USING CUSTOMER INTERACTION WITH FUNCTIONAL PROTOTYPES TO SUPPORT INNOVATIVE PRODUCT DEVELOPMENT

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Abstract

Rapid prototyping models have often been used to facilitate customer evaluation and approval of design concepts. This paper presents a method known as customer interaction with functional prototypes (CIFP) aimed at enabling customers to make a more creative input into the new product development process. The basic premise is that the solid freeform fabrication (SFF) technologies used for rapid manufacturing also enable more representative prototypes that can be used for full and frequent customer interaction in the design process. This paper reports an extended investigation where CIFP was used successfully within a small company to introduce a new range of innovative motion analysis products.

Introduction

Rapid prototyping (RP) models are frequently used to facilitate customer evaluation and approval of design concepts. However, for several reasons, the use of these models has often been limited to later stages in the design process. The models themselves have been expensive to produce, seen as "precious" by designers and therefore not to be exposed to rough handling by potentially careless customers (Cain, 2005). Also, the design process may be understood in such a manner that fully functional physical prototyping is not seen as necessary until the final design has already been determined (Kayis and Hoang, 2005). Finally, the limited range of materials available might mean that the RP models could never be fully-representative of the final product. From an engineering test perspective, this last issue can be compensated for by using mathematical techniques, for example (Cho et al, 2005), but this is not possible with direct user evaluation. With more recent developments in RP, particularly the ability to create robust models in representative materials at lower costs, these reasons are losing their validity.

This paper presents a method known as customer interaction with functional prototypes (CIFP) that has been jointly developed by Loughborough University and the Central University of Technology, Free State in South Africa (de Beer and Campbell, 2005). This method is aimed at enabling customers to make a more creative input into the new product development process. Such interaction can help to elevate the customer from a fairly passive verification role within the design process to a much more participatory role. The value of such customer interaction through frequent physical prototyping has been recognised by Mascitelli (2000) who states that it is a powerful way of obtaining tacit knowledge from customers. The CIFP method seeks to formalise this approach and present designers with guidelines for its effective implementation. It has been used successfully within both an academic environment and as part of commercial product development projects undertaken through university/industrial collaboration (Campbell et al, 2007). However, this paper relates the first application of CIFP within a purely industrial setting, albeit with design input from an academic who was working as a part-time designer in the company. In addition, all the products were designed for final manufacture using SFF and so the paper also demonstrates good practice in the field of design for rapid manufacturing (DfRM).

Justification for using CIFP

The new product development (NPD) process of many companies tends to have limited customer involvement (see Figure 1). A requirement for a new product from the customer initiates the process, there is probably a "sign-off" of the design before manufacture and then the product would be made and delivered. The sign-off would most likely take place on the basis of drawings, computer aided design (CAD) renderings, prototypes or perhaps pre-production samples. By the time the customer gets to see the design, virtually all of the major design decisions have been made and there is limited scope for optimisation. Some companies, particularly those who see themselves as "customer focussed" will also bring customers in at the end of the Conceptual Design stage to provide opinions on alternative design concepts. However, it is unlikely that these concepts will be presented in the form of a functional prototype, but rather as visualisations or mock-ups. The customer opinions would therefore be made on the basis of very limited information and there would be no opportunity to use the product in its normal use environment. Such limited customer involvement served the purpose of most companies for many years but as customers have become more discerning and global competition increases, it is increasingly being recognised as inadequate. Instead, more companies are adopting user-centred design strategies since the best-designed products and services result from understanding the needs of the people who will use them (Black, 2008). However, for user-centred design to work, designers must have a medium through which they can communicate all aspects of the product design. Ideally, the product design itself becomes the central medium of communication (Kälviäinen and Pontecorvo, 2000).

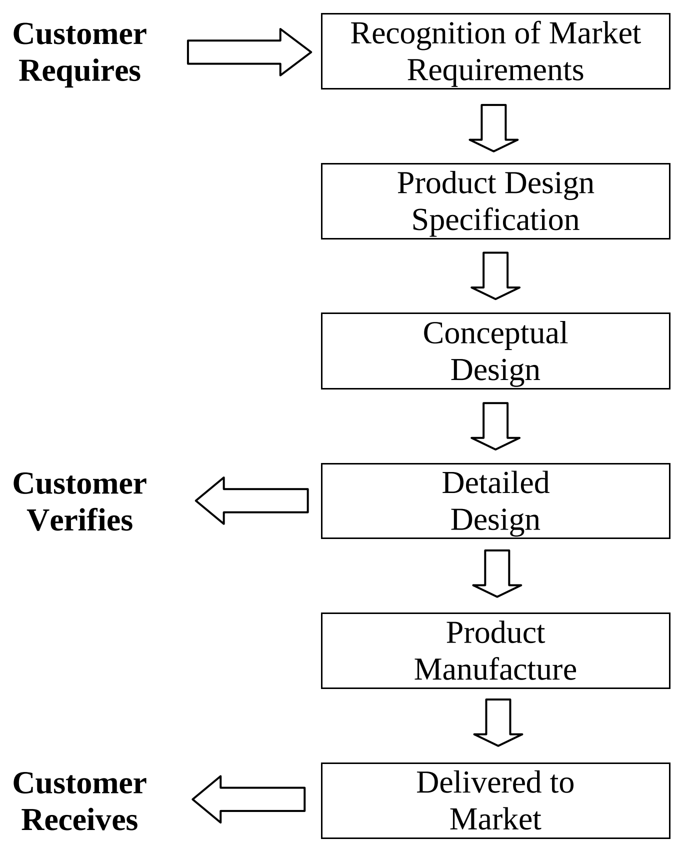


Figure 1. Limited role of customer in the NPD process

The basic premise behind the implementation of CIFP is that the SFF technologies used for rapid manufacturing also enable fully representative functional prototypes that can be used as the basis for communication between designer and customer. The early availability of physical prototypes that closely resemble the final product enable full and frequent customer interaction throughout the entire NPD process (see Figure 2). This is something that until recently has not been feasible in many industries because physical prototypes were too expensive and time consuming to be made except when absolutely necessary. RP has changed this in that physical prototypes, even those with complex geometry, can be made quickly and at a lower cost than hand-made models. This is demonstrated by the fact that the RP industry has grown steadily over the previous 20 years and is now worth over $1 billion (Wohlers, 2008). Over the past five years, the expansion in the range of RP materials and the confidence in material properties has reached a stage where rapid manufacturing (RM) of finished items is becoming increasingly common. For products produced through RM, there is little difference between a prototype produced for evaluation and the final product. Therefore, all the evaluations that are necessary to assess the quality of the product can be undertaken as soon as a fully-defined CAD model is produced, often very early in the design process. The nature and outcome of the evaluations will change at various stages in the NPD process but the medium of communication will remain consistent. Of course, this does not exclude the use of other media to help develop design thinking, e.g. manual sketches and CAD renderings.

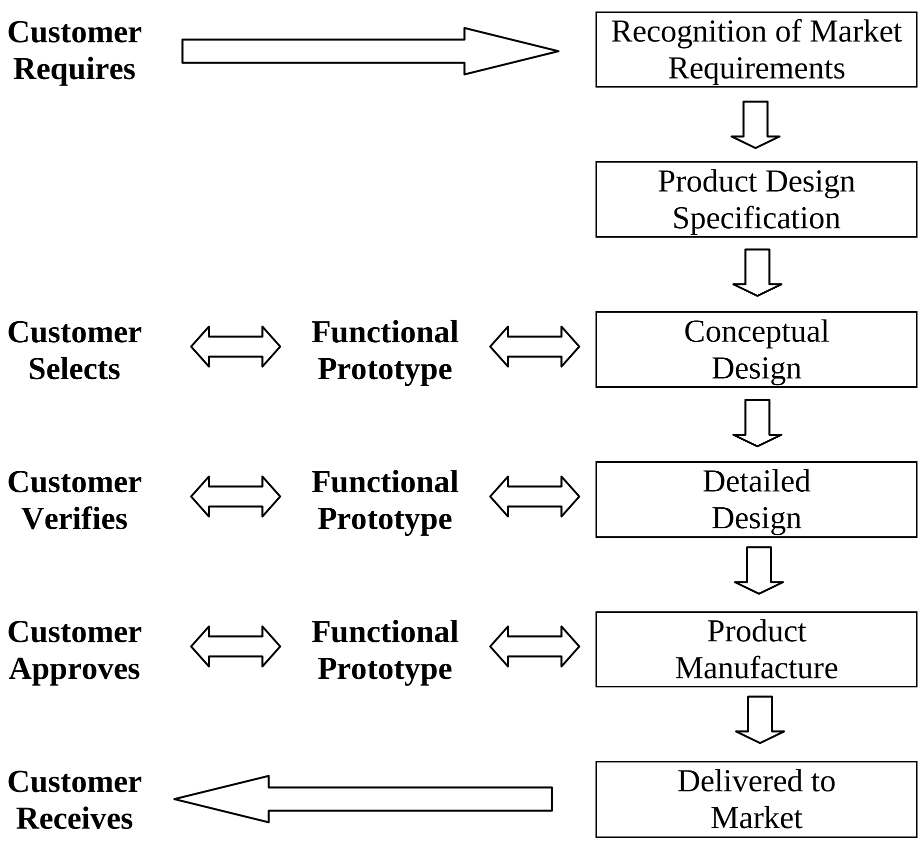


Figure 2. Increased role of customer in the proposed CIFP method

In many cases, product evaluations can be simulated within a virtual environment using such techniques as finite element analysis, computational fluid dynamics, mechanical simulation, photo-realistic rendering and so on. These technologies are often referred to as virtual prototyping (VP). For most engineering analyses, and even some aesthetic evaluations, VP is accurate, fast and extremely cost effective. It is no wonder that it has become ubiquitous in virtually every manufacturing industry. Never-the-less, there are still some key reasons why VP has not yet fully replaced physical prototyping, and probably never will. Amongst these are legal aspects, e.g. the need to crash real cars to achieve safety certification, accuracy aspects, e.g. where the VP still has to be calibrated and validated by physical tests, and, of particular interest to this paper, situations where non-specialists are involved in the evaluation, e.g. ergonomic evaluation of a product by a range of potential users. There are some situations where it is just not feasible to expect the ordinary "person on the street" to interact fully with a totally virtual product. Obvious examples of this are toothbrushes, car seats, mobile phones and other "physical contact" products; but even where virtual interaction is possible, e.g. a computer printer, it may not be fully representative of every aspect of the product and the results of the evaluation are therefore likely to be flawed. This phenomenon has been observed even with physical prototypes (Rooden, 1999). Therefore, if a means of producing a fully representative physical prototype can be found that is not prohibitively slow or expensive, VP should always be used in tandem with it, rather than as a replacement.

There is yet another, perhaps even more compelling, argument for considering CIFP, the emergence of so-called mass customisation. Mass customisation has been interpreted in numerous ways but has usefully been defined by Piller (2004) as a "customer co-design process of products and services, which meets the needs of each individual customer with regard to certain product features". Currently, much of the co-design aspect of mass customisation happens via web interfaces and configuration software, e.g. NikeID, and is limited to aesthetic or predictable performance characteristics. It is impossible to convey aspects such as comfort using this approach. It is risky for a company to sell such a product to a customer who has never handled it or tried it on for size. The customer is given no opportunity to optimise the design once the order has been placed. Some manufacturers are realising the inherit weakness of this method and are now storing the customised design and offering customers the ability to re-design their product once it has reached the end of its life in service (Piller, 2008). It would be much more preferable (at least from the customer's viewpoint) to get it right first time by allowing design optimisation to take place before purchase. This could be achieved if fully-representative physical prototypes of the product were available. Thus, CIFP could be seen as an enabler for more efficient mass customisation, particularly for modular products where much of the prototype could be reused after customer evaluation.

Implementing CIFP: a Case Study

This section reports on an extended investigation where CIFP was used successfully within a small company to introduce a new range of innovative motion analysis products. Charnwood Dynamics is an SME which designs, develops, manufactures and markets a motion analysis system known as Codamotion. Codamotion works by placing infra-red emitting markers on the target object (often human anatomy) and tracking their movements using one or more portable sensor units (shown in Figure 3). The change in 3D position of each marker over a period of time is calculated using dedicated analysis software. Further calculations are then used to interpret this raw data into real-time motion visualisation images for the target object (see Figure 4 for an example of this). The system is used for a range of applications including clinical movement analysis, sports performance analysis and ergonomics evaluation of products.

Figure 3. Portable sensor unit and infra-red emitting markers (www.codamotion.com)

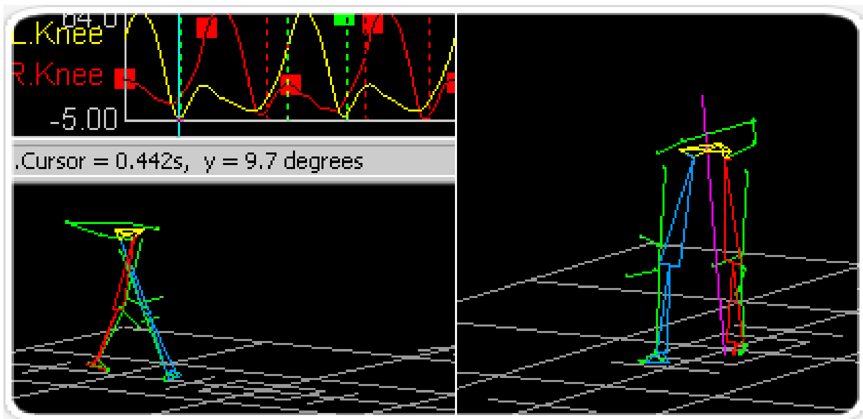


Figure 4. Visualisation of real-time motion (www.codamotion.com)

To enable the Codamotion system to operate accurately, there must be consistent and robust placement of markers around the human frame. This includes placement on limbs, torso and head. Currently, this is achieved through a number of methods, including the use of so-called “marker wands” which are held onto limbs using Velcro and elasticated straps. A set of pelvic and leg wands is shown in Figure 5. It can be seen that the components used are simple in shape so that they can be manufactured using laser cutting of sheet plastic. Numerous manual assembly operations are then required to finalise the product.

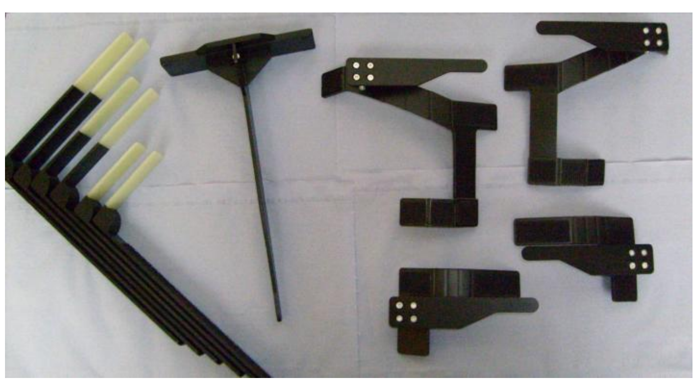
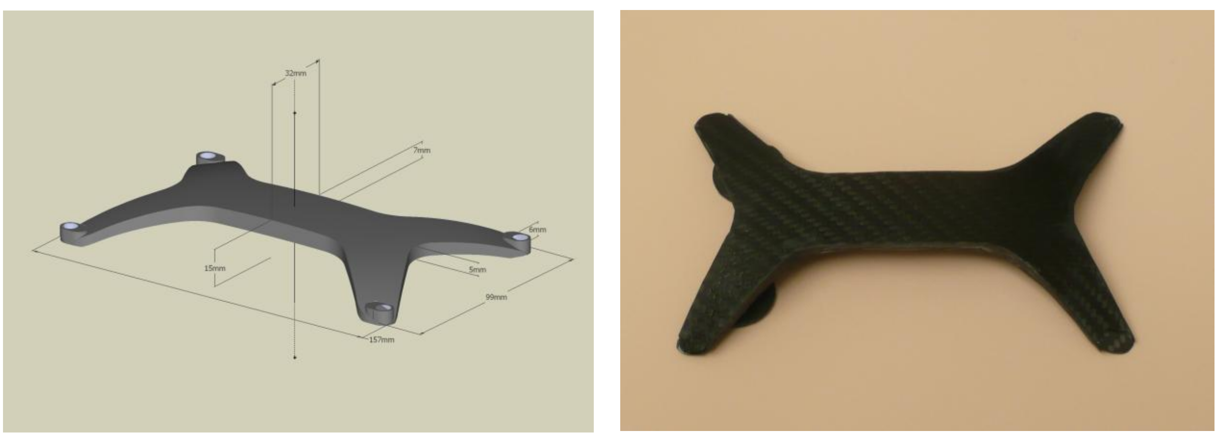


Figure 5. Existing design of pelvic and leg wand set

A new development in the Codamotion system software required four markers to be located in a “cluster box” rather than placed individually. The cluster box had several key design requirements:

- quick and easy attachment to the upper or lower legs of various girths
- minimal relative movement between markers
- capable of housing on-board battery, circuitry and wiring
- easy access for recharging plug
- minimal assembly operations
- suitable for small batch manufacture
- non-reflective surface finish
- attractive appearance

An initial design concept was created by the company’s Managing Director using Google SketchUp (sketchup.google.com), as shown in Figure 6a. This showed the overall desired shape of the cluster box and the location of the four markers. This model was supplemented by a 3D physical mock-up that had been fabricated from woven carbon fibre sheeting (see Figure 6b.) The company had already identified rapid manufacturing as a potential solution for economic small-batch production but had little experience in the 3D CAD modelling that would be required to facilitate this route. Loughborough University was therefore contacted as a known source of DfRM expertise.



(a) (b)

Figure 6. Original concept (a) modelled in Google SketchUp, (b) as a physical mock up

Right from the outset, it was decided that CIFP would be implemented with the Managing Director acting as the internal customer. This would enable his extensive knowledge of the Codamotion system and the requirements for the cluster box to be incorporated into the product design. The starting point for the design process was to replicate the original concept design using Pro/ENGINEER Wildfire 4 CAD software, incorporating additional aspects that had already been identified as being beneficial to the design (integrated ball-joint pads, snap-fit lid, strap hooks and a rocker device). This was designated as version 1a of the cluster box and can be seen in Figure 7.

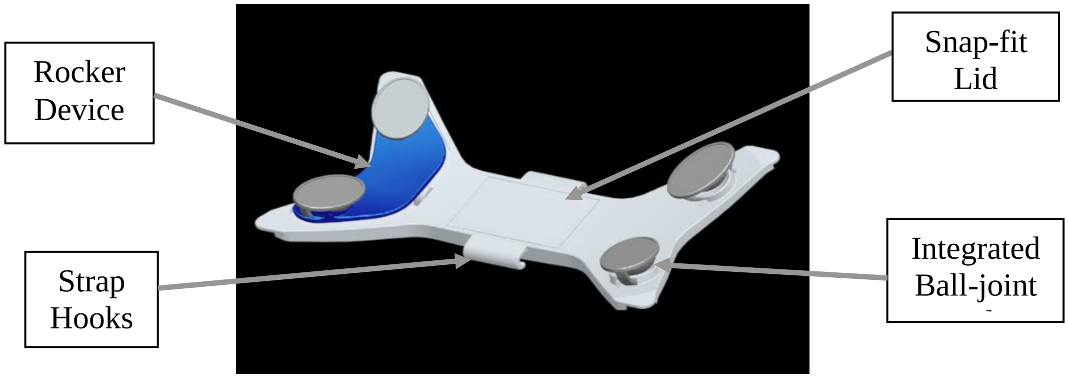


Figure 7. CAD design of cluster box version 1a

The central tenet of CIFP is that the customer/user must be closely involved throughout the entire design process. This was achieved through frequent meetings of the designer and customer (typically once or twice per week) and through the use of fully representative functional prototypes. The customer was able to fully evaluate all the characteristics of the cluster-box using these prototypes and feedback his opinions, both positive and negative, to drive the next iteration of the design. Five major versions and sub-versions of the cluster-box were developed and reproduced as physical prototypes over a six month period. A list of these design versions and the design improvements that occurred are provided in Table 1. In addition, many more iterations were undertaken within the CAD system and presented to the customer as shaded images, exploded assemblies, cross-sectional views and animations.

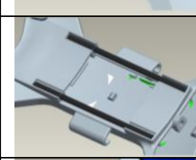
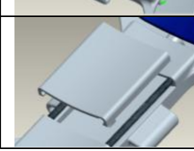
Design Version	**Design Improvement(s)**	**CAD Image**
Version 1b	Hollowing out of pads, flattening of ends of pads (to remove material and save weight)	
Version 2a	Adding carbon rod stiffener (to improve torsional rigidity)	
Version 2b	Internal wiring ducts, longer side hooks (to ease assembly)	
Version 3a	Twin carbon rod stiffeners (to further improve rigidity and ease of assembly)	
Version 3b	Enclosed location of carbon rods (to improve aesthetics and reduce component count)	

Table 1. List of cluster box design versions

The functional prototypes for each version were produced using an EOSINT P700 Laser Sintering machine from EOS. The material chosen for final manufacture was glass-filled polyamide PA3200 (although some of the prototypes were produced using unfilled polyamide PA2200). The choice of process and material were made through consultation between the authors, the staff at Charnwood Dynamics and the RP/RM supplier who built the parts. The final product and most of the prototypes were also dyed black by the supplier, prior to delivery. This was to improve aesthetics and to reduce infra-red reflectivity, an important issue for the Codamotion system. The final version of the product, with all electronics assembled, is shown in Figure 8. Assembly operations for the product are as follows:

- gluing of twin carbon rods into location recesses
- insertion of infra-red markers at four corner locations
- soldering of marker wires to circuit board
- insertion of circuit board and battery
- clipping rocker and lid into position
- addition of high friction material to bottom of pads

The new product has been shown to several of the company's customers and presented at two workshops. Initial feedback from users has been extremely positive and full beta-testing will commence shortly.

Figure 8. Fully-assembled cluster box (version 3b)

In addition to the new cluster box product that was developed, several new designs for existing Codamotion accessories were also created, all with RM in mind. Most of these accessories were body-worn products that would enable markers to be distributed around various parts of the human anatomy. In each case, RM offered some unique geometric solutions, including ready-assembled ball joints, internal ducting and snap-fit assembly features. The development of the accessories followed a similar route as for the cluster box, i.e. CIFP was used as the main means for achieving design optimisation. Detailed description of all the parts and their design characteristics is beyond the scope of this paper but a list of the parts (including the cluster box) and a brief review of the benefits RM brought are given in Table 2. All parts were made using Laser Sintering in glass-filled polyamide.

Component	RM Benefits
Cluster box	• Internal ducting • Ready-assembled ball-joints • Customisable logo • Snap-fit assembly
Leg braces	• Internal channels • Ready-assembled ball-joints and spacer • Snap-fit assembly
Marker wands	• Internal ducting • Integrated sprung hinge • Snap-fit assembly • Parts consolidation
Pelvic wand	• Internal ducting • Ready-assembled ball-joints • Carbon-fibre rod framework • Snap-fit assembly
Pointer device	• Internal ducting • Integrated trigger • Snap-fit assembly

Table 2. List of parts designed for rapid manufacturing

Results

The case study had been undertaken with the aim of proving the efficacy of CIFP when used within an industrial environment. Previous research had indicated that its use should lead to

- increased customer involvement in the design process
- greater understanding of customer needs by the designer
- improved design optimisation
- increased opportunity for product customisation
- provision of a widely understood communication medium

Following in-depth discussions with several staff from Charnwood Dynamics, a number of tangible benefits derived from the use of CIFP were identified. The ability to undertake rapid design iterations with full customer input meant that the cluster box design was fully optimised before entering production. As well as providing input into the design process, the customer was able to take each iteration of physical prototype and subject it to a full user evaluation. This included aesthetic evaluation, assembly checks, torsional stiffness analysis, ergonomic evaluation and performance testing. The outcomes of each of these evaluations drove the next iteration, as would be expected. However, beyond this, perhaps the greatest benefit was that the customer repeatedly generated new design ideas. Many of these only came about through actual handing and use of the product, e.g. the inclusion of internal ducting to aid the threading of wires through the cluster box. This phenomenon proved that CIFP is indeed capable of elevating the customer from the role of verifier to co-designer. The functional prototypes proved to be a very effective means of communication, not just between designer and customer, but also with the marketing team, application engineers and production operatives. In this regard the functional prototype can be compared to the virtual prototype used within product data management (PDM) but is more widely accessible, even to members of the public who may not be computer literate (see Figure 9). Although not pursued at present, product customisation opportunities were also identified, e.g. replacing the Codamotion logo with a customer logo, tailoring the shape of the cluster box to niche application areas such as horse racing motion analysis. In short, all the anticipated benefits were either realised or their potential confirmed.

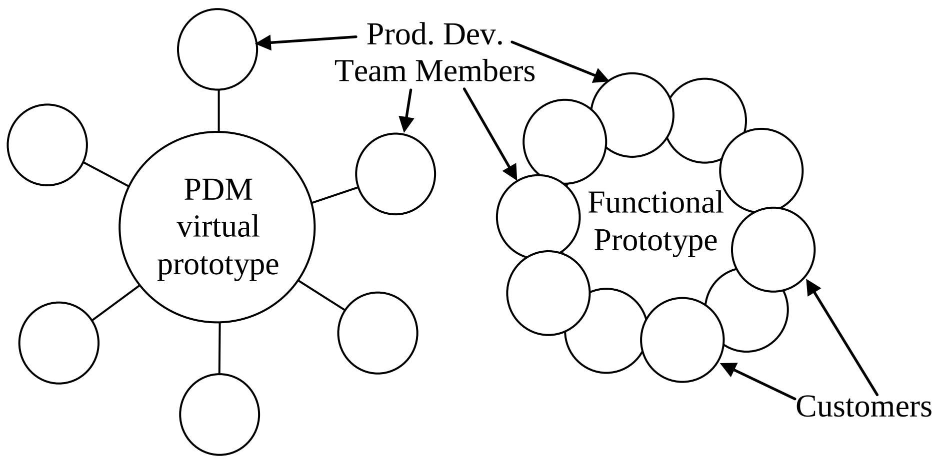


Figure 9: Comparison between PDM network and functional prototype

As well as the benefits that came from using CIFP, there were several other benefits afforded by the use of CAD, DfRM and RM.

- The introduction of CAD enabled additional tasks to be undertaken within the design process, e.g. creating libraries of component families, automatic volume and hence weight estimations and animation of product assembly/functionality for training/marketing purposes.
- The geometric freedom associated with RM enabled much greater design flexibility since virtually any shape could be manufactured.
- The avoidance of tooling costs meant that economic small batch production became viable since the cost of RM is not closely linked to production numbers.

As a means of quantifying these benefits, a multi-criteria comparison of the current design and RM design for a complete set of leg and pelvic wands was undertaken (see Table 3). It can be seen that the RM design has given some benefit against every criteria, with assembly time seeing the greatest improvement.

Criteria	**Current Design**	**RM Design**
Relative cost	1	0.95
Component count	>50	40
Assembly time	5 days	2 days
Lead time	2-3 weeks	1 week
Weight	0.8 kg	0.5 kg

Table 3. Multi-criteria comparison of benefit for leg and pelvic wand set

It must be stated there were some negative aspects of using RM, i.e. the fact that there were some new limitations on design as well as new possibilities. In particular, the achievable accuracy of assembly tolerances was generally poor compared to injection moulded or machined components. This was a function of the build accuracy of the RM machine that was used. The RM supplier would only guarantee an accuracy of +/- 0.25 mm and 0.25 mm differences between CAD dimensions and physical dimensions were quite typical. However, the degree of variation between successive parts was typically much less and so a design compensation factor could be used. There were also considerations to be made for minimum feature size and the need for access to allow removal of unsintered powder. Finally, the level of confidence in material properties for RM parts is some way off that for conventional processes, and this had to be catered for in the design, usually by designing for the worst expected condition.

Conclusion

This work has shown that as well as bringing many benefits of its own, RM can facilitate a new means of interacting with customers. For a product which is going to be manufactured using an SFF technology, it can be argued that there is little distinction, in terms of functionality, between the final product and the prototypes that are produced during the NPD process. Therefore, customers can be provided with fully representative prototypes at a very early stage of design and asked for comments, opinions, ideas, etc. Even for products where RM will not be the final manufacturing route, the range of SFF materials now available means that this equivalence between product and prototype is becoming increasingly prevalent. As a means of exploiting this relatively new opportunity, CIFP has shown itself capable of delivering benefits at a number of levels, most importantly as a means of elevating the role of customer involvement in design and establishing a more widely accessible medium of communication between all NPD stakeholders.

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