Custom-Fit

The Shape of Things to Come

An introduction to the design, manufacturing and business opportunities of customized products.

Berenschot

Delcam

Edited by

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This book in based on the outcomes of the EU-funded Custom-Fit project and makes extensive use of the reports, presentations and demo cases that were delivered in the project. These deliverables and this book are the result of the joined effort of Custom-Fit project partners:

Introduction

Over 30 European Organizations gathered together on 21 and 22 September 2004 at CAD/CAM software specialist Delcam's headquarters in Birmingham. Here they started their work to jointly create a 'fully integrated system for design, production and supply of individualised products using rapid manufacturing techniques' within the framework of the Integrated Project Custom-Fit. Now, after 54 Months the project has come to an end and many innovations have been achieved.

The work has resulted in several surprising outcomes and interesting points of view on the implication of the 'Custom-Fit technology' for further business deals and for consumers. Newly developed was also the ability to transform all kinds of captured geometrical and non-geometrical data into a standard neutral format to enable bespoke product design. For this, three new design modelling software suites were developed for designing functionally differentiated products (including graded structures and materials) which could also integrate non-geometrical requirements. To enable the rapid manufacturing of customized products, three new manufacturing processes were developed suitable for the rapid production of complex, bespoke products including the development of novel materials and material combinations. The various innovations have been demonstrated in 'real life' situations. For this five case studies have been defined in which the full sequence from geometry capture, product design and manufacturing, and use by the consumers is being evaluated.

The project results have continuously been disseminated by using all possible tools for broadcasting the new possibilities as created in the Custom-Fit project varying from Newsletters to YouTube, but also Wiki-entries and Newspapers etc. The project outcomes have also been used to create innovative e-training modules for engineers, managers, scientist and educators. This allows the developments from the project to be made available to those organizations in Europe who where not involved in this 'flagship' project.

The Custom-Fit consortium has faced in these 54 months several challenges. Not only on the 'technological' side they have faced these challenges but also on the side of managing such a large project with so many partners from so many (12) countries. However with the cooperation of the Advisory Board and representatives from the European Commission and the leadership shown and atmosphere created by coordinator Delcam in and with the management board and the consortium, these challenges were overcome.

The results have established a new state of the art in this exciting area of technology and will be the basis for future R&D and innovations. Custom-Fit fostered the European cohesion in the field of science and technology for RM and RP processes, thus leading towards a real and sustainable European initiative.

29 January 2009

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Chapter one: Rapid Manufacturing is shaping our future

The future is personal

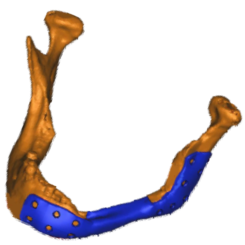
Imagine..

..a world where you can print any product on demand and on location. You no longer buy gifts and furniture in the store, but you design your own vases or lamps on the computer which you then print with help of your 3D printer at home.

Imagine..

.. you put on your customised sunglasses and hop on your bike. Your customised helmet and seat make sure you arrive in comfort and safety. You need to drop your bike at the garage later on for a service check, but you are sure you will have it back that same afternoon because the garage, that no longer has spare parts on stock, can print any part it needs directly from the CAD files in his computer on the 3D printer in his workshop.

Imagine..

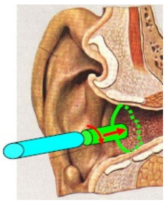


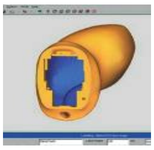
[1]..your mother in the hospital. The doctors removed from her jaw a tumour and she received a customised jaw implant. The surgery, the patient's well being and recovery time and the costs of this operation have been much improved because based on a CT scan that was transferred into a CAD file, a Rapid Manufacturing machine build a customised implant from biodegradable materials. This new procedure was so successful that the hospital has decided to apply the same process for all geometrically customised products. This means that all other implants and for customised sockets for prosthesis will now be made on the Rapid Manufacturing machine.

[1] Courtesy of AZM / Jules Poukens, Netherlands

Imagine..

.. at work, you discuss the old days in the hearing aid industry with a colleague. It seems unimaginable now that hearing aids were once handmade by craftsmen and that





customers had to settle for ill fitting aids and long lead times. The fact that you now receive the audiogram and the in-the-ear scan directly from audiologists throughout Europe, enables your company to make Custom-Fit hearing aids that exactly fit the needs of your end user[2]. You have handsome profits last year because the new process has allowed you to set up an entirely new business model where the middle men were cut from the value chain, where direct marketing is made possible through your direct end user-manufacturer contact and where production with help of Rapid Manufacturing machines is now common. Your colleague is a software expert of which your company had none up until three years ago when Rapid Manufacturing was introduced. In fact, the customisation through Rapid Manufacturing process has had impact on everyone's job, from marketing to product design to production. Also your supply base is now totally different. Instead of buying inject moulding tools and standard plastics on the world market, you now source highly specialized RM machines and high tech materials from your European supply base for your central production location in Europe. A location, that would long have been moved to low labour cost countries if it was not for Rapid Manufacturing.

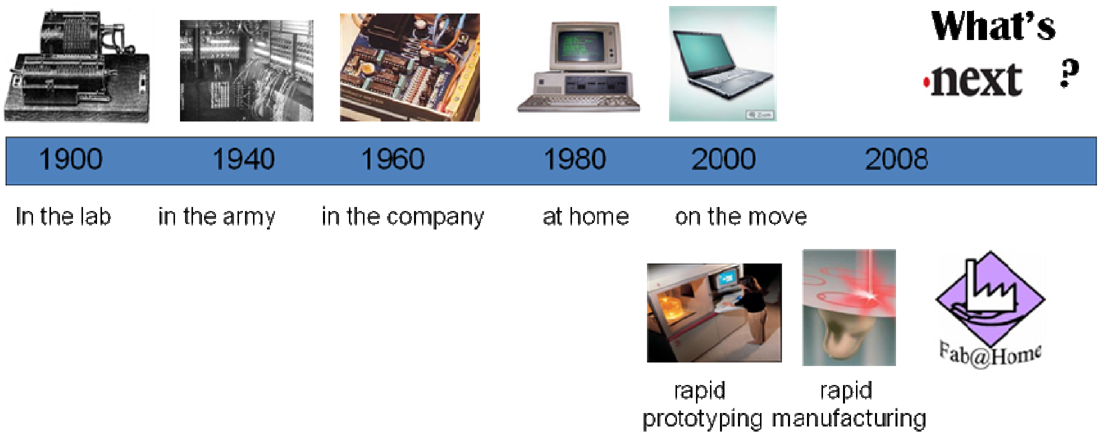
Imagine..

.. when you go home on your customised bike, you pack your personally designed gift for your wife, you sit down in your customised chair, you think of how well your mother and your company are doing and you conclude that the world has indeed become a better place thanks to customisation and Rapid Manufacturing.

[2] Courtesy of Phonak and Siemens

Introducing geometric customisation through Rapid Manufacturing

The world that we live in today does not yet look like the situation that was described above, but the developments in Rapid Manufacturing and the contributions of the Custom-Fit project have brought that world a lot closer. Where computers have taken one hundred years to transform the industrial society into an information based society, Rapid Manufacturing has become a force that is re-shaping the future of the production of goods in many sectors in far less time.

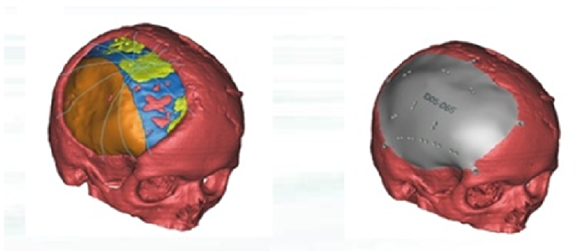


In 1986, the team of Charles Hull in the USA devised the first layer by layer manufacturing process. The process quickly caught on and from the early nineties onwards was used extensively in rapid prototyping. Now, breakthroughs are being made that will actually allow Rapid Manufacturing and not just rapid prototyping. 3D printers are now finding their way into the medical and consumer goods arena and some 3D printers have already found their way into people's home[3].

[3] Pictures ; courtesy of IBM, Fab@Home, NRC Next and Phonak

A specific application of the Rapid Manufacturing is the geometric customisation of goods. In this process, a part of the body is scanned. In the picture, a body scan as it is used in the clothing industry is shown[4]. This scan is then transferred into a CAD file. A Rapid Manufacturing machine is then able to print a solid 3D object directly from that CAD file. This product or part is unique (one-of) and perfectly fits the user's body. This application has great potential for medical and consumer durable markets. These markets are worth billions of Euro's, but these industries are not yet capable of producing geometrically customised products with high satisfaction for all members of the value chain for an acceptable price. The case below on geometrically customised and rapid manufactured skull implants gives a good example of how Rapid Manufacturing can turn this around.

Custom-Fit case 1: skull implants[5]



In the medical market, implants are a high risk, high cost procedure. In a project in the AZM hospital in Maastricht, The Netherlands, Rapid Manufacturing was used for the reconstruction of a girl's skull that was severely damaged in a car accident. The design of the implant was done by using 3-matic software[6]. This is usually a rather complex and time-consuming task but 3-matic works directly on the data generated by the image processing software, which results in considerable time-savings. The titanium implant was manufactured by means of melting thin layers of titanium powder on top of each other in a Rapid Manufacturing machine. The implant was built to net shape in 12 hours and met all medical standards. The mechanical properties are excellent with 100% density of the material. The implant had a perfect fit during the operation and the implant healed in without any complications. The entire operation took less than 2 hours, and the procedure

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[4] Courtesy of Human Solutions - Germany

[5] Courtesy of AZM / Jules Poukens, Netherlands

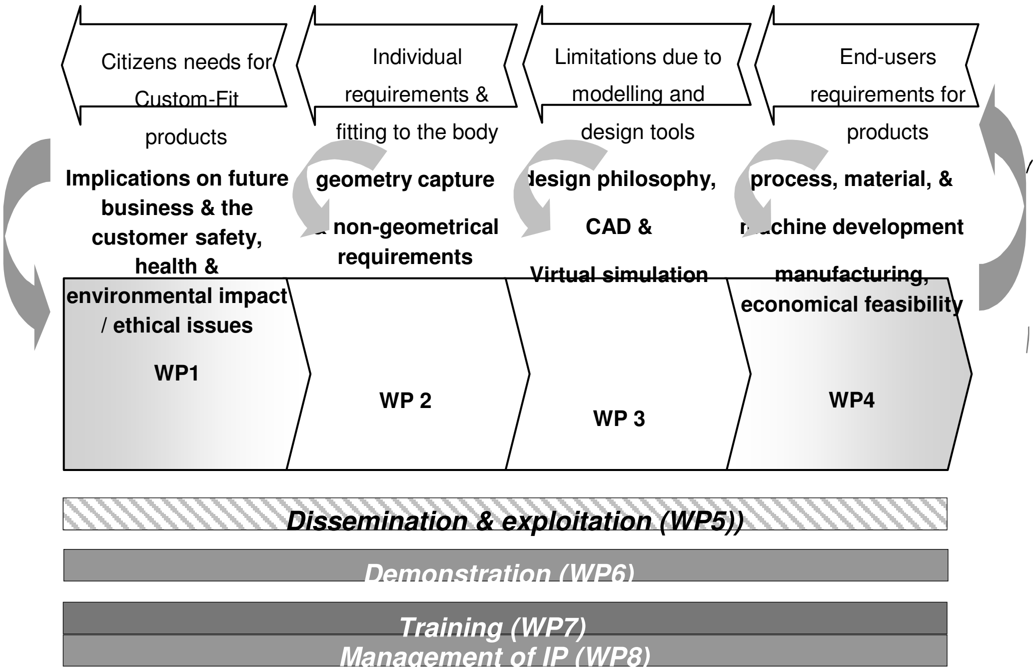
[6] Software by Materialise, Belgium

made it possible to restore the girl's normal aesthetics, normal brain function and normal protection of the brain. The implant was faster and cheaper to manufacture compared to the traditional procedure.

Introducing the Custom-Fit project

The case described above was taken from the Custom-Fit project. The Custom-Fit project is an EU sponsored innovation project. An European consortium of universities, companies and research institutes managed by Delcam PLC (UK) succeeded in developing geometrically customised goods with help of Rapid Manufacturing in the medical and consumer durable sectors. The partners and their contact details are listed in annex 1. This project was done in the light of the Lisbon, Gothenburg and other EU key-objectives that state that Europe should, in 2010, be the most competitive and dynamic knowledge-based economy in the world. It should be capable of sustainable economic growth, with more and higher quality jobs, making better use of its research efforts by creating an internal market for science and technology- the "European Research Area". The aim of Custom-Fit was to make a contribution to the transformation of the manufacturing sector of Europe into high-tech industries in order to regain competitiveness. The project was supported by the EU in the light of the Framework 6 development programs. Custom-Fit set out to develop and integrate a completely new and breakthrough manufacturing process delivering unrestricted geometrical freedom, gradient structures of different material compositions using less labour efforts and improved Rapid Manufacturing (RM) machines and processes. The project emphasized on products that will increase the quality of life of the European citizen and on applications were large market potential existed. Hence the focus on medical goods and the customisation of consumer durables.

To achieve breakthroughs in these fields, the project was split into different work packages:



In this book, many examples will be used to illustrate the opportunities and pitfalls of Rapid Manufacturing. The focus will be on the sub-projects that the Custom-Fit consortium has worked on. As an introduction of the process of turning a body scan into a geometrically customised and rapid manufactured product, we will first present the case of the customised seat that allowed a handicapped child to enjoy a safe and free ride on a toy car for the first time in his life.

Custom-Fit case 2: customised seats on toy cars for disables children[7]

In toy cars, disabled children have great difficulty in staying upright. The pictures show how the Custom-Fit process was used to produce a geometrically customised seat by means of Rapid Manufacturing.

First, an imprint was made by means of a special cushion. Next, with laser scanning, the imprint on the cushion was captured. Using specifically by Delcam developed software, a CAD model was made based on this imprint. Based on the CAD model, a customised seat was rapid manufactured and placed on the toy car. As a result, the disabled child could enjoy the ride on his own toy car without having to fear to fall off.

[7] Courtesy of AIJU, Delcam and Famosa.

Introducing this book

This book was made for people that are interested in Rapid Manufacturing and customisation, but that do not have a clear picture yet in what Rapid Manufacturing actually is and what it can and cannot do. It is also intended to present a broad overview of the activities and achievements of the Custom-Fit project, so that the participants, their companies and their business and research relations might enjoy an attractive and easy to read overview of a job well done. Finally, the book is intended to disseminate the insights of Custom-Fit to the broad public in an accessible way. This book will take a helicopter view on all different aspects of design and manufacturing of customised products. The reader is kindly invited to contact the Custom-Fit partners that are listed in the annex for more detailed information on the individual subjects.

The remainder of the book will therefore be organized as follows:

- Chapter 2: current status of technology. In this chapter, we will explain what Rapid Manufacturing actually is. Also, per process step the main technologies and their current status of affairs will be discussed (from scan to software to machines to materials).
- Chapter 3: advantages and challenges of Rapid Manufacturing. In this chapter, the opportunities and challenges of geometric customisation through rapid manufacturing will be discussed. This related mainly to the technical possibilities and limitations of the process.
- Chapter 4: business aspects of Rapid Manufacturing. In this chapter, legal, financial, commercial and other business aspects of geometric customisation through Rapid Manufacturing will be discussed. It will make clear that even if the technology works perfectly, several challenges in the value chain will have to be overcome before it becomes a profitable business
- Chapter 5: the future and beyond. In this chapter, we will look at what is to come and what might be possible in the years ahead.

Chapter two: The current status of technology

In this chapter, the current status of the technology will be discussed. The Custom-Fit process steps from scanning to data processing to Rapid Manufacturing provides the basic structure for this chapter. Per step, the state of the art of the different technologies will be presented. This chapter is largely based on the training materials that have been developed in the Custom-Fit project[8]. The Custom-Fit case of customised, rapid manufactured helmets and the case of the jaw implant will be used to illustrate the story. It is the intention of this chapter to give a broad overview of what is currently available in the market. The advantages and limitations of the main technologies will be discussed in chapter three. The future technology outlook will be presented separately in chapter five.

The history of Rapid Manufacturing

As stated in chapter one, in 1986 the SLA-1 of A. Herbert, C. Hull and M. Kodama was the first Rapid Manufacturing machine ever build. Since then, RM has made a long journey from prototyping to manufacturing. It has been developed into a promising technology, which according to some is triggering a new industrial (digital) revolution[9]. Rapid Manufacturing is seen as the final step in product formation process. The idea, conception and design phase have already been accelerated by new technologies like solid imaging and functional prototyping. Product development, product tool development and production tool manufacturing have lately been speed up thanks to rapid prototyping. Now Rapid Manufacturing is speeding up the *total* production and product formation process including manufacturing and part production. This makes it an ideal production method for end products as well as parts.

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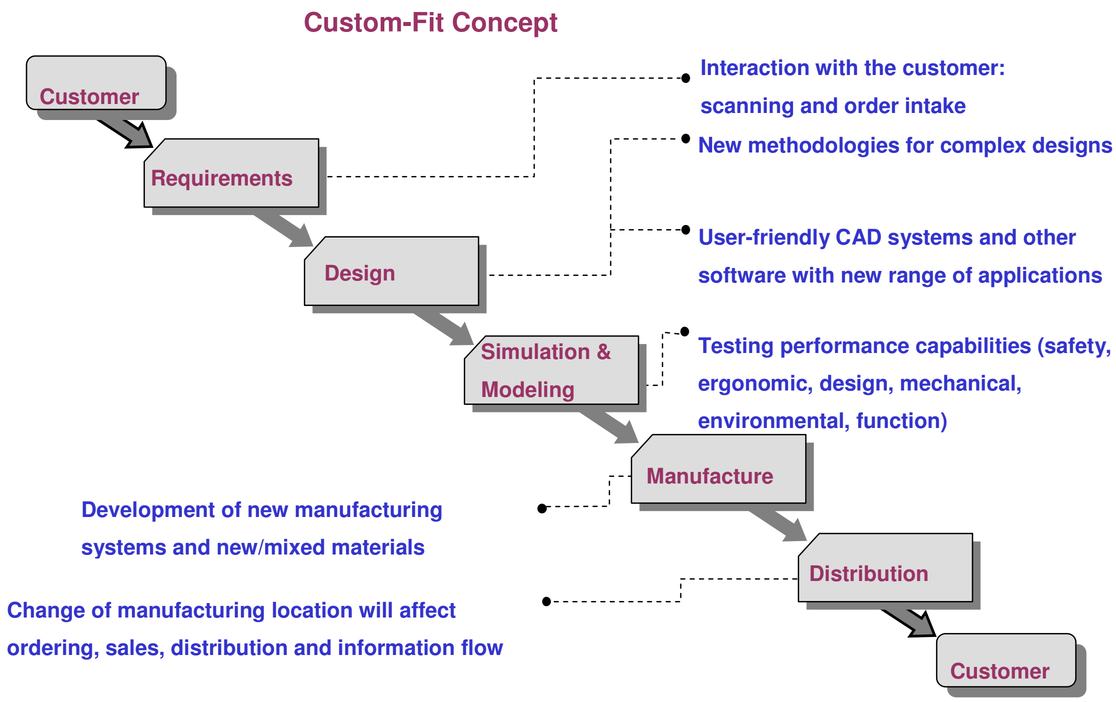
[8] Courtesy of DeMontfort University, UK

[9] Hopkinson, Hague and Dickins, Rapid Manufacturing: An Industrial Revolution for the Digital Age, Wiley & Sons Ltd, Chicester, UK, 2005

The basic technologies of customised, rapid manufactured goods

The basic steps in the Custom-Fit process of customised Rapid Manufacturing are outlined in the figure 1below:

Figure 1 : the basic steps and technologies in the Custom-Fit process



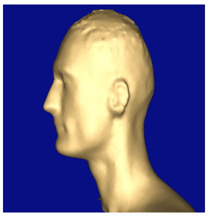
This chapter will first discuss the capture of (customer) requirements by means scanning and processing of geometric data. Second, the design process including simulation & modelling will be outlined. Third, in the section on manufacturing systems, the most used machine processes will be described. Last, the different materials will be examined. The business aspects related to customer needs and commercial aspects regarding distribution and customer delivery (the beginning and end of the Custom-Fit process) will be described in chapter 3.

Custom-Fit case 3: customised motor helmets[10]

Introduction

A helmet is an obliged safety article for every bike rider. To make a helmet more safe and comfortable, a perfect fitting helmet was designed and produced in the Custom-Fit project. The helmet will give better protection: there is less risk of pulling off, and crash forces are more evenly routed across the skull. Additionally, it might be more easily to sell: customising the helmet increases the sense of ownership and pride which increases both the selling price and brand loyalty.

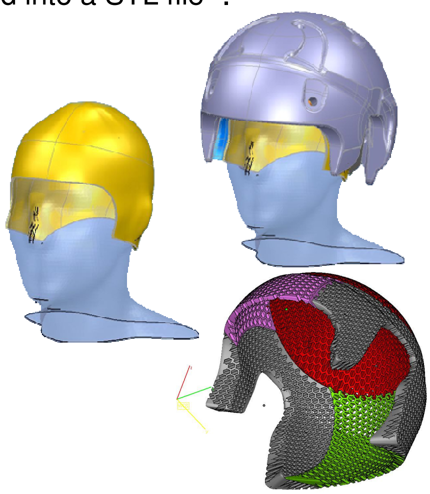
Customisation of a helmet can be achieved by making a custom made liner (green bar in the picture) and insert it between the outer shell (guaranteeing safety) and the padding. Rapid Manufacturing makes it possible to do this faster and cheaper. The process of producing a Custom-Fit helmets contains all the basic steps of the Custom-Fit process.



Scanning

First of all a scan was made of the end user of the helmet. The head's geometry was captured with a body scanner from partner Human Solutions. The end user of the helmet was also inquired about his preferences (tight fit for example). The scan was transformed into a STL file[11].

Design and simulation



After scanning the head, a Custom-Fit liner is designed with software using an automated procedure.
The liner is customised to fit evenly around the head with a small gap for the comfort liner (gold) and matching the exact shape of the outer protective shells of the helmet (grey).

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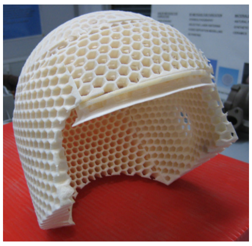
[10] Courtesy of Mavet, Italy

[11] **STL** file means StereoLithography file. It is a file format widely used for computer-aided manufacturing. STL files describe only the surface geometry of a three dimensional object without any representation of color, texture or other common CAD model attributes.

The final structure of the grading is then created. A lattice structure has been chosen to reduce weight and improve shock absorption. In addition, cooling channels can be added for refreshment.

After designing the helmet, virtual testing is performed by partner BPO to determine the safety of the helmet. A Final Element analysis[12] to verify shock absorption behaviour and to fine tune the lattice structure is executed.

Manufacturing and materials



The custom-fit liner model is sent to a Rapid Manufacturing machine. First the model is 'sliced'. As such the machine instructions for layer by layer production are generated. The Rapid Manufacturing process used in this case was a newly developed Powder Printing Process, based on the concept of electro photography as developed by partners DMU, MTT and CTG-PrintTec. The material used is a polymer HDPE, but other polymers could also do the trick.

Finalizing the product

The custom-fit liner model was finally assembled with standard parts (EPS and outer shell) and ready for testing and take off!

Based on this case and the main process that was outlined above, the basic technologies that are used will now be discussed per process step. Below, an overview will be given of the main scanning technologies, product design and software, materials and machines.

Scanning

Rapid Manufacturing starts with the identification of the requirements of the final product. This relates to the functional and aesthetic specification of the product, but also the geometric data from the end user must be captured if you want to create custom fitted

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[12] This analysis can also be done at other stages in the process. An extensive analysis with multiple FE simulations can ensure the mechanical performances of the helmet.

products. The geometric data are translated into 3D data which will then be imported into a CAD file. In physical products, reverse engineering is a common way to capture 3D shapes. Reverse engineering is the reproduction of a physical object with the aid of drawings, documentation or computer model data. Reverse engineering is used when a shape needs to be produced for which no CAD data exist, like is the case with hand crafted products or natural products including human shapes.

3D data of such objects will mostly be captured by scanning it. Several scanners and scanning techniques are available. Three general scanning techniques can be identified that can be used for Rapid Manufacturing:

- Contact probes. This is a scanning technique that generates an 3D imaging through contact of a highly sensitive sensor on a object.
- Laser and LED techniques. A wide variety of lasers and LEDs can be used to scan an object. With this technique an object is scanned by light without contacting the object.
- Medical scanning. In hospitals, several scanning techniques are used to scan (through) bodies. Computed Tomography (CT) and Magnetic Resonance Imaging (MRI, see picture[13]) scans are well known scanning techniques to generated 3D images of (internal) body parts[14].

Scanning is in many Rapid Manufacturing processes needed, while CAD files of objects (including bodies) are often missing. But just scanning an object is not the only challenge of generating a 3D CAD file. Highly accurate scanning of an object depends of the coverage and density of the scanner. After scanning, data post processing is crucial to generate precise images of the object. This post processing has proven to be a major hassle in many customisation and Rapid Manufacturing projects. Next to the technical aspects of scanning, there are still some legal and practical barriers along to road. As

[13] Courtesy of Philips

[14] X-ray scans on their own only deliver 2D pictures

chapter four will show, the gathering, storage and dissemination of body scans are legally debatable. As will be made clear in chapter four, in projects that aim to geometrically customize products, the decision to use ‘on-location’ mobile (but lower resolution) scanners versus centralised (but high quality) scanners is an important one when making the business case. Both the costs of scanning and customer acceptance of being scanned depend on this decision.

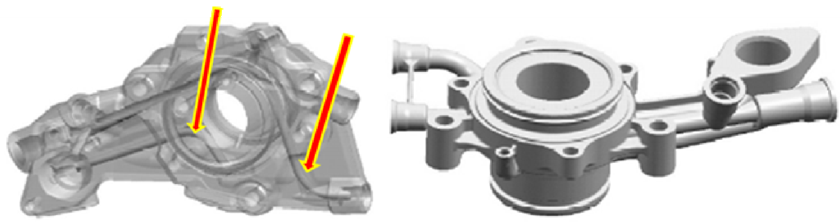
Next to the data capture via scanning also all other relevant customer data must be captured. For instance information on allergies, preferred wear or use of products and of course information on product specifications as colour and on process like delivery times.

Product design

One of the major drivers for the development of Rapid Manufacturing is the potential for radically different product designs. Rapid Manufacturing has the ability to produce parts of virtually any shape complexity without the need for any tooling. Increasing the complexity is largely independent of costs, whereas in conventional manufacturing there is a direct link between complexity and costs. The possibility to make complex products is especially interesting for:

- Design optimization of products
- Parts consolidation (parts manufactured in one piece and one go)
- Body – fitting customisation (adapting to geometry of the body)
- Multiple materials and assemblies manufactured as one

The picture below shows the kind of part that can be manufactured only by Rapid Manufacturing machines[15]. The design for manufacturing and design for assembly criteria of regular injection moulds would make such a part impossible. The rapid manufactured part has the same functionality as the conventional part on the left, but could be optimized for minimal weight thanks to the freedom of design of Rapid Manufacturing.



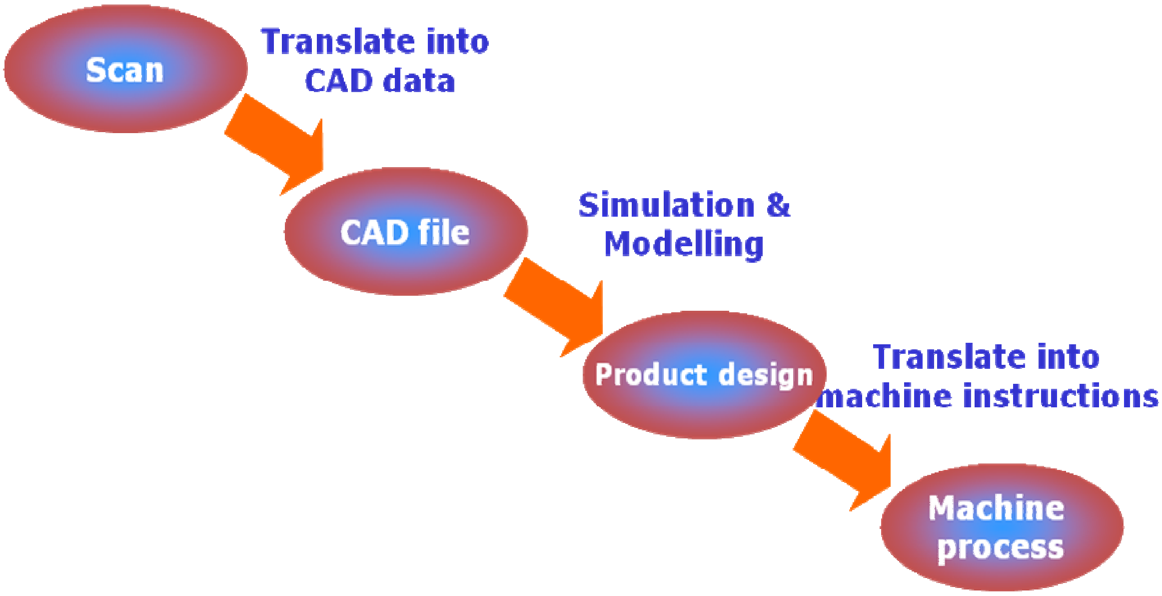
The CAD design of a rapid manufactured product is crucial. The quality of the CAD determines whether the product will be first time right. Especially when the consumer will become co-creator of the final product, excellence in the design process is becoming increasingly important. The software that was developed in Custom-Fit has made a significant contribution in making this possible, but as the next paragraph will show, creating the perfect CAD-file from scanned data is not yet trivial.

Software

For Custom-Fit products three data modification steps are needed to generate machines instructions for rapid production from a scanned object. Software plays a crucial role in these three steps:

[15] Courtesy of Loughborough University

Figure 2: data modification steps in the Custom-Fit process

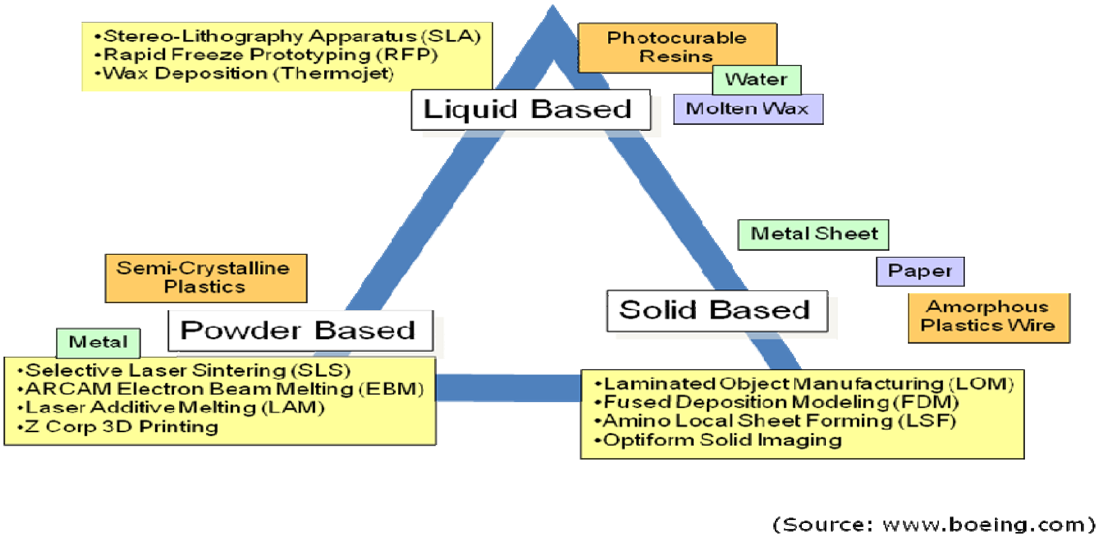


First, scanned data will be translated into a CAD file. This CAD file can be used to generate the final design of the product. In conventional production processes, before the final design of a product is created, testing of a prototype or first of tool is normally performed. For the unique, one-off products that are rapid manufactured, testing is not an option; there is only one product produced. Virtual simulation and modelling will allow optimization of a product design at low cost. After simulation and modelling the final design of the product is created. This CAD file should then be translated into machine instructions. These are crucial if the Rapid Manufacturing machine is to produce an exact 3D physical replica of the CAD file. Without a proper software link between the CAD file and the machine instructions, even the best Rapid Manufacturing machines will not produce the desired end results.

Rapid Manufacturing machines

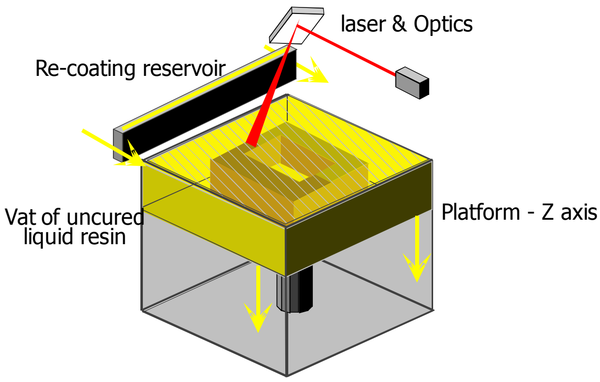
There are several techniques to manufacture a product rapidly. Four most used techniques for Rapid Manufacturing or Rapid Prototyping will be described here. These techniques are Stereo Lithographic Apparatus (SL), Laser Sintering (LS), Fused Deposition Modelling (FDM) and 3D printing. These four techniques use three basic materials to build products layer by layer: SL is liquid based, LS and 3D printing are powder based and FDM is solid based, as visualized below:

Figure 3: basic principles of Rapid Manufacturing technologies[16]



SL

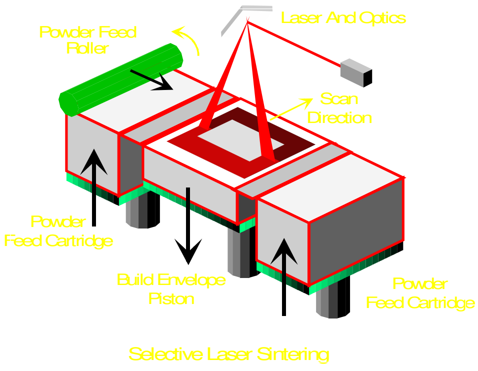
Stereo Lithography (SL) is a process that builds plastic parts one layer at a time using an ultraviolet (UV) laser that traces across the surface of a vat of liquid photopolymer to solidify a thin layer. The worktable then lowers a fraction of a millimetre further into the vat and the process repeats several time to a build a 3-dimensional model.

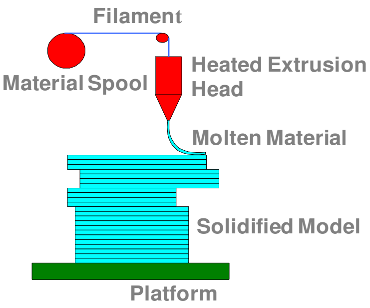


[16] Courtesy of Boeing

LS

Laser Sintering (LS) is a process which uses lasers to melt and fuse powder material into a 3-D object. A major distinction between LS and other rapid prototyping technologies is the wide variety of materials available.



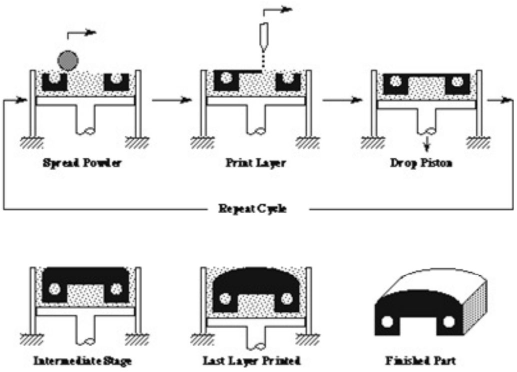


FDM

With fused deposition moulding (FDM) the molten plastic is extruded by a nozzle and after being squirted from the nozzle hardens immediately. As such a 3D object is generated layer by layer.

3D printing

3D printing stands for ink-jet and jet modelling like processes. A print head or an injection jet deposits a material to form a shape or part. A photopolymer is deposited in the desired shape that is immediately cured with an ultraviolet lamp (comparable with LS). With its high precision and velocity this technique is widely used to produce products that require little, if any, post processing work.



For the above described printing processes, different SL, LS, FMD and 3D printing machines are available from several suppliers. The current Rapid Manufacturing processes are now typical Rapid Prototyping machines that have been “upgraded”. They have several limitations like accuracy, speed, strengths, reliability, material flexibility, colour, dimensions and costs. These limitations will be discussed separately in chapter 3. Only some Rapid Manufacturing systems are fully dedicated and designed to achieve the full benefits of Rapid Manufacturing. For most applications, further development is required to meet all market and business requirements.

New machine concepts from the Custom-Fit project

The Custom-Fit project has taken a lot of the basic machine technologies that were discussed above, one step and sometimes a giant leap further. The main achievements in machine enhancement are highlighted below.

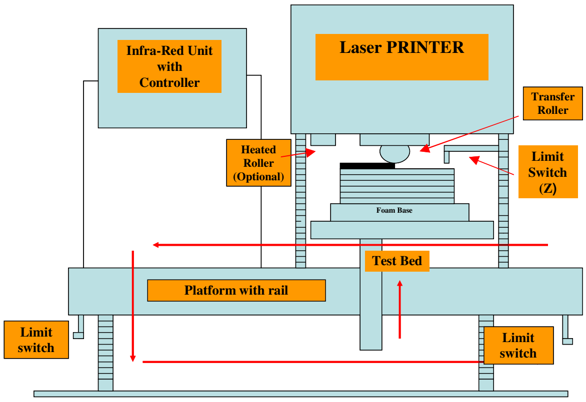
New machine concepts from the Custom-Fit project

TNO has developed an inkjet based system which is capable of jetting and solidifying fluids with a relatively high viscosity making stronger end products possible. Print-heads have been designed to generate droplets that are stable over time. It prints high viscous resins at ambient temperatures in order to create multi-material and graded material structures. The system has proved to be able to process biocompatible material and can generate droplets of the required dimensions. The process is able to print small parts as well as complete end products.

Loughborough University’s screen printing system uses a high viscosity jetting process. The concept is to control a block of multi-jets in parallel to deposit a layer of a desired pattern. The jetting process has proved capable to handle material of high mechanical properties.

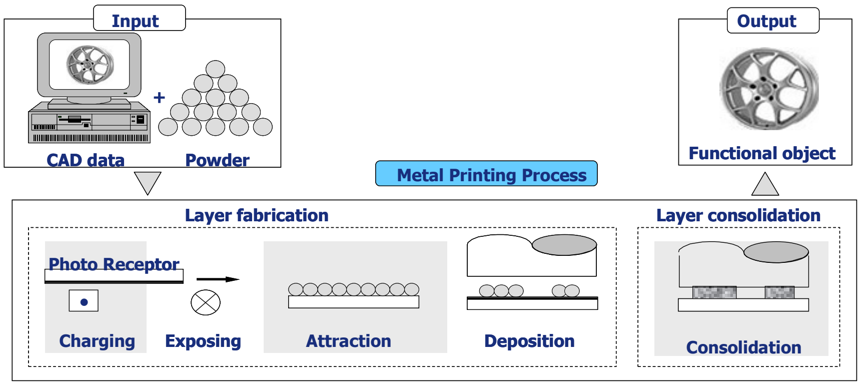
DMU's plastic powder printing, developed together with MTT and CTG-PrintTec, is a novel and integrated RM process based on digital LED technology (electrophotography), incorporating a colour digital LED printer integrated with transfer mechanism of movable build platform and infra-red fusing system.

DeMontfort University's plastic powder printing machine



Sintef's metal printing process generates layers of powder by attracting the metal or ceramic powder to a charged photoreceptor under the influence of an electrostatic field. The attracted layer is transferred to a punch and transported to a consolidation unit. It is a high temperature system able to handle biocompatible materials like titanium and cobalt-chromium.

Sintef's metal printing process



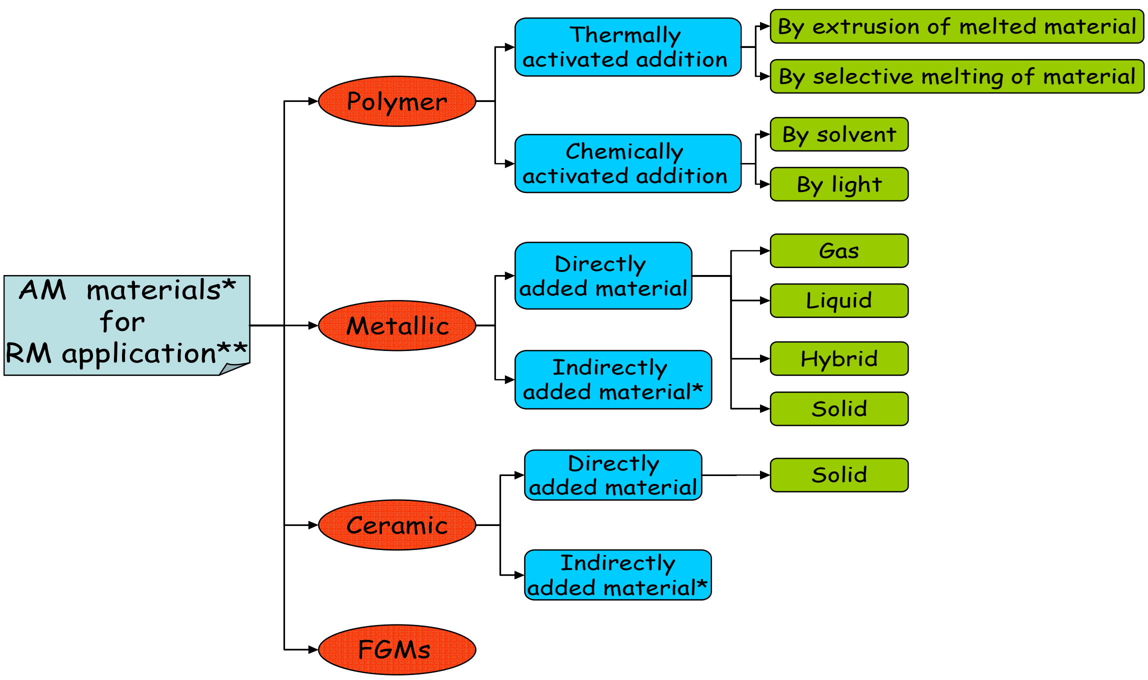
Their invention opens up the way for multi-material machines that can handle polymers and multi-material machines that can handle metals in different grading. With these kinds of new machines, whole new fields of application are available, which will be described in chapter 5. The development of these new machine concepts is typical for the rapid developments in RM and the successive introduction of new generations of machines.

Rapid Manufacturing materials

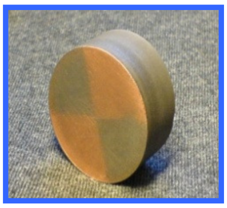
After an object is scanned, designed and translated into machine instruction and the machine is available, the only thing left are appropriate materials to produce the rapid manufactured products. Rapid Manufacturing is based on so called Additive Manufacturing Technologies. This implies that the materials used for Rapid Manufacturing have to have the right characteristics to be produced layer by layer. The materials should adhere fast during the process and finalized the products should have the right functional properties like strength, durability etc. Material properties and machine processes are highly interconnected. The successive layer by layer adding of materials imply that the final material properties of the end product depends as much on the process parameters of the machine as on the type of material used.

The most commonly used materials for Rapid Manufacturing are polymers and metals. The overview below visualizes which materials, attaching method and main process match.

Figure 4: basic materials and processes in Rapid Manufacturing



There are already several different polymers available for Rapid Manufacturing. Metals are also possible. For example, in the jaw implant case presented below, titanium is used for its optimal functional properties in medical applications (strength, corrosion free, non-toxic). Ceramics, Functional Graded Materials (combination of different materials in an integrated process like in the picture), gradient materials and biodegradable materials are currently being developed.



Custom-Fit case 4: jaw implants[17]

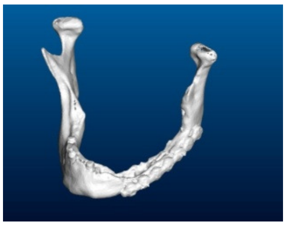
This chapter has given a bird's eye view on the current status of affairs regarding Rapid Manufacturing technologies. In the case below, these technologies will be discussed in an applied case. It describes how the progress in scanning, software and Rapid Manufacturing machines together with newly developed biodegradable materials, allows surgeons in the AZM hospital in the Netherlands to perform jaw implants that are better for the patient, faster for the hospitals and cheaper for the insurance companies.

The customer need

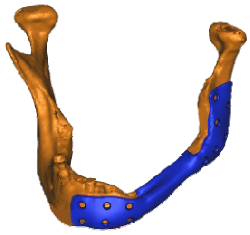
Due to cancer, a patient has lost a part of his jaw. This needs to be replaced by an implant. Normally, a scan is made and an implant is manufactured by hand. But speed and a customised fit are key: in order to prevent further damage, the operation (implantation) is to be carried out as soon as possible with an implant that fits as best as possible.

[17] Courtesy of AZM/Jules Poukens

Scanning and design



From an engineering and manufacturing point of view, the jaw implant needs to be designed (and manufactured) custom to the patients defect. The major issue here is to make the implant exactly fitting to the defect and to add connecting elements for fixing the implant to the healthy bone. There is little room for error: the implant must be “first time right” The patient was first scanned using a CT-scan. The images were processed into a digital CAD model using the 3-matic software of Materialise. In this design process, the cutting positions were determined based on the surface model of the scanned mandible and the missing part was designed based on mirroring the right side of the mandible.

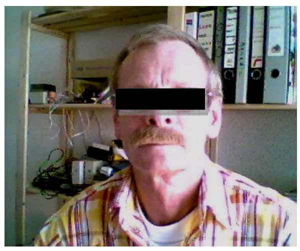


Manufacturing and materials

The requirements of materials for implants (in human bodies) are high. The material should not be harming the human body (e.g. toxic or irritating), be strong and durable. The material traditionally used for the jaw implant is titanium. This material can be rapid manufactured and has the right material properties to be allowed in medical applications. Using the latest metal printing Rapid Manufacturing process, the actual implant was produced and the operation was executed. An implant made from biodegradable material would even have been better, but there is no biodegradable material suited for RM commercially available yet. Significant work has been done in the Custom-Fit project in the field of metal and polymeric materials, including on the development of biodegradable RM materials by DSM.

The results

This case shows three advantages: how Rapid Manufacturing can reduce operation time which is crucial in many medical cases (in some cases Rapid Manufacturing resulted in 68% reduction of the design time, 53% reduction of the production time and 50% reduction of the time needed in the operation theatre), how Rapid Manufacturing can create exact fitting implants which benefit the patient immensely, and that Rapid Manufacturing materials are available which



meet even the strictest of criteria. Hospitals and insurance companies enjoy reduced costs. In the future, the introduction of bio-degradable materials which allow in-growth of bone tissue into the implant, will further improve the process.

Chapter three: Why Rapid Manufacturing – advantages and challenges

In this chapter, the main advantages and disadvantages of the technology that is used in the Custom-Fit process are discussed. With help of examples and the Custom-Fit case of customised, rapid manufactured sockets for prosthesis, the opportunities to add value or to reduce costs will be shown. The limitations of the current Rapid Manufacturing machines, materials and processes that were introduced in chapter two will also be highlighted here. The business opportunities and threats will be specifically addressed in chapter four and the future outlook of the technology will be discussed separately in chapter five.

Advantages of Rapid Manufacturing

Rapid Manufacturing has many advantages, but it depends on the application what benefits count most. In this chapter, after an initial overview, the different advantages will be discussed separately. Introducing three cases from the Custom-Fit project, it will be made clear how these advantages can be applied in real life.

Basically, there are four occasions where Rapid Manufacturing can bring significant advantages over the current way we do business and manufacture products. For products that are currently mass produced, Rapid Manufacturing can enhance the value of the products by adding customised parts or by fully customizing the entire product. For products that are currently produced in small batches or as one-of products, Rapid Manufacturing can bring significant cost advantages, but can also add value. Table 1 summarizes these possibilities:

Table 1 : basic opportunities of Rapid Manufacturing

	Cost saving	Value adding
Mass production	On demand, on location	Customisation Environmental gains
Small batches / one-of	Process economies	Engineering the impossible

On demand, on location

Mass produced goods like machines, consumer durables or industrial parts generally rely on high volumes and economies of scale to be produced efficiently. Even in modern, agile supply chains, small batches or specials disrupt the production process, make the logistic flows unpredictable and cause high stock levels throughout the value chain. Rapid Manufacturing generally is not the way to make these processes more efficient. Still, there are mass produced goods where Rapid Manufacturing can lead to significant cost advantages.

An example of cost saving can be found in spare part management. Spare parts are now mass produced and then stored on central locations where they lay and wait until they are needed somewhere in the world where a product breaks down. With Rapid Manufacturing, the substantial costs of spare part inventory stocks (which takes up working capital that need to be financed) can be reduced significantly. A company would no longer hold physical spare parts on stock, but just keep the CAD file stored. Whenever and wherever the parts are needed, the file is sent to the de-central location, where it is printed with help of an RM machine. This process is called ‘on demand, on location’ and is already used in the aerospace industry. Needless to say, also in the military, this application has large appeal:

from...

‘anyone that has any spareparts on him?’

To...

on demand and on location printing of spareparts

Customisation

Rapid Manufacturing can also enhance the value of mass produced goods by customizing them. Especially mass produced goods that have a modular product architecture, are well suited for customisation of a specific part. In mobile phones, for example, the fronts and ringtones of mass produced phones can already be customised. In fact, a whole new industry has evolved because of this process. With Rapid Manufacturing, a personal touch and great value can be added to many products. The helmet example that was described in chapter 2 for example where the inner shape of the helmet is customised by turning the scan of someone's head via CAD file into a customised helmet, adds value in different ways. The functionality and effectiveness of the helmet in terms of safety and comfort is enhanced because of the better fit. Equally important, having a personalized helmet means a great deal of status and exclusivity to the motor enthusiast owner. In the markets of top end luxury goods, customisation and personalization has even greater appeal. Examples are known where millionaires shaped the door handles of their yachts and houses in the shape of….. themselves!

Environmental gains

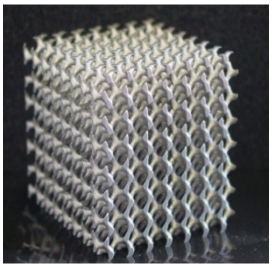
In production processes that use vast amounts of energy and where a large proportion of the raw materials is lost in waste, Rapid Manufacturing can bring cost and environmental advantages. In the metal industry for example, laser sintering of parts can improve the energy consumption and raw material output/input ratio of traditional milling processes. This way, Rapid Manufacturing can contribute to sustainable production and shrinkage of the ecological footprint of manufacturing companies.

Process economies

For products that are produced in small series or even one-of items, Rapid Manufacturing can provide significant process efficiencies and cost savings. Most one-of products are hand crafted. This goes for medical goods like the sockets for prosthesis, but also for specific parts of custom build machines in for example the mining or shipping industry. Handcrafted goods are costly because of the many hours of skilled labour that they require, but also because of the many loops and adjustments they need in the production process.

For example with medical implants, the patient's recovery takes long, with long hospitalization and high post-surgery treatment. In medical implants, the product costs are only around 12% of the total cost of treatment. A geometrically customised, rapid manufactured implant saves money not only by reducing these product costs, but also reduces total process costs by almost 50% thanks to faster recovery, less hospital days and less post surgery treatment.

Engineering the impossible



With Rapid Manufacturing, freedom of shape can add substantial value to products. In fact, the added value can even be 100%, since shapes can be made that were not possible before. Rapid Manufacturing allows for complex structures that are impossible to manufacture with traditional production technologies[18]. Especially honeycomb like structures that provide high material strength yet saves weight, are very difficult to injection mould, but are feasible in almost any shapes and structure with Rapid Manufacturing.

Whether it is cost saving or value adding that a company is after, it is important to specify what kind of benefit is expected in what part of the value chain. The examples given in paragraph 3.1 already indicate that the advantages of the technology are multiple.

[18] Courtesy Batsheba Grossman

To summarize them, table 2 gives an overview of the main benefits for the customer, the company financials and the supply chain.

Table 2 : customer, financial and supply chain benefits of Rapid Manufacturing

Customer benefits	Financial benefits	Supply chain benefits
• effectiveness • well being • status / exclusivity	• lower costs • lower tool investment • lower working capital	• freedom of shape • first time right / time • environment

The challenges for Rapid Manufacturing

The examples described in paragraph 3.1 give a brief overview of when and where Rapid Manufacturing can enhance company and product performance. The possibilities and number of applications are in fact unlimited. Before digging further into the benefits of Rapid Manufacturing though, it is good to review the current status of affairs also of what the technology cannot (yet) do. Both in terms of technical limitations and in terms of business issues, Rapid Manufacturing is still facing challenges that can prevent the benefits from materializing. The machines and materials have limitations, but also cost and organizational issues still need time and work to overcome. Table 3 presents the main challenges that exist today.

Table 3 : challenges and drawbacks of Rapid Manufacturing

Factor	issue
Machines	• process speed • size limitations • repeatability • reliability
Materials	• functional properties • support material removal
Costs	• material costs • machine costs
Business	• legal • commercial • organizational

Process speed

Rapid Manufacturing machines so far still take long processing times to produce even simple parts. The layer by layer principle that is used in most machines, intrinsically means that only very thin layers of material can be produced in one process step. The fastest machines to date produce up to 100 microns per polymer layer. For metals, this is 20-30 microns per layer. This means that for a simple shape of 20x20x20 centimeters, a full day (12 hours) of production time is needed. The production time depends heavily on the process, shape (Z-axis dimension and geometric complexity) and material used. Drastic improvements are being made, but nevertheless process speed remains an issue in all applications. When adding the lead times of CAD model making and fine-tuning and the time that is needed to remove support materials and final finishing of the product, the production lead times of many rapid manufactured parts are still well below market requirements. With every generation of new RM machines, including those developed in the Custom-Fit project, speed increases. But the challenge still remains.

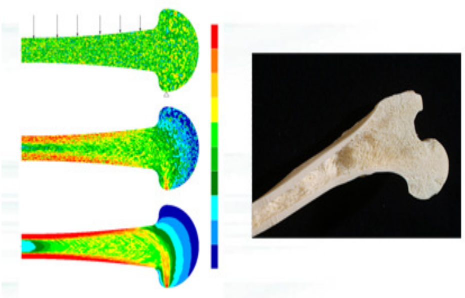
Size limitations

Most Rapid Manufacturing machines cannot yet handle (very) large objects. The standard machines on average produce sizes up to 40x40x40 cm, with upscale machines that can produce up to a meter in length. Again, especially the Z-axis dimensions are the main issue. The **size** limitations are an issue for the use of Rapid Manufacturing in for example the mining and construction business, but also have hindered the speed of RM technology diffusion in many industries.

Another limitation to the adoption of RM technology is the reliability of repeated production runs. The **repeatability** of RM machines has in the past years been a major issue, but with new generations machines available, the accuracy has become better and more stable.

The **materials** that can be used for Rapid Manufacturing applications often do not yet meet the technical, financial and design specifications that the market requires. Especially material strength and colour freedom is still limited. Also the durability of the parts or products produced still has issues in the sense that the wear and tear of some materials and shapes is still quite severe.

To overcome these issues, new materials have been developed (also) in the Custom-Fit project. Examples include multi-graded materials and metal alloys that allow parts and products to be made that meet the functional requirements of even demanding applications. As the picture shows, software and materials that allow for multi-graded structures are now used in the medical field to produce bone implants. Work has already started on biodegradable materials that dissolve once the patient's own bone start to grow back into the implant.



A specific issue in Rapid Manufacturing is the removal of **support materials**. Nearly all complex shapes need support structures during the layer by layer process in order to hold the shape in place and keep it from collapsing during the production process. The freedom of design is a key strength of RM, but the flip side of this coin is that rapid manufactured products and parts often have narrow slots, deep holes or honeycomb-like structures. It is very difficult to remove the support materials from these openings and from the sides of the rapid manufactured shape afterwards. The introduction of air based cleaning systems and water-soluble support materials means progress is being made, but the problem still needs quite some work to be solved.

The **cost effects** of Rapid Manufacturing are highly debated. As indicated in paragraph 3.1, Rapid Manufacturing already has substantial cost advantages over the total process costs of small series or one-of products that are now produced by craftsmen in workshops. Still, for regular products, the material costs of rapid manufactured plastic parts are significantly higher than parts that are injection moulded. The determining factor here next to the size of the object are **batch sizes**. In a study made by Loughborough university, it was found that modern Rapid Manufacturing machines have their break even point at 5000-6000 pieces.

Professional Metal Laser Sintering RM machine €50.000 and up

The Laser Sintering machine by EOS[19] claims economies up to 14.000 pieces. Above these numbers, it is cheaper to buy a mould and depreciate it over the volumes that are produced by it. Below these numbers, buying an RM machine that can do any shape anytime makes more sense than buying a mould that can do just one shape repeatedly. Still, these numbers depend heavily on the type of application, market prices of the products and type of machines and materials used. For example, Rapid Manufacturing machines are available from €5000 and this price is expected to drop to €1000 within three years. Professional, high quality machines start for €50.000 and up (even up to € 1 million). With the increasing popularity of RM machines and applications, also these prices are decreasing rapidly though.

Finally, Rapid Manufacturing is facing some critical **business issues**. These will be dealt with in detail in chapter 4. The business issues include legal issues (like certification and data ownership), commercial issues (like the pricing and distribution of customised goods) but also organizational issues (like training of people and the relation with traditional suppliers in the supply chain). All these aspects will change drastically when shifting to Rapid Manufacturing. It is therefore not just a new manufacturing technology. It is a paradigm shift in how we do business. Not only the production process, but the whole supply chain structure and the entire business model will change once we adapt customisation through Rapid Manufacturing. In chapter five, these consequences will be

[19] Courtesy of EOS

discussed with help of cases where the Rapid Manufacturing revolutionized the entire value chain.

Custom-Fit case 5: customised sockets for leg prostheses[20]

Prostheses are artificial body parts that enable the patient to function as normal as possible after an amputation. In Europe, over 700.000 people have a limb amputated each year. Ill-fitting sockets cause issues for the patient, hospitals and insurance companies. For the patient, a customised socket would increase his wellbeing substantially. Not only would it cause less pain and irritation, but the patient would also be away from home less long and less often. But hospitals and insurance companies, forming the dominant part of the value chain, would benefit even more. In most European countries there is a constant pressure on hospital budgets. Being able to reduce time while delivering a solution that has the same or even better quality would be very interesting for these parties. A customised, first time right socket would reduce the number of days a patient would need for treatment and rehabilitation. This treatment today is about 25 days. If Rapid Manufacturing and customisation technology was used, experts estimate that this could be reduced to with approximately 30%.

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[20] Courtesy of DemoCenter-Sipe and Inail

Table 4 shows that this could lead to a saving of nearly € 2 billion a year in Europe.

Table 4: saving potential of prosthesis based on reduction of treatment

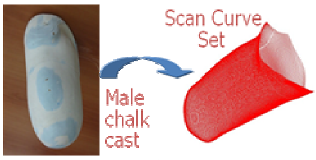
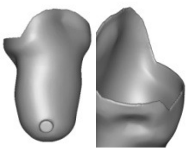
Number of amputations	Current average days in rehabilitation	Cost/day in rehabilitation (€)	Reduction treatment	Benefit from time reduction in treatment
706.800	25	€ 350	30%	€ 1,9 billion/year

In the Custom-Fit project, an effort was made to achieve these cost saving potential and to improve the well being of the patients. This case 5 describes the process steps and how the opportunities and issues were dealt with.

In order to capture the benefits described above, the team of Custom-Fit expert companies and institutions have developed a geometrically customised socket for prostheses. The old sockets are made by means of a plaster or thermo formable imprint of the person's stump. Based on this part, an outer socket is made which is cushioned inside for comfort. Via a trial and error process, the socket is adjusted several times before it is acceptable for both the doctor and the patient. This is a time consuming and costly process.

The Custom-Fit team then set out to plan and develop a new process, which would be a step change compared to the old process. Table 5 shows the critical steps and improvements made:

Table 5 : issues and breakthroughs in the customised socket case

Paradigm step	Step description	Issues	CF Innovation
Customer data capture and processing  	• Acquisition of the male chalk geometry and external surface requirements for the socket	• Capture the right shape • Transform the scan into a high quality CAD file	• CAD/CAM techniques by INAIL and Politechnico di Milano
Design customisation 	• Design rules for socket • Automation of Design procedure	• Current software not suitable for design procedure	• Automation of socket design by Materialise
Manufacturing and testing  Thermal test of RM socket	• Selection and test of materials for socket • SL printing of the socket prototype • First Tests and material validation with the RM socket prototype on the patient	• Issues with material properties • Issues with RM machine process optimization • Business issues with value chain partners (who does what and pays for what)	• New manufacturing procedure for high quality socket using the new RM process: Powder Printing Process • New graded structure with increased thickness in zones to be reinforced • Practical experience in business model based on partner cooperation

The custom-fit socket proved to be a success when it was actually tested and evaluated with the patient and the doctors. Most of the hurdles that have been identified in this chapter were overcome (see table 5) and most of the benefits that were described earlier materialized in this project. Table 6 provides a summary of the realised benefits.

Table 6: customer, financial and supply chain benefits of Rapid Manufacturing

Potential customer benefits	Custom-Fit achievements
• effectiveness • well being • status / exclusivity	• new process is easy to manage by an orthopaedic technician • the shape obtained suits the patient's needs perfectly (significant improvement in well being) • the mechanical features of the new material are lower than traditional process but adequate to socket use • large potential for mining victims in war countries (mobile scanners, central dataprocessing, local rapid manufactured sockets in any medical infrastructure)
Potential financial benefits	
• lower costs • lower tool investment • lower working capital	• 50% saving on total process time is expected at project end which means substantial cost decreases • No tools and manual re-work needed
Potential supply chain benefits	
• freedom of shape • first time right • environment	• software and RM machines can be used repeatedly for different patients who will each have their customised socket first time right

Conclusions

Rapid Manufacturing can bring cost savings and added value to mass produced products as well as unique or in small batches produced products. These benefits come for many application areas. Its main advantages are increased well being for users, increased effectiveness of products, savings on costs and (tool) investments and gains in design freedom, process efficiency and environmental footprint in the supply chain. This makes Rapid Manufacturing a promising way of doing business in many fields. Currently, there are still drawbacks in the machines (speed, repeatability and size limitations), materials (functional properties) and several business and financial issues. The prosthesis case from the Custom-Fit project shows, however, that these challenges can be overcome. This way, the benefits of geometric customisation through Rapid Manufacturing present themselves in the form of happy patient, doctors and insurance companies alike.

Chapter four: The business aspects of Rapid Manufacturing

Customisation of goods has become common practice in today's world. Customers can personalise the goods they wish to purchase. The fronts and ring tones of mobile phones are a good example of how consumers can customize their goods. Increasingly, customers are unwilling to accept trade-offs and compromises. They will demand products targeted at them directly, and would love to co-design their own, unique products. So far, production technology was what stopped companies to comply to these wishes. Simply put: it was not feasible to serve niches of N=1, both from an economic standpoint as well as a technical one. Where traditional manufacturing techniques aim for customisation of products produced in great volumes, RM allows for unique products and thus per definition for customised products. With Rapid Manufacturing, the technology has become available that is specifically designed to make one-of products in an economically sensible way.

In this chapter, the business aspects of customisation through Rapid Manufacturing will be discussed. The strategic, financial, legal and supply chain impact of switching to a business model of customisation through Rapid Manufacturing will be discussed. With help of actual business cases these implications will be illustrated. The case of dental implants will show how customisation through Rapid Manufacturing can turn the value chain upside down. The case of backpacks will show that business wise, sometimes it is better not to go for customisation through Rapid Manufacturing, even if the application is technically feasible.

Mass customisation, marketing and Rapid Manufacturing

Marketers around the world are discovering that the Internet is rapidly killing mass marketing and mass advertising. Instead, we see customisation of products and personalisation of information taking over as the main marketing trends for the future. Rapid Manufacturing offers companies a tool to respond to this trend in an economically viable way. Distribution of many goods has moved to the internet, where customers can easily search for - and find - that one product that caters to their exact needs. An increasing number of companies have attempted to respond to this trend by mass customisation. But mass customisation is limited to the modular parts of an otherwise standardised (and mass produced) product. Rapid Manufacturing is not: fully customised products are within everybody's reach.

Realising the business potential of Rapid Manufacturing

Rapid Manufacturing has long been considered to be a promising technology with few real life applications other than rapid prototyping. While in its infant stages, it wasn't much more than an R&D tool for large OEM's. Now, reality is proving the broader potential of this technology. And it has a significant impact on business, society, economy, and environment, as new applications are being made possible and technological advancement makes the process more reliable and economic.

Custom-Fit case 6: backpacks

Custom-Fit has shown that Rapid Manufacturing is a feasible production method for customised consumer durables and medical products. But a feasible technology does not necessarily make a good business case. There are strategic, financial, legal and supply chain consequences to consider. In fact, these business issues can be reason to abandon the technology before investing in it. The backpack case from the Custom-Fit project is a good example where customisation through Rapid Manufacturing did not make business sense despite the fact that the technology was feasible.

The customer need and market opportunity

In the Custom-Fit project, a large brand of outdoor equipment had the idea to customise the hip belt of the backpack with help of the Custom-Fit process. This is the vital part of the product that carries most of the weight. In addition, the shoulder padding and straps could be customised for optimal fit and comfort.

The back of a customer would be scanned. The scan would be transferred into a CAD file and a Rapid Manufacturing machine would produce the customised parts. The backpacks themselves are produced in China. This innovation was strategically important to the brand because the producer is the innovation and image leader in its category. Without innovation leadership, it would lose its market position to cheaper alternatives. Also, the strategic goal of entering export markets in the high end segment required innovation leadership. Customising backpacks is a hot item in the market. Some competitors were already offering thermal formable backpacks.

In terms of technology, the first feasibility studies indicated that the scanning, software, material and machine issues in the customisation through Rapid Manufacturing process could be overcome. Still, the project was dropped after an intensive session with management. Business issues were the reason for doing so.

The business issues

In terms of consumer acceptance, the added value of a rapid manufactured backpack was questioned. The added value over alternative solutions like the company's own bio-flex system would be hard to explain to end users and retailers. Second, end users questioned the added value of a Custom-Fit backpack in different weather conditions: what good is a customised shape on top of three layers of thick clothes? Third, end users demanded customisation of aesthetics in any functionally customised backpack: they demanded their own colours and prints. Retailers were reluctant too. They would require real functional proof that customisation will actually reduce fatigue or (shoulder) pain on long hikes. Also, the specialist stores have little space, competences and financial means to support the required scanners, ICT and training of people. Finally, the specialised stores were weary of direct marketing actions by the producers once they would have the consumer's personal and geometric data.

To overcome these issues, a large upfront investment in R&D, training and scanners would be needed by the producer. Although consumers were willing to pay price premiums up to 25% for the customised products, margins would be limited due to these investments. Also, the company's supplier in China was unwilling to cooperate because it would have to adjust its mass production processes and factories to the needs of just one customer. Since product design was not modular, the customised parts could not be easily added in Europe. Even in case it would have been, the supplier had legal objections to the product changes in terms of liability in case of safety issues.

These business issues were enough though to kill customisation through Rapid Manufacturing despite that it was technically feasible. The hassle in the small retail outlets, the objections of the end users, the supply chain issues and financial challenges in the business plan justified this decision.

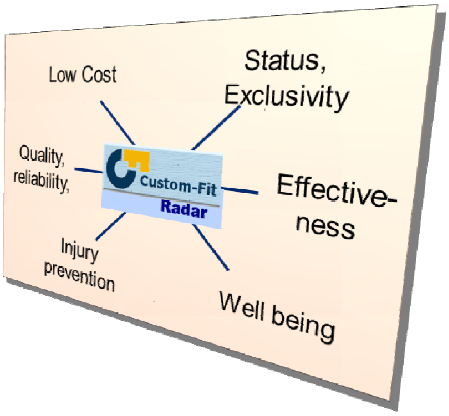
The backpack case shows that companies who embark on the Rapid Manufacturing journey, will have to consider some business issues up-front. These can be strategic, commercial, financial, supply chain and legal issues. These issues will be discussed separately next.

Strategic fit

Offering fully customised products or adding customised parts to a mass produced consumer product can play a pivotal role in the desired competitive positioning and innovation leadership. But as the backpack case shows, organising customisation in the traditional value chain is far from easy. A first condition for success is that customisation fits in the overall strategy of the company, and as such connects with the companies vision and mission statement. Companies that see it as just another feature will fail to provide the endorsement that a true customisation project needs in order to go from idea to market actualisation. As such, having a strategic fit is first and foremost a precondition for making any Rapid Manufacturing customisation project work. As a stand-alone project, customisation through Rapid Manufacturing will always fail.

Commercial fit

Image is key in obtaining commercial gain for mass consumer goods manufacturers. Giving the consumer the sense that a company cares for him as an individual and caters for his unique needs is an important driver of consumer acceptance and customer retention. However, customised parts cannot simply be innovative for the sake of being innovative: without a clear functional benefit, they will have only limited market appeal. Customers do not buy because something is rapid manufactured, they buy because a rapid manufactured products gives him extra benefits. The possible benefits of customised and rapid manufactured products are summarized in the Custom-Fit radar. If the benefit of the new product is not unique, evident and sustainable, Rapid Manufacturing should be reconsidered. Even if it is, a strong brand to endorse the innovation is often needed to achieve market acceptance and price premiums.



A second commercial issue is the cooperation of value chain partners. In consumer durables, retailers are likely to be reluctant to accept the hassle of scanning end-customers in their stores. Alternatives to overcome these issues are scanning in flagship stores, mobile scanners at events and scanning in regional centres. To make customisation a success in consumer goods, retailers must either be aligned fully (with knowledge and financial support) or else eliminated from the process altogether. This would mean that customised products would be marketed directly to the end user or consumer. This would require a significant organisational redesign to facilitate direct marketing and sales.

A final commercial issue is what customisation can do to the brand. Image building and reputation is of strategic importance in most consumer markets. The backpack case showed already that the first thing customers want to customize is the design and colours of their product. As the picture of the 'customised' My-Adidas shoes shows, involving customers as co-designers will have quite an impact on the brand image, design harmony and minimal safety and functionality requirements. It also means a major shift in mentality from engineers and designers. What you do, and how you do it, needs to change in very fundamental ways, as a result from the fact that these activities are shifting towards the consumer. And an even bigger mind shift is needed when not just aesthetics but the product itself (or parts of it) through RM is fully customised by customers.

Financial fit

Customised products offer promising business opportunities. Price premiums up to 30% will be paid by the market, thanks to the unique selling points that customised Rapid Manufacturing offers. Cash flow gains are another financial benefit of Rapid Manufacturing : stocks of mass produced goods can be eliminated and up-front payment is widely accepted for customised goods. Rapid Manufacturing allows for made-to-order products, thus greatly reducing the number of parts on the shelf at any time, as well as the logistic and transport cost of the products. The biggest cash gain comes from the absence of tools. Injection moulding tools are expensive and must be depreciated over large volumes. Not having to buy these tools reduces the risk and capital expenses of a company considerably.

On the flipside, Rapid Manufacturing does require other upfront investments. Before a customised, rapid manufactured product is marketable, solid investments are needed in R&D, market research, scanners, software and Rapid Manufacturing machines. Higher material costs, the cost of training people and the switching costs like terminating old contracts with old suppliers, write offs of old machines and quality costs due to the newness of the products and processes are common (see also chapter 3: cost issues of Rapid Manufacturing). This means that Rapid Manufacturing is not likely to be a financially attractive replacement for all mass injection or compression moulding.

For low volume products or for the customisation of specific parts though, it is highly attractive already. With the cost of machines and materials rapidly eroding, the process is likely to become more economically viable for many applications in the years to come. It remains clear, however, that individual business cases for individual applications will have to determine in what cases switching to a customised and rapid manufactured product makes economic sense.

Supply chain fit

Industrially, insertion of a customised part can be handled as long as the factory is already set up to deal with diversity. If product architecture is modular and flexibility in the final assembly already exists, customised add-ons are not an issue. If brands rely on OEM suppliers and have non-modular products, organising the value chain to cope with customised products is a major hassle. In terms of supply chain management, individualisation of parts requires the set up of a well organised (local) supply chain consisting of geometric data capturing, virtual product design and rapid production. For maintenance, repair, and overhaul (MRO), implications for the supply chain and the business model are paramount. First, as mentioned previously, Rapid Manufacturing could seriously reduce the need for spare part inventory, as well as the need for many different tools. Secondly, third parties could administer software models of parts, making them the new (digital) spare part suppliers. In addition to regular operations, this model may also serve to improve asset utilization, as alternative products may be created when no regular products are needed at a given time. This may mean that the entire supply base of a company might have to change.

Another major supply chain challenge is to educate engineers to think differently. This goes well beyond basic education on Rapid Manufacturing machines, CAD modelling software and material properties. The culture and mindset of engineers has to change. For years, engineers have been trained to deal with the limitations of conventional technologies. Now, with virtually unlimited freedom granted by Rapid Manufacturing, designers will need to be much more imaginative to make full use of the new opportunities. This requires a major mind shift for engineers, management, procurement, sales, mechanics, suppliers, and manufacturers.

Finally, Rapid Manufacturing stipulates a major basic question in relation to supply chain design: who will do what in the value chain? Who does the scanning, who will capture, process and own the data? Who will invest in what and how are the revenues going to be distributed? These questions relate to a very fundamental issue regarding supply chain design and power distribution. As the case 7 of dental implants will show, supply chain design and power distribution can make a major shift when a value chain switches to Rapid Manufacturing.

Legal fit

The Custom-Fit project has identified several legal issues that need to be dealt with when customizing products by means of Rapid Manufacturing. There are a few issues with intellectual property rights (IPR), liability, certification and data ownership / privacy.

With customised products, it is often unclear who owns the IPR on the products and processes. To produce geometrically customised product by means of Rapid Manufacturing takes the patents and licenses of several software, material and machine builders in order to work as a complete package. Complexity is added when the end user is the co-designer of his own product. Business wise, this means that companies who are thinking of such products, need to take into account that most likely a consortium of partners is needed.

In terms of product liability, current legislation is unclear and differs per country. The debate concentrates around safety and injury related accidents where the user might sue the company. In a customised, rapid manufactured product, it is often unclear who is to blame for product failure : was the scan not good enough, was the data processing in the CAD file insufficient, were the material properties not good enough, did the RM machine not properly execute what the computer told it to do or was it that the end user changed the design so radically that liability has shifted from the producer to the end user all together? This shows that legally, customised and rapid manufactured products are more complex and risky than injection moulded products.

Data ownership is another issue. The main debate is over who performs the data capture (i.e. scanning and order intake), and who owns the captured data. The right to the commercial use of these data is the main point of argument between manufacturers and retailers in consumer durables. In the medical field, contemporary legislation on personal data does not allow for the use of medical data (data concerning health) by others than medical professionals. To design and manufacture a Custom-Fit implant, specific patient data need to be shared with others too though. Finally, privacy laws are becoming stricter, which contains the free flow of personal information that is needed to make geometrically customised products with RM machines. Again, European legislation on this topic has not been harmonized and seems not yet up-to-date to the new information flows that are a part of the new realities of customised and rapid manufactured products.

The final legal issue is certification. In Europe, equipment and products are obliged to carry the CE marking before they are allowed to be sold. In the medical field, product release and certification for innovative materials, processes and products is even harder to obtain and can take up to10 years to organize. The current CE marking procedures are unsuitable for customised, rapid manufactured products. For example, in customised motor helmets, seven destructive crash tests are required to get certified. Yet it would not make sense to destroy seven customised helmets in order to sell one. A possible solution may be offered by virtual testing. There are many ways to do this, but one of the more popular methods is by means of a so-called Finite Element Analysis (FEA). In this type of computer aided design, non-linear materials such as polymers, but also linear materials like most metals can be modelled and stress tested without performing destructive tests. When linked with the same software that is used to build the customised products, this can be done fairly efficiently and effectively, and with a high accuracy. Unfortunately, there are no real provisions in EU legislation at the moment that allow for the bypassing of physical testing for the benefit of virtual testing.

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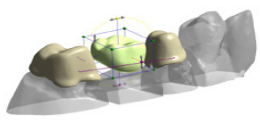
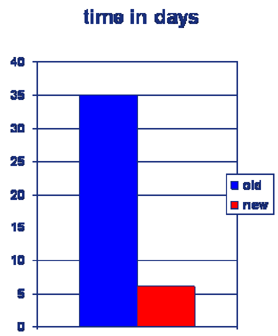
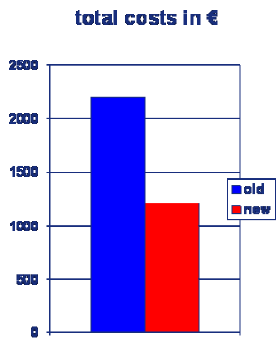
Custom-Fit case 7: dental implants[21]

The strategic, financial, supply chain and legal opportunities and issues when switching to customised, rapid manufactured products, will now be illustrated by the case of dental implants. This case was not actually developed by the Custom-Fit consortium itself, but was studied as a benchmark. It describes how the business model and the value chain can change based on the German market for crowns and caps. This market was revolutionized by the introduction of customisation and Rapid Manufacturing.



Dental implants, like the caps and bridges for crowns, are a €114 billion industry that is characterized by a complex value chain, little customer focus and very expensive, manually customised products. The liberalization of medical markets in Europe, the advance of broadband internet and the centralization of medical ‘production labs’ offer commercial dental centers like Dental Care Lübeck the opportunity to set up high tech centers that integrate the full process of getting a dental implant (from scan to production). They use the latest scanning equipment and software and Rapid Manufacturing machines to produce the caps and bridges. For the end user, the quality, lead time and service is improved in this centre. For insurance companies and national health services, the costs of dental implants declines sharply, from >€2500 to €1300. This development is reshaping the value chain. By treating the customer within a week in an integrated centre or by providing the dentists the possibility to go from wax model to high quality end product faster and cheaper than the traditional way, the very existence of traditional labs is under fire. Over 4000 dental lab workers lost their job in the past years. The business model that was based on Rapid Manufacturing has thus been strategically important for the producers of dental implants. Through direct contact with the end users and elimination of a dominant part of the value chain, they have regained power. The financial gains for the whole chain are also evident.





[21] Courtesy of Dental Lab Lübeck, Germany

Supply chain wise, the new model has drastically re-shifted supply relations, and communication and logistic flows in the chain. Due to issues with software, material limitations of RM machines and increased competition, the new process has been less successful in the past two years, but the way customer's, dentists, insurance companies and manufacturers of bridges and crowns are dealing with dental implants, has changed for good.

Conclusions on the business aspects of Custom-Fit products

The backpack case shows that customisation through Rapid Manufacturing is not for everybody. The dental case shows it can be highly profitable for some. Companies should well consider the business aspects of the technology before investing in it. This chapter has shown that the market potential for Custom-Fit products is large. The Custom-Fit process already brings financial and commercial gains in both the medical and consumer durable sector. In these applications, companies have overcome the strategic, commercial, financial, supply chain and legal barriers. They did so largely by taking these business considerations into account before embarking on the technological development. If the business case adds up, customisation and Rapid Manufacturing is a promising path to a profitable future. To help companies to embark on this exciting journey, the main do's and don'ts below summarize the business lessons learned:

DO:

- Think about the business implications of RM upfront;
- Have an integral view on RM: manage your buy-in in the chain;
- Regard RM as strategic priority. It will fail as an innovation trial or mere status symbol;
- Go for the Total business gain of RM, instead of merely a reduction in tools.

DON'T:

- See RM as the only way forward. Other innovations might provide better solutions to your problem;
- Overestimate the market impact of RM: customers care about what products bring them, not how they are made;
- Isolate scanning, software, machines, materials, and processes from each other in the R&D process

Chapter five: The future of Rapid Manufacturing

Rapid Manufacturing has proven its potential, it is here to stay. In fact, many believe RM to hold the future. In this chapter, a vision of that future will be given. Starting from a historical perspective, the breakthroughs realised in the Custom-Fit project will be highlighted and the foreseen next steps of RM will be disclosed. Also new application areas of RM, where organisations are already working on, will be unveiled. The second part of this chapter will provide a step-by-step approach how to make this future of RM yours. This approach is based on years of experience in the industry. The chapter will finish with an outlook on the not unthinkable (but as yet unrealisable) future of RM.

Rapid Manufacturing: the new industrial revolution

As indicated in previous chapters, the additive manufacturing principle popularised by systems for rapid prototyping has been used since the late 1980s. The most common application has been the fabrication of models and prototypes for form, fit and function. The continuous improvements in processes and materials have laid the foundations for broader use in industrial production.

In recent years, the trend towards customised products coupled with the growing parts complexity and a need for shorter time-to-market have pushed the used beyond the limited area of rapid prototyping to aim at the direct production of end-products. Today, a number of varied applications that have been presented in the cases in this book already hint at the significance of RM as an extraordinary class of manufacturing technologies in consumer markets, medical markets and industrial markets. As the technology improves and organisations embrace it, RM is expected to expand exponentially the coming decades[22].

In fact, the "new industrial revolution in the digital age"[23] has the potential to change the world of physical products and, in line with the Lisbon and Gothenburg objectives mentioned chapter one, will stimulate the evolution of manufacturing in Europe towards a customer-oriented, service-based and largely digital activity. This can improve the competitiveness of European based manufacturing firms versus US and Asian based firms substantially.

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[22] Wohlers reports 2005-2006-2007-2008

[23] Hopkinson, Hague and Dickins, Rapid Manufacturing: An Industrial Revolution for the Digital Age, Wiley & Sons Ltd, Chicester, UK, 2005

Next steps of Rapid Manufacturing

In the Custom-Fit project many of the promises that RM holds have been realised: new proven concepts in machines and software have been achieved. Scanning, product design through CAD and Rapid Manufacturing have been integrated and automated on new and higher levels. In material development, new standards has been set on multi-graded and even bio-degradable materials. But next to technological breakthroughs the project has also contributed tremendously to the adoption of RM in consumer and medical markets, by showing the business potential and technical feasibility in many different applications. In this sense, the Custom-Fit Project has opened the door to a new era of customised and rapid manufactured products. But more is still to come.

Our society and way of living have been shaped in the last centuries by standards and patterns of mass production and RM does not fit those. With developments underway in RM, it is however expected that in the coming decades many industries will discover the benefits of RM and in parallel, many of the current disadvantages of RM will be overcome. RM will so enable a transition from mass production to an individualised, need-oriented and eco-efficient manufacturing process of the future. Current RM technologies will improve manufacturing capabilities, sizes, reliability/repeatability and speed rapidly in the coming years, to deliver on that promise. Next to these continuous improvements to current type of RM machines, new machines will be introduced that can handle multiple materials and/or allow for multi-graded prints. Even RM machines that will be able to manufacture biological products, such as bio-degradable implants, are already in research. Unlike the improvement of current RM machines, the introduction of new RM machines will depend heavily on the availability of the appropriate materials. In the coming years a vast array of improved and new polymers, ceramics, composites, metal powders, hybrid materials and biodegradable materials will become available. However these developers of completely new materials depend on the availability of RM machines that can handle them. This chicken-and-egg dilemma might hold back developments.

Another trend is design software and 3D-modelling software becoming more widespread with the introduction of low level, (almost) free to use software for consumers and business alike. Also design and scanning will become more and more interlinked, resulting in new features, like webcam interfaces. In the long run, there will be less and less limitations to designs as most software will have multiple optimization tools to enable nearly absolute freeform design.

As more and more companies will start using RM, costs of RM-machines will drop further. Especially the operating costs (i.e. cost of material, service etc.) will significantly decrease. At the same time, learning effects will occur with organisations implementing RM. It will be easier for them to have staff trained as more courses become available or to find business partners that already understand RM. A bit further away will be the adoption of RM as a (new) mainstream manufacturing method. The promised benefits of RM will then become fully apparent, including zero waste, stockless and/or sustainable manufacturing. As illustrated in the dental implant case in chapter four, supply chains will be overhauled and on-demand, on-site manufacturing will become an alternative to mass production plants. RM enables new supply chain setups where manufacturing is closer (again) to consumption.

Think about remote areas in the World or developing regions, where with RM it will be possible to beam in data through cellular or satellite technology, and then build it right there, rather than trying to transport products from around the world. No matter where in the world, consumers will also be able to co-create products fully customised to their own specific wishes and needs, so introducing all kinds of RM products. According to RM-expert Terry Wohlers: “All you need is an Internet connection, a machine, and a fair amount between the ears”.[24]

[24] www.rapidtoday.com, interview with Terry Wohlers, September 2008

New routes and application areas for Rapid Manufacturing : the short term

In the coming years more and more industries will adopt RM as a manufacturing technology. Also industries that do not automatically address niche markets for highly customised products with small production runs. RM will be introduced as a manufacturing technology that holds great potential and will firstly be used to reduce tooling or even used to produce tools more efficiently. Next (or parallel) step in the adoption of RM will be the use of RM for small series of 'premium' or special products or product parts. Organisations should actively seek these 'safe places' to get acquainted with RM. Only then will the technology get more widely spread. Next to the cases mentioned throughout this book, we foresee RM being (more widely) adopted in many industries in the coming years:

Possible next application areas for RM:

- Automotive: seats, limited edition cars, manufacturing tools, all aesthetic and/or mechanical (spare) parts including (driver adapted) interiors, functional test products, mechanical devices, aerodynamic parts, engine parts;
- Aerospace: seats, helmets, (customised) pilot equipment, manufacturing tools, all aesthetic and/or mechanical (spare) parts including cabin interior, air ducts, functional test products, mechanical devices, aerodynamic parts, engine parts and other parts
- Medical: (customised) scaffolds, body models, bioactive bone, skin tissue, (customised) surgical tools, lab-on-chip, orthopaedics;
- High-end equipment: tools, grips, turbines, machine parts, energy appliances, electronics, packaging, complex clamping devices, contoured cutting tools, batteries / fuel cells, sensors, actuators, all (other) complex and high performance parts;
- Construction and Architecture: scale models (maquettes), bricks, tools and (hand) equipment, body protection gear, hearing protection, (construction) helmets;
- Furniture: chairs, stools, tables, cupboards, computer mouse;
- Household appliances: lamps, vases, jugs, art (sculptures);
- Military: equipment packs, body protection vests, helmets, backpacks, gas masks, gear, hearing protection;
- Fashion: (sun-)glasses and lenses, mobile phones and devices, caps/hats, braziers, (under-)garment, shoes / (ski-)boots, jewellery, watches;

- Sports: shoes, (shin or mouth) guards, masks, grips, helmets;
- Toys: cars, bikes, puzzles, avatars.

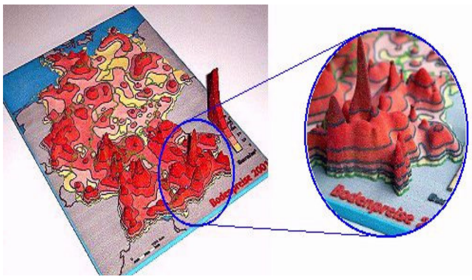
Six main routes can be foreseen how RM is likely to develop. These are linked to certain application areas where RM is likely to develop into a key technology first:

1. The first is the entry of RM as 'mainstream' technology in industries that already experiment with RM such as the Aerospace, Automotive, Medical and Manufacturing industries with high-end equipment. A good example are the customised headlights that Materialise made to make an already exclusive car even more exclusive. Especially in Formule1 race cars, many components and parts are actually already built with RM.

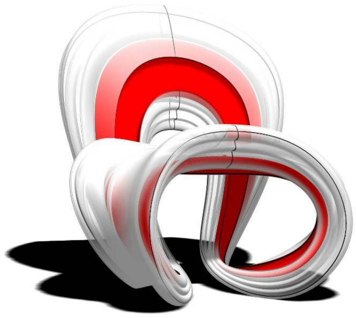
2. The second route is driven by RM enabling 3D modelling[25]. This will be in any industry that uses models as key element in its value chain, such as the construction industry. The more complex the architectural design or the more complex the topographic model, the more difficult and expensive it will be to make a good model to scale. With RM it becomes possible to make these models and maquettes cheaper and easier. In the coming years, better and cheaper RM machines, combined with increasingly CAD-savvy architects, will lead to more and more 3D-printed scale concept models. Other typical application for topographic models includes terrain, urban and sub-surface maps. Geographic or demographic data can be combined with a physical model to create new levels of understanding of certain areas, as the picture of the wealth distribution in Germany shows.

[25] Courtesy of the Bundesamt für Bauwesen und Raumordnung, Bonn, Germany

3. For universities, the military, the oil and gas industries, urban planners and landscape architects, such 3D maps have significant added value. They will also make a great gift for the local inhabitants.



4. The third route is driven by RM enabling products being made directly from computer aided designs. This will be in any industry that designers can have big impact on, such as furniture, household appliances and fashion. RM allows for furniture with (geometrically) designs impossible for traditional manufacturing. At University College London, the Osteon chair has been made by dr Siavash Mahdavi and Assa Ashuash. The chair is designed with precise mechanical characteristics, including lightness, extra strength in areas that are under greatest stress, and minimum material usage. On top of that, the design itself is also geometrically complex: it appears to be seamless. In the past, such a structure would have been impossible to build. With 3D-printing, the virtual design could be realised, resulting in an unique chair with optimum strength whilst remaining visual aesthetic and artistic flair "[26]



[26] www.eos.info and www.assaashuach.com

5. The fourth route will be driven by health, safety and environmental issues. In the field of medical equipment this especially is of value, as customisation will improve the comfort and safety of the user and could optimise the health benefits offered (for example by improved blood circulation). Already wheel chair manufacturers, but also manufacturers of other chairs that people sit on for long periods (like office chairs or truck driver seats) are investigating customised seating. It appears that the process of (body-) scanning and designing geometrically shaped chairs already offers great value. RM is the technology that links these possibilities with manufacturing methods that allow economic viable realisation of these individual designs.

6. The fifth route for RM will be in industries that allow consumers to co-create virtual shapes. Consumers will want their own designs realised and so create demand for a technology that can deliver all that. As generations have grown up with dolls as Mattel's Barbie to be dressed the way you like and construction kits as Lego or Meccano, allowing you to built any object you like, next generations will grow up with their own customised 3D toys made with RM. Already the entertainment business has started using RM to create unique, fully customised action figures, dolls and collectible plaster figurines of any movie character, character from your favourite video games or avatar. Since 2006 'printed' avatars are commercially available: tangible versions of the digital persona created by the consumer in a virtual world or videogame. Already tens of thousands customised dolls and statues, being exact replica's of online figurines, have been produced with RM[27]. With the popularity of online worlds and video games increasing ever more, and entertainment studios actively teaming up with toy manufacturers, we might not even have seen the tip of the iceberg for this application area yet.

[27] Courtesy of FigurePrints.com

The future is yours….but how to get there

RM is said to hold the future and with many developments underway, a lot of organisations are already investigating what RM holds for them. As was indicated in chapter three and four, RM is not plug-and-play (yet) and multiple technical and business barriers must be overcome before you can make a profitable business. But RM could also be your promise for the future. Based on many years of experience in RM, a five-step approach can help to first asses and then realise the potential of RM for your organisation:

Step 1	Step 2	Step 3	Step 4	Step 5
scoping	as is situation	feasibility	business case	implementation

Step 1 Scoping. To start with, a clear definition of the scope of the desired RM application is needed. What is the ambition that should be realised with RM? Clear targets and success criteria are needed upfront. The business scope should also be clear : for what part of the business (products, customers, supply chains) does RM apply? Already in this stage, RM should be weighed against other alternative technologies and solutions. When a clear picture exists of why and where RM is to be introduced, a detailed project plan can be made.

Step 2 Current Situation. In this step, market research will identify customer demand give insight in the RM potential in terms of market capitalization. The current product design (modularity, fully customised or partly customised?) and the current supply chain and production set-up should be analysed for RM-ability. The legal, commercial and financial business barriers discussed in chapter four should also be analysed here. Combined with a forecast on competitive response, these analyses will result in a more clear outline of what RM can do for you.

Step 3 Feasibility Study. The third step is to investigate whether RM can actually deliver on the ambition that has been stated in step 1. This requires a technical feasibility study into the physical principles and a function versus process check. Also study should be made into additional equipment and/or software needed and their compatibility with current tools and processes.

Step 4 Business Case. The business case includes the expected gain over current operations RM will bring and the investments needed to achieve them. It should include the proposed supply chain setup, the proposed business processes, the marketing proposition and the financial implications of the plan. This step will give conclusions on the commercial feasibility of the RM solution.

Step 5 Implementation. This plan should provide the development path for the company towards the adoption of RM. It should include milestones, timelines, detailed planning, clarity on roles and responsibilities and action plans towards the introduction of RM. Also change management should be organised to facilitate the transition from current operations to RM including the necessary paradigm shifts as all employees should stop thinking in terms of products and volumes and start thinking about personal customer service and individually required product functionalities.

Future visions for Rapid Manufacturing : the long term

The coming years we will see RM become more and more widespread adopted in many different industries. Real enthusiasts even believe that RM will spread to the home, lending new meaning to the term "cottage industry". 3-dimensional home printers may seem far-fetched, but the same could have been said for colour laser printing just twenty years ago. Already machines of less than 1000 USD have been announced[28]. Although the performance of these desktop machined is far from perfect (low availability of materials, low ability for colouring, low dimensional accuracy, size and speed limitations), the introduction of a 3D printer at home would truly democratise innovation and manufacturing.

Theoretically, you can even go one step further then having a 3D printer in every home. In theory, an RM-machine can produce an RM-machine. This theory has already been put into practices at universities in 2005[29]. Both in the UK and the USA, simple open-source build-it-yourself systems have been invented with the stated goal to be able to build a replica of itself. The machines do work, but are not yet able to meet their stated goals. It will take some more years of research and invention, but already much of the literature discusses the potential of these systems[30].

[28] Desktop Factory announcement on www.rapidtoday.com in February 2008

[29] E.g. RepRap started in 2005 at the University of Bath in the UK and Fab@Home started in 2006 at Cornell University in the USA.

[30] E.g. Bright Magazine, 3D printen kan je (bijna) zelf (in Dutch: 3D printing do it yourself), april 2008

Other future visions of RM can be imagined when thinking of the technological nature of RM. By adding layers a product is built. This process enables the use of different materials per layer or even the use of different material particles in one layer. RM thus allows for the inclusion of tiny parts, having the size of a only few particles, in a product that is being manufactured. These tiny parts are already developed in the very exciting, rapidly growing field of nanotechnology. Generally nanotechnology deals with structures 100 nano meters or smaller - hence the name - and involves developing materials or devices within that size. Already nanotechnology is finding applications in numerous consumer products, ranging from sunscreen and cosmetics to sporting goods and food. In the future, products made with RM can include nano technological applications, like RFID chips of only a few nano meters small. This offers enormous advantages to new product development teams. The combination of RM technologies with nano technological applications will eventually lead to another paradigm shift in the future as all products - even the smallest - can be manufactured in one run and will be fully-inclusive of all functionalities and parts.

The same (theoretical) principle can be applied on large(r) scales than with nanotechnology. Combining materials can complete change the characteristics contemporary building and construction industries[31]. One could for example manufacture a (cubical) wall[32] including all the electric and ICT wiring out of one piece. At MicroTEC, parts with integrated RFID chips are already being rapid manufactured in substantial numbers.

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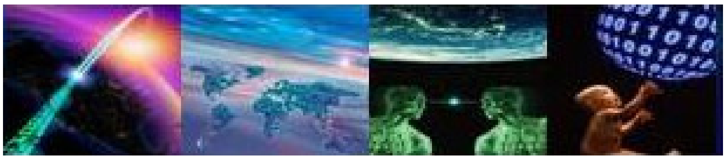
[31] Gideon N. Levy, Ralf Schindel, J.P. Kruth; 2003; "Rapid Manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives"; Annual of the CIRP Vol 52/2/2003

[32] 'Migrating Formations' by Contemporary Architecture Practise, commissioned to Home Delivery: Fabrication of the modern dwelling, Exhibition in Museum of Modern Art, New York, 2008.

A great future vision for RM is in the medical field, especially in the printing and growing of living tissue. There is a lot of work going on at universities and hospitals all over the world in this area. The same technological principle of additive production as with RM is used. Only this time there is no polymer powder or metal involved, but living cells. Already in 2003 public newspapers picked up the work of biophysicist Gabor Forgacs, who has developed a ‘printer’ (a ‘mechanical dispenser’) that drops cells in a controlled manner on a nutritious gel. He so could build muscle tissue. In 2008 the company Genentech surprised the world with their successful regeneration of an organ from stem cells (with mice). It might sound like science fiction, but growing bladders, kidneys, livers, skin tissue, brains, mammary glands, gastrointestinal tracts, and so on are really not as far off as one might think. In 2006 the University of Michigan already successfully produced customised, rapid manufactured heart valves. The odd of the human body rejecting the printed body part reduces almost to zero because both the material and the shape of the new organs are taken from the patient himself. This is not only a very exciting development in medicine but also holds a very exciting future for RM.



Chapter six: Summary and conclusions

This book has aimed to give a general introduction of geometric customisation of rapid manufactured goods. With the Custom-Fit project as the main inspiration, the basic principles regarding the technology and business aspects of this exciting new development have been laid down. In chapter one, the development of the technology from rapid prototyping to Rapid Manufacturing was presented. Given its unlimited potential, this development is hailed by experts as the new industrial revolution for the digital age. Based on the cases of customised and rapid manufactured skull implants and seats for disabled children on toy cars, the cost saving and quality of life enhancing capabilities of the new process was illustrated. The achievements of the Custom-Fit consortium have opened the door for geometrically customised, rapid manufactured goods in many other areas as well.

In order to make customised, rapid manufactured goods, state of the art scanning, software, machines and materials are needed. Custom-Fit has created a deeper understanding and improved versions of all these aspects. In chapter two, contact probes, lasers and medical scanners such as MRI and CT were introduced as appropriate scanning technologies. It was made clear that software plays an essential role in transferring scan data into CAD files, in simulation and modelling of the product design and in controlling RM machine processes. Stereo Lithography (SL), selective laser sintering (LS), fused deposition moulding (FDM) and 3D printing were presented as the main ways in which RM machines are able to transfer digital CAD files into 3D physical objects. In terms of materials, polymers and metals are commonly used, but exciting new developments in ceramics, functionally graded and biodegradable materials are on their way. The case of jaw implants shows how titanium implants are now being customised and rapid manufactured to the delight of the patients, the surgeons and the insurance companies.

These technologies have different advantages in different application fields. Table 1 presents the basic cost saving and value enhancing opportunities of Rapid Manufacturing.

Table 1 : basic opportunities of Rapid Manufacturing

	Cost saving	Value adding
Mass production	On demand, on location	Customisation Environmental gains
Small batches / one-of	Process economies	Engineering the impossible

As the table shows, cost saving can be achieved by on demand, on location printing of for example spare parts. For products that are already customised by hand, Rapid Manufacturing can bring significant cost gains through process efficiencies in the entire value chain. Also on the revenue side, Rapid Manufacturing has proven its potential. Through customisation, unique products can be created for which consumer are willing to pay price premiums. Also, the technology can be an environmentally friendly way of producing goods that normally would involve huge amount of energy and waste. The freedom of shape enables companies to engineer the impossible and artist to create unique pieces of art and furniture that are often co-created by the end user.

Despite good progress made in the Custom-Fit project, there are also still some challenges to rapid manufactured products:

Factor	challenge
Machines	• process speed • size limitations • repeatability
Materials	• functional properties • support material removal
Costs	• material costs • machine costs

The RM machines are quite slow and are limited in the sizes and colours they can print. Development of materials is on the fast track, but functional properties and the removal of support material remains an issue for now. The materials and machines can be quite costly, although these costs are dropping rapidly. Due to these issues, Rapid Manufacturing is not yet ‘plug and play’. The Custom-Fit project has made good progress on these issues though, and it is expected that within short, Rapid Manufacturing will be able to meet the market requirements of many different sectors. The Custom-Fit case where a customised, rapid manufactured socket for a leg prosthesis was created, shows how these obstacles can be overcome if a motivated and knowledgeable team put its mind to it.

Customisation through Rapid Manufacturing is a promising business opportunity, but not for all companies. As the backpack case in chapter four shows, strategic, legal, financial, supply chain and commercial business issues must be thought of in advance in order to make profitable business out of a promising technology. For example, IPR, liability, data ownership and certification issues might present legal barriers to market success. If support of the partners in the value chain like retailers and approval boards can be gained, customisation through Rapid Manufacturing will benefit the brand as well as the company’s bottom line. As the case of the dental caps and crowns shows, customisation through Rapid Manufacturing can turn a complete supply chain upside down and can bring great benefits to companies that embrace the new business models that the new technology enables. This requires upfront business planning, full dedication and a shift in mindset though.

Finally, the short term and long term outlook was discussed in chapter five. In the short run, with dropping costs and enhancements in materials and machines, Rapid Manufacturing will become a wide spread phenomena. It is becoming a mainstream technology in the aerospace and automotive industry. It is allowing new and customised 3D models for architects. It is giving total design freedom to furniture designers and is allowing gamers to get 3D physical prints of their virtual avatars.

In the long run, 3D printers will find their way into people's homes. Multi-materials and the incorporation of nanotechnology in rapid manufactured goods will revolutionize the manufacturing industry. Surgeons will be able to print customised, rapid manufactured implants from biodegradable materials.

The future of customised, rapid manufactured goods is unlimited and full of potential. The Custom-Fit project has brought the world a great leap forward into this exciting future!

Custom-Fit

Annex 1: Partners of the Custom-Fit Project

Custom-Fit

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This book is an easy 'accessible' introduction to the design, manufacturing and business opportunities of customized products based upon the outcomes of the Custom-Fit project.

Custom-Fit is an industry-led Integrated Project coordinated by Delcam (UK) and originally initiated by the Rapid Manufacturing Group at Loughborough University (UK) and TNO Science and Industry (NL).

The project outcomes have led to new possibilities for high-added-value manufacturing in Europe beyond the life time of the Custom-Fit project.

The results have established a new state of the art in this exciting area of technology and will be the basis for future R&D and innovations.

Christophe Lesniak (Project Officer EC, DG-Research)

Custom-Fit has fostered the European cohesion in the field of science and technology for RM and RP processes, thus leading towards a real and sustainable European initiative.

Prof. Ulrich Berger (Project Reviewer, Brandenburg Univ. of Techn.)