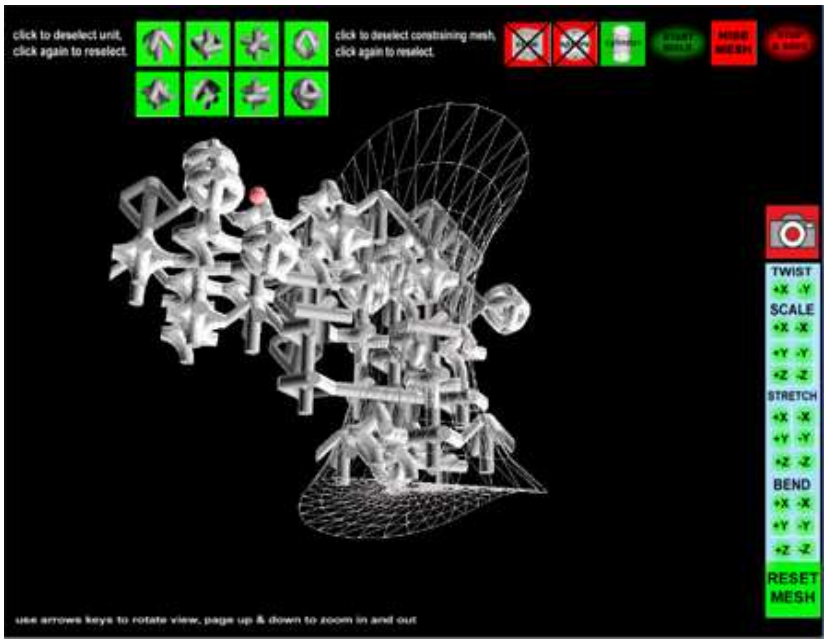


Figure 7: Example of a build where the form has 'leaked' out of the constraining mesh.

## *Development of 'Random Fill' software*

This more recent system was developed in order to counter some of the limitations of the 'Matrix build' software, specifically the high level of memory use and the highly regimented, rectilinear format of the structures. The 'Random Fill' system creates structures from the same basic units as the 'Matrix build' software but the mechanism for construction is significantly different. Instead of forms growing through the random placement of units, they are created by dropping units into a hollow form or 'mould'.

The use of 'physics engine' capabilities within Virtools allows each unit to be given a different set of characteristics (e.g. weight, elasticity etc.) and the complex interactions between objects to be modelled. Initially, spheres were used to represent the units and a simple hollow bowl form was filled (Figure 8). The use of different scaled spheres helps create both variety in the density of the generated form and greater structural coherency. Once the mould has been filled, (or the user chooses to stop the process), the spheres are replaced by the corresponding units and the complex, non-rectilinear structured form can be reviewed and saved for production (Figure 9).

Due to using spheres rather than the more geometrically complex units during the build process and because adjacent units do not control each of the unit's movements, this system has a considerably more efficient use of RAM than the 'Matrix build' systems. Therefore, the number of units that can be used within a single build can be increased by at least a factor of 5 before memory usage becomes an issue.

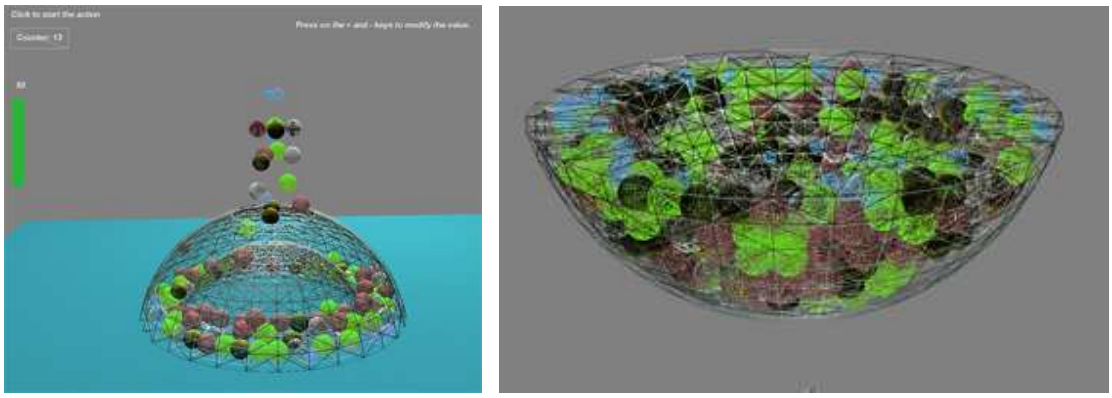

Figure 8: First `random fill' software using spheres to represent units during the build process

Figure 9: `Random Fill' Bowl

Significant developments have been made with this system, which can now use actual units in the build process. As an example of how complex a form can be created, a pre-existing CAD model of a horse has been employed as the `mould' and further refinements and optimizations have been undertaken which allow many thousands of units to be used in a single build (Figure 10). When fully functional it is believed that this method will result in a more engaging experience for the user than the `matrix build' systems and have the potential to create novel and aesthetically engaging new works.

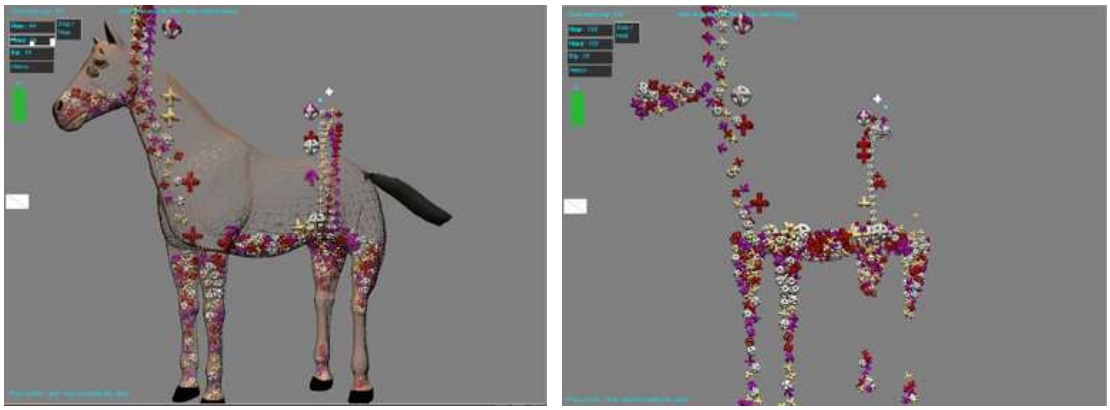

Figure 10: Example of build in progress, with and without the 'mould' mesh visible

## Post processing

Although one of the aims of the research was to create a method by which objects could be designed online and data could be generated from this process to directly create physical works, currently post processing involves a number of stages. The software automatically creates output files once the user has finished creating their designs. The matrix forms are then recreated in 3D CAD software by running a script that places appropriate units in the coordinates provided by the text file and saving the resulting file in an appropriate file type for the intended digital production process. The development of this system has been crucial to the success of this project and is considered one of its most significant results. In theory, the files exported from the CAD software should then be able to be used directly for producing physical objects. However, this is rarely the case. The final stage for the production of rapid prototyped or rapid manufactured objects involves using specialist file preparation software. stl models of complex forms, such as the matrixes being generated by our software, are rarely perfectly constructed and require 'mending' before they can be physically produced.

## *Digital production of generated forms*

A range of digital production technologies has been employed within this project. A Z-corp 3D printer has been used to produce some test forms. Compared to many other Rapid Prototyping technologies, it is a cheap and quick form of digital production. However it is not appropriate for small scale or intricate designs (Figure 11).

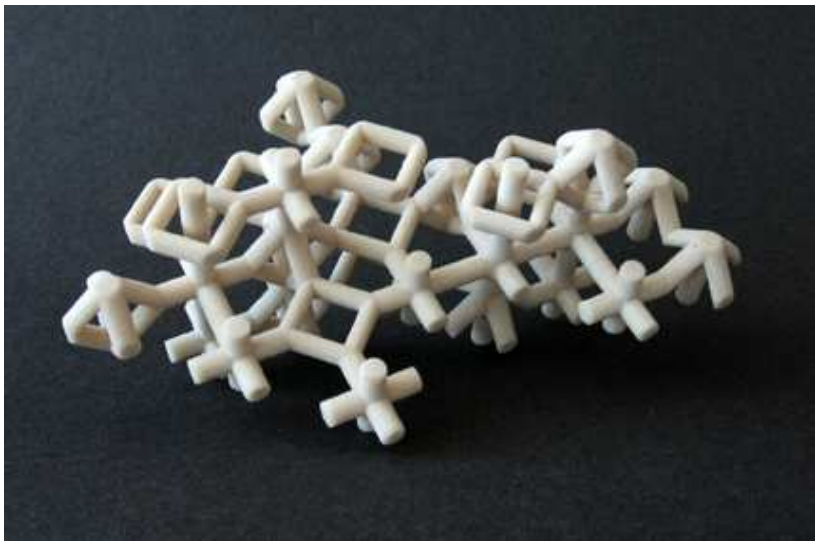

Figure 11: Generated matrix test piece created using Z-corp technology, 150x80x60mm

An Invision 3D printer has also been used to produce a range of test pieces. This system has the capability of producing relatively cheap, highly detailed

and delicate structures. However, models from this process are not durable enough to produce final works (Figure 12).

Figure 12: Bangle form created using Invision 3D printer

It was intended that rapid manufacturing technologies would be investigated which can produce artefacts in metals and ceramics and so produce functional parts rather than prototypes. However, access to these more recently developed technologies proved difficult within the budget available. The well-established Selective Laser Sintering (SLS) process that produces durable nylon parts will be used in the production of medium scale artefacts designed by users. Rapid prototyped parts can also be used as an intermediate stage in the production of final works. Specialist RP technologies have been used to produce wax models for the casting of silver jewellery (Figure 13).

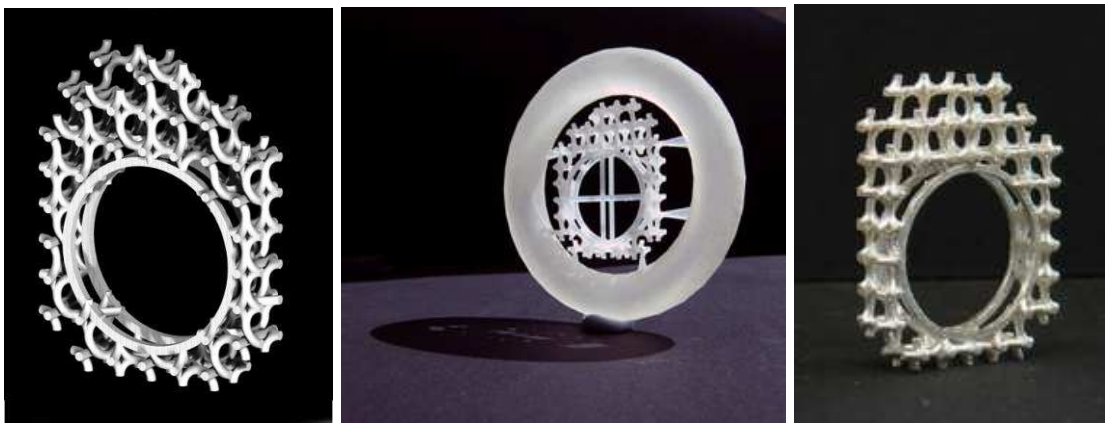

Figure 13: CAD Visualisation of a ring , Wax RP model for casting, final silver ring

## Undisciplined Design

It is clear from the work already produced that PIMS is dealing with a new kind of designing – one which has the potential to create a new, certainly different role for the designer where design decisions are made jointly or collectively by the designer, the computer software and the user. The most significant outcome of both FutureFactories and Automake (as far as PIMS is concerned) is not the development of the generative systems themselves, but the integration of a number of processes and procedures to create a range of systems that have the potential to engage individuals in a form of design and production that questions their familiar relationship with consumer products.

If seen in the wider context of a post industrial manufacturing era involving increased use of smart technologies and the development of personal fabrication techniques, these systems can be considered as part of a growing number of speculative projects and theoretical debates that seek to redefine the relationship between people and objects. Bruce Sterling, for one, has considered the effect on this relationship when the integration of technology grows to the state where the embodied information within a product becomes more important than its physical manifestation (Sterling, 2005). Research projects into advanced manufacturing such as the FAB Lab (Gershenfeld, 2005) and forums such as MAKE magazine also consider the social impact of these technologies.

In relation to established practices, it could be argued that the digital systems developed within PIMS do not conform to a traditional, discipline-based approach, and instead propose an undisciplined design process - a new way of creating objects which can be related to the older tradition of bespoke commissioning, but potentially in a more democratic and widely available way (once the production techniques become more commonplace and costs fall). Therefore this type of system has the potential to rekindle and expand a craft tradition in which maker and client work together to develop a design that is unique to the individual. However, as Emily Campbell argues, craft contains the idea of personal meaning, which she feels has been lost in much recent product design (Campbell, 2006). This personal meaning for the owner of a craft object is created through a complex range of psychological associations. There is a question whether the new design and production systems described here have the potential to produce objects which have enough 'craft' characteristics to retain the ability to create personal meaning. On the one hand they produce unique objects, but on the other hand, they are not 'handmade'. There is a range of skills employed within the development of the systems that allow the creation of new artefacts, however they are not the traditional skills associated with craft practice. Furthermore, the aesthetic characteristics of the objects produced are inherently a balance between the generative system, the software designer and the user, rather than solely the vision of the maker. As users begin to try the software and the systems are tested, the significance of these issues can be reviewed and the hybrid nature of the projects assessed.

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## Dr. Paul Atkinson

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### Lionel Dean

Lionel is a graduate engineer and has a Master's Degree from the Royal College of Art, London. His work explores the boundaries between Art and Design and focuses exclusively on additive digital manufacturing techniques (www.futurefactories.com). Using this medium he has created a host of iconic designs ranging from gallery pieces to retail products for well-known manufacturers.