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Rapid manufacturing facilitated customisation

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Abstract

This paper presents a novel method for the production of body-fitting customised seat profiles utilising the following digital methods: three dimensional laser scanning, reverse engineering and Rapid Manufacturing (RM). Seat profiles were manufactured in order to influence the comfort characteristics of an existing ejector seat manufactured by Martin Baker Aircraft Ltd. The seat, known as the Navy Aircrew Common Ejection Seat (NACES), was originally designed with a generic profile. This paper shows the replacement of this profile with shapes captured from fast jet pilots. Pressure mapping of occupied seats, has shown that the pressure distribution under the buttocks can be influenced using body-fitting design and thus comfort is directly affected. The paper discusses the relevance of RM with respect to mass customisation and personalisation and, in addition, recognises RM as a Next Generation Manufacturing System (NGMS) capable of satisfying increasingly diverse products and lower volume production. A generic customisation process is reviewed to identify areas of technical difficulty and key issues in the cost-effective customisation of products.

Keywords: Customisation, Reverse Engineering, Rapid Manufacturing, Comfort

AMS Subject Classification:

Introduction

Aircrew face increasing performance demands due to governmental pressures, which is leading to a growth in mission times and a consequent degradation on aircrew comfort levels. This deficiency in comfort levels has particular resonance, as it is acknowledged that comfort has an impact of the physical and mental wellbeing of the subject and importantly their lethality (Ransley 2004). The aim of this paper is to show the novel use of reverse engineering techniques coupled with additive manufacturing technology to influence seating comfort. The production of individual seating profiles has been achieved through the use of three-dimensional (3D) laser scanning methods and Rapid Manufacturing (RM). The process from design to production is given; and consequently, the use of RM for customisation is highlighted and compared with existing mass customisation examples. The process described in this paper highlights the use of digital capture, data manipulation and manufacturing methods for

customisation and discusses the issues inherent with their application for customisation. Indeed the customised seat platform exists solely in a virtual environment from conception until production and is an application of computer integrated manufacturing (CIM). Customisation work was based on the Navy Aircrew Common Ejection Seat (NACES) developed by Martin Baker Aircraft Ltd.

Rapid Manufacturing

RM has developed over recent times from technologies previously developed for Rapid Prototyping (RP). Rapid Manufacturing has been defined by Hopkinson *et al.* (2006) as:

‘the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components’.

The foundation of RM is based on the reproduction of 3D CAD data in an additive or layer-by-layer manner. The additive nature of the process means that RM differs from traditional manufacturing processes, *i.e.* those that are formative or subtractive in nature, as tooling is superfluous to the manufacturing process. This removal of tooling provides RM with two intrinsic advantages over traditional processes. Firstly, utilising 3D CAD data, components of virtually any geometry (Hague *et al.* 2003) can be produced. Secondly, recent studies have concluded that RM can be suitable for the production of low to medium volumes (Hopkinson and Dickens 2003). Mansour and Hague (2003) have expanded on the use of RM and its design possibilities, particularly when compared to injection moulding. Current design for manufacture (DFM) rules for injection moulding such as constant wall thickness, avoidance of sharp corners and minimisation of weld lines, sink marks, ejection pins, gate marks and draft angles are not applicable to RM as the technology requires no tooling. Therefore, the geometries available to be manufactured are suddenly increased. Furthermore, the wait for such tooling to be manufactured is negated and the cost of such tooling removed. This has significance when considering the production of low or custom volumes as tooling is not required to be amortised over a large number of units in order to make the final product economical. In fact, as the RM process does not require tooling the RM process could be particularly interesting for practitioners of mass customisation (Davis 1987).

Mass Customisation

The concept of mass customisation as expanded by Pine II (1993) has the focus of:

‘developing variety and customisation through flexibility and quick responsiveness’.

The merchandise produced for mass customisation differ from those produced in mass production as shown in Table I.

Insert Table I

Table I. Mass Customised product characteristics contrasted with mass production (Pine II 1993)

The product characteristics for mass customised items, as shown in Table I, show alignment with the characteristics of RM. As mentioned previously, Hopkinson and Dickens (2003) point to the use of RM for low volume production and the benefits that RM has over traditional manufacturing technology. When comparing manufacturing systems with the product characteristics shown in Table I it is clear that existing manufacturing systems have their roots in the development of the mass production environment where the production of goods and services are founded upon high volumes with homogeneous market characteristics. Considering injection moulding, the characteristics of the manufacturing process are

intrinsically linked to the volume of components required by the firm and ultimately the market. As such, the development of mass customised products has required a different ideology for development. The use of *modularisation* has been of particular use as a method for increasing variety whilst attempting to maintain the economies of scale that a mass produced product allows (Salvador *et al.* 2002). In addition, the concepts of agile (Maskell 2001) and postponement (Van Hoek 2001) are used to further the spread of mass customisation as a business model.

Existing customisation

Existing examples of customisation are numerous when considering conventional manufacturing techniques. Several industries have used management tools and paradigms to change the way the product is taken from customer order to delivery; in particular, footwear, Mi Adidas (Berger 2005), mobile telephones (Nokia X-Press On covers) and the automotive arena. However, the methods for customisation, certainly for the automotive and mobile telephone markets, follow the methods of customisation outlined by Alford *et al.* (2000). Three strategies for customisation in the automotive sector have been defined:

- 1 **Core** - Direct customer involvement in the design process of the vehicle. This method of customisation requires a low volume product due to the nature of the manufacturing processes possible and the interaction of the customer.
- 2 **Optional** - Focused on high volume manufacture of vehicles where the purchaser chooses customised "options". These options can then be integrated into the vehicle during assembly.
- 3 **Form** - The concept of form customisation is to change the form of the standard product at the distributor for example, changing the finance package, service and warranty specifications.

These three customisation strategies have defining characteristics. Each requires different properties in the manufacturing process (such as, low, medium or high volume) or requires different perceptions from the customer as to what customisation really is. The definitive aim for customisation should be that based on core customisation, where the customer specifies the product in such a way that the item meets their needs completely. This requires a move away from the term mass customisation to full customisation for the individual. As mentioned previously, this can only occur currently with low volume goods as the knowledge and skills to produce such a product are not easily transferable to a mass production environment. For these reasons, cost effective core customisation of items is not currently a reality for the majority of consumers. Mi Adidas (Berger 2005) approaches core customisation for footwear; here the customer is intimately involved in parts of the design process, namely the development of a custom fitting sole. However, in actuality, having taken custom data from the consumer the measurements are compared to a large library of pre-existing shoe lasts, rather than producing a fully custom made last for the individual, as such the product utilises optional customisation, but with a large degree of consumer input.

Piller and Muller (2004) have discussed the propensity of consumers to purchase mass customised products with particular reference to customised shoe products. They report that (for shoes) there is a large market within Europe (approx. 40 million pairs), but that it is unlikely that mass customised products will dominate the shoe market. In addition, the willingness to pay for customised goods varied from country to country, as did acceptance, with the main marketing opportunity lies in the customisation experience. Further research is necessary in developing the customisation procedure and flexible manufacturing systems to exploit the mass customisation concept.

Seating comfort

The issues surrounding seating comfort have received significant attention in the past. Initially it would be prudent to outline the causes of discomfort that can affect a seat's performance. For vehicles, Mehta *et al.* (2000) have defined a number of different sources for discomfort:

1. Transmission of vibration to the occupant
2. Body pressure distributed under the buttocks, thighs and back of the operator that supports the operator's weight.
3. Control of posture either statically or dynamically through different loading paths.
4. Clothing and seat covering materials.
5. Perceptions and interior ergonomic characteristics.

These factors may stimulate discomfort and even pain in a number of different ways. Viano and Andrzejak (1992) have summarised these pain mechanisms with respect to road vehicles.

Insert Table II

Table II. Causes of Seating Discomfort (Viano and Andrzejak, 1992)

It is clear from this information (Table II) that the majority of pain issues occur due to the seat and its construction. Therefore, design is crucial to change seat comfort for removing some of the pain mechanisms.

Several methods for increasing levels of comfort are possible, e.g. cushioning or changing the seat shape. Both these methods have the result of changing the pressure distribution of the occupant on the seat. Chow and Odell (1978) and Sanders and McCormack (1992) both suggest that the weight of the seated occupant should be distributed evenly throughout the buttocks but minimised under the thighs and suggested altering the seat shape to accommodate this. Pressure distribution has been discussed by several authors: (Habsburg and Middendorf, 1977), (Iwasaki *et al.*, 1988), (Ng *et al.*, 1995) for evaluating seating comfort. Thakurta *et al.* (1995) discuss a study of short and long-term seat comfort. They found that pressure distribution across other parts of the body, in particular lumbar, shoulder, thigh and Ischial regions resulted in increased comfort.

In contrast to this work, Gyi and Porter (1999) have studied the measurement of seat and buttock interface pressure for the evaluation of car seat discomfort. Pressure mapping equipment was used in order to identify areas of increased pressure and subsequent discomfort, in order to identify a direct relationship between pressure distribution and comfort. Some correlation between mean pressure under the Ischial Tuberosities (IT), thighs and lower back and discomfort was found for men, though for women this association was reversed. In conclusion, they reported the results as being inconclusive for justifying the use of high-pressure areas as indicators of discomfort.

Simpson and Porter (2003) have studied the affects of cockpit and seat design on musculoskeletal pain and discomfort in pilots of both rotary and fixed wing aircraft. They surmise that pain mechanisms are borne out of poor seat and cockpit design that leads to poor posture and fatigue during extended flight. It is important to note that unlike car seating, aircraft seating (especially military) is much more restrictive and this results in a reduced capability of using movement of the body to relieve pain. The affect of these pain mechanisms ultimately leads to increased fatigue. They suggest that the most desirable solution to this

problem is to redesign the cockpit and seating to include a wider range of pilot sizes. However, this is a costly process and, with conventional techniques of manufacture, impractical. The requirement, therefore, is for a manufacturing route that will enable economic production of seating for a narrower range of aircrew sizes, or indeed customised to the individual, a possible route for this is now discussed, utilising 3D scanning, digital data manipulation and Rapid Manufacturing.

Customised Aircrew Seating Project

The existing seat profile used for the NACES seat is based on anthropometrical data collected by Barwood (1963) at the Institute of Aviation Medicine. Plaster casts were made of numerous posteriors in order to evaluate differences in seated anatomy. Barwood's work concluded that differing shape and size of pilots was, at that time, insufficiently dissimilar within gender groups to warrant a number of different seat types. Thus, a generic seat platform was developed and has been used since. The platform is affectionately known as the "Barwood Bottom" (shown in Figure 1).

Insert Figure 1

Figure 1. NACES Seat with Barwood profile

Importantly, modern pilots now cover a larger profile of sizes and also pilots are now selected from both genders. Seating systems now have to cover a larger percentile range (Bolton *et al*, 1971) and so the generic Barwood shape is proving unsatisfactory for many pilots. As mentioned previously, this paper presents a novel approach to producing customised seat profiles for a range of pilots utilising RM as a manufacturing technique.

RM requires the production of suitable digital data in the form of a .STL file; this file can be produced in most 3D CAD packages and then be transferred to the RM system. The STL file is then sliced by software into discrete layers that are reconstructed by the system hardware to form the physical part or component. The data can be produced in the form of a totally new CAD design or can be a reproduction of an existing shape. In the latter case, reverse engineering (RE) techniques are often used as a precursor to the CAD modelling task. The study described here was based around the concept of body fitting customisation for a seating application. As such the subjects' interaction with the seat in question had to be carefully considered. The steps for the customisation process were as follows:

- 1 Geometry capture
- 2 Scanning
- 3 Data manipulation
- 4 Manufacture

Finally, pressure mapping of pilots in a range of seating platforms has been carried out in order to quantify and demonstrate the changes in pressure distribution caused by the different seat profiles manufactured by the method described above.

Geometry Capture

The first step was to capture the shape data from the subject under investigation. In order to obtain the correct geometry for the seated profile, it was necessary to devise a method that could reliably capture the reaction between the seat and the buttocks. In order to do this a method of "moulding" the buttock shapes whilst in contact with the seat was devised. Through studying methods of production for other types of

customised seating (most notably Formula 1 Racing) a method was identified to capture the necessary geometry. A beanbag device (Indi Seat 2005) is often used by racing teams to produce a mould of the driver. The driver is placed on the beanbag in the race position and on the attainment of a comfortable position the beanbag is filled with expanding two-part foam that encases the driver. The driver is then cut out of the cured foam and his profile is used as a mould to produce a carbon fibre shell. This system is wasteful in two ways, firstly much of the “cured” beanbag is cut away and of no further use and secondly once the mould has been used for moulding the carbon fibre, it is thrown away.

A second method of producing custom seats for F1 exists, it uses the same bean bag method, however, once the mould is taken of the driver, the bean bag is scanned using a laser scanner and the resulting data used to produce a 3D CAD file which can then be machined to produce a negative mould, and once again laminated in carbon fibre to produce the seat.

An adaptation of these techniques was sought, which enabled geometry to be captured in-situ and was reusable. The capture mechanism was based on that of a Burnett bath seat produced by RBF Products Ltd (2005). The system consisted of a polymeric bag filled with polystyrene beads with a valve placed where air can be sucked out when required. This resulted in a stiffening of the bag, thus capturing an imprinted shape (Figure 2).

Insert Figure 2

Figure 2. Photograph of Burnett Seat in position, shown with a custom profile imprint.

Geometry capture was carried out using seating profiles taken from Royal Air Force (RAF) trainee fast jet pilots. In all, 15 pilots were used as test subjects; each pilot was dressed in full flight gear including G-Trousers and any necessary harnesses. Pilots ranged in size, weight and gender in order to get a representative sample. Table III shows the range of sizes in percentile terms (Bolton *et al.* 1971) of the pilots used.

Insert Table III

Table III. Percentile range of pilots used for seat customisation.

Scanning

In order to produce the necessary 3D CAD model, data for both the seat shape and the customised profile was needed. This data was captured using a 3D non-contact scanner, Model Maker X70, produced by 3D Scanners (2005). The scanner was connected to a co-ordinate measuring arm; in this case a FARO Technologies Inc (2005) Gold Arm. All scanning was done on-site, a photograph of the system in use is shown in Figure 3.

Insert Figure 3

Figure 3. Non-contact 3D Scanner in use.

The scanner system produced a series of points based on the position of the arm and data collected by the laser scanner. Such a series of points is often referred to as a point cloud. One example of the point clouds generated from the 3D scanner with a custom profile is shown in Figure 4.

Insert Figure 4

Figure 4. Point cloud of custom seat profile.

The point cloud represents a number of individual data points collected by the scanner; each point is allocated an x, y and z co-ordinate in free space. The point cloud was only the first stage of the data manipulation process. During subsequent modification of this data, RE software was necessary to convert the point cloud data into a 3D CAD model.

Data Manipulation

Following the data collection process, specialist RE software, Raindrop GeoMagics Studio (2005) was used to process the raw point cloud data and produce a final CAD file for the customised impressions. Point clouds were imported as a neutral ASCII format from the scan software, the data was subsequently *cleaned* to remove unwanted points. After the erroneous data had been removed, a second process, known as decimation, was performed to reduce the point cloud further. The main reason for performing this operation was that the initial point cloud contained more points than necessary, thus increasing the file size. The larger the file the more time consuming operations on those data sets become. Reducing the point cloud data allowed more efficient manipulation of the data.

A polygonal point surface was then “wrapped” onto these points and any holes bridged or filled in order to blend the customised surface with the seat shape. The surface was then smoothed sufficiently to remove unwanted creases from the scanning operation but leaving the custom profile intact. When a satisfactory polygonal surface had been produced, a Non-Uniform Rational B-Splines (NURBS) surface was created to import the file into a CAD package for further editing or manipulation. Three sets of seating data were manipulated to form the CAD models shown in Figure 5.

Insert Figure 5

Figure 5. Seat CAD files

Once the NURBS surfaces had been created the part was then converted to the STL format for production on additive manufacturing equipment.

Manufacturing

The customised seats were produced using a 3D Systems SLA 7000 stereolithography (SL) (3D Systems 2005) machine, the build orientation was with the seating surface facing upwards (Figure 6a) in order to minimise build time and produce a good quality upper surface. In total, 13 customised seats were manufactured using the RM method; one of these is shown in Figure 6b. The seats fitted well into the existing product package with minimal requirement for finishing operations.

At this point it must be mentioned that the materials used for the production of the customised seating profiles would not be suitable for such a demanding application as ejection seating. However, the production of these components through the RM route serves to prove the concept of digital customised manufacturing. Indeed, though the materials may not be suitable in this specific application they could be suitable elsewhere, for example, wheel chair or automotive seating.

Insert Figure 6a & b

Figure 6. (a) Screen shot of virtual build set up on SLA 7000 and (b) completed SL model in-situ

Once the seat profiles were manufactured, the seats were taken back to the RAF site for pilots to test each seat (including their own) for comfort. Pressure mapping equipment was used in order to ascertain changes in pressure distribution across the buttocks.

Pressure Mapping

In order to monitor possible changes in comfort produced by the customised seat platforms, a method of capturing the pressure distribution under the buttocks of the individuals was used. Using TEKSCAN pressure mapping equipment (TEKSCAN, 2005) clear changes in the pressure distribution compared to the pre-existing NACES seat platform were attained. Table IV shows four, two-dimensional (2D) plots of the pressure distributions seen for an individual pilot sitting on different profiles.

Insert Table IV

Table IV. 2D pressure plots of an individual pilot sat in four different seating profiles; NACES (original); Custom 1, 2 and 3.

The pressure distributions shown in Table IV show the results from being sat in each seat for a period of three minutes, the pressure levels indicate the average pressure level over this time. Relating the seats to the individual, NACES is the original 'Barwood Bottom' seat; custom 1 is the individual's own profile, whereas custom 2 and 3 are other custom profiles.

Discussion

The use of digital scanning, reverse engineering and Rapid Manufacturing methods has been successful in the production of a number of body-fitting customised seating arrangements. The development of this customisation strategy has a number of issues as a consequence, namely:

- 1 Comfort implications
- 2 Customised production
- 3 Next generation manufacturing

Comfort implications

The production of the individual seating profiles has changed the pressure distribution under the buttocks of the test subjects. Using TEKSCAN (2005) pressure mapping equipment the change in the pressure distribution can be seen. The images shown in Table IV highlight the change in seated pressure distribution for an individual. In accordance with the work by Mehta *et al.* (2000) the use of RM for producing individualised seating has enabled changes to two of the four sources of discomfort, namely:

- 1 Body pressure distributed under the buttocks, thighs and back of the operator that supports the operator's weight.
- 2 Control of posture either statically or dynamically through different loading paths.

In addition, the ability to change the seating profile and specifically tailor it to the individual directly influences the seat contour, identified by Viano and Andrzejak (1992) as a source of discomfort.

The images shown in Table IV, illustrate how the seat pressure distribution can be changed through the production of different profiles. The NACES seat pressure distribution shows two circular areas of low pressure surrounded by a ring of higher pressures (up to 11 kPa). These two areas of low pressure are characteristic of the 'Barwood Bottom' profile (see Figure 1). Seats custom 1 and 2 show much more even distribution of pressure over the buttocks and minimal pressure under the thighs, which according to Chow and Odell (1978) and Sanders and McCormack (1992) is optimal in terms of seating comfort, whereas, custom 3 shows an area of higher pressure under the buttocks. In terms of aircrew comfort, the case study has shown that the customised design approach certainly has an impact upon load distribution. However, the relationship between load distribution and comfort is not trivial and may not be representative of comfort levels over an extended period. More research on the impact of personalised seating designs on aircrew comfort over periods of several hours is required. In addition, the assumption was made that a seating design that is conformal to the shape of the individual would be the optimum in terms of comfort because it would reduce areas of high pressure. Although this seems an intuitively sound assumption, further work is necessary to prove this. It is possible that different users will prefer different pressure distribution patterns and this must be taken into account in the design process.

Customised production

The use of RM meant that the labour requirement usually seen in the production of customised goods was moved from the manufacturing process into upstream processes such as design. Figure 7 shows the typical timeline for each of the processes involved in the manufacture of a single seat. In total, from capturing the geometry to completing the seat the process took around 48hrs to complete. The vast majority of this time (35 hrs) was taken building the parts using the SLA 7000. However, this time required little to no operator involvement. In fact, the major labour content was involved in the data manipulation or design phase of the operation.

Insert Figure 7

Figure 7. Timeline for RM custom seating.

Comparing the process described here with that developed by Masters *et al.* (2006) for In The Ear (ITE) hearing devices, initially the processes seem similar. However, the production of customised ITE devices has not yet reached the realm of complete computer integrated manufacturing. The mould taken of the patient's inner ear is still required by the manufacturer and can be a source of error due to the moulding and manual shaping processes necessary to produce a comfortable device. The customisation scenario presented in this paper requires no manual fashioning of the component, indeed the only manual operation involved through production is done when removing the components from the RM machine.

Conventional methods of manufacture lie in a spectrum that ranges from using labour intensive processes at one end to the use of expensive general machinery at the other. Figure 8 shows a typical manufacturing

paradigm for low to high variety products and respective production volumes. The dotted line is the line of least cost for the manufacturer. Traditional customisation occurs in the top left of the Figure whereas mass produced items are suited to the bottom right.

Insert Figure 8

Figure 8. Manufacturing supply characteristics for differing product variety and volume

The labour intensive processes of professional customisation and service shop manufacturing result in a very high unit cost (at least in developed economies). Mass production can result in low unit costs but only at the expense of high product standardisation. This conflict between product volume and variety has been spanned by concepts such as flexible manufacturing systems and mass customisation. RM can be considered as a new type of agile manufacturing system that is capable of high product variety but without the requirement for high labour input. This is due to the fact that no tooling is required and a high degree of automation. This leads to a possible alternative manufacturing supply paradigm as shown in Figure 9.

Insert Figure 9

Figure 9. Manufacturing supply characteristics including RM.

The development of RM for the manufacture of customised products is undergoing increasing research. This has culminated in a specific research project looking at the development of an entire customised process chain that has RM at its core. The project, known as Custom-Fit, is a European Union funded Framework 6 Integrated Project (IP) (Custom-Fit 2005); specific aims for the IP are to develop affordable custom fitting products such as, prosthetics, seats, medical implants and consumer goods using RM as the manufacturing method.

To outline the benefits that this method of customised production has over that previously presented in the literature a comparison is presented in Table V. A comparison with the following applications of customised production is made:

- Prosthetic ear, Chandra *et al* (2006)
- Burn masks, Chandra *et al* (2006)
- In the Ear (ITE) hearing aid devices, Masters *et al* (2006)
- Customised Shoes, Berger (2005)

Insert Table 5

Table V. Comparison with existing customisation technology.

Of the examples given in Table V, only one of the examples combines the technologies and concepts presented in this paper. The closest example is that given by Masters *et al* (2006) however, as mentioned previously, a large degree of manual finishing of the ear impression, taken by a clinician, is necessary before scanning can take place thus influencing the scan and the final production item. The medical cases have used different production methods than those used for custom seating. In fact, RP equipment was used for the production of a mould and then conventionally vacuum formed or filled with silicone elastomer to produce the final component; this is more commonly known as Rapid Tooling (RT). The production of customised shoes by Adidas (Berger 2005) has utilised many different scanning and

geometry capture techniques such as pressure mapping and foot measurement, however, the final production of the shoe is based around a traditional shoe “last” chosen from a library and which matches the measurements as closely as possible, this leads to lead time of around 4-6 weeks for delivery.

Map of Customisation Process

The process of customisation has been mapped using an IDEF0 modelling technique (Meta Software Corporation, 1995). The “parent” model identifying the generic customisation process using the equipment previously described is shown in Figure 10.

Insert Figure 10

Figure 10. Overall IDEF0 representation of generating 3D conformal products

The parent representation shows how the generic model for customising a component has only one real input: the individual. This is the fundamental issue for customisation of any product, the service offered to the individual must meet their requirements and so correct data on the individual is key for a successful “custom” part. Decomposing this generic representation into its constituent parts it is possible to identify the different facets that will affect the end component, and ultimately, the customer’s satisfaction. The “child” diagram is presented in Figure 11.

Insert Figure 11

Figure 11. Sub-level “child” IDEF0 representation of the operational structure for producing 3D customised components.

The four operations necessary for producing a body-conformal component are as follows:

1. Geometry Capture (including scanning)
2. Conformal Data Manipulation
3. Design Combination
4. Rapid Manufacture

Analysing each operation it is possible to define the technical challenges and necessary issues for developing custom parts using the CIM route described in this paper.

Geometry capture is the process of capturing the individual’s geometry for a component. Though this item has operations and equipment (such as digital scanning) that are necessary for any body-fitting customisation operation; the method of capturing the desired geometry depends upon the application envisaged. This paper has described the interaction between an individual and a re-formable medium to capture the seated position. At this point possible errors in the geometry are introduced. Firstly, if the customer is not correctly placed by the operator then the captured geometry will be incorrectly (i.e. too far forward, twisted, tilted or too far backwards) leading to problems as identified by Simpson and Porter (2003). For each application of body-fitting customisation the process needs to be standardised in order to minimise the introduction of errors into the scanned geometry.

Secondly, by using a medium to capture geometry, the reaction between the medium and the area of the body under study is captured. If the medium is too hard, too soft or non-uniform in density then the

reaction between the body and the medium will differ over the area under consideration. This can lead to areas of further discomfort, i.e. possible pressure points in the design. In contrast, on many occasions it is possible to scan the body directly using 3D scanners; however, here a further problem is apparent, as the body-part is not situated in the same environment as when it is loaded and performing a function (i.e. sitting etc.). The most important aspect of geometry capture is to capture the body in its environment when using the product to be customised. For static applications (such as the seating) this is a relatively simple exercise, but for dynamic environments there are obvious difficulties. But even for static applications such as seats and hearing aids, issues will arise especially when manual manipulation of the scanned item has taken place.

Manipulating the scanned data, in general, requires the skills of a design engineer to form the requisite surface necessary to form the final product. The introduction of the design engineer brings into the process chain a degree of uncertainty into the final design of the conformal portion of the product. This will affect the performance of the customised component. Without standardised design practices, which do not currently exist for many customisation applications, the designer is able to manipulate the point cloud data received from the scanner in any way that they see fit. Operations performed by the designer (smoothing, noise reduction etc.) will directly influence the final design and hence its eventual interaction with the customer.

Some methods of automation do exist for manipulating the point cloud data generated by a 3D scan (Phonak, 2006) and automatically producing a customised component. However, the scanned article (in this case a wax impression of the inner ear) is manually finished by a skilled technician and as such digital manipulation of the raw data is minimised to producing a surfaced “shell” rather than removing erroneous data or subjectively smoothing and manipulating the data to form a surface the designer is happy with.

Design combination again requires the skills of designers or specific design software to be written for each case (Phonak 2006). The placement of the customised surface in relation to other design entities, in this paper the general seat structure and placement pins, is again down to the designer’s skill and judgement.

The area of design and capture of geometry for customised products requires the developments of suitable standards and practices in order for a true and fair representation of the product to be formed. Without this the subjectivity created by the manual nature of this process (though in a digital environment) will lead to ill fitting and ultimately products that do not perform

Rapid Manufacture has a number of issues associated with its future development, these surround the development of materials and processes that produce robust parts with a degree of longevity required for products rather than prototypes. A number of authors (Hopkinson *et al* 2006) have discussed these issues and it is not the intention to discuss these in detail in this paper, however, it must be acknowledged that although RM materials and equipment are by no means optimal, a growing number of applications exist and as such the processes should, on many occasions be accredited with manufacturing rather than prototyping status.

Next generation manufacturing

The need for flexible manufacturing systems to support mass-customised production was highlighted in a report by the Iacocca Institute (1991) and by the Next Generation Manufacturing (NGM) report (1997). Molina *et al.* (2005) have reviewed the current literature from a next generation manufacturing systems

(NGMS) viewpoint, their particular focus is on the development of manufacturing systems that enable the production of components and products directly for mass customisation. They report that NGMS requires research in the following four areas:

- 1 Manufacturing Paradigms
- 2 Methodologies (best manufacturing practice)
- 3 Design, planning and execution of manufacturing systems
- 4 Web-based information systems

In addition ten technological areas are purported to be vital to the success of NGMS, of particular relevance to RM are:

- 1 Adaptable integrated equipment, processes and systems that can be readily reconfigured.
- 2 Innovative processes to design and manufacture new materials and components
- 3 Technologies that can convert information into knowledge for effective decision making
- 4 Product and process design methods that address a broad range of product requirements

However Molina *et al.* do not take into account additive manufacturing technologies for net shape reconfigurable manufacturing. Indeed the only mention of additive techniques is in the uses of RP to support product development. However, the use of RM for the production of functional products has previously discussed by the authors (Tuck and Hague 2006) with particular reference to the effects RM could have on current supply chain paradigms, including mass customisation. In addition the use of RM for the production of functional parts and components has been illustrated by a number of applications. As mentioned previously, ITE hearing aid devices (Masters *et al.* 2006); others include a number of automotive applications (Tromans 2006) and aerospace parts (Fox 2006).

Conclusions

This paper has described a novel, fully integrated, digital manufacturing approach for customised seating profiles. The method has used off-the-shelf products in order to define a methodology of producing parts that are customised to body shape in order to influence the comfort of the individual. Using a pressure mapping technique a significant change in the pressure distribution under the buttocks was shown for varying seat profiles. According to the literature, changing the pressure distribution throughout the buttocks can change the comfort levels experienced by the user. In terms of aircrew comfort, the development of customised seating could have an impact on future comfort levels and importantly lethality, though further long term testing of the custom profiles is necessary. The application of RM in this instance, for customisation, shows a route forward initially identified by Simpson and Porter (2003) for the reconfiguration of aircrew environments that are otherwise impractical (usually too expensive) for conventional manufacturing technologies.

With comparison to existing methods of seating customisation the technique developed in this paper has reduced waste and reduced the number of manual operations necessary. Secondly, using the described scanning and reverse engineering techniques to produce a suitable 3D CAD file the seat is able to be produced directly (without the need for further tooling) using suitable RM equipment. In addition, all the work presented in this paper to produce a customised seat profile has been performed in a virtual environment. Further advances of this technology could realise a number of benefits for those permanently seated such as the disabled. However, further development of the comfort mechanisms spoken of in this paper will be necessary.

In conclusion, the techniques described here have the ability to change the paradigm for not only mass customised products but also those that are truly individual in either aesthetics or design. The use of digital scanning, reverse engineering software and RM has the promise of removing a great deal of the current labour content that exists in customised products. Further development of these techniques is necessary, for examples a greater degree of automation during the reverse engineering stage would reduce the labour content of the exercise significantly. In addition, improvements to manufacturing speed for RM machines will speed the production of the customised items during manufacture. The development of a standardised process for customisation is of importance, especially with regard to future applications. Little work exists for the standardised manipulation of customised data and its incorporation within products, however, without this standardisation components that are marketed and sold as customised may not serve their customer as well as hoped or desired.

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Mass Production	Mass Customisation
Stable demand	Fragmented demand
Large homogeneous markets	Heterogeneous niches
Low-cost, consistent quality, standardised goods and services	Low-cost, high-quality, customised goods and services
Long product development cycles	Short product development cycles
Long product life cycles	Short product life cycles

184x48mm (96 x 96 DPI)

Human Experience Mode	Biomechanical		Seat/Environment
	Physiological Causes	Engineering Causes	Source
Pain	Circulation Occlusion	Pressure	Cushion Stiffness
Pain	Ischemia	Pressure	Cushion Stiffness
Pain	Nerve Occlusion	Pressure	Seat Contour
Discomfort	-	Vibration	Vehicle Ride
Perspiration	Heat	Material Breathability	Vinyl Upholstery
Perception	Visual Auditory Tactile	Design or Vibration	Vehicle Cost

153x68mm (96 x 96 DPI)

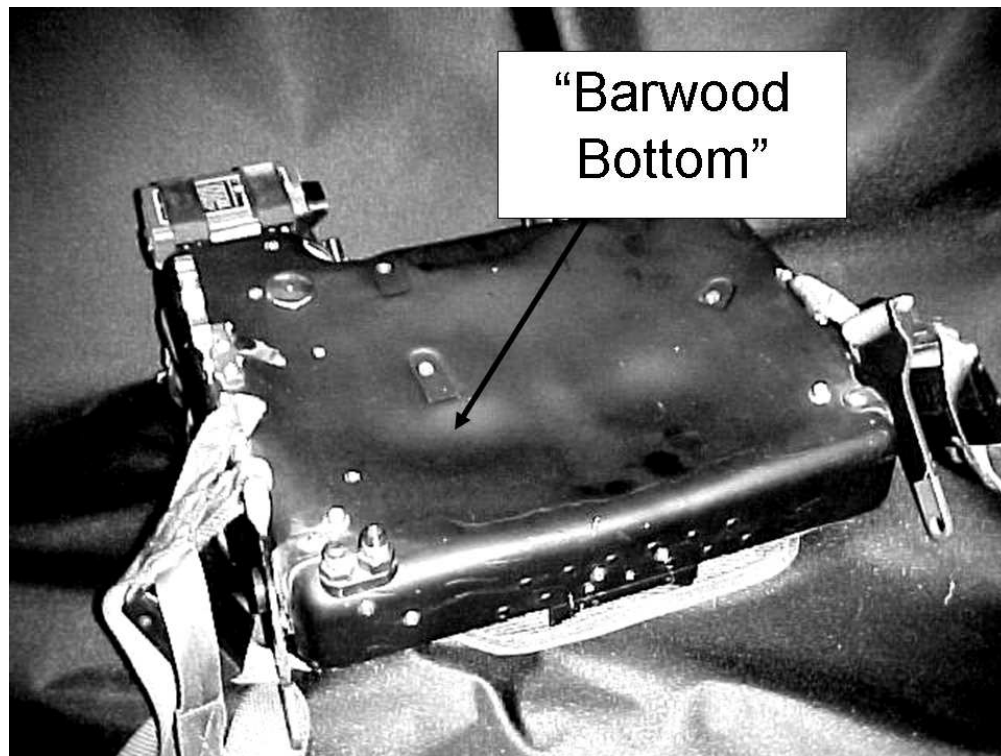


Figure 1. NACES Seat with Barwood Profile
254x190mm (96 x 96 DPI)



Figure 2. Photograph of Burnett Seat in position, shown with a custom seat profile
254x190mm (96 x 96 DPI)

Physical Attribute	Percentile Range	
	Maximum (%)	Minimum (%)
Stature	95	30
Weight	98	40
Hip Breadth	99+	70
Shoulder Height	98	30
Thigh Circumference	95	65

Table III. Percentile range of pilots used for seat customisation
84x66mm (96 x 96 DPI)



Figure 3. Non-contact 3D scanner in use
254x190mm (96 x 96 DPI)

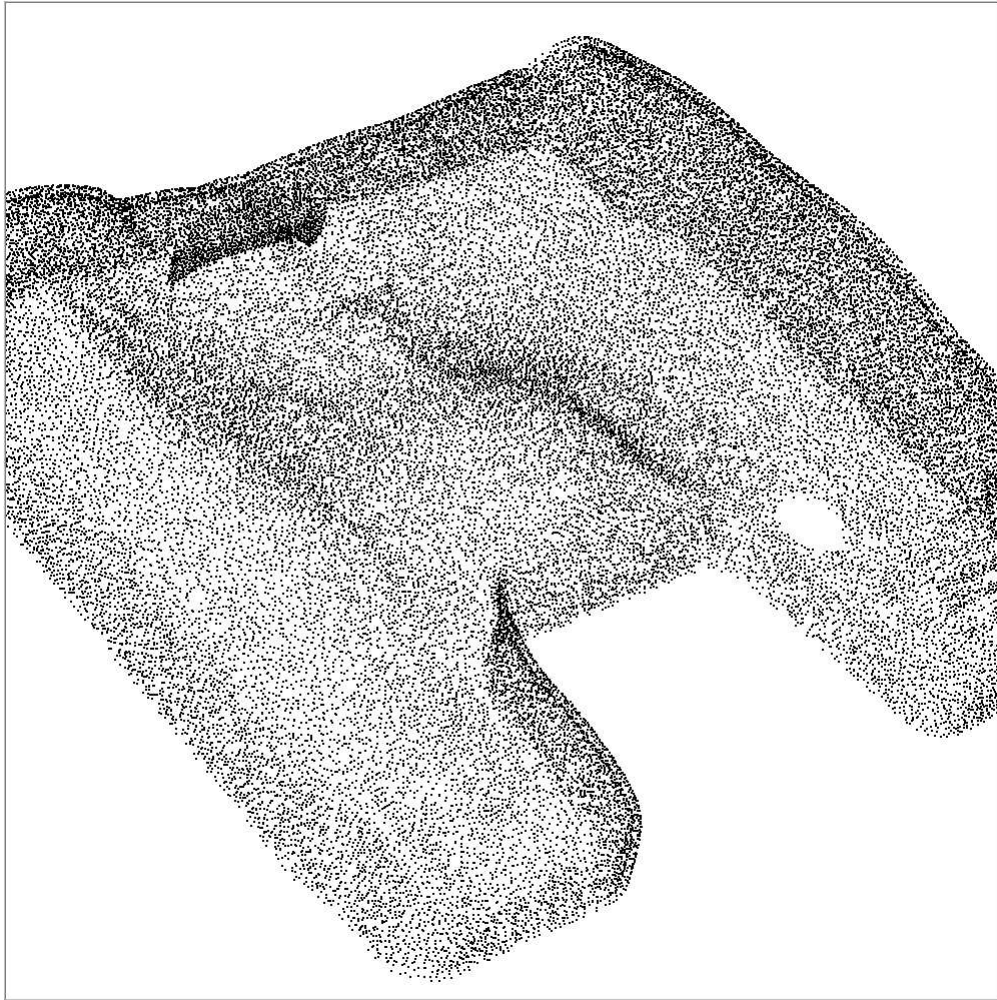
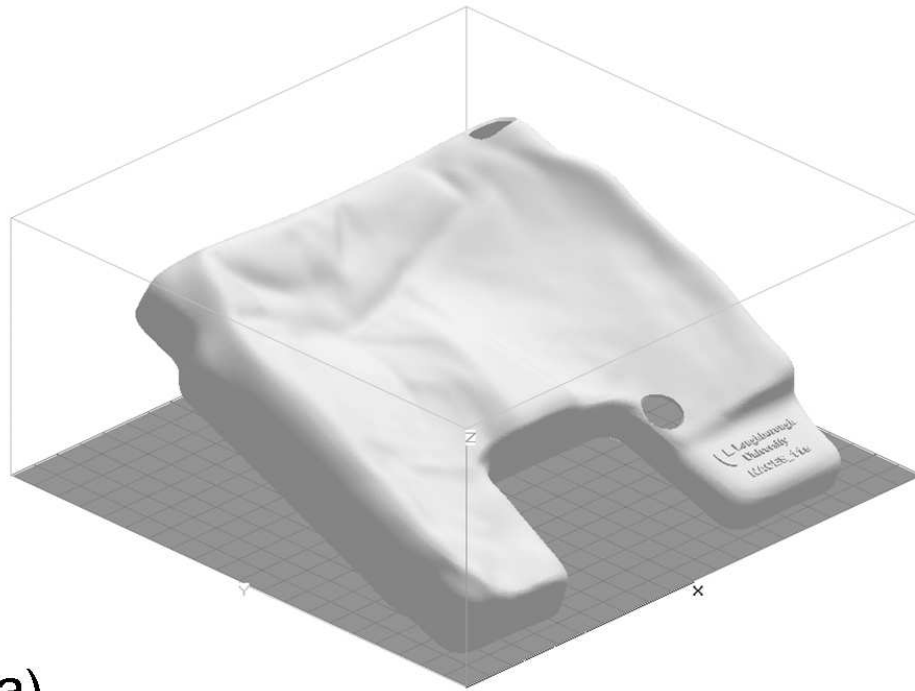


Figure 4. Point cloud of custom seat profile
264x264mm (96 x 96 DPI)



Figure 5. Seat CAD files
254x190mm (96 x 96 DPI)



(a)

Figure 6a. Screen shot of virtual build setup on SLA7000
254x190mm (96 x 96 DPI)

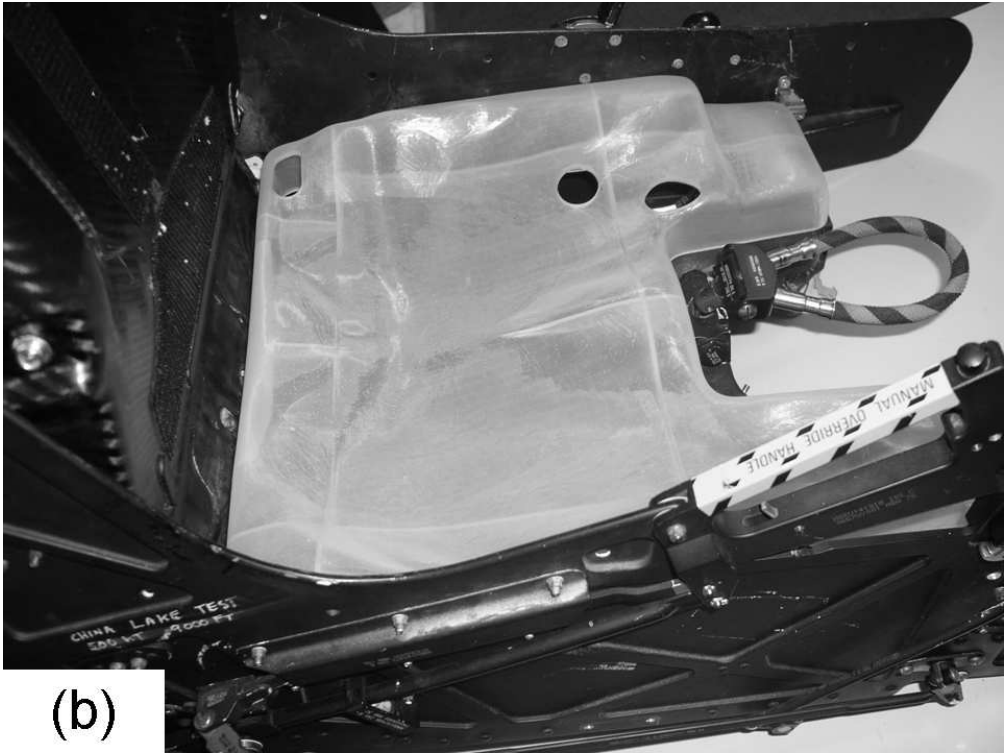


Figure 6b. Completed SL model in-situ
254x190mm (96 x 96 DPI)

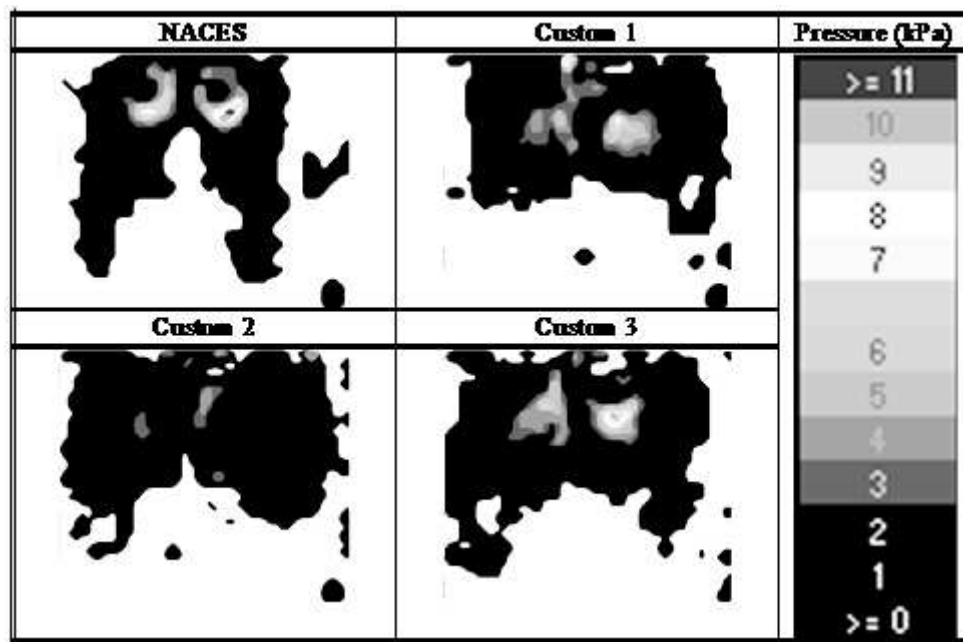


Table IV. 2D pressure plots of an individual pilot sat in four different seating profiles; NACES (Original); Custom 1, 2 and 3.
128x85mm (96 x 96 DPI)

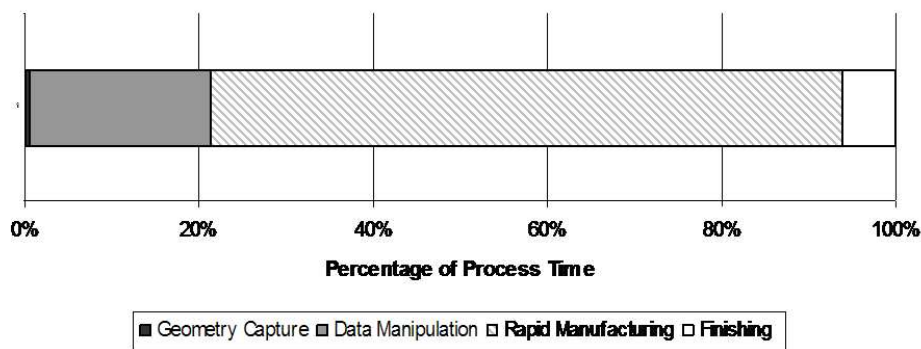


Figure 7. Timeline for RM custom seating
254x100mm (96 x 96 DPI)

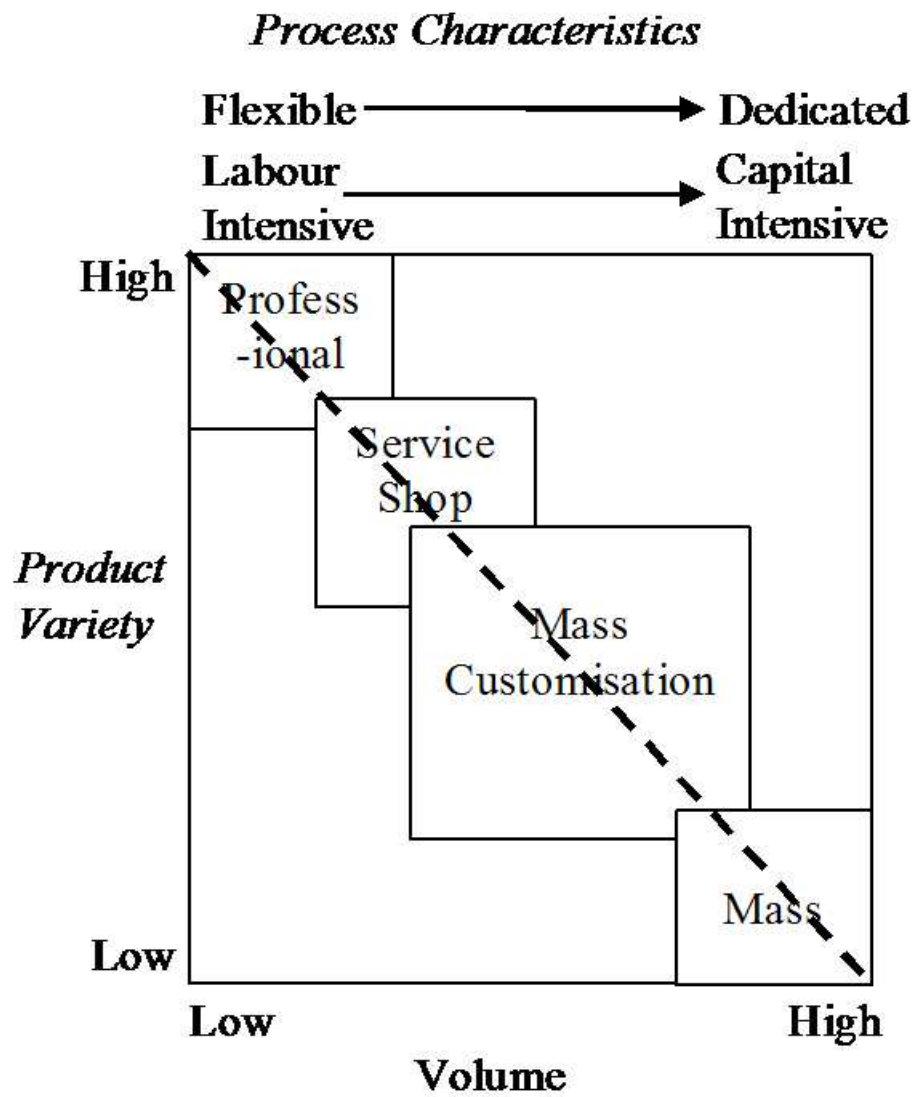


Figure 8. Manufacturing supply characteristics for differing product variety and volume
165x190mm (96 x 96 DPI)

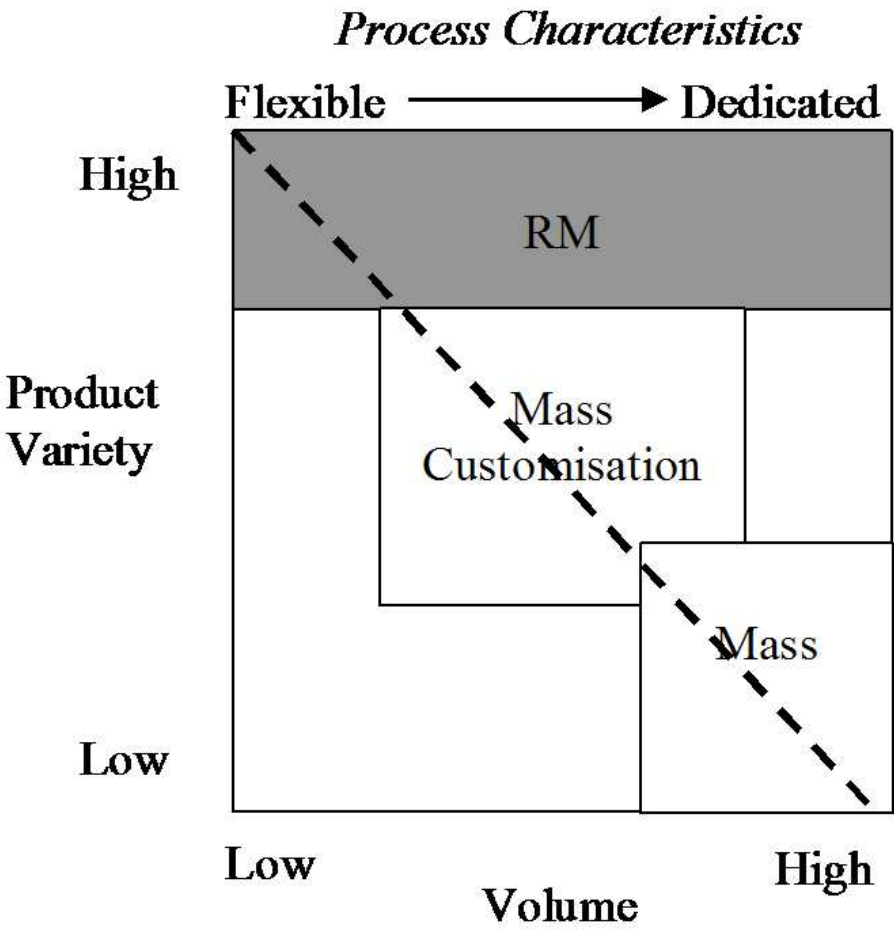
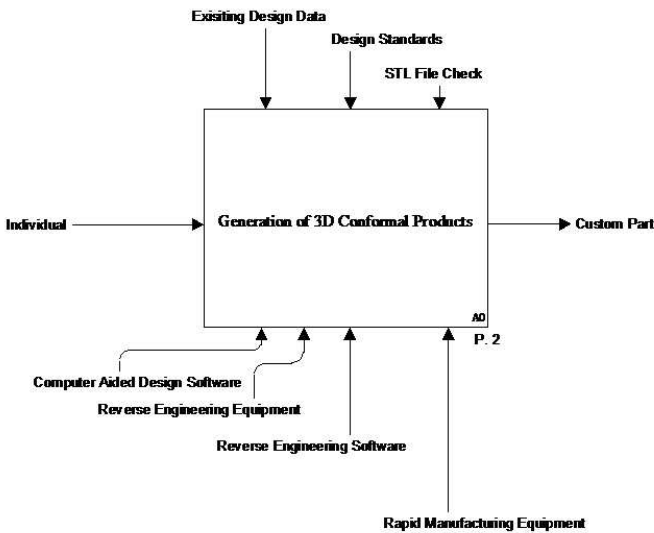


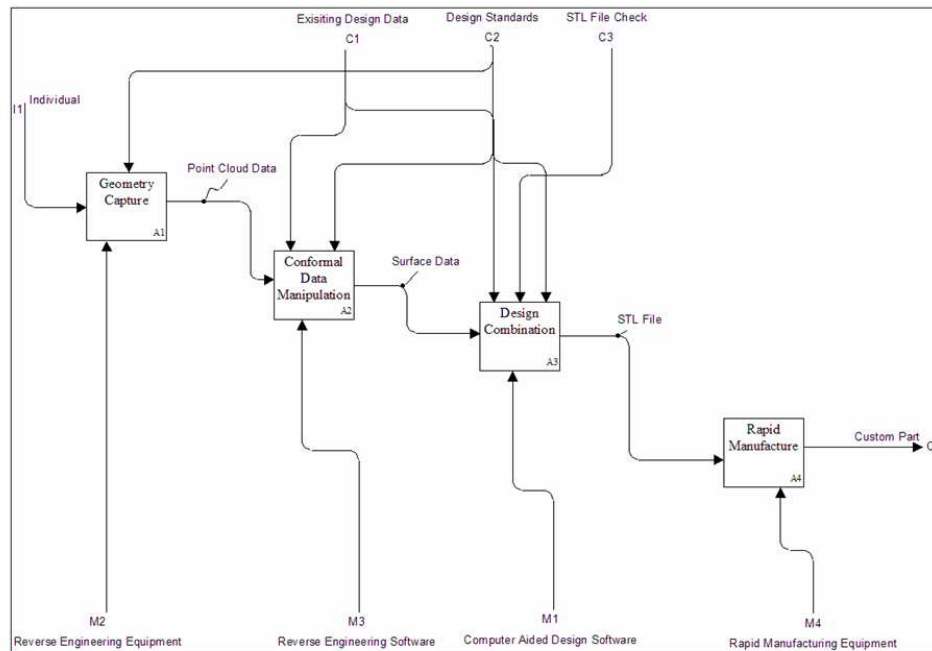
Figure 9. Manufacturing supply characteristics
194x190mm (96 x 96 DPI)

Application	Geometry Capture	Scanning Method	Manufacturing Method
Custom Seating	Direct scan of seated impression	Digital scanning	Rapid Manufacturing
Prosthetic ear	Direct scan of remaining ear	Digital Scanning	Mould constructed from a Thermojet wax printing, then implanted with Silicone elastomer
Burn Mask	Direct scan of the face	Digital Scanning	Mould manufactured using fused deposition modelling (FDM) the final mask produced by vacuum forming
ITE Devices	Wax mould of inner ear	Manual manipulation of wax impression followed by digital Scanning	Rapid Manufacturing (e.g. LS and SL)
Customised Shoe production	Weight distribution and measurements of foot	Pressure mapping and manual measurement	Comparison with existing shoe "lasts" to find best fit

Table V. Comparison with existing customisation technology
141x131mm (96 x 96 DPI)



Overall IDEF0 representation of generating 3D conformal products
254x190mm (96 x 96 DPI)



Sub-level "child" IDEF0 representation of the operational structure for producing 3D customised components
254x190mm (96 x 96 DPI)