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1 INTRODUCTION

It has been estimated that more than 200 million product packages are being opened in EU countries everyday (Klooster and Lutters 2009). The fundamental aim of the vast majority of packaging is to enable environment buffering to prevent damage and product contamination during storage and transportation. The generation and creation of a design for this packaging is an integral part of the overall design of the product or even sub-assembly or part. It is quite a tricky issue and tends to be left to the last minute resulting in sub-optimal or expensive solutions. The design of packaging varies widely, from functional to purely aesthetic, but still has the core requirement to protect the product or part. The majority of product packaging is typically for mass produced products which can include, foam inserts types to fully moulded plastic blister packaging. Forming technologies are primarily used for packaging of mass produced products, components and parts for delivery to customers. These methods typically cater for high volumes and presents challenges for high value and low volume products, due to their complex shapes and fragility. Typical products include niche manufactured parts and unique artefacts such as museum artworks and pieces which can often require transportation from different museums (Aboe 2012). Furthermore, with increasing design trends towards mass customisation and personalisation (Mugge et al. 2009, Ferguson et al. 2014) the need for individual, component packaging will increase.

Perfect-fit packaging provides the best contact interface between the packed component, artefact and the packing material, to provide the best possible level of protection and has the potential to give the important feel to the actual product. The low quantities, however, make the use of traditional approaches for producing this type of packaging (i.e. creating a mould and using forming technologies) infeasible; as a mould would be required for each individual product. Today, transporters of museum artefacts resort to using pieces of Styrofoam, bubble wrapping, polyethylene, spun-bonded olefin fibre sheeting (to line supports and wrap artefacts), acid free tissue paper, polyethylene foams and cotton tape to house different types of artefact (Aboe 2012). This is far from ideal as the interface between the artefact and the packing material is irregular, uncontrollable and the protective qualities could consequently be variable. This has the potential to lead to damage of the artefact during use.

This paper describes and presents a novel solution for the creation of individualised packaging of high value products through the design and manufacture of directly produced perfect-fit packaging for one-off or low batch products. The paper initially outlines the functional requirements of packaging in general, and more specifically the requirements for individualised packaging. A novel integrated method is then proposed consisting of scanning of the geometry of the artefact/ component, followed by rapid design and manufacture of the soft elastomer packaging using a cryogenic computer numerical control (CNC) machining technique. Two examples of high value parts and products, the first from a niche bicycle manufacturer and the second a Royal Doulton figurine are used as case studies to demonstrate the viability and complete flexibility of the designed approach. This not only provides enhanced packaging solutions but will also give designers a valuable tool in their portfolio of design support methods.

2 THE FUNCTION OF PACKAGING

Packaging is essentially a means by which to contain, protect, handle, deliver and present goods of varying nature and is typically manufactured from a number of different materials, including, plastics, cardboard and foams (Lutters and ten Klooster 2008). Whilst the primary function of packaging is to protect the product in transport, it can have broader implications. Expensive and artistic packaging, for example, is likely to aesthetically enhance a luxury product, increasing its customer appeal and marketing value (Rundh 2009). Perfume industry, frequently exploits this, as packaging can represent up to 40% of the cost of the product (Prendergast and Pitt 1996). Moreover it is universally acknowledged that packaging decisions can also have a significant impact on sales (Young 2002).

The majority of mass produced products require packaging solutions that protect the product during delivery and transportation, which are simply discarded once this primary function has been fulfilled.

Several types of packaging are used for this purpose; these include: blister packaging, foam packaging, presentation type packaging (e.g. wooden boxes) bubble wrap etc. Of these types, the perfect fit packages offer the widest contact interface between the artefact and the packaging and thus provide the most predictable and controllable protection.

Mass produced packaging is typically produced from thermoformed material and manufactured using specifically designed mould tools. This produces geometrically accurate packaging solutions from low-density soft elastomer polymer materials. Figure 1 illustrates a typical example of the current process chain used for creating mass produced perfect-fit packaging; the chain consists of production of the machined mould and the injection moulding process.

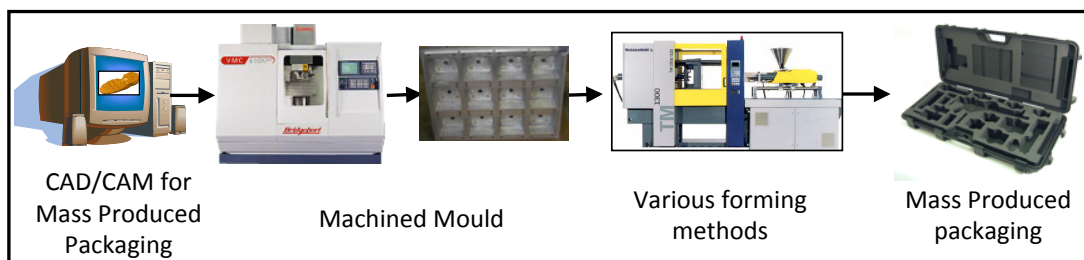


Figure 1. Mass produced perfect-fit packaging production chain

The method in figure 1 is difficult to implement when quantities are low as the high cost of mould production makes the process infeasible. Currently, for low quantity artefacts (i.e. high value individual products or precious museum pieces and artefacts), packaging is arbitrary, time-consuming and labour intensive, using simple, cut-to-fit foam inserts, polystyrene, and bubble wrap as shown in figure 2. These artefacts are often complex in shape and thus the interface between the packaging and the artefact is not uniform. This results in unpredictable protection of the artefact. Other methods that are used include expandable and cure hardened foams, which fit the geometry of the part exactly. Although these solutions provide excellent damage protection, the packaging is usually destroyed in order to gain access to the part, posing a risk to the integrity of the part.

It is therefore evident that a new method for creating perfect-fit, individualised packaging for complex shapes on a per-part basis would benefit industries ranging from high-value niche production facilities to museums who transport high-value and often irreplaceable artefacts.



Figure 2. Polystyrene and bubble wrap packaged museum artefact

3 REQUIREMENTS ANALYSIS FOR INDIVIDUALISED PACKAGING DESIGN

The requirements for individualised packaging can be defined by the product, part or artefact that requires protection, storage and transportation. Figure 3 presents a holistic view of the necessary requirements for the generation of product and part-specific packaging solutions. It is divided into five key areas with independent attributes related to part, data capture, design, material, manufacturing and packaging. The packaging attributes describe the requirements of the complete packaging solution. This provides a holistic view of the aspects required for the generation of fully individualised part / component packaging and is subsequently used to generate the method in figure 4. There are also secondary factors affecting the process and these include health and safety requirements for cryogenic machining. These have not been included in figure 3 as they are considered as a subset requirement of the manufacturing process.

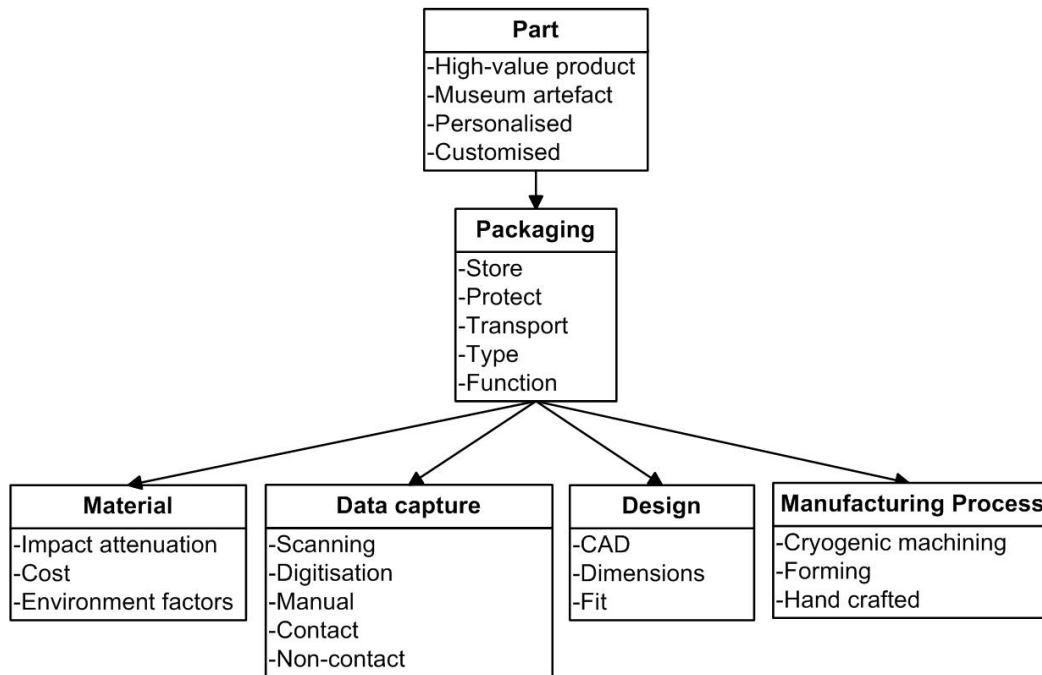


Figure 3. The requirements for individualised packaging solutions

4 A METHOD FOR DESIGN AND MANUFACTURE OF INDIVIDUALISED PRODUCT PACKAGING

A method is proposed for the design and manufacture of individual product package solutions consisting of 3 major stages namely, scanning of the product/artefacts, design of the individualised packaging solutions and cryogenic CNC machining of packaging as shown in figure 4.

Scanning of products/artefacts consists of using either contact or non-contact scanning technologies to capture the part's geometric information. This is subsequently used in computer aided design (CAD) software and is refined using a series of splined and meshed surfaces to generate the required design with added functionality and or modifications where required. This adapted CAD model is subsequently used to generate a fully surfaced model, which can then be used to generate the mould packaging design solutions. The mould is typically designed in two halves, completely encapsulating the part or parts allowing for complete part protection for storage and transportation throughout its lifecycle. A cryogenic CNC machining process is then used to produce the required packaging solutions from a low-density soft elastomeric material with high impact attenuating properties. The major contribution of this process is the ability to design and generate perfect fit packaging solutions for irregular, complex countered products and parts.

5 SCANNING OF THE PRODUCT/ARTEFACTS

There are different types of scanning solutions that can be used depending on the part/artefact. The use of non-contact scanning is the ideal solution for the vast majority of products and particularly in the case of priceless and fragile artefacts. It is recognised that for products which have glossy, shiny material surfaces contact scanning is more appropriate.

Regardless of the scanning technique employed, a CAD representation of the part geometry is required for correct generation of the individualised packaging. This can be either obtained from the CAD part file or from using reverse engineering techniques to produce accurate 3D digital representations of features and geometries. This is useful when scanning a legacy part or artefact as CAD models are unlikely to exist. This holds particularly true for museum artefacts. In order to generate a CAD model of the part/artefact a non-contact scanning method is used to capture the part. The captured point-cloud data is then manipulated using specifically defined control points, which are then segmented or stitched together to form the functioning model.

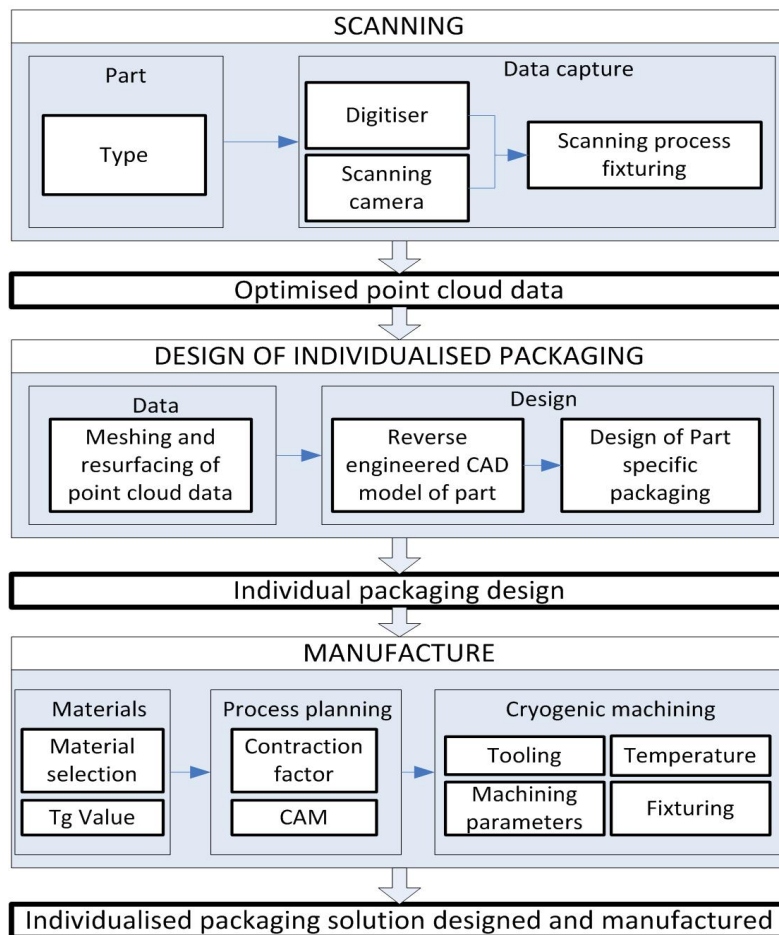


Figure 4. Individualised packaging design and manufacturing process

6 INDIVIDUALISED PACKAGING DESIGN

Using the functioning model, individual negative moulds of the part can be generated. These moulds can then be altered depending on the geometry of the part in order to provide controlled areas of precise fitting. In addition, the computer-generated designs can then be altered, adjusted and manipulated to increase part-packaging support. The packaging solutions are machined to the exact size of the part, so as to enable a complete protective fit. Part numbers can also be engraved directly into the material. Using the generated individualised packaging design moulds (the number of moulds depends on the part being packaged, but typically a packaging mould will consist of a top section and a bottom section) appropriate CAM strategies and techniques can be used to generate machine specific CNC code. In addition, the CAD model is contracted by a certain percentage based on the material and is discussed in section 7.1 The Cryogenic CNC machining process is then used to directly freeze the material to below its glass transition temperature (T_g) value. The designed individualised packaging is machined from a pre-selected soft elastomeric material.

7 CRYOGENIC CNC MACHINING OF SOFT ELASTOMERS

The facilitator for the direct rapid production of fully individualised designed packaging solutions is dependent on a novel manufacturing process based on cryogenic machining developed at the University of Bath. Whilst other methods exist, including injection moulding, foam inserts and rapid prototyping, cryogenic CNC machining has been chosen as it allows for high quality precision foam packaging to be generated for individual artefacts and parts from a high impact attenuating material. Cryogenic machining is a technology traditionally used for hard metal machining (Umbrello et al. 2012, Pusavec et al. 2011) but here, it is utilised for direct machining of soft elastomers. The concept of soft material machining is based on the need to remove the moulding process, which can be expensive and does not allow for constant design change and inhibits individualised design and manufacture (Dhokia et al. 2011b). Direct CNC machining of polymers provides the ability to change

designs instantaneously emphasizing the realistic opportunity to produce individualised product packaging solutions. However, the major challenge of machining soft elastomers is the inability to impart sufficient chip bending moments, which can result in significant deformation, tearing and burning of the material. This also causes increased surface degradation leading to poor quality parts being produced.

The cryogenic CNC machining facility (Dhokia et al. 2011a) has been designed to machine a range of materials typically used in packaging including, neoprene foam, EPDM rubber and ethylene vinyl acetate (EVA). As these materials are already accepted in the packaging industry, they provide an excellent interface between the standardised geometry of primary packaging (like boxes, containers etc.) and the individual geometry of the products/parts to be packaged. This process involves freezing a block of material to below its T_g , before directly machining it using a Bridgeport vertical CNC machine tool with 8000rpm spindle, 500x450mm table and standard tooling. The T_g is the temperature at which a material shows similarities to that of a glass type structure in that it becomes, rigid, stiff and brittle (Kakinuma et al. 2012). Only at this temperature can the material be correctly and efficiently machined. Each material has its own specific T_g value, which is determined using dynamic mechanical thermal analysis methods (DMTA). Machining above the material specific T_g can induce material-tearing leading to deformed features and inferior parts, and potentially reduced tool life as result of friction induced cutting edge damage and excessive heat generation.

The cryogenic CNC machining facility consists of a cryogenic fixture designed to securely clamp material, a vacuum jacketed piping that feeds directly from a high pressure Dewar into a custom designed fixture and a multi nozzle spray jet unit. The temperature of the fixture is monitored using a series of low temperature thermal probes. The material block of size 400 x 300 x 100 mm is securely located inside the fixture and is cooled directly using liquid nitrogen (LN_2), with the use of the spray jet unit. The spray jet unit is activated using a timer mechanism, which enables the control and regulation of LN_2 used during a given machining cycle. The LN_2 is regulated based on the materials specific T_g value, achieved by determining the time taken to achieve the T_g value. This material dependent information can then be subsequently used to regulate the consumption and use of LN_2 by adjusting the spray times and intervals. The cryogenic facility has been designed to retrofit to a wide range of vertical machining centres. The control unit for controlling the rate of flow of LN_2 at any given time in the machining process is independent of the machine tool and was developed as part of another study (Dhokia et al. 2011b). The process also requires adequate health and safety consisting of appropriate oxygen monitoring and cryogenic safety equipment in the form of gloves and visors.

7.1 Contraction factors for Cryogenic Machining

To be able to develop individual packaging solutions for the soft elastomer materials a series of material contraction factors were determined in order to augment the final geometrical size of the manufactured packaging (Dhokia et al. 2010). This is important as the cryogenic process contracts the material and subsequently the packaging mould being machined. Contraction factors are material dependent and were developed based on the thermal coefficient of expansion in terms of X, Y and Z dimensional values. In accordance with this, the CAD model was then appropriately adjusted. The information in table 1 illustrates the cryogenic machining data with an 8mm ballnose cutter for neoprene foam.

Table 1: Compensation values for Cryogenic machining of Neoprene foam

Cryogenic Machining data	
Material	: Neoprene Foam
T_g Value	: -45°C
Time to achieve T_g	: 80 Seconds
Contraction factor for X, Y, Z	: 0.96%
Tooling	: 8mm ballnose cutter
Machining parameters	: Feed 2425mm/min, RPM 7959rpm.

7.2 Cryogenic Machining

The cryogenic process is highly efficient with the freezing of the soft elastomers taking 30 to 90 seconds before machining can start. Ballnose cutters of size 8mm to 16mm were used providing a surface finish equivalent to injection moulded packaging. The typical set-up time is 5 minutes and machining time for a single side complex 3D packaging mould is 25 minutes. Thus the approximate time to cryogenically manufacture a complete individualised product packaging is approximately 50 to 60 minutes.

8 CASE STUDIES AND RESULTS

Case study 1: Moulton Bicycle

Moulton Bicycles is a UK company that specializes in custom bicycles retailing between £9000 to £14000 (Moulton 2014). A handle bar holder was chosen as the case study example, as this part requires damage-free transportation around the production site for different manufacturing operations. In addition, this part is often sent to the customer directly as part of a consignment to be assembled by the customer, or as a replacement part. In addition, each handlebar is different as it is a hand-produced component. Figure 5 illustrates an example of the bicycle and handle bar holder used in this case study. The process for designing individualised packaging begins with the digital capture of part geometry and feature data. No actual CAD part file exists, as each handlebar holder is custom made. The handle bar holder is scanned using a 3D laser-stripe non-contact scanner to capture the geometry of the part. The part requires three different scans, which are then meshed together to generate a point-cloud model. The density of the point-cloud is controlled so as to reduce the number of redundant points captured, which is likely to increase processing and design time. The orientation of the part during the scanning process is critical for capturing all the necessary data. The point-cloud data is converted into surfaces providing a functional CAD model with which to design the part packaging around. Figure 6 shows the scanned re-digitised part and the final CAD model of the part with uniform surfaces.



Figure 5. Case study part: Moulton cycle handlebar

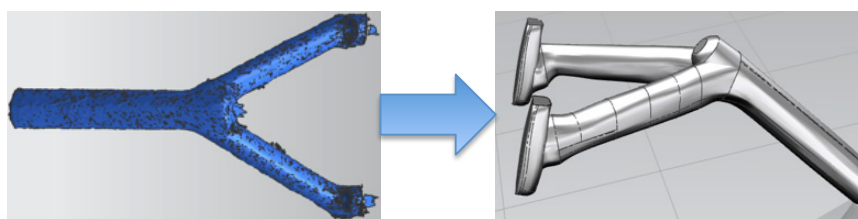


Figure 6. Re-meshed and surfaced CAD model

The packaging solution is then designed using a sandwich type configuration in order to encapsulate the part within the central section and by doing so provide consistent impact resistance around the part. Also, as the part has two additional assembly items, these are positioned within the packaging solution. Figure 7 illustrates the CAD designed packaging. For this case study neoprene foam was selected as the material due to its impact attenuating properties and the machining data is taken from table. The total time to scan design and manufacture the case study example was five hours, which included one hour for direct cryogenic machining. Figure 8 depicts the finished neoprene foam individualised Moulten handle bar packaging solution.

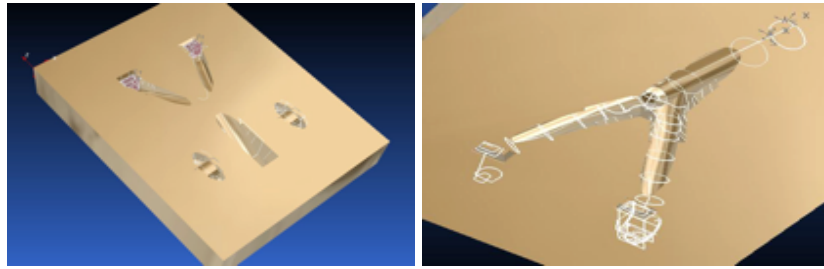


Figure 7. CAD designed packaging moulds



Figure 8. Finished example packaging manufactured from neoprene foam

Case study 2: Example of pottery artefacts

A second case study shows the application of the individualised design and manufactured packaging method to an example high value Royal Doulton figurine which represents small intricate sculptured product shapes found typically in museums. The figurine example is significantly more geometrically complex than case study one and is shown in figure 9.

This figurine was scanned, segmented and CAD modelled using the same method as the first case study and is shown in figure 10. The individualised packaging mould was subsequently cryogenically CNC machined to enable the full part to be incorporated within a single perfect fit packaging solution using a low density, high impact attenuating neoprene foam. Figure 11 shows the final packaging solution with the figurine placed secularly in situ. The final solution as shown in figure 11 was tested using ISO 2248, which includes impact testing based on a number of different heights. The packaging met the requirements set in the standard and the artefacts showed no signs of damage.



Figure 9. The front and back view of the Royal Doulton Figurine

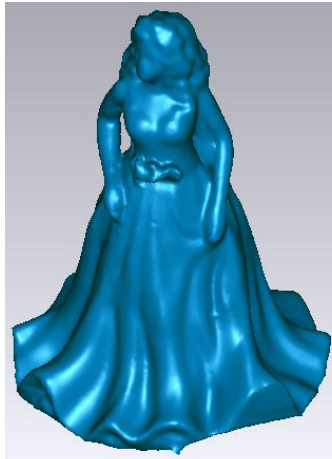


Figure 10. Re-stitched and meshed CAD model of the figurine

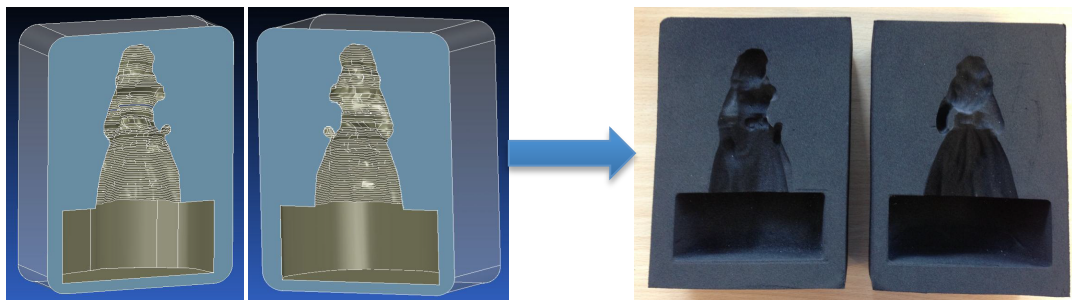


Figure 11. CAD model and final manufactured packaging solution



Figure 12. Final packaging solution with figurine placed securely in situ.

9 CONCLUSIONS AND FUTURE WORK

Today solutions for mass produced product packaging using forming methods are well established and highly efficient, providing excellent fit properties. In the case of low volumes or single high value components packaging solutions are bespoke, inconsistent and unpredictable.

This paper has demonstrated a new approach for designing and rapidly generating individualised packaging solutions using reverse engineering, computer aided design methods and cryogenic machining methods to enable a perfect fit to be achieved between the component / artefact and the packaging. With the complete interface between the two it is possible to design, model, predict and control the protective specifications of the packaging beyond the current state of the art. The design of this new packaging using the described approach provides enhanced component / artefact environmental buffering and also additional enhanced marketability, which could have positive impact on revenue generation.

The concept for individualised perfect –fit packaging is described with two supporting example case studies presented. This demonstrates the feasibility and flexibility to design and manufacture high quality precision-machined perfect-fit individually designed packaging, for high value products and artefacts. In addition, the proposed approach has the potential to provide designers with a highly

valuable tool in their portfolio of design support methods, targeted specifically at individualised packaging for high value low volume parts and museum artefacts. Further research avenues will be explored consisting of identifying life cycle costs of the design and manufacturing approach to ascertain commercial viability. In addition, an impact map of the constraining part / artefact feature will also be investigated to devise design solutions that provide critical points of contact between packaging surface and part.

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